# SWEPT FREQUENCY ACOUSTIC TIME DOMAIN REFLECTION MEASUREMENTS OF LGT

by

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# ABSTRACT

An inverse Fourier transform of frequency domain $S_{11}$ reflection measurements obtained from precisely cut cube shaped piezoelectric materials produces highly accurate time domain reflection data with the aid of mathematics and processing. A completely automated system has been developed to produce time domain reflection measurements over a temperature range of almost 200°C. The target of the process is the analysis and extraction of elastic constants of new man made piezoelectric materials such as langasite (LGS) and langatite (LGT), with the proof of concept based on the analysis of quartz, a piezoelectric material with well-known physical constants, and the mathematical simulation of the measurement system.

# ACKNOWLEDGMENTS

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# CHAPTER 1

# INTRODUCTION

Traditionally, velocity measurements in solids have been made using time-based pulse-echo techniques [1,2,3,4,5]. These techniques used a short, wide-band pulse, or a gated RF CW signal, to excite a transducer and create an acoustic wave in a solid. The reflected waves are then measured and recorded in real time. These measurement methods have limitations due to the required time-base accuracy and have typically been accomplished by labor intensive manual measurements. Calibration of time delay of the experimental setup is often difficult and needs great care. Dynamic range and signal to noise is limited due to the finite input pulse length.

Currently, new technology offers a potentially better method of analyzing time domain reflection data by acquiring data in the frequency domain and using Fourier transform and other more advanced signal processing techniques to obtain the time domain data. Hewlett Packard network analyzers allow for the easy extraction of S-parameter data using radio frequencies. Measuring $S_{11}$, the reflected energy in the frequency domain, of a piezoelectric transducer mounted to a cube of test material allows for highly accurate acoustical information to be obtained on the material. The network analyzer allows for calibration to the point of the measurement pins, so the measured data

is a representation of the transducer/cube system only, and not additional circuit parameters introduced by measurement electronics or connection wires.

It will be shown how measured velocities are only limited in accuracy by the accuracy with which the dimensions of our cubes of test material can be obtained, and by the interpretations of time domain pulse shapes and phase changes.

This thesis is a proof of the validity of the approach to time domain echo analysis by using swept frequency measurements and then signal processing to obtain time domain data. A mathematical model will be used. Experimental data on the well-known properties of quartz will be presented and compared to industry standard data. Time domain data from experiment and simulation will be presented and analyzed.

New piezoelectric materials offer increased Q and higher coupling coefficients over quartz, and are currently a popular research topic with the surface acoustic wave and bulk acoustic wave communities. The simulation presented is a tool to assist in the characterization of these new materials.

# CHAPTER 2

# PHYSICAL AND MATHEMATICAL CONCEPTS

## Physical Concepts

Complete characterization of a piezoelectric material requires the extraction of the elastic constants, piezoelectric constants, and the dielectric constants. These constants are functions of temperature and piezoelectric crystal orientation. Acoustic velocity measurements over the X, Y, Z, and a 45° axis allow for extraction of 6 elastic constants, $c_{11}$, $c_{13}$, $c_{14}$, $c_{44}$, $c_{33}$, $c_{66}$, . These constants can then be used to derive the remaining two elastic constants [6].

Acoustic velocities are necessary to extract elastic constants. The equations relating elastic constants to the acoustic velocity of a piezoelectric material, are given in Auld [6]. Acoustic velocities are obtained from the material by measuring the time it takes for an acoustic wave to traverse a known distance.

It will be shown how measured velocities are only limited in accuracy by the accuracy with which the dimensions of our cubes of test material can be obtained, and by the interpretations of time domain pulse shapes and phase changes. This measurement technique is efficient and accurate over any frequency range of interest, and can be fully automated using computer control and network analyzers.

Reflection time is determined by analyzing pulses in the time domain. *Table 1* shows possible inaccuracies due to physical measurements of the 1 cm cubes used in the experiment, as well as velocity errors that could result from quantization.

Measurement Errors

| Measurement Error | Total Cube Round Trip Distance | Round Trip Time Measured | Measured Velocity | Velocity Error | % Error |
|---|---|---|---|---|---|
| 0 um | 2.0000 cm | 4.0000 us | 5000.0 m/sec | 0.0 m/sec | 0.000 % |
| 50 um | 2.0100 cm | 4.0000 us | 5025.0 m/sec | 25.0 m/sec | 0.500 % |
| 10 um | 2.0020 cm | 4.0000 us | 5005.0 m/sec | 5.0 m/sec | 0.100 % |
| 5 um | 2.0010 cm | 4.0000 us | 5002.5 m/sec | 2.5 m/sec | 0.050 % |
| 1 um | 2.0002 cm | 4.0000 us | 5000.5 m/sec | 0.5 m/sec | 0.010 % |
| 2.7 ns | 2.0000 cm | 4.0027 us | 4996.6 m/sec | 3.4 m/sec | 0.068 % |
| 1.36 ns | 2.0000 cm | 4.0014 us | 4998.3 m/sec | 1.7 m/sec | 0.034 % |

*Table 1: Possible inaccuracies in velocity results from physical measurement limitations.*

## Mathematical Concepts

Frequency data produced by a piezoelectric transducer mounted to a piezoelectric cube has finite bandwidth. A finite bandwidth implies that there is no frequency information of interest out of band. This fact allows for the padding of 0dB data points to

an $S_{11}$ frequency data file for the purpose of increasing time domain resolution after a Fourier transform is executed. Time resolution is limited by *Equation 1* when performing an inverse Fourier Transform.

$$\Delta t = \frac{1}{bandwidth} \tag{1}$$

It is easy to see that resolutions on the order of nanoseconds can be obtained by creating a signal bandwidth on the order of hundreds of megahertz. *Table 2* shows specific examples of time domain accuracy obtainable in the experiment.

Zero Padding Accuracies

| # of Points | Bandwidth | Time Resolution 1/BW | Equivalent Velocity Resolution | Equivalent Length Resolution | % Error |
|---|---|---|---|---|---|
| 1601 | 18 MHz | 55.5 ns | 34 m/sec | 277.5 um | 0.680 % |
| 2^15 | 368.63 MHz | 2.71 ns | 1.7 m/sec | 13.6 um | 0.034 % |
| 2^16 | 737.27 MHz | 1.36 ns | 0.8 m/sec | 6.8 um | 0.016 % |
| 2^17 | 1.475 GHz | 0.68 ns | 0.4 m/sec | 3.4 um | 0.008 % |
| 2^18 | 2.95 GHz | 0.34 ns | 0.2 m/sec | 1.7 um | 0.004 % |
| 2^19 | 5.9 GHz | 0.17 ns | 0.1 m/sec | 0.85 um | 0.002 % |

*Table 2: Examples of time domain accuracy obtained by padding zeros in frequency domain.*

For a transducer/cube combination, the $S_{11}$ frequency data contains information from the acoustical and electrical properties of the devices. By smoothing the $S_{11}$ frequency, it is possible to remove the electrical effects of the devices under test and leave only the acoustic effects. The smoothed curve averages the existing $S_{11}$ frequency data and the result is a frequency response that approximates a transducer attached to a cube of infinite size (no acoustic reflection). Both data files are inverse Fourier transformed to the time domain, and the smoothed transformed function is then subtracted from the now transformed $S_{11}$ data file in time to produce a time domain plot of the acoustic only frequency response. This resultant time domain data is less noisy and easier to analyze, as will be shown later.

# CHAPTER 3

# EXPERIMENTAL MEASURING DEVICES

## Transducer

The transducers used for this experiment were manufactured by Valpey Fisher. These transducers were 5 millimeter diameter coax style chrome gold plated Lithium Niobate overtone polished piezoelectric transducers. The center portion of the transducer measured 3.3 millimeters.

Both shear and longitudinal mode transducers were used. 36° Y-cut Lithium Niobate was used for the longitudinal mode data, and 41° X-cut Lithium Niobate was used for the transverse mode data.

## Transducer Mounting

Transducer mounting was a very difficult and important issue in this research project. Finding a very thin bonding material that would survive a 200°C temperature range took many weeks of testing, and in the end only partial success was achieved.

Photoresist, a readily available liquid used in microelectronics manufacture, was the first bonding candidate, and ultimately the best. The heat-hardening (curing) properties of this material, susceptibility to solvents, and the ability to spin the material down to a sub-micron thickness made it an exceptionally attractive possibility.

Other materials were tried in addition to photoresist. Common Krazy Glue was tried, but fractured the cube internally during the heating/hardening process, most likely due to the different thermal expansion properties of the transducer and cube. Good room temperature results could be obtained with Krazy Glue, if the initial heating/hardening process was eliminated.

Automotive gasket sealer was also used in several experiments. The gasket sealer worked well as a couplant, but fell short in two respects. The coupling generally failed below a minus 30°C, and the consistency of the material was such that it could not be spun down to sub-micron thickness.

Various other epoxies were tried but did not perform as well as photoresist. Four different types of photoresist were experimented with. HNR-120 works over the largest temperature range and was our bonding material of choice. Transducers are easily removed in a heated bath of xylene after several hours of soaking.

Transducers were mounted by first cleaning both the cube surface and the transducer with acetone and methanol. A special fixture was made to hold the cube as it was placed in a spinner. Two drops of photoresist were place on the cube which was then spun at 6000 rpm for 30 seconds. A mounting plate was then placed on top of the cube. This plate has a hole just slightly larger than the transducer, and allows for transducer centering on the cube.

After removing the plate, the transducer/cube combination is placed in a spring loaded compressional device, displayed in *Figure 1*. Pressure is applied to the transducer with this apparatus, and the entire device was placed in an oven for 30 minutes or more at 150°C. After the baking process, the transducer mounting is complete.

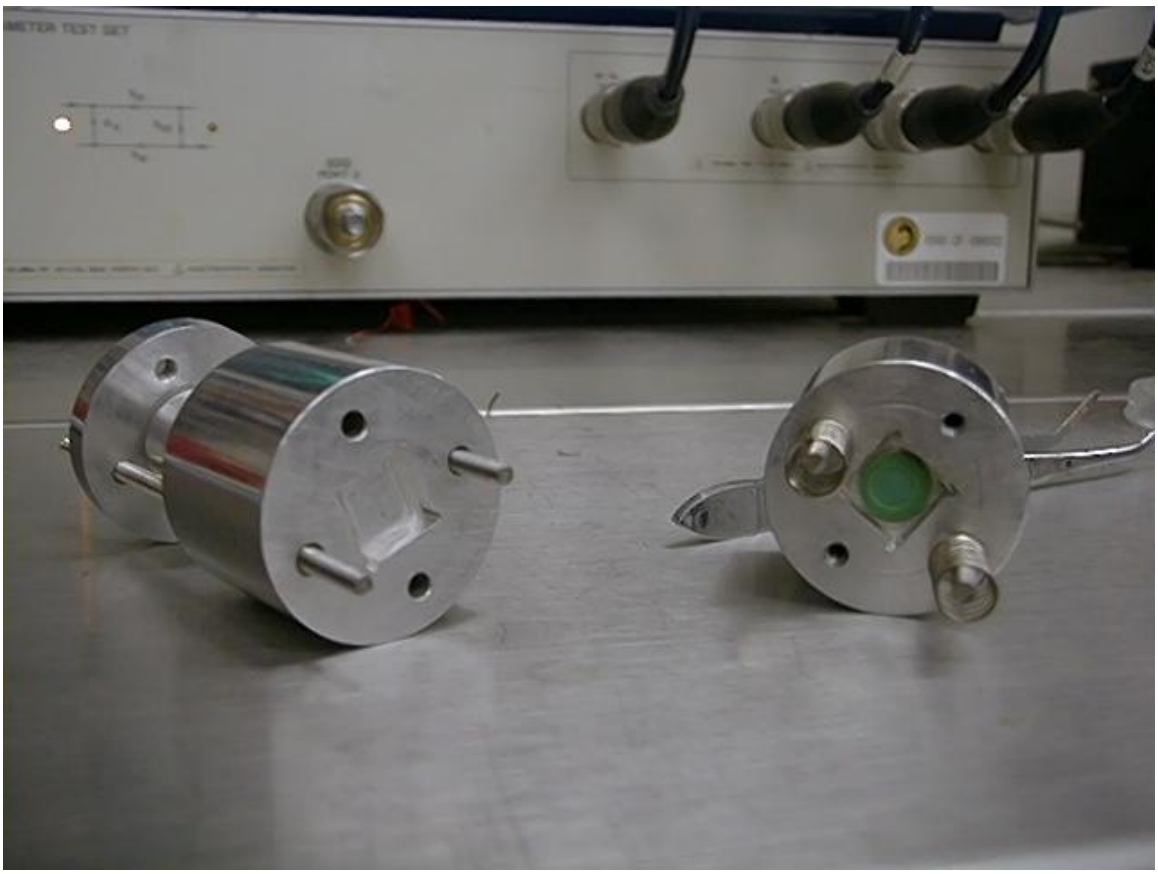


*Figure 1: Picture of transducer mounting compressional device.*

## Measurement Apparatus

A fixture with high thermal conductivity and thermal mass was designed and manufactured to hold the transducer/cube during measurement over temperature. This fixture was constructed from a solid copper cylinder. Two piece construction allowed for the insertion of transducer/cube material into a cube-shaped chamber. Holes were drilled to hold Omega 25W cartridge heaters. Another hole was drilled to facilitate the addition of a semi-rigid piece of coax with pogo pins mounted on one end and a female SMA connector on the other, to make contact with the transducer. A final wire for the T-style thermocouple was inserted to complete the setup, as shown in *Figure 2*.

The thermal housing was inserted into a heat tolerant foam, which was then placed on top of a liquid nitrogen dewar with a small amount of liquid nitrogen in the bottom. After cooling the housing by direct submersion into liquid nitrogen, the above setup was then used to gradually heat the housing and transducer/cube over temperature.

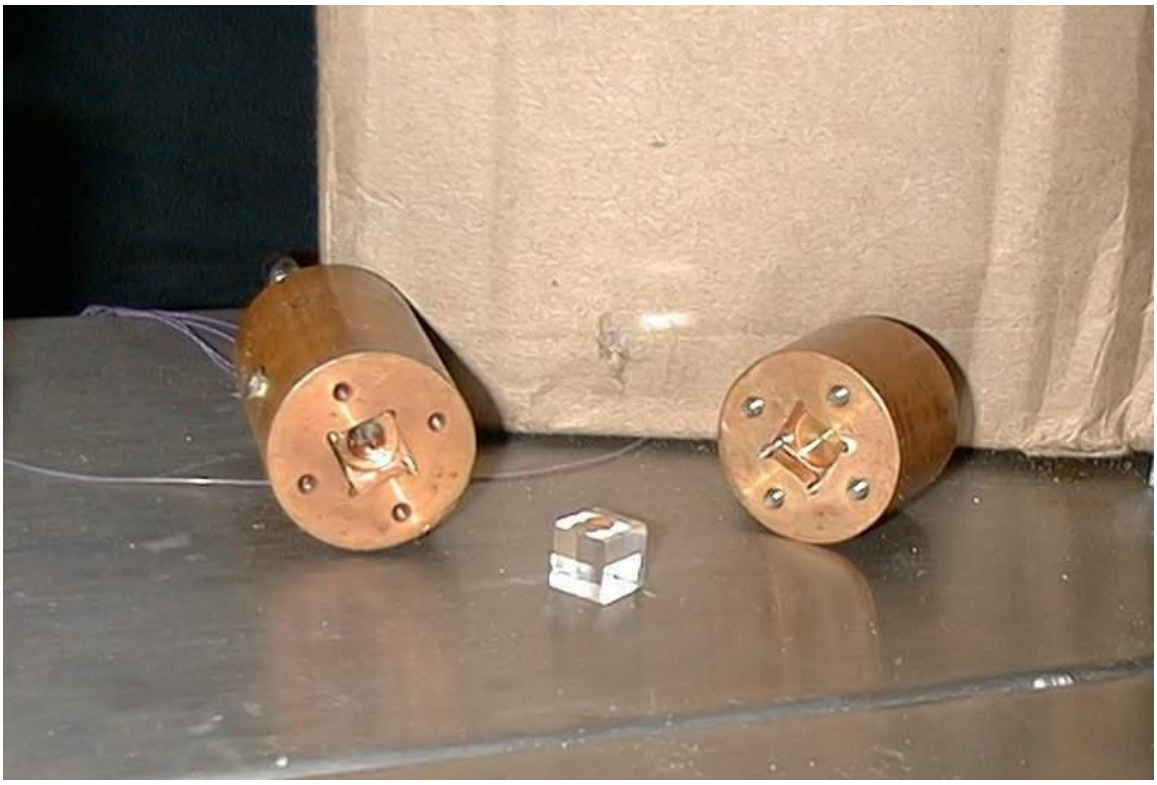


*Figure 2: Picture of copper housing used to hold cube during measurement process.*

## Measurement Tools

Measurement hardware consisted of a Hewlett Packard 8753B network analyzer, Yokogawa UP-550-01 temperature controller with T-style thermocouple, and a 400MHz desktop personal computer with a Windows 95 operating system. *Figure 3* shows the complete data taking setup. The computer used a National Instruments GPIB-AT card to interface the GPIB bus of the network analyzer. The Yokogawa controller interfaced the computer via a serial port.

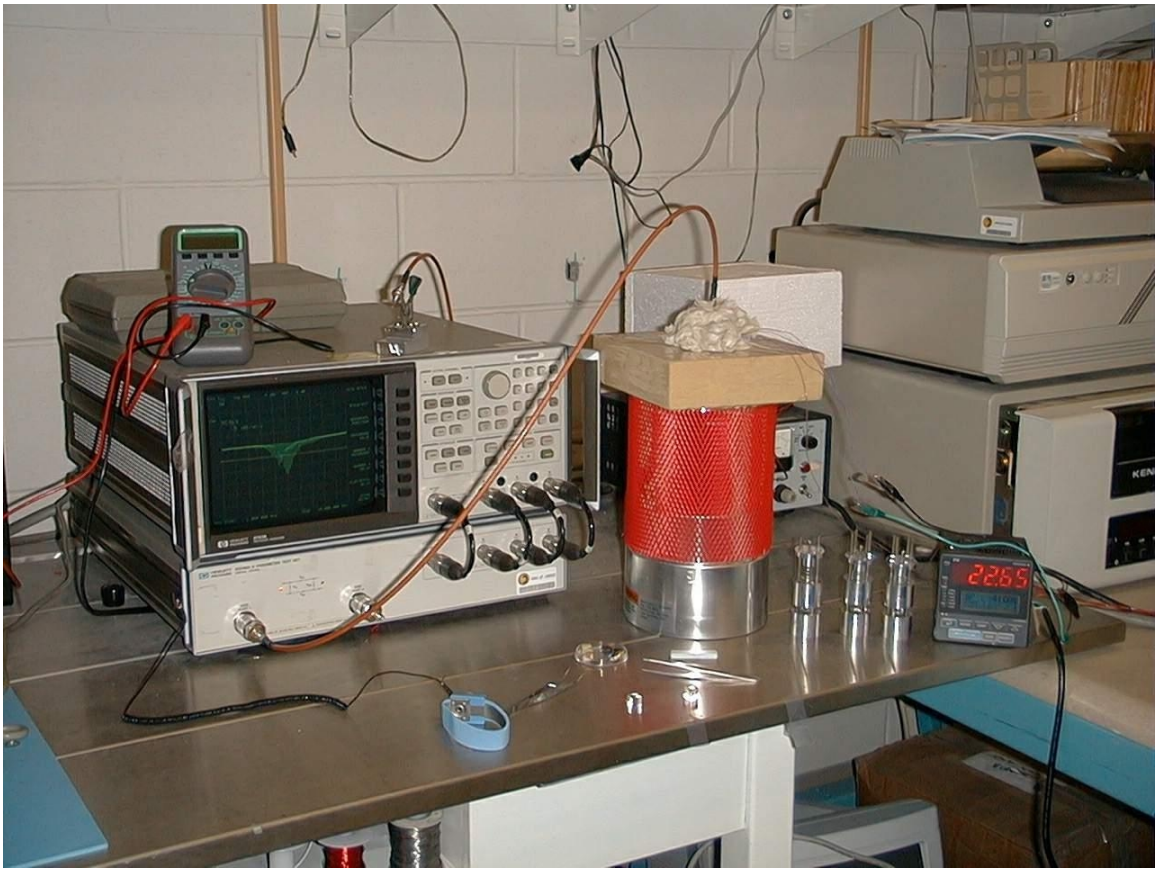


*Figure 3: Picture of complete data taking setup.*

Measurement software consisted of National Instruments LabWindows/CVI version 5.0, and Yokogawa's own programming software for the UP series controllers. National Instruments furnishes a template for controlling the network analyzer on their website, but this code required substantial modification to take calibrated data across the bus, take automated measurements over a temperature range, and concurrently monitor the temperature output of the Yokogawa controller on the serial port of the PC. The code is included in *Appendix A*.

The Yokogawa controller used its own processing abilities to ramp temperature at 5°C increments with a five minute ramp time and a three minute soak time, starting at minus 50°C and ending at positive 150°C. The Yokogawa programming software provides a graphical interface for setting the control parameters and temperature profiles in the controller. The LabWindows program was only used to monitor temperature output from the Yokogawa and then take data when the temperature of the cube/transducer had been stable over several minutes. Stability was determined by recording temperature history in the LabWindows program. Temperature was measured every 30 seconds. If each of the last 5 temperature measurements were within 0.5°C of their average, a data run was taken on the cube/transducer and the temperature was recorded.

# CHAPTER 4

# MATHEMATICAL MODEL

## Acoustical and Electrical Parameters

A transmission line model will be developed to provide a performance simulation. The Mason model is a commonly used T-style transmission line model that produces highly accurate simulations [9,10,11,12]. The system modeled here has four parts: transducer, bond, cube, and parallel load resistor. The transducer is a 3 port device with one electrical port and two acoustic ports. The bond and cube both have two acoustic ports, and the load resistor is a single acoustic port device [9,11,12]. The electrical analogue to our mostly acoustic system is made valid by the assumption that one electrical ohm equals one acoustical ohm.

$$1\ ohm = 1\ \frac{kg}{\sec} \tag{2}$$

This equation is used to calculate the characteristic impedance of the transducer, bond, and cube in terms of electrical ohms [9,11,12]. Once the characteristic impedance of each part is known, the impedance is used to create an impedance matrix using a lossy T-format model as shown in *Figure 4*. The bond and cube are modeled with a similar

diagram that omits the transformer (no electrical port). Impedance matrices are then converted into S parameter matrices. S parameter matrices are converted into transmission matrices, and then cascaded. The resultant single transmission matrix is converted back to an S parameter matrix and $S_{11}$ is easily extracted and graphed.

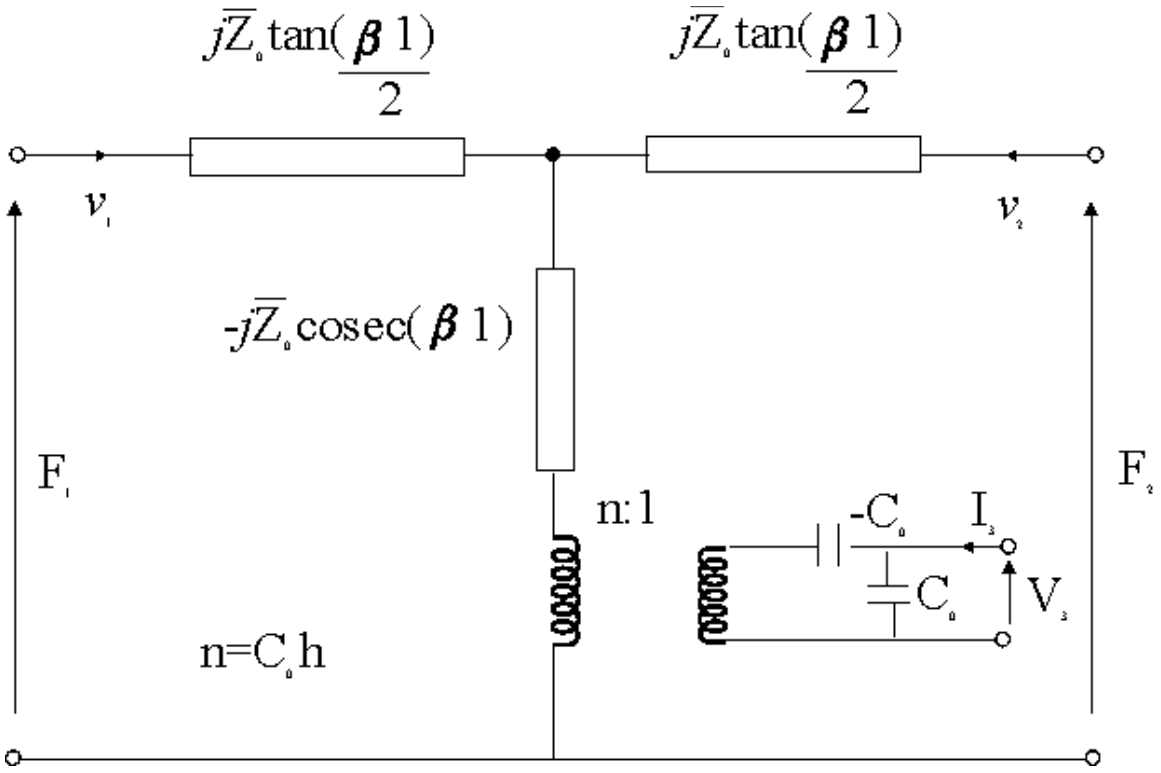



*Figure 4: Electrical representation of piezoelectric material.*

Input impedance and time domain data are then obtained from the $S_{11}$ plot. *Appendix B* shows a sample simulation for an LGT cube material with a longitudinal transducer. The details of the appendix will be discussed in the rest of this chapter.

Transducer Only

The characteristic impedance of the transducer is obtained by the following formula in units of kilograms per second [6,11]:

$$Z_0 = A_T \cdot \rho_T \cdot v_T \tag{3}$$

where $A_T$ is the transducer surface area, $\rho_T$ is the density of the transducer material, and $v_T$ is the acoustic velocity of the transducer material. Note that this formula produces only a real impedance. For a non-ideal case, a loss term is required. The imaginary impedance term for the transducer is given by [11]:

$$Z_0 = j \cdot \sqrt{2\pi f \cdot \eta_T \cdot \rho_T} \cdot A_T \tag{4}$$

where $\eta_T$ is a loss term in units of Newton-seconds per square meter, and $f$ is the frequency at which the impedance will be measured. For the model, the loss term was not changed with frequency, and the center frequency of the transducer was used (10 MHz). A loss term on the order of 0.5 generally produces good imaginary impedance values in the simulation. Some references list this loss term at 0.005 or less [11]. To obtain the total characteristic impedance of the transducer material, the imaginary and real terms are simply added together.

Once the characteristic impedance is known, it is used in a 3x3 Z matrix [9,11], shown in *Equation 5*, which represents the model shown previously in *Figure 4*. Note that force, *F*, is in units of newtons and can be obtained by multiplying stress by area; it is

the acoustic equivalent to volts. Here, area is determined in the plane perpendicular to the acoustic wave propagation, and represents the active area of the transducer. The velocity, *v*, is the acoustic equivalent of current. This matrix is reduced algebraically to a two port matrix by making the force on the open air end of the transducer equal to zero [9]. It is very important to make sure the electrical port ($V_3$) becomes port 1 so that later matrix manipulation will be successful. This requires only algebraic matrix manipulation.

$$\begin{bmatrix} F_1 \\ F_2 \\ V_3 \end{bmatrix} = -j \cdot \begin{bmatrix} Z_0 \cdot \cot(\beta l) & Z_0 \cdot \csc(\beta l) & \frac{h}{\omega} \\ Z_0 \cdot \csc(\beta l) & Z_0 \cdot \cot(\beta l) & \frac{h}{\omega} \\ \frac{h}{\omega} & \frac{h}{\omega} & \frac{1}{\omega C_0} \end{bmatrix} \cdot \begin{bmatrix} v_1 \\ v_2 \\ I_3 \end{bmatrix} \tag{5}$$

The other values in the matrix are $C_0$, the static capacitance, and *h*, a factor that relates *n*, the number of turns in the transformer model, to $C_0$. The transformer models the coupling of the electrical signal into the piezoelectric material. *Equations 6* and *7* show how $C_0$ and n are derived [9].

$$C_0 = \frac{\varepsilon_s \cdot A_T}{l_T} \tag{6}$$

$$n = h \cdot C_0 \tag{7}$$

In *Equation 6*, $\varepsilon_s$ is the material permittivity, or dielectric constant in Farads per meter, $A_T$ is the transducer surface area, and $l_T$ is height of the piezoelectric disk transducer, ideally a half wavelength of the resonant frequency. In *Equation 7*, $h$ is also a representation for the piezoelectric constant, $e_T$, divided by the dielectric constant, $\varepsilon_s$.

If the piezoelectric constant is not known, it can also be derived using *Equation 8* [11].

$$e_T = \sqrt{k^2 \cdot c_T \cdot \varepsilon_s} \tag{8}$$

This term is given in units of coulombs per meter squared, where $k$ is the dimensionless coupling coefficient, easily obtained for most commonly used piezoelectric material cuts, and $c_T$ is the transducer stiffness constant. The stiffness constant can be approximated by known terms as shown in *Equation 9*, and the units are given in pascals [11].

$$c_T = v_T^2 \cdot \rho_T \tag{9}$$

Using the equations in this section, *Appendix B* shows how the 2x2 Z matrix is represented for the transducer model. The appendix also shows how the free air transducer $S_{11}$ response is obtained by setting the remaining acoustic port force term equal to zero. Throughout *Appendix B*, most impedances are normalized to 50 ohms. A typical free air transducer response for a simulated longitudinal transducer is shown in *Figure 5*.

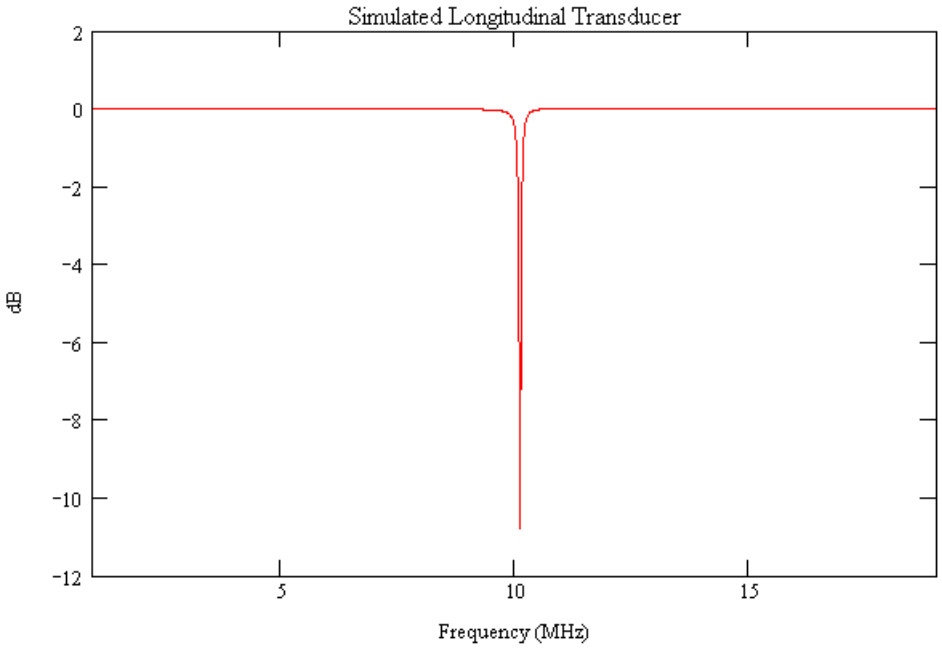



*Figure 5: Simulated longitudinal transducer $S_{11}$ response prior to mounting on cube.*

## Transducer / Cube System

Imaginary and real impedances are obtained for the bond and cube as they were for the transducer, substituting the appropriate terms as they relate to the bond or the cube material. The material properties of the bond material are not readily known, and the simulation is used to help predict these properties. The material properties of the cube are easily measured from our experiment and other physical analysis. It should be noted that modifying the material properties of the bond in the simulation had little effect in the

frequency domain simulation, and even less in the time domain transform. It is assumed that the density of the bond is low and the velocity is slow with respect to the transducer and cube materials, yielding a low characteristic impedance. The load resistor, attached in parallel to the free end of the cube, allows for adjustments to the effective reflection due to non-idealities such as diffraction scattering and power flow angle effects. In the ideal case, this resistor would be zero. Small resistance values, with respect to the normalizing impedance, are used in practice to yield an effective acoustic reflection.

Once all of the 2x2 scattering matrices are obtained from the Z matrices, each scattering matrix is converted to a transmission matrix. These transmission matrices are cascaded algebraically into a single transmission matrix which is then converted back to a scattering matrix that represents the entire system being simulated. *Figure 6* shows the $S_{11}$ output of the simulation for a longitudinal lithium niobate transducer mounted to a cube face of LGT perpendicular to the X axis. *Figure 7* shows the total input impedance of the same system, easily obtained from *Equation 10*.

$$Z_0(f) = \frac{1 + S_{11}(f)}{1 - S_{11}(f)} \tag{10}$$

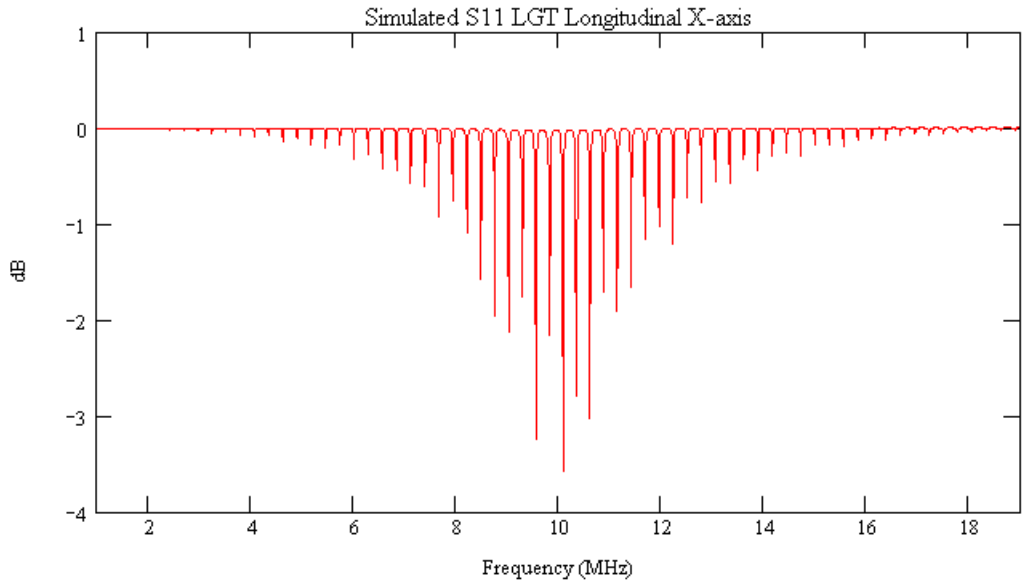



*Figure 6: Simulated $S_{11}$ response of a longitudinal transducer bonded to a one cm LGT cube.*

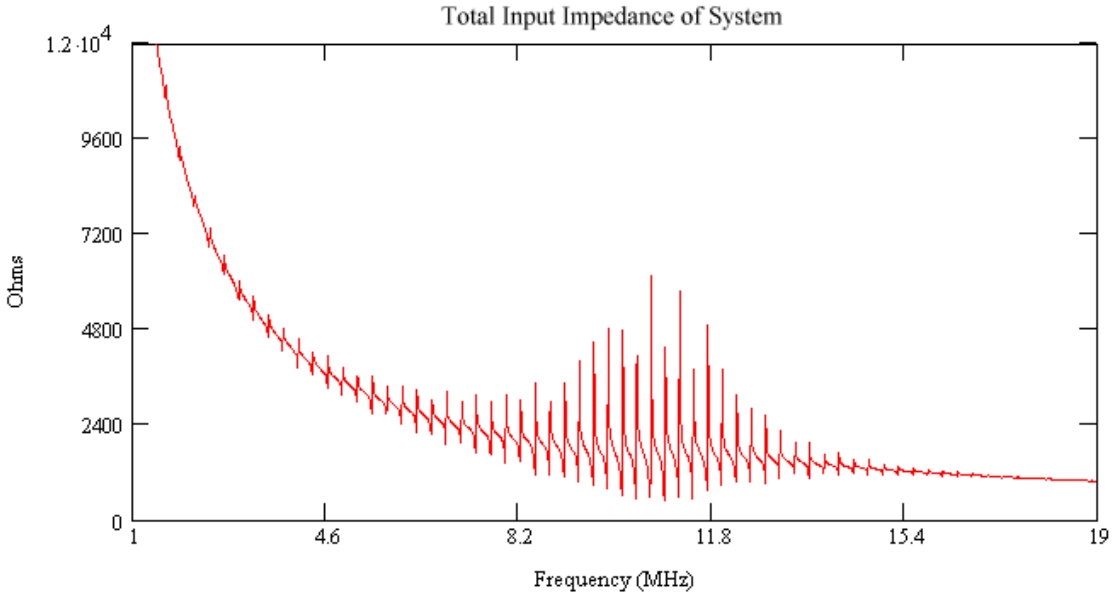



*Figure 7: Simulated total input impedance of a longitudinal transducer bonded to a one cm LGT cube.*

The most important material parameters used to generate the simulated figures in this chapter are shown in *Tables 3* and *4*. These tables also show material parameters that can be used to generate simulations of other materials and velocity modes.

Fundamental Material Properties

| Material Property | Longitudinal Mode Lithium Niobate Transducer | Shear Mode (fast) Lithium Niobate Transducer | Bond |
|---|---|---|---|
| Velocity | 7315.0 m/sec | 4525.0 m/sec | 2900.0 m/sec |
| Density | 4644.0 kg/$m^3$ | 4644.0 kg/$m^3$ | 2400.0 kg/$m^3$ |
| Radius | 0.165 cm | 0.165 cm | 0.160 cm |
| Loss term | 0.9000 N*s/$m^2$ | 0.9000 N*s/$m^2$ | 4.000 N*s/$m^2$ |
| Impedance | 290 + 4j ohms | 180 + 4j ohms | 57 + 6j ohms |
| k | 0.33 | 0.33 | N/A |
| Dielectric Const. | 32.0 | 32.0 | N/A |

*Table 3: Fundamental material properties at room temperature*

Fundamental Material Properties

| Material Property | X cut Quartz Longitudinal | X cut Quartz Shear (fast) | X cut LGT Shear (fast) |
|---|---|---|---|
| Velocity | 5749.0 m/sec | 5103.0 m/sec | 3144.0 m/sec |
| Density | 5154.0 kg/$m^3$ | 5154.0 kg/$m^3$ | 6150.4 kg/$m^3$ |
| Radius | 0.115 cm | 0.115 cm | 0.115 cm |
| Loss term | 0.4 N*s/$m^2$ | 0.4 N*s/$m^2$ | 0.7 N*s/$m^2$ |
| Impedance | 93 +1j ohms | 83 + 1j ohms | 80 + 2j ohms |

*Table 4: Fundamental material properties at room temperature*

## Frequency Smoothing

Referring to *Figure 6*, the large ripples are due to the acoustic echo reflections. If the cube were infinite in dimension, there would be no ripple (acoustic reflection) and there would be a smooth $S_{11}$ profile corresponding to the transducer's electrical bandwidth when bonded to the cube. This electrical reflection can be approximated by smoothing the measured data. This was accomplished by convolving, in the frequency domain, the measured data with a Hamming window. The resulting smoothed curve is a good approximation to the $S_{11}$ that would be obtained with a cube of infinite length (no

reflection), leaving only the electrical $S_{11}$ (see *Figure 8*). This smoothed curve is then subtracted from the original raw data to yield the pure acoustic frequency response curve.

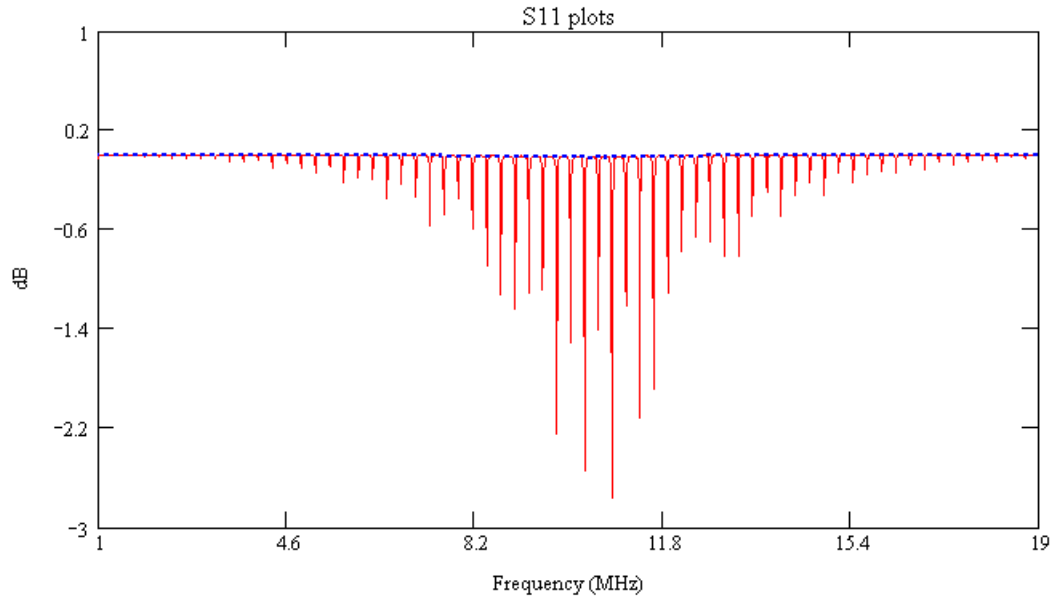



*Figure 8: Simulated $S_{11}$ response of a longitudinal transducer bonded to a one cm LGT cube (solid line) with a smoothed curve superimposed (dotted line).*

## Inverse Fourier Transform

*Figure 9* shows the Inverse Fourier Transform of the previous frequency domain $S_{11}$ signal after padding with zeros out to the frequency where $2^{15}$ frequency points are obtained. Three methods of padding were tested. Padding with 0dB and 0 phase down in frequency to near 0 hertz and up in frequency until desired number of points was obtained, padding with 0dB and 0 phase while smoothing points near the actual measured data, and padding with the last point measured in the frequency domain when padding to

higher frequencies, and padding with the first point measured when padding down to near 0 Hz. In addition, these three methods were experimented with while padding the measured data only with higher frequencies (no padding between 0 Hz and 1 MHz). All of these methods are about the same, with variations of pulse start times being a maximum of 20 nanoseconds, or less than 8 $\Delta$t's. It is somewhat intuitive to realize that padding with a slightly non-zero phase term can cause a slight shift in the time domain.

The best results, or most noise-free time domain, are obtained when padding with the last data point in the data set to the highest frequency of interest and padding with the first data point down in frequency to near zero hertz. These points are always VERY close to 0dB, so the term 0 dB padding is still used throughout this paper. This method was also chosen for analysis here since it was the current method used for data analysis on most of our existing data. Furthermore, when discussing pulse start times, this paper is always referring to the smoothed time response, where the electrical effects have been removed. Again, *Table 1*, in Chapter 2, shows the resolutions in time that can be obtained by padding with various numbers of frequency points. Padding is required to obtain the 0.1% velocity accuracy desired from this project.

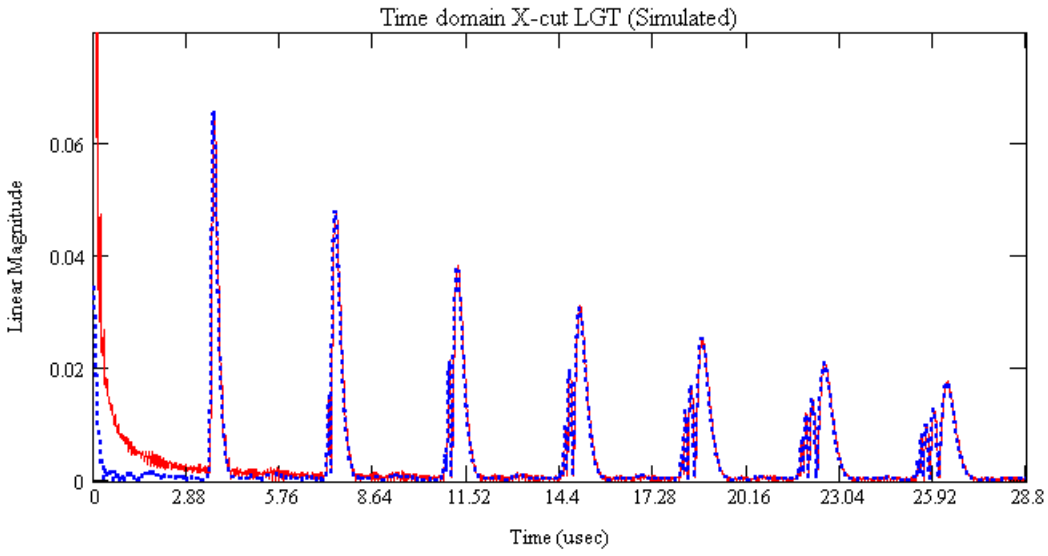



*Figure 9: Simulated (transformed) time domain response of a longitudinal transducer bonded to a one cm LGT cube (solid line) with a smoothed curve superimposed (dotted line).*

The pulse separations seen in *Figure 9* during the later reflections were first observed in experiment. The first acoustic reflected pulse has a sharp, clean transition from the noise floor. Subsequent pulses begin to show the internal constructive and destructive interference produced in the cube-bond-transducer system, indicated by the multiple zeros within a pulse. The simulation showed that this separation is due to the cube/transducer interface. Pulses reflect off the cube as well as the back of the transducer. Note that the electrical response occurs at time of zero and the reflected pulses occur at regular intervals in time.

# CHAPTER 5

# EXPERIMENTAL DATA

## Transducer Only

As mentioned previously, $S_{11}$ is the parameter measured from the network analyzer for a transducer or a transducer/cube system under test. *Figure 10* shows the $S_{11}$ data from a longitudinal transducer, and *Figure 11* shows the $S_{11}$ data from a shear transducer. It was already known that these transducers are not pure or single mode, and the minor peaks show evidence of the multiple modes. The magnitude of the subordinate modes is not sufficient to affect the time domain response of the primary mode response when the transducer is mounted to the cube being tested.

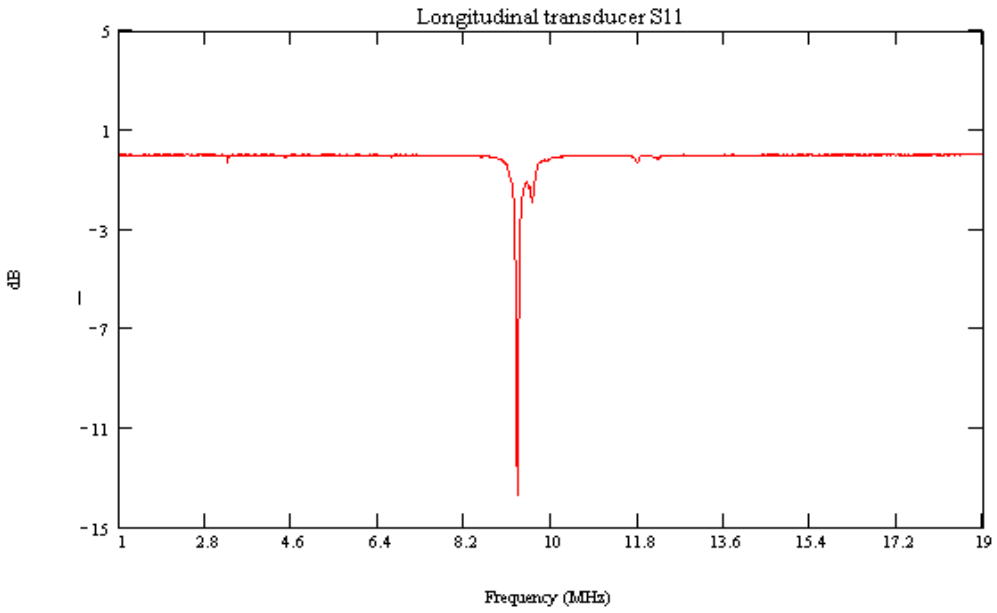



*Figure 10: Measured $S_{11}$ response of a lithium niobate longitudinal transducer prior to mounting to a cube.*

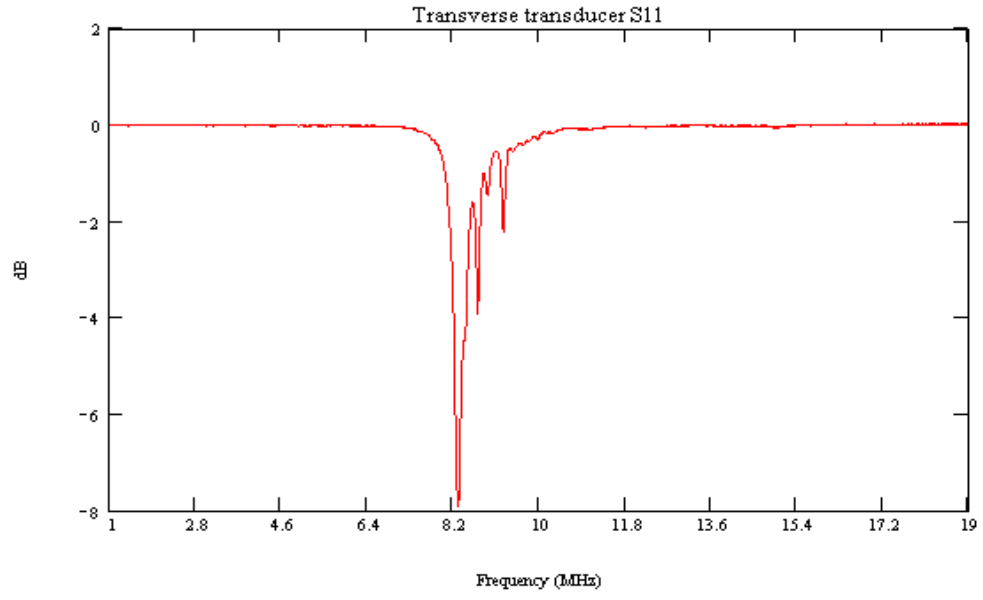



*Figure 11: Measured $S_{11}$ response of a lithium niobate shear mode transducer prior to mounting to a cube.*

## Transducer / Cube

Data of various transducer/cube systems will now be presented. Analysis in the next chapter will concentrate on longitudinal transducers mounted to LGT and quartz, but shear mode data is presented here as well for visual reference. All of the data in this chapter was obtained at room temperature (about 23 degrees C), and a transducer mounted to the X-face (face perpendicular to the X-axis) was used. All cubes were 1 cm square within a few microns.

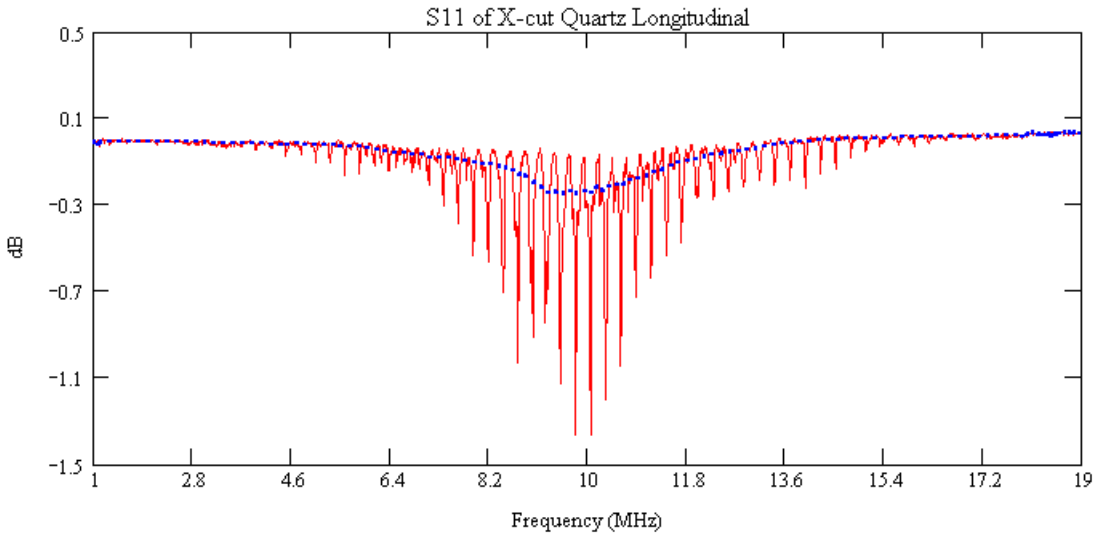



*Figure 12: Measured $S_{11}$ response of a lithium niobate longitudinal mode transducer (solid line) bonded to the X-face of a quartz cube. The smoothed curve (dotted line) is obtained using a Hamming function to smooth the measured $S_{11}$ data.*

*Figure 12* is a representative graph of an $S_{11}$ frequency data plot of an X-axis longitudinal data file obtained from a quartz cube. The dotted line in this graph is the smoothed frequency response. *Figure 13* is the total input impedance of the same cube/transducer system shown in *Figure 12* this graph is used as an additional step to verify results of the simulations.

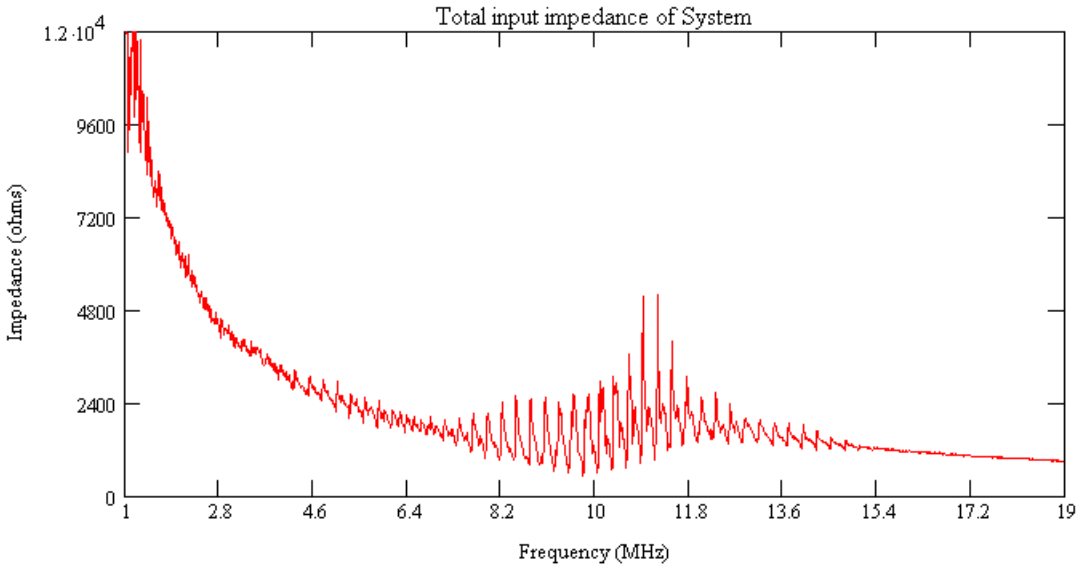



*Figure 13: Measured total $Z_{in}$ of a lithium niobate longitudinal mode transducer bonded to the X-face of a quartz cube.*

*Figure 14* shows the IFFT time domain information for the $S_{11}$ frequency data in *Figure 12*. The dotted curve is the plot that results from removing the smoothed data which approximates the removal of the electrical effects of the cube/transducer combination. This file was produced by padding zero dB points in the frequency domain until $2^{15}$ points were obtained, using the method described in Chapter 4. *Figure 15* shows a close up of the first pulse (first reflection) in the time domain. Again, the dotted curve

is the curve without the electrical effects. In this example, there is less than 10 nanoseconds difference in the start time of the smoothed curve and the non-smoothed (raw data) curve. This represents a velocity difference on the order of 15 meters per second for our one centimeter cube of quartz.

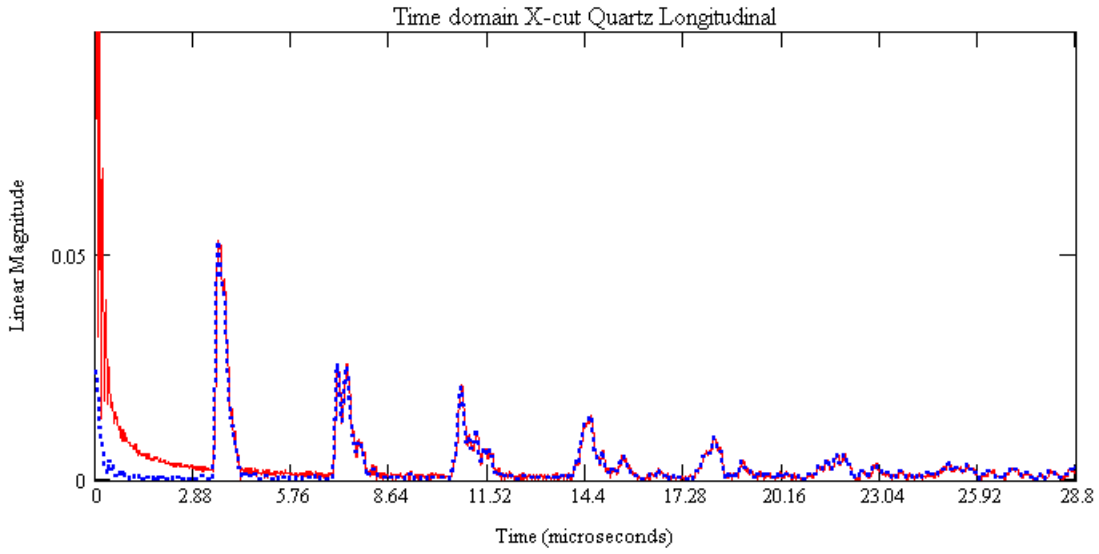



*Figure 14: Measured (transformed) time domain response of a lithium niobate longitudinal mode transducer bonded to the X-face of a quartz cube (solid line), and the smoothed curve response (dotted line).*

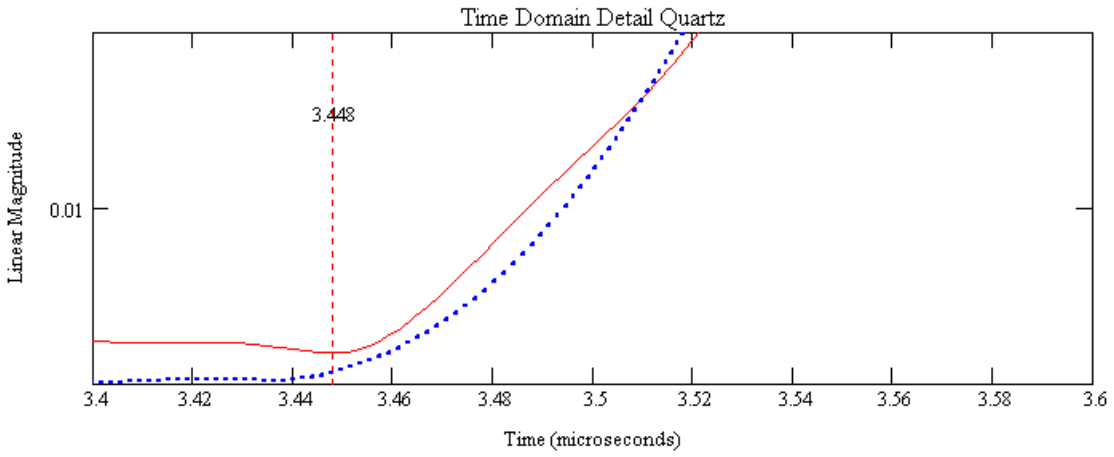



*Figure 15: Measured (transformed) time domain response of a lithium niobate longitudinal mode transducer bonded to the X-face of a quartz cube (solid line), and the smoothed curve response (dotted line).*

The velocity obtained from the start point shown in *Figure 15* is 5800 meters per second, which is faster than expected for the room temperature X-cut longitudinal velocity in quartz of 5750 meters per second, shown in James [1].

*Figure 16* is a representative graph of an $S_{11}$ frequency data plot of an X-axis longitudinal data file for LGT. The dotted line in this graph is the smoothed frequency response. *Figure 17* is the total input impedance of the cube/transducer system for the data shown in *Figure 16*.

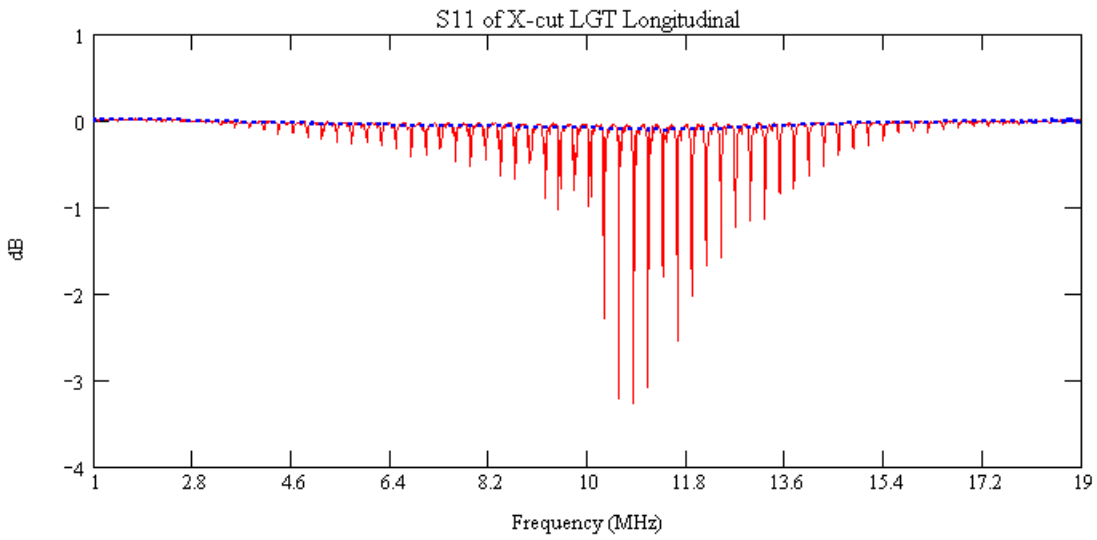



*Figure 16: Measured $S_{11}$ response of a lithium niobate longitudinal mode transducer bonded to the X-face of an LGT cube (solid line), and the smoothed curve response (dotted line).*

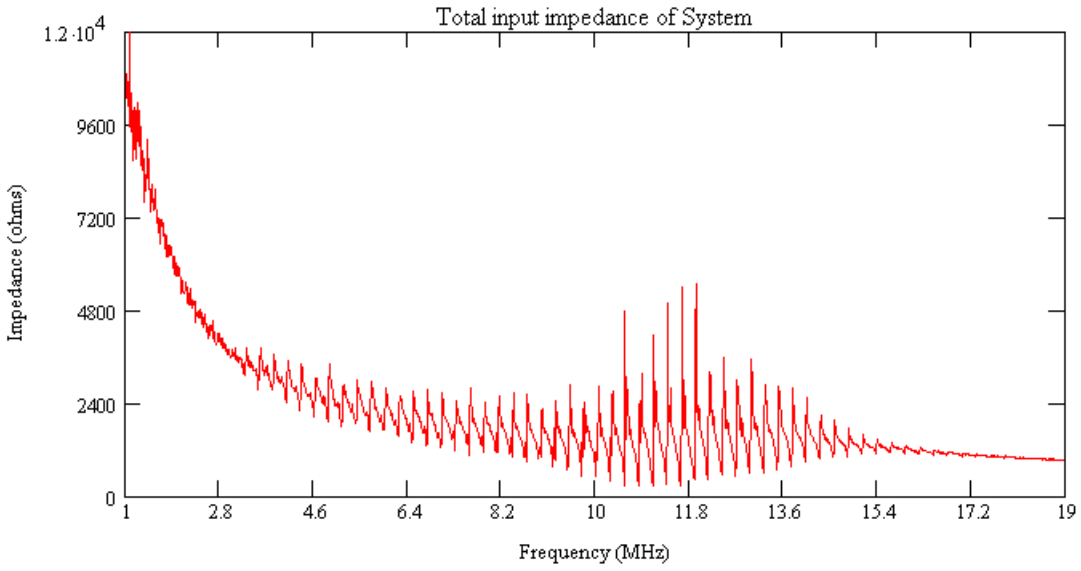



*Figure 17: Measured total $Z_{in}$ of a lithium niobate longitudinal mode transducer bonded to the X-face of an LGT cube.*

*Figure 18* shows the IFFT time domain information for the $S_{11}$ frequency data in *Figure 16*. Again, the dotted curve in the time domain is the plot that results from removing the electrical effects. This file was produced by padding zero dB points in the frequency domain until $2^{15}$ points were obtained as described in chapter 4. *Figure 19* shows a close up of the first pulse (first reflection) in the time domain. Again, the dotted curve is the curve without the electrical effects. The start time here is chosen when the smoothed curve has clearly begun to move out of the noise floor. The start time chosen in *Figure 19* corresponds to a velocity of 5602 meters per second.

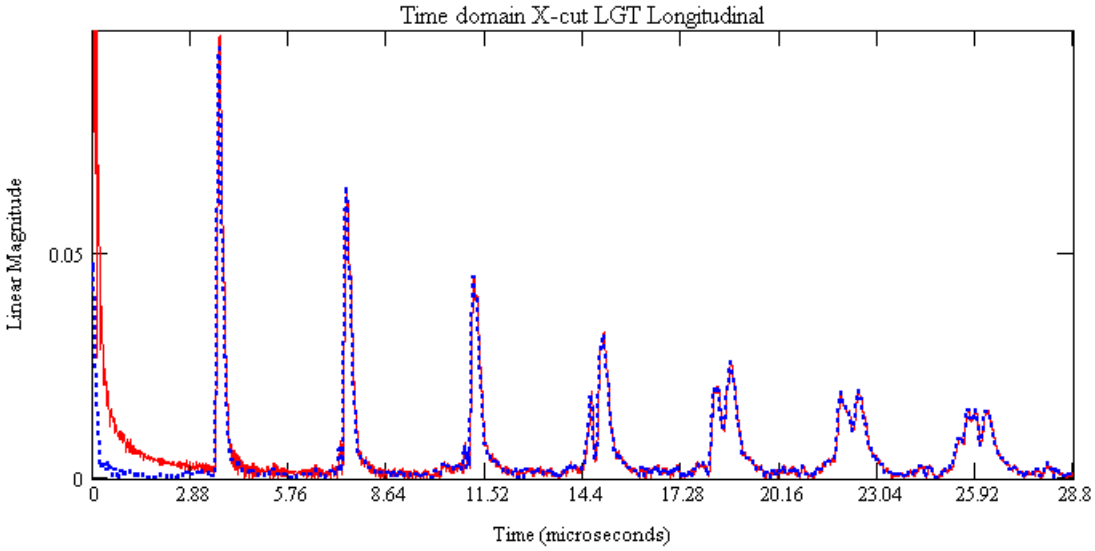



*Figure 18: Measured (transformed) time domain response of a lithium niobate longitudinal mode transducer bonded to the X-face of an LGT cube (solid line), and the smoothed curve response (dotted line).*

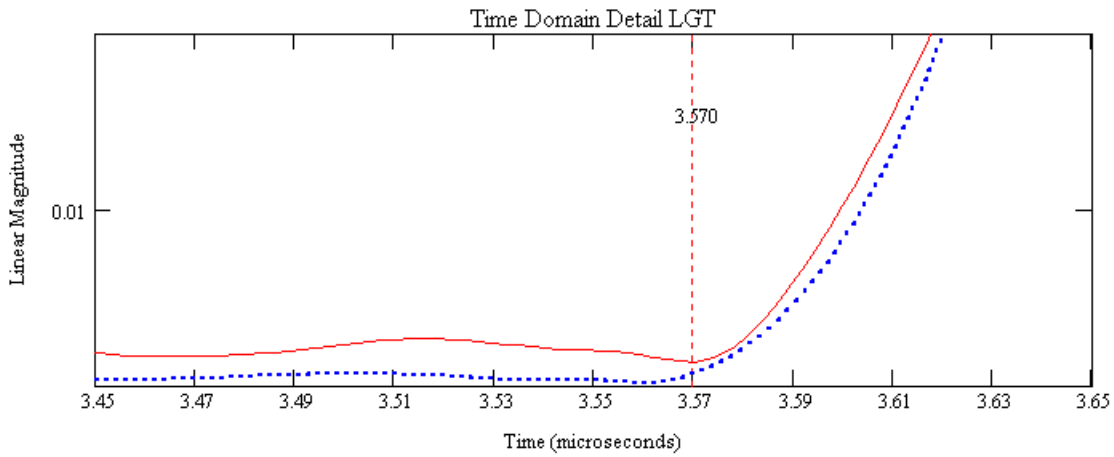



*Figure 19: Measured (transformed) time domain response of a lithium niobate longitudinal mode transducer bonded to the X-face of an LGT cube (solid line) with smoothed response (dotted line).*

*Figure 20* and *Figure 21* show the $S_{11}$ data and IFFT of a shear mode transducer quartz cube combination (X-axis), respectively. Again, the dotted plots are the smoothed functions. Shear mode data usually has a larger dip in the smoothed curve, indicating stronger electrical coupling into the cube material. *Figure 21* shows evidence of multiple shear modes generated by the shear wave of the transducer. It was difficult to obtain some slow shear data in cases where fast and slow shear modes were similar in velocity. The simulation part of the experiment allows for a better approximation of some of the overlapping modes with its ability to only simulate a single mode response. It was also shown in the experiment that the orientation of the flat of the shear mode transducer would allow for the maximizing or minimizing of various shear modes depending on the mounting angle with respect to the axis of the cube not being measured. When measuring the X-axis, the orientation is given with respect to the Y and Z axis.

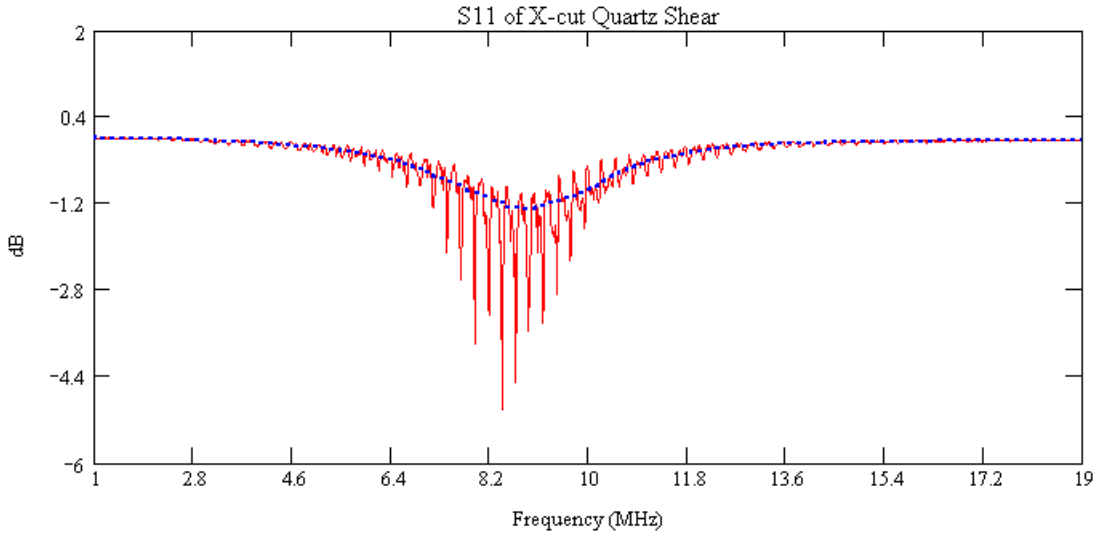



*Figure 20: Measured $S_{11}$ response of a lithium niobate shear mode transducer bonded to the X-face of a quartz cube (solid line), and the smoothed response (dotted line).*

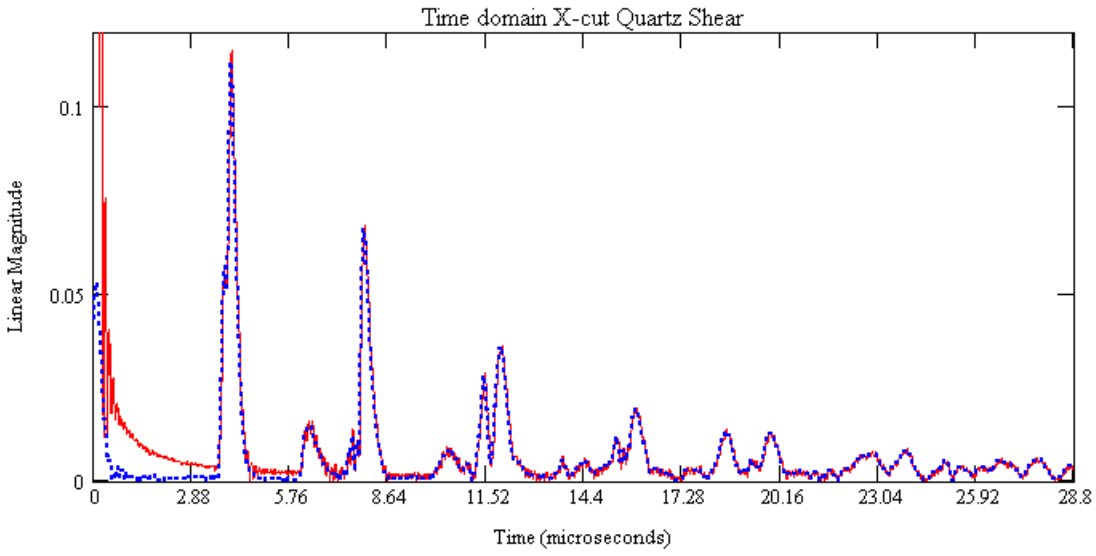



*Figure 21: Measured (transformed) time domain response of a lithium niobate shear mode transducer bonded to the X-face of a quartz cube (solid line) including smoothed response (dotted line).*

*Figure 22* shows the $S_{11}$ plot of a shear mode transducer bonded to the X-axis face of an LGT cube. The frequency ripples are closer together here, showing evidence of the slow shear mode velocity of X-cut LGT. *Figure 23* shows the IFFT of the data in *Figure 22*, and the very slow shear mode velocity, on the order of 2400 meters per second. Evidence of subordinate longitudinal and fast shear data is noticeable in this figure as well.

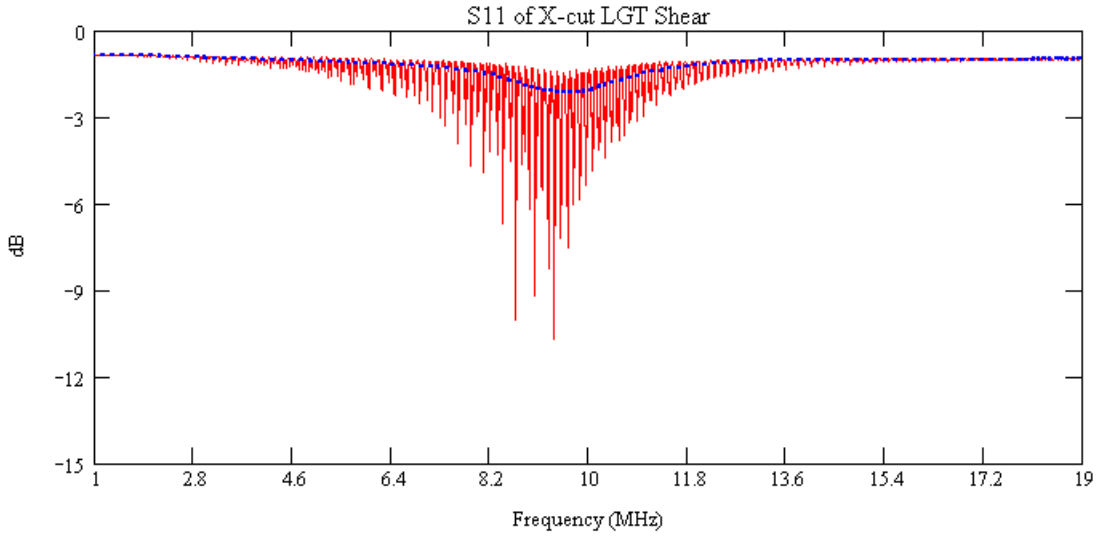



*Figure 22: Measured $S_{11}$ response of a lithium niobate shear mode transducer bonded to the X-face of an LGT cube (solid line) and the smoothed response (dotted line).*

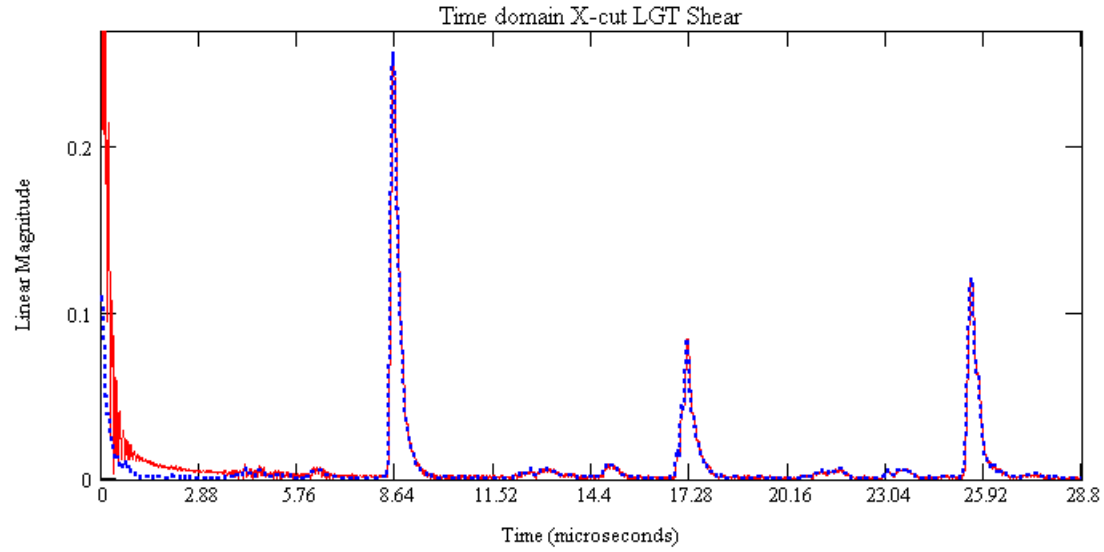



*Figure 23: Measured (transformed) time domain response of a lithium niobate shear mode transducer bonded to the X-face of an LGT cube (solid line) and the smoothed response (dotted line).*

The amount of data taken during this project was overwhelming. All of it can not be presented here. Processing and analysis is identical for the other axis of measurement. It is very possible that the resolution of the time domain data exceeds our ability to pick proper starting points. When selecting starting points in the time domain of a transformed frequency domain signal padded with $2^{15}$ points, it often seems that a point +/- 2 $\Delta t$'s on either side of the point would be an equally acceptable choice. This could produce an interpretation error on the order of +/- 3 meters per second of our measured acoustic velocities. Averaging multiple samples is a possible way to help reduce interpretation error.

# CHAPTER 6

# ANALYSIS AND RESULTS

This chapter will analyze the similarities and differences of the measured data with respect to simulated data. Mathematical processing and data interpretation will also be discussed further.

## Transducer Only

The transducer model was the most difficult part of this project, and served as a benchmark for model correctness, as the $S_{11}$ plots of free-air transducer are easy to obtain and use for comparison. One of the difficulties in this comparison is the actual definition and physical interpretation of a single port $S_{11}$ measurement. Physically speaking, this is simply the $S_{11}$ measurement obtained by attaching two electrodes to a free air transducer. Mathematically speaking, it is the $S_{11}$ obtained only *after* reducing the 3x3 scattering matrix of the transducer to a single (electrical) port by making the force applied to both acoustical ports zero. It is not the $S_{11}$ matrix item from the 2x2 or 3x3 S matrix of the transducer model. Furthermore, the simulation allowed for a highly accurate estimation of the loss term required by the transducer. Increasing the loss term increased the bandwidth of transmitted energy into the transducer.

Knowing the other material parameters of our specific cuts of lithium niobate transducers to good accuracy, the loss term was adjusted to give a waveshape that matched measured transducer data. This model does not account for subordinate modes present in the actual transducers, most notably in the shear mode transducer. This feature will prove to be useful when predicting slow shear modes that can be lost in fast shear modes of a time domain signal when the velocities are only a few hundred meters per second different.

Comparing *Figures 5* and *10*, it can be seen that the modeled transducer $S_{11}$ response in *Figure 5* is similar in magnitude and bandwidth to the actual $S_{11}$ response measured in *Figure 10*. It should be noted that magnitude is closely associated with k and $C_0$ and can vary by a few dB between different transducers. In simulation and in experiment, this magnitude difference did not affect the start times of pulses in the time domain.

## Quartz

Quartz was chosen as a standard for simulation and for verifying the accuracy of the experimental data taking process. The physical properties of quartz are easily found from many publications, although many times this involves extracting properties from given elastic constants by manipulating formulas found in Auld [6].

*Figures 24* and *25*, show a close up of the first reflected pulse from an actual transformed $S_{11}$ data set taken from the X-axis of a quartz cube mounted with a longitudinal transducer, and the same simulated data, respectively. This is the same data set shown in chapter 5. *Figures 26* and *27* show the same comparison for the second reflected pulse, and *Figures 28* and *29* show the same time domain close ups for the third reflected pulse. Again, these time domain plots were obtained from frequency plots padded with zeros to obtain $2^{15}$ data points in the frequency domain, and a time resolution of 2.7 nanoseconds. The markers shown in the figures are the chosen start times, when the smoothed response curve has clearly left the local noise floor.

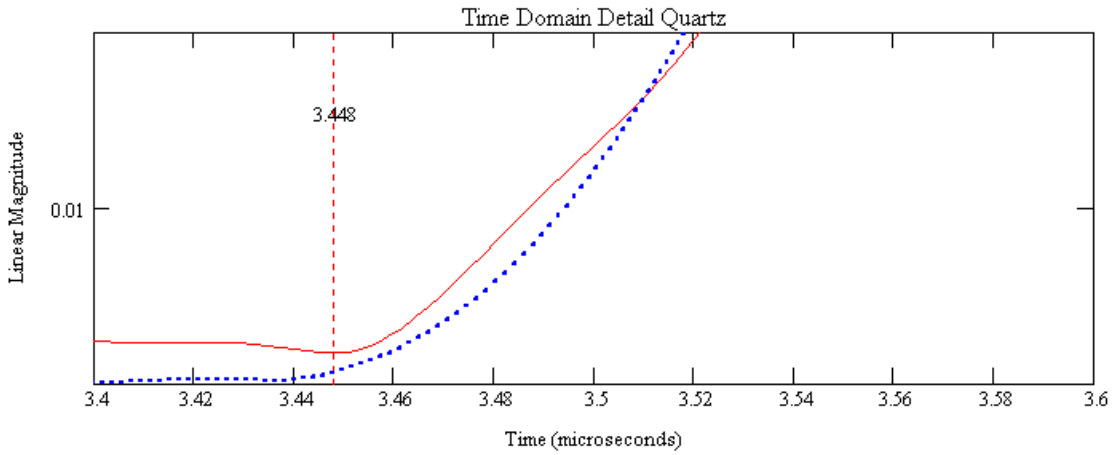



*Figure 24: Measured (transformed) time domain response of a lithium niobate longitudinal transducer mounted to the X-face of a quartz cube, detail of first reflection (solid line), and the smoothed response (dotted line).*

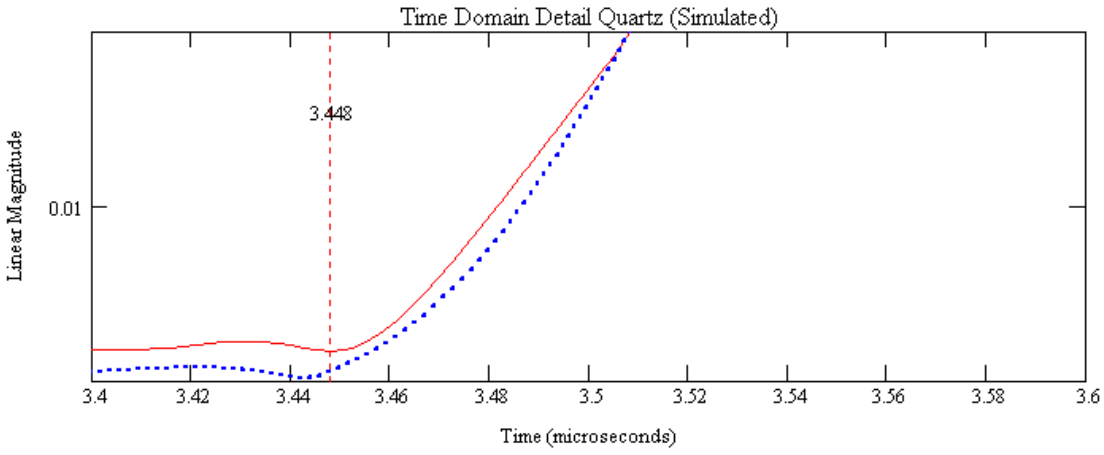



*Figure 25: Simulated time domain response of a lithium niobate longitudinal transducer mounted to the X-face of a quartz cube, detail of first reflection (solid line), and the smoothed response (dotted line).*

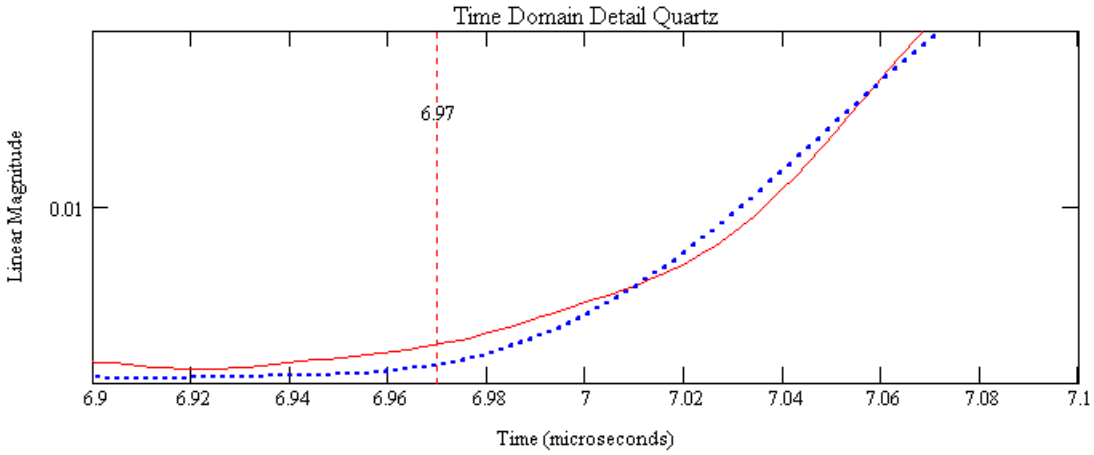



*Figure 26: Measured (transformed) time domain response of a lithium niobate longitudinal transducer mounted to the X-face of a quartz cube, detail of second reflection (solid line), and the smoothed response (dotted line).*

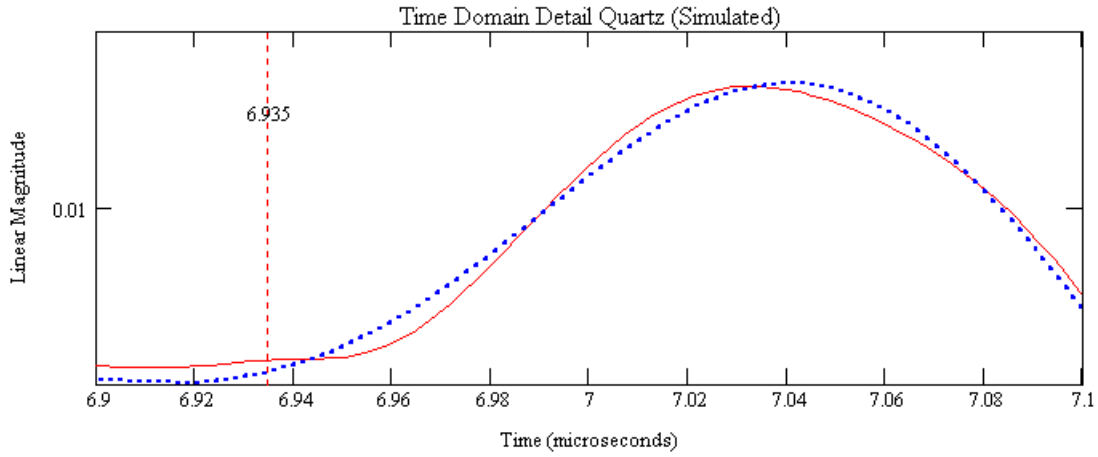



*Figure 27: Simulated time domain response of a lithium niobate longitudinal transducer mounted to the X-face of a quartz cube, detail of second reflection (solid line), and the smoothed response (dotted line).*

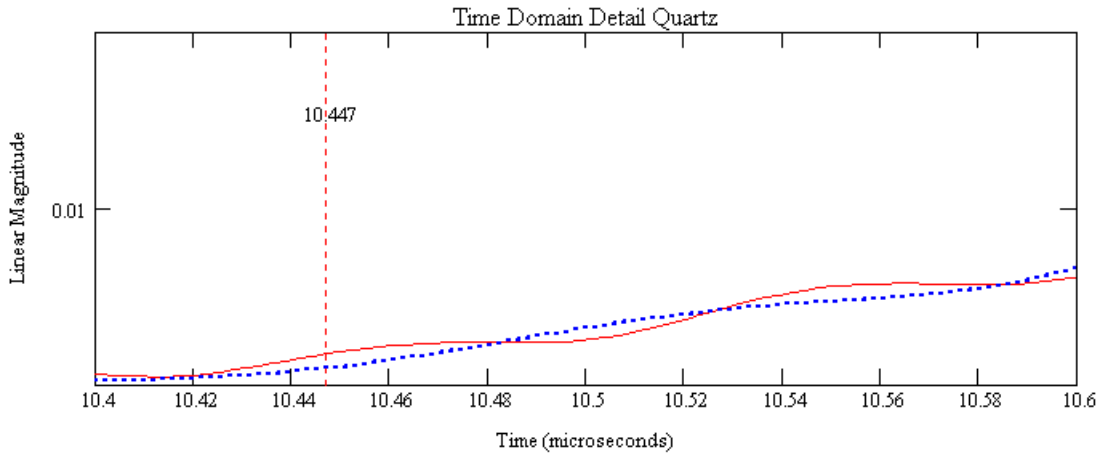



*Figure 28: Measured (transformed) time domain response of a lithium niobate longitudinal transducer mounted to the X-face of a quartz cube, detail of third reflection (solid line), and the smoothed response (dotted line).*

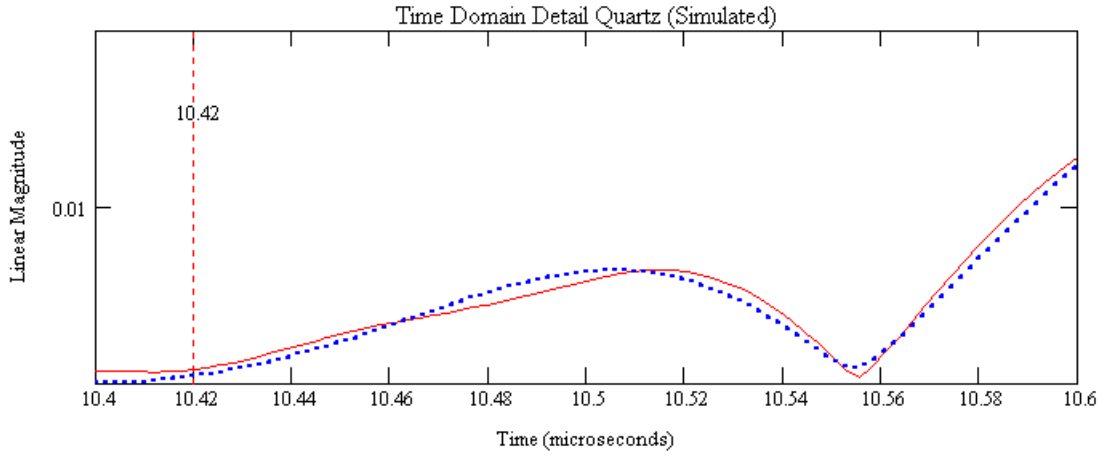



*Figure 29: Simulated time domain response of a lithium niobate longitudinal transducer mounted to the X-face of a quartz cube, detail of third reflection (solid line), and the smoothed response (dotted line).*

Analysis of the previous six figures yields a velocity of 5800 m/s for the first pulse, both measured and simulated; a velocity of 5739 m/s for the measured second pulse and 5768 m/s for the simulated second pulse; a velocity of 5743 m/s for the measured third pulse and 5758 for the simulated third pulse. The expected velocity, and the velocity used in the simulation sheet to develop the physical constants outlined in chapter 4 is 5750 m/s [1], which is virtually identical to velocities derived from elastic constants presented in Brice [7] and Salt [8].

A complete analysis of the time domain signal, and the frequency padding method used to obtain it would be necessary to explain what appears to be a 1% deviation in our results for the velocity obtained from the first reflected pulse. This analysis is beyond the scope of this research, and does not seem to be explainable from the basic equations of the Fourier transforms. Fortunately, this analysis is not required to produce highly accurate velocities of piezoelectric materials under test if our deviation is consistent.

## LGT

The same comparison shown for quartz will now be shown for LGT. *Figures 30* and *31*, show a close up of the first reflected pulse from an actual transformed $S_{11}$ data set taken from the X-axis of a quartz cube mounted with a longitudinal transducer, and the same simulated data, respectively. This is the same data set used in chapter 5. *Figures 32* and *33* show the same comparison for the second reflected pulse, and *Figures 34* and *35* show the same time domain close ups for the third reflected pulse.

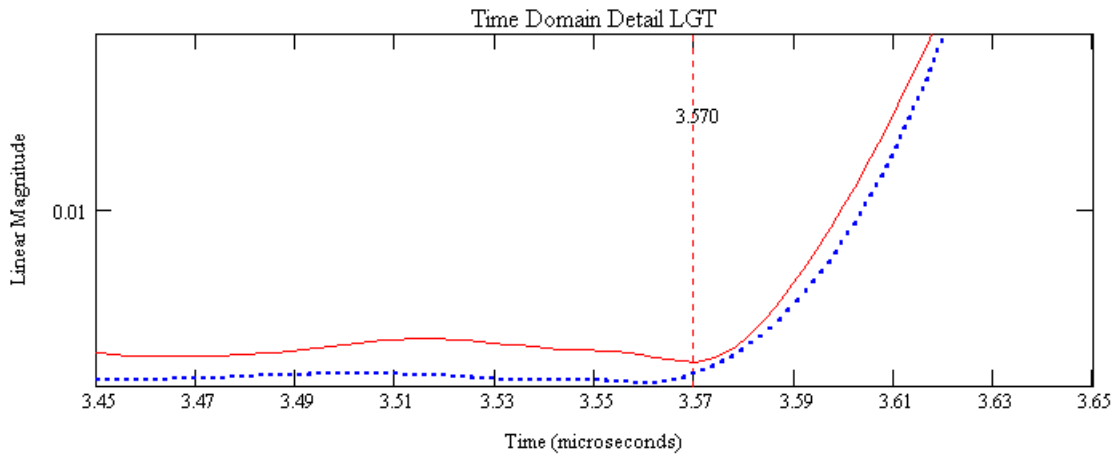



*Figure 30: Measured (transformed) time domain response of a lithium niobate longitudinal transducer mounted to the X-face of an LGT cube, detail of first reflection (solid line), and the smoothed response (dotted line).*

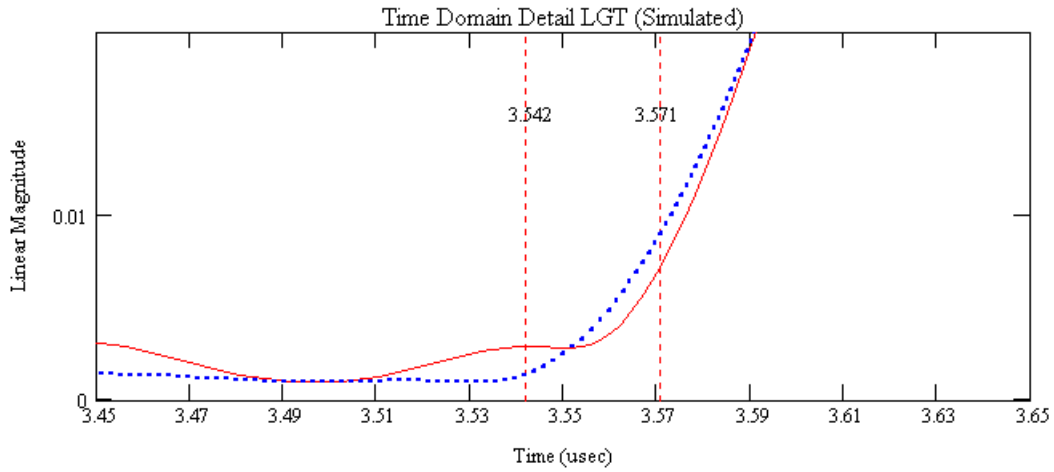



*Figure 31: Simulated time domain response of a lithium niobate longitudinal transducer mounted to the X-face of an LGT cube, detail of first reflection (solid line), and the smoothed response (dotted line).*

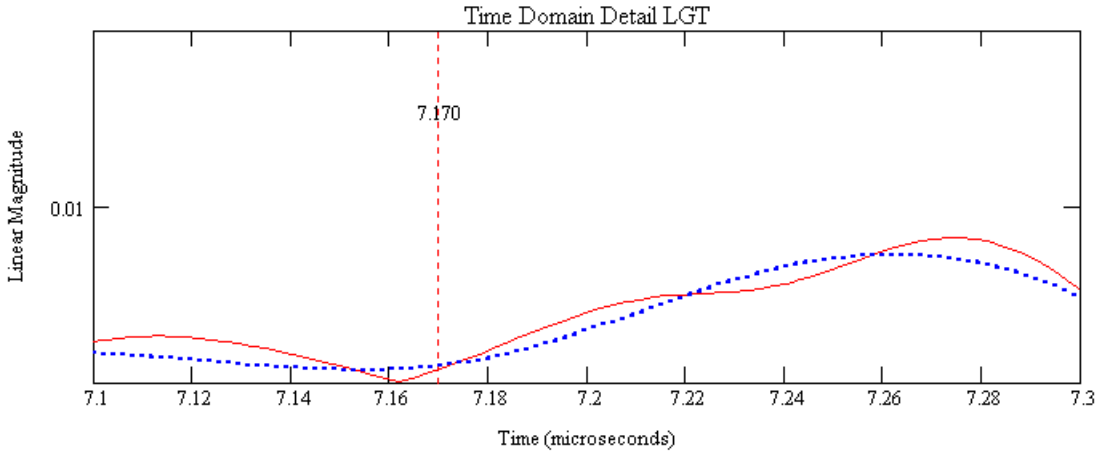



*Figure 32: Measured (transformed) time domain response of a lithium niobate longitudinal transducer mounted to the X-face of an LGT cube, detail of second reflection (solid line), and the smoothed response (dotted line).*

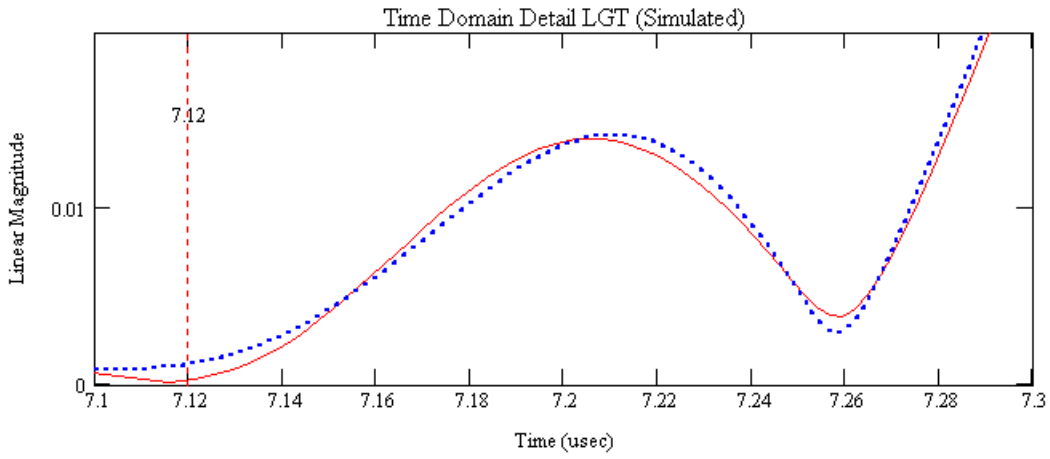



*Figure 33: Simulated time domain response of a lithium niobate longitudinal transducer mounted to the X-face of an LGT cube, detail of second reflection (solid line), and the smoothed response (dotted line).*

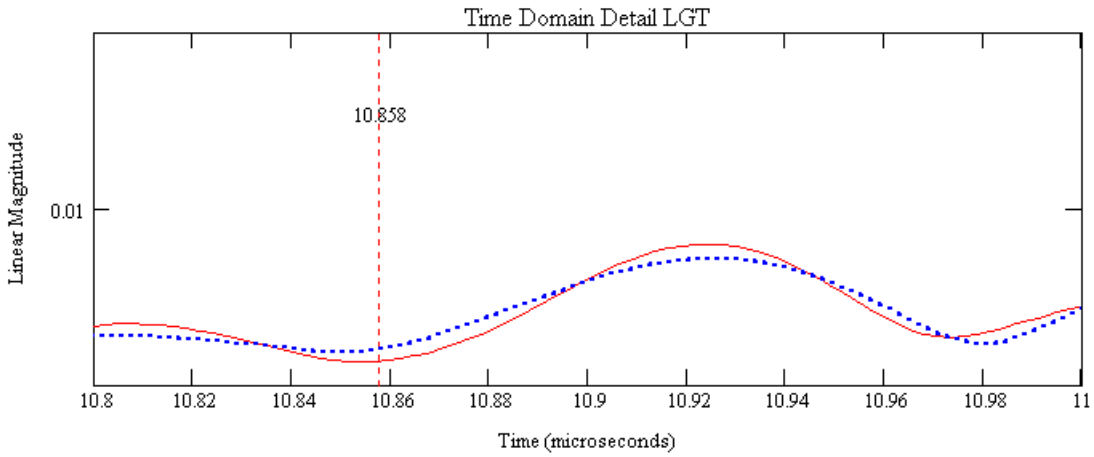



*Figure 34: Measured (transformed) time domain response of a lithium niobate longitudinal transducer mounted to the X-face of an LGT cube, detail of third reflection (solid line), and the smoothed response (dotted line).*

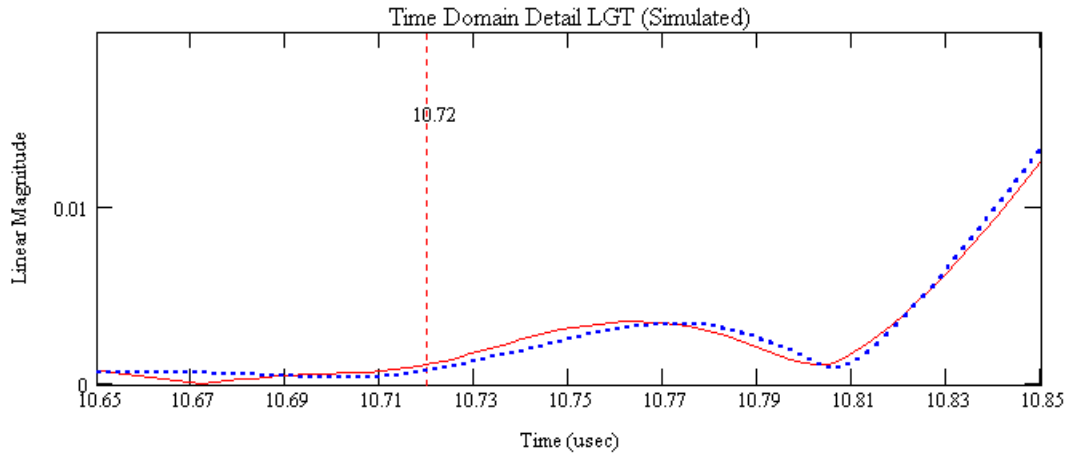



*Figure 35: Simulated time domain response of a lithium niobate longitudinal transducer mounted to the X-face of an LGT cube, detail of third reflection (solid line), and the smoothed response (dotted line).*

Analysis of the previous six figures yields a velocity of 5602 m/s for the first measured pulse, and 5647 m/s for the simulated first pulse; a velocity of 5579 m/s for the measured second pulse and 5618 m/s for the simulated second pulse; a velocity of 5526 m/s for the measured third pulse and 5597 for the simulated third pulse. The expected velocity, and the velocity used in the simulation sheet to develop the physical constants outlined in chapter 4 is 5601 m/s, obtained from our measured (transformed) data on LGT.

The results are as expected from the information we learned from the quartz simulation. The data produced by the simulation produces fast velocities with respect to the velocity used to determine physical constants of the material. If the expected velocity is reduced to 5558 m/s in the simulation, simulated and measured data become the same for the first two pulses, and very similar for the third reflected pulse. It could therefore be assumed that the room temperature longitudinal bulk wave velocity for X-cut LGT is 5558 m/s, which agrees favorably to the 5565 m/s presented in Pisarevsky [13]. This type of backward analysis and simulation needs to be performed just once for each axis and mode to find the number of meters per second to subtract from the measured velocity in question as it is computed from the first reflected pulse.

## More Simulation Results

To further prove the validity of the mathematical simulation and gain some insight into some of the unknown parameters of the physical experiment, modifications were made to various parameters of the simulation. Varying the bond thickness and density showed very little difference in the time domain. Doubling the length of the cube material showed an exact doubling of the delay of the first reflected pulse. Varying the coupling coefficient, k, had a large effect on $S_{11}$ magnitude.

Simulation results allow for some insight into the various zero padding methods discussed in *Chapter 4*. *Table 5* shows the start times of the first reflected pulse after performing the IFFT for various methods of zero padding that were used on frequency domain data obtained from simulation (similar results were obtained by padding actual experimental data sets). The actual start time determined from the velocity of the cube material that was input into the simulation is 3.571 microseconds, given the 1 cm cube dimensions, and setting the velocity of LGT to 5601 meters per second. While the smoothed curve (no electrical effects) has a fairly stable start time for different padding methods, the transformed raw data start times vary by 14 nanoseconds, or about 5 $\Delta t$'s. The two leftmost columns in *Table 5* show the number of nanoseconds to add to the first reflection time to obtain the proper velocity. Our analysis method of choice involves using the smoothed data and the retrofit method described in the previous section to obtain velocity errors on the order of 0.1%. It should be noted however, that the transformed raw data could be used as is without time domain adjustment, and still

produce errors of less than 0.6%. This table is not absolute, and varies by material and propagation mode.

First Reflected Pulse Start Times

| Padding method | Smoothed IFFT Time Response Curve | Raw Data IFFT Time Response Curve | Adjustment Required for Smoothed Curve | Adjustment Required for Raw Data Curve |
|---|---|---|---|---|
| Last frequency point up to desired bandwidth | 3.542 usec | 3.562 usec | 29.0 nsec | 9.0 nsec |
| Zero dB and zero phase up to desired bandwidth | 3.542 usec | 3.551 usec | 29.0 nsec | 20.0 nsec |
| First frequency point down to near zero hertz and last frequency point up to desired bandwidth | 3.542 usec | 3.548 usec | 29.0 nsec | 23.0 nsec |
| Zero dB and zero phase down to near zero hertz and up to desired bandwidth | 3.539 usec | 3.551 usec | 32.0 nsec | 20.0 nsec |
| down to near zero hertz and up to desired bandwidth | 3.542 usec | 3.561 usec | 29.0 nsec | 10.0 nsec |
| Zero dB and zero phase up to desired bandwidth with gradual transition to zero dB | 3.539 usec | 3.551 usec | 32.0 nsec | 20.0 nsec |
| Zero dB and zero phase down to near zero hertz and up to desired bandwidth with gradual transitions to zero dB | 3.539 usec | 3.551 usec | 32.0 nsec | 20.0 nsec |

*Table 5: Zero padding and first reflected pulse start times.*

In addition to simply choosing a start time from the first reflected pulse, it is possible to subtract the time of the first reflected pulse from the time of the second reflected pulse to obtain a round trip travel time in the cube. This can be done for subsequent pulses as well. It is very important to realize that the start of a subsequent pulse is not necessarily the start of the pulse with the highest magnitude in a "cluster." It is generally the start of one of the smaller magnitude pulses that precedes the pulse with the highest magnitude. Velocities calculated in this manner were within measurement error of velocities calculated just using the first reflected pulse with respect to zero time.

Time between pulse peaks was also measured, but this method would be expected to produce skewed results, as it has now been shown that the major peaks of a pulse involve reflections off the back of the transducer (introduces a time delay). Somewhat of an improvement over this method is to use the derivative of the time domain to obtain a peak at a point of maximum slope. This method produces good results for a single temperature measurement, but is somewhat difficult to automate over temperature. The analysis program must be given a window in which to look for a peak in the derivative graph, but the window can be small when dealing with the subordinate pulses that are close together. As the time domain shifts with temperature, our maximum point can move outside of the window, making automation over temperature difficult or impossible.

Although not shown in this report, a set of time domain data over temperature can be entered into a Matlab program, written primarily by Mitch Chou and Dr. Malocha, to display a 3-D plot of magnitude vs. time and temperature. These plots show the final product of this preliminary work, (easily transformed to elastic constants from equations

in Auld [6]), and give the experimenter a feeling for how the velocity of the material under test changes over temperature. It also shows the deterioration of the transducer/cube bond at high temperatures.

# CHAPTER 7

# CONCLUSION

This research has shown the implementation of a measurement system that was developed to obtain acoustic velocities of new piezoelectric materials. The validity of this system was shown using measurements of quartz, a piezoelectric material whose properties are well known. The validity of the system was also shown using a mathematical simulation. Basic material properties of the test cubes, transducers, and bonding material were used as a basis for deriving the impedances used in transmission line theory, the model used for simulation. A small parallel load resistor was attached to the end of the cube in the simulation to account for some second and third order effects.

Frequency padding in the time domain was used to increase time domain accuracy beyond our ability to resolve individual quantization points at the start of a pulse in the time domain. The results of simulations and measured data sets show the slight time shifts that can results from padding with even a very small magnitude and phase component. These shifts in time were consistent and repeatable, and a method of compensating for time shifts was discussed.

The measurement and simulation process was used on langatite (LGT), a new piezoelectric material, and results at room temperature of X-axis longitudinal mode velocity were presented and discussed. Experimental results with quartz verify that the

measurement process presented is valid for velocity measurements on any axis of a cubed material for both shear and longitudinal mode velocities.

# APPENDIX A

# LABWINDOWS CODE

The majority of this program was obtained from National Instruments web site. It is included here to show the additions required to automate the data taking process over temperature and obtain calibrated data across the bus of the HP network analyzer. The variable dtype is used to select calibrated data readings from the HP. This change is made in the user interface (code not shown here). This variable was added to some of the functions in the code, and the integer for calibrated data was not an option in the original user interface. Major modifications were made to "configMeasurement," and "SaveData," while "DataRun" and "GetTemp" were created to perform the automation and temperature retrieval, respectively. Several global variables were also added. Note that other basic code segments are required to interface the HP network analyzer, and these segments are included in the basic package downloaded from National Instruments.

```
// modified on 02/22/99 to handle long filenames for datafiles in datarun routine. //



#include <ansi_c.h>
#include <utility.h>
#include <analysis.h>
#include <formatio.h>
#include <stdlib.h>
#include <userint.h>
#include "hp8753x.h"
#include "hp8753xu.h"
#include "ykut.h"                              /*for Yokogawa */
#include "rs232.h"                     /*for Yokogawa */

// Before running the UIR you should make sure that the Stack Size is at least 150K
// The Stack Size is set in the Project's Options -> Run Options Menu
/*= Global Variable Definitions ============================================*/
short uirCode;
long panelHandle[10];
unsigned long instrHandle;
double realData[1601], imagData[1601], gFreq[1601];
ViStatus uirErr;

int timerstart = 0;
double temprecord[2000], templimit;
int count, count2, setflag;
const char standardstr[20];


/*=================== Utility Function Declarations =========================*/
long abortApplication (void);

float GetTemp(void);   /*added by skf 11/98 */

/*= Message Arrays ==========================================================*/
static char *initCtrlsHelpStr[] = {"\nThis control selects the address of the device that
is to be\n"
                                   "initialized.\n\n"
                                   "Valid Range:  Address 0 to 31\n\n"
                                   "Default Value:  Address 16",

                                   "\nThis control specifies if an ID Query is sent to
the\n"
                                   "instrument during the initialization procedure.\n\n"
                                   "Valid Range:\n"
                                   "VI_OFF (0) - Skip Query\n"
                                   "VI_ON  (1) - Do Query (Default Value)",

                                   "\nThis control specifies if the instrument is to be
reset to its\n"
                                   "power-on settings during the initialization
procedure.\n\n"
                                   "Valid Range:\n"
                                   "VI_OFF (0) - Don't Reset\n"
                                   "VI_ON  (1) - Reset Device (Default Value)"};

static char *configCtrlsHelpStr[] = {
                                   "This control selects the instrument's example
functionality. The\n"
                                   "items from the top to the bottom provided
instrument's reset,\n"
                                   "configuration of desired parameters and result
measurement.\n\n"
                                   "Valid Range:\n"
                                   "0 - Reset Instrument\n"
                                   "1 - Reconfigure Instrument (Default Value)\n"
                                   "2 - Measure Only",

                                   "This control selects the desired channel.\n\n"
                                   "Valid Range:\n"
                                   "VI_OFF (0) - Channel 1 (Default Value)\n"
                                   "VI_ON (1) - Channel 2",
```

```
                                "This control selects the stimulus mode.\n\n"
                                "Valid Range:\n"
                                "VI_OFF (0) - Continual\n"
                                "VI_ON  (1) - Single (Default Value)\n\n"
                                "Notes:\n\n"
                                "(1) Continual:\n"
                                "Select continual sweep.\n\n"
                                "(2) Single:\n"
                                "Execute a single group of sweeps, then hold.",

                                "This control selects number of measured points for
both channels.\n\n"
                                "Valid Range:\n"
                                "3\n"
                                "11\n"
                                "26\n"
                                "51\n"
                                "101\n"
                                "201 (Default Value)\n"
                                "401\n"
                                "801\n"
                                "1601",

                                "Desired S-parameter (S11, S21, S12, S22).\n\n"
                                "Valid Range:\n"
                                "0 - S11 (Default Value)\n"
                                "1 - S21\n"
                                "2 - S12\n"
                                "3 - S22",

                                "This control sets the entry frequency stimulus start
value.\n\n"
                                "Valid Range: 0.3 to 500000.0\n\n"
                                "Default Value: 100.0 MHz",

                                "This control sets the entry frequency stimulus stop
value.\n\n"
                                "Valid Range: 0.3 to 500000.0\n\n"
                                "Default Value: 200.0 MHz",

                                "I added this control."};

static char backgroundPnlHelpStr[] = {
                                "This example presents how to use this instrument
driver\n"
                                "which supports HP 8753x Network Analyzer.\n\n"
                                "Before running the UIR you should make sure that the
\n"
                                "Stack Size is at least 150K!\n"
                                "The Stack Size is set in the Project's Options Menu -
-> Run Options SubMenu"};

static char initPnlHelpStr[] =     {"This panel performs the following initialization
actions:\n\n"
                                "- Opens a session to the Default Resource Manager
resource and a\n"
                                "session to the specified device using the interface
and address\n"
                                "specified in the Resource_Name control.\n\n"
                                "- Performs an identification query on the
Instrument.\n\n"
                                "- Resets the instrument to a known state.\n\n"
                                "- Sends initialization commands to the instrument
that set any\n"
                                "necessary programmatic variables such as Headers Off,
Short\n"
                                "Command form, and Data Transfer Binary to the state
necessary\n"
                                "for the operation of the instrument driver.\n\n"
                                "- Returns an Instrument Handle which is used to
differentiate\n"
                                "between different sessions of this instrument
driver.\n\n"
                                "- Each time this function is invoked a Unique Session
is opened.\n"
```

```
                                    "It is possible to have more than one session open for
the same\n"
                                    "resource."};

static char configPnlHelpStr[] = {"This panel configures the instrument."
};

static char measPnlHelpStr[] =   {"\nThis panel displays the measured values.\n"
                                    "Configuration of the instrument is not\n"
                                    "possible with this panel. Press the\n"
                                    "\"Configure\" button to return to\n"
                                    "the configuration panel."};

/*= Main Function ==========================================================*/

void main ()
{
    // Load panels.
    panelHandle[BCKGRND] = LoadPanel (panelHandle[BCKGRND], "hp8753xs.uir", BCKGRND);
    panelHandle[MEAS] = LoadPanel (panelHandle[BCKGRND], "hp8753xs.uir", MEAS);
    panelHandle[CONFIG] = LoadPanel (panelHandle[BCKGRND], "hp8753xs.uir", CONFIG);
    panelHandle[INIT] = LoadPanel (panelHandle[BCKGRND], "hp8753xs.uir", INIT);
    // Display panels.
    DisplayPanel (panelHandle[BCKGRND]);
    DisplayPanel (panelHandle[INIT]);
    SetActiveCtrl (panelHandle[CONFIG], CONFIG_CONTINUE);
    SetActiveCtrl (panelHandle[MEAS], MEAS_MEASUREMENT);

    uirCode = RunUserInterface ();
}

/*===========================================================================*/
/* Function: Initialize Instrument                                           */
/* Purpose:  This is a callback function of the Continue button on the       */
/*           Initialize panel. It initializes the instrument and switches to */
/*           the panel Configure.                                            */
/*===========================================================================*/
int CVICALLBACK initInstrument (int panel, int control, int event,
        void *callbackData, int eventData1, int eventData2)
{

    ViChar instrDescr[256], errorMessage[256], errBuffer[256];
    ViInt16 response, addr, rst, id;

    switch (event) {
        case EVENT_COMMIT:
            SetWaitCursor(0);
            GetCtrlVal (panelHandle[INIT], INIT_ADDRESS, &addr);
            GetCtrlVal (panelHandle[INIT], INIT_ID, &id);
            GetCtrlVal (panelHandle[INIT], INIT_RST, &rst);
            Fmt (instrDescr, "GPIB::%d[b2]", addr);
            SetWaitCursor(1);
            if ((uirErr = hp8753x_init (instrDescr, id, rst, &instrHandle)) < 0 ) {
                hp8753x_errorMessage (VI_NULL, uirErr, errorMessage);
                Fmt (errBuffer, "%s<Initialization Error:\n\n%s\n\nCheck your "
                        "connections and make sure you have the right GPIB address.",
                        errorMessage);
                MessagePopup ("ERROR!", errBuffer);
                SetWaitCursor(0);
                return(0);
            }
            SetWaitCursor(0);
            HidePanel (panelHandle[INIT]);
            DisplayPanel (panelHandle[CONFIG]);
            break;
        case EVENT_RIGHT_CLICK:
            MessagePopup ("Help","This button causes the instrument to be initialized.");
            break;
    }
    return 0;
}

/*===========================================================================*/
/* Function: Configure Measurement                                           */
/* Purpose:  This is a callback function of the Continue button on the       */
```

```
/*           Configure panel (configure & measure).                          */
/*===========================================================================*/
int CVICALLBACK configMeasurement (int panel, int control, int event,
        void *callbackData, int eventData1, int eventData2)
{
    char errMsg[256];
    int datatype = 0;
    int action, channel, stimulus, display, sparam, points =1601;
    double startFrq, stopFrq;

    switch (event) {
        case EVENT_COMMIT:
            SetWaitCursor(0);
            HidePanel (panelHandle[CONFIG]);
            DisplayPanel (panelHandle[MEAS]);
            GetCtrlVal (panelHandle[CONFIG], CONFIG_SIGTYPE, &datatype);
            GetCtrlVal (panelHandle[CONFIG], CONFIG_ACTION, &action);
            GetCtrlVal (panelHandle[CONFIG], CONFIG_CHANNEL, &channel);
            GetCtrlVal (panelHandle[CONFIG], CONFIG_STIMULUS, &stimulus);
            GetCtrlVal (panelHandle[CONFIG], CONFIG_SPARAM, &sparam);
            GetCtrlVal (panelHandle[CONFIG], CONFIG_START, &startFrq);
            GetCtrlVal (panelHandle[CONFIG], CONFIG_STOP, &stopFrq);
            SetCtrlVal (panelHandle[MEAS], MEAS_LF, startFrq);
            SetCtrlVal (panelHandle[MEAS], MEAS_HF, stopFrq);
            GetCtrlVal (panelHandle[CONFIG], CONFIG_POINTS, &points);
            DeleteGraphPlot (panelHandle[MEAS], MEAS_GRAPH, -1, VAL_IMMEDIATE_DRAW);
            SetCtrlAttribute (panelHandle[MEAS], MEAS_GRAPH, ATTR_XAXIS_OFFSET, startFrq);
            SetCtrlAttribute (panelHandle[MEAS], MEAS_GRAPH, ATTR_XAXIS_GAIN, (stopFrq-
startFrq)/points);
            SetWaitCursor(1);

            if ((uirErr = hp8753x_appExample (instrHandle, action, sparam, points,
startFrq*1000000.0,
                    stopFrq*1000000.0, channel, realData, imagData, stimulus, datatype)) <
0) {
                if (uirErr >= 0xBFFF0000) {
                    abortApplication ();
                }
                else {
                    SetWaitCursor(0);
                    hp8753x_errorMessage (VI_NULL, uirErr, errMsg);
                    MessagePopup ("Error", errMsg);
                    return 0;
                }
            }
            PlotY (panelHandle[MEAS], MEAS_GRAPH, realData, points, VAL_DOUBLE,
VAL_THIN_LINE, VAL_NO_POINT, VAL_SOLID, 1, VAL_BLUE);
            SetWaitCursor(0);
            break;
        case EVENT_RIGHT_CLICK:
            MessagePopup ("Help","This button will configure the instrument to take a
measurement.");
            break;
    }
    return 0;
}

/*===========================================================================*/
/* Function: Take Measurement                                                */
/* Purpose:  This is a callback function of the button Measure on the        */
/*           panel Measure. It returns a measurement value without           */
/*           reconfiguring of the instrument.                                */
/*===========================================================================*/
int CVICALLBACK takeMeasurement(int panel, int control, int event,
        void *callbackData, int eventData1, int eventData2)
{
    long error, sparam, points = 1601;
    short dataStatus;
    int dtype;
    double primaryValue, secondaryValue;
    char errMsg[256], rdBuf[256];

    switch (event) {
        case EVENT_COMMIT:
            SetWaitCursor(1);
```

```
            GetCtrlVal (panelHandle[CONFIG], CONFIG_SPARAM, &sparam);
                            GetCtrlVal (panelHandle[CONFIG], CONFIG_SIGTYPE, &dtype);

            if ((uirErr = hp8753x_appExample (instrHandle, 2, sparam, points,
                1.0e+8, 2.0e+8, VI_OFF, realData, imagData, VI_OFF, dtype)) < 0) {
                if (uirErr >= 0xBFFF0000) {
                    abortApplication ();
                }
                else {
                    SetWaitCursor(0);
                    hp8753x_errorMessage (VI_NULL, uirErr, errMsg);
                    MessagePopup ("Error", errMsg);
                    return 0;
                }
            }
            DeleteGraphPlot (panelHandle[MEAS], MEAS_GRAPH, -1, VAL_IMMEDIATE_DRAW);
            GetCtrlVal (panelHandle[CONFIG], CONFIG_POINTS, &points);
            PlotY (panelHandle[MEAS], MEAS_GRAPH, realData, points, VAL_DOUBLE,
VAL_THIN_LINE, VAL_NO_POINT, VAL_SOLID, 1, VAL_BLUE);
            SetWaitCursor(0);
            break;
        case EVENT_RIGHT_CLICK:
            MessagePopup ("Help","This button will return the new meaurement value.");
            break;
    }
    return 0;
}

/*=========================================================================*/
/* Function: Cancel                                                        */
/* Purpose:  Called by the init panel this function pops up a confirmation   */
/*           dialog box and then quits the user interface, if desired.       */
/*=========================================================================*/
int CVICALLBACK Cancel (int panel, int control, int event,
        void *callbackData, int eventData1, int eventData2)
{
    SetWaitCursor(0);
    switch (event) {
        case EVENT_COMMIT:
            if ((ConfirmPopup ("Exit Application",
                   "Are you sure you want to quit this application?")) == 1) {
                QuitUserInterface (uirCode);
            }
            break;
        case EVENT_RIGHT_CLICK:
            MessagePopup ("Control Help", "Closes the application.");
            break;
    }
    return 0;
}

/*=========================================================================*/
/* Function: Control Help                                                  */
/* Purpose:  This is a callback function of all controls that configure the  */
/*           instrument. On the right mouse-click on the control a help      */
/*           window describing its purpose is displayed.                     */
/*=========================================================================*/
int CVICALLBACK controlHelp (int panel, int control, int event,
        void *callbackData, int eventData1, int eventData2)
{
    SetWaitCursor(0);
    if (event == EVENT_RIGHT_CLICK) {
        if (panel == panelHandle[INIT])
            MessagePopup ("Help", initCtrlsHelpStr[control-4]);
        if (panel == panelHandle[CONFIG])
            MessagePopup ("Help", configCtrlsHelpStr[control-2]);
    }
    return 0;
}

/*=========================================================================*/
/* Function: Launch Configure Panel                                        */
/* Purpose:  This is a callback function of the button Configure on the      */
/*           panel Measure. It returns back to the Configuration panel to be */
/*           able to change configuration without having to re-run this      */
```

```
/*          program.                                                          */
/*============================================================================*/
int CVICALLBACK launchConfig (int panel, int control, int event,
        void *callbackData, int eventData1, int eventData2)
{
    SetWaitCursor(0);
    switch (event) {
        case EVENT_COMMIT:
            HidePanel (panelHandle[MEAS]);
            DisplayPanel (panelHandle[CONFIG]);
            break;
        case EVENT_RIGHT_CLICK:
            MessagePopup ("Help","This button will recall the configuration panel.");
            break;
    }
    return 0;
}

/*============================================================================*/
/* Function: Panel Help                                                       */
/* Purpose:  This is a callback function of the menu bar. It displays a help */
/*           window describing panel being used.                              */
/*============================================================================*/
void CVICALLBACK panelHelp (int menuBar, int menuItem, void *callbackData,
        int panel)
{
    SetWaitCursor(0);
    if (panel == panelHandle[BCKGRND])
        MessagePopup ("Help", backgroundPnlHelpStr);
    if (panel == panelHandle[INIT])
        MessagePopup ("Help", initPnlHelpStr);
    if (panel == panelHandle[CONFIG])
        MessagePopup ("Help", configPnlHelpStr);
    if (panel == panelHandle[MEAS]) {
        MessagePopup ("Help", measPnlHelpStr);
    }
    return;
}

/*============================================================================*/
/* Function: SaveData                                                         */
/* Purpose:  This is a callback function of the button Save on the            */
/*           panel Measure. It pops-up a panel that will prompt for           */
/*           a file name to save data to.                                     */
/*============================================================================*/
int CVICALLBACK SaveData (int panel, int control, int event,
              void *callbackData, int eventData1, int eventData2)
{

    static double datapoints[1602];
    static char pathname[MAX_PATHNAME_LEN], dirname[MAX_PATHNAME_LEN];
    int status, num, i, points;
    double startFrq, stopFrq;
    static FILE *file_handle;

        switch (event)
               {
               case EVENT_COMMIT:
                       GetProjectDir (dirname);
            status = FileSelectPopup (dirname, "datafile.dat",
                                      "Datafiles (*.dat)", "DataFile Storage",
                                      VAL_SAVE_BUTTON, 0, 1, 1, 1, pathname);

            if (status != VAL_NO_FILE_SELECTED)
               {
               GetCtrlVal (panelHandle[CONFIG], CONFIG_POINTS, &points);
               GetCtrlVal (panelHandle[CONFIG], CONFIG_START, &startFrq);
               GetCtrlVal (panelHandle[CONFIG], CONFIG_STOP, &stopFrq);
                file_handle = fopen (pathname, "w+");
                for(i=0; i<points; i++)
                       {
                                              gFreq[i] = startFrq + (stopFrq-
startFrq)*i/(points-1);
                  num = fprintf (file_handle, "%f, %f, %f\n", gFreq[i], realData[i],
imagData[i]);
```

```
                                        }
                fclose (file_handle);
                }
                        break;
                case EVENT_RIGHT_CLICK:
        MessagePopup ("Save Button Help",
                  "This button saves the waveform to a data file");
                        break;
                }
        return 0;
}

/*=========================================================================*/
/* Function: DataRun                                                       */
/* Purpose:  This is a callback function of the button DataRun on the      */
/*           panel Measure. All temperature values are built in for now.   */
/*                              This part of the program automates the data "measure" and
"save"*/
/*                              buttons on the user interface.  Data is aquired and saved
        */
/*                              according to an algorithm that keeps track of the last 5
measured
/*                              temperatures.  The program terminates on a specific
temperature  */
/*                              that is entered in the code of the program and a record of
all  */
/*                              the measured temperatures is recorded.  Temperature
measuring   */
/*                              intervals are set in the user interface panel (30 seconds),
but */
/*                              can be easily changed.  Yokogawa temperature controller
runs a  */
/*                              temperature ramp on its own.  This revision is from 11/98
by SKF*/
/*=========================================================================*/
int CVICALLBACK DataRun (int panel, int control, int event,
                void *callbackData, int eventData1, int eventData2)
{
        const double deltat = .5;                   /* reduce as temp profiles are
studied */
        const double templimit = 150.0;
    static double datapoints[1602];
    static char pathname[MAX_PATHNAME_LEN], dirname[MAX_PATHNAME_LEN];
    const char newfile[100], test1[100];
    int status, num, i, points;

    double startFrq, stopFrq, degrees, avgtemp;
    static FILE *file_handle;
    long error, sparam;
    short dataStatus;
    int dtype;
    double primaryValue, secondaryValue;
    char errMsg[256], rdBuf[256],tempstr[5], pol[2];


       switch (event)
                {
                case EVENT_COMMIT:
                        timerstart = 1;               /*global variable initially assigned
to zero */
                        ResumeTimerCallbacks();
                        count = 0;                                      /*count keeps track of
the number of times data is recorded and saved */
                        count2 = 0;                                     /*count2 keeps track
of the number of times temperature is measured */
                        setflag = 0;
                        degrees = 19.0;

                        printf("enter the default string to use in each file name.\n");
                        printf("use the format: XXX_YYY_ZZZ_A_B  where X is measurement
type (S11),\n");
                        printf("Y is the material type (QTZ for quartz),  \n");
                        printf("Z is the material identifier (012 for example), \n");
                        printf("A is the axis of measurement, and B is the type of wave (L
ongitudinal or S hear).\n");
```

```
                        scanf("%s", standardstr);
                        SetStdioWindowVisibility(0);


                case EVENT_TIMER_TICK:

                        setflag = 0;
                        /*measure and display temp */
                        degrees = GetTemp();
                        SetCtrlVal (panelHandle[MEAS], MEAS_CSLIDE, degrees);

                        /*process degrees here - set flag if degrees is same for last 5
temperature readings*/
                        /* this is the algorithm for taking and saving a datarun. Use
templimit +1 to guarantee */
                        /* a data run at templimit */
                        if ( (degrees < (templimit+.5)) && (timerstart != 0) )
                                {
                                temprecord[count2] = degrees;
                                if (count2 >= 4)              /* you have atleast 5
temperature measurements */
                                        {
                                        avgtemp =  (temprecord[count2]+temprecord[count2-
1]+temprecord[count2-2]+
                                                                        temprecord[count2-
3]+temprecord[count2-4])/5;
                                        /*printf("avg  %f",avgtemp);  */
                                        if  ((fabs(avgtemp-temprecord[count2])<=deltat) &&
         /* last five temperature readings are */
                                                (fabs(avgtemp-temprecord[count2-
1])<=deltat) &&         /* within deltat of each other then set flag*/
                                                (fabs(avgtemp-temprecord[count2-
2])<=deltat) &&
                                                (fabs(avgtemp-temprecord[count2-
3])<=deltat) &&
                                                (fabs(avgtemp-temprecord[count2-
4])<=deltat))
                                                setflag = 1;
                                        }

                                count2 = count2+1;
                                if (setflag)                    /*you want to measure and
save data*/
                                        {
                                        count = count+1;
                                        /*measure data and display*/
                                        GetCtrlVal (panelHandle[CONFIG], CONFIG_SPARAM,
&sparam);
                                        GetCtrlVal (panelHandle[CONFIG], CONFIG_SIGTYPE,
&dtype);
                                        GetCtrlVal (panelHandle[CONFIG], CONFIG_POINTS,
&points);
                                        SetWaitCursor(1);
                if ((uirErr = hp8753x_appExample (instrHandle, 2, sparam, points,
        /* if there is an error getting data*/
                        1.0e+8, 2.0e+8, VI_OFF, realData, imagData, VI_OFF, dtype)) < 0)
                        {
                if (uirErr >= 0xBFFF0000) {
                        abortApplication ();
                                }
                                else
                                {
                        SetWaitCursor(0);
                        hp8753x_errorMessage (VI_NULL, uirErr, errMsg);
                        MessagePopup ("Error", errMsg);
                        return 0;
                                }
                        }  /* end if there is an error*/

                DeleteGraphPlot (panelHandle[MEAS], MEAS_GRAPH, -1, VAL_IMMEDIATE_DRAW);
                GetCtrlVal (panelHandle[CONFIG], CONFIG_POINTS, &points);
                PlotY (panelHandle[MEAS], MEAS_GRAPH, realData, points, VAL_DOUBLE,
VAL_THIN_LINE, VAL_NO_POINT, VAL_SOLID, 1, VAL_BLUE);
                SetWaitCursor(0);
```

```
                                    /*create file name - pathname from above*/
                                    if (count <= 9)
                                            Fmt (newfile,
"d:\\dataruns\\%s_%f[p0w3]_00%d.dat", standardstr, degrees ,count);
                                    else if ((count > 9)&&(count < 100))
                                            Fmt (newfile,
"d:\\dataruns\\%s_%f[p0w3]_00%d.dat", standardstr, degrees ,count);
                                    else
                                            Fmt (newfile,
"d:\\dataruns\\%s_%f[p0w3]_00%d.dat", standardstr, degrees ,count);
                                    /*save data  to file in path above */
                GetCtrlVal (panelHandle[CONFIG], CONFIG_START, &startFrq);
                GetCtrlVal (panelHandle[CONFIG], CONFIG_STOP, &stopFrq);
                file_handle = fopen (newfile, "w+");
                gFreq[0] = startFrq;
                num = fprintf (file_handle, "%f, %f, %f, %f\n", gFreq[0], realData[0],
imagData[0], degrees);
                for(i=1; i<points; i++)
                        {
                                    gFreq[i] = startFrq + (stopFrq-
startFrq)*i/(points-1);
                   num = fprintf (file_handle, "%f, %f, %f\n", gFreq[i], realData[i],
imagData[i]);
                                    }
                fclose (file_handle);
                setflag = 0;
                                    }        /* end if(setflag)  */
                               }            /* end if less than temp limit */
                               if ( (degrees >= (templimit+.5)) && (timerstart != 0) )
                                    {
                                    /*save temperature record - you are done*/
                                    SuspendTimerCallbacks();
                                    timerstart = 0;
                                    Fmt(newfile,
"d:\\dataruns\\%stemprec.dat",standardstr);
                                    file_handle = fopen (newfile, "w+");
                for(i=0; i<count2; i++)
                        {
                   num = fprintf (file_handle, "%f\n", temprecord[i]);
                                    }
               fclose (file_handle);
                                }
                        break;          /* EVENT_TIMER_TICK */
                case EVENT_RIGHT_CLICK:
                MessagePopup ("RunData Button Help",
                   "This button runs a program snd temperature dependent algorithm for
multiple data runs.");
                        break;
                }                        /* end switch (event) */
        return 0;
}                                       /* end CVI callback DataRun */

/*=========================================================================*/
/* Function: Launch Close Panel                                            */
/* Purpose:  This is a callback function of the button Close on the        */
/*           panel Measure. It pops-up a panel that will close the         */
/*           instrument.                                                   */
/*=========================================================================*/
int CVICALLBACK launchClose (int panel, int control, int event,
        void *callbackData, int eventData1, int eventData2)
{
    ViChar errorMessage[256], errBuffer[256];
    ViInt16 response;

    SetWaitCursor(0);
    switch (event) {
        case EVENT_COMMIT:
            if ((ConfirmPopup ("Exit Application", "Are you sure you want to quit "
                "this application?")) == 1) {
                if ((uirErr = hp8753x_close (instrHandle)) < 0) {
                    hp8753x_errorMessage(VI_NULL, uirErr, errorMessage);
                    Fmt (errBuffer, "%s<Application failed to close the "
                        "instrument.\n\n%s\n\nExiting Application.", errorMessage);
                    MessagePopup("ERROR!", errBuffer);
                }
```

```
                QuitUserInterface (uirCode);
                exit (-1);
            }
            break;
        case EVENT_RIGHT_CLICK:
            MessagePopup ("Help","This button will pop-up a panel to close the
instrument.");
            break;
    }
    return 0;
}

/*****************************************************************************/
long abortApplication (void)
{
    ViChar errorMessage[256], errBuffer[256];
    ViInt16 response;

    SetWaitCursor (0);
    hp8753x_errorMessage(VI_NULL, uirErr, errorMessage);
    Fmt (errBuffer,"%s<The following error caused the application to fail:\n\n%s\n\n"
        "Attempting to Close Instrument Driver and Exit Application",
        errorMessage);
    MessagePopup("ERROR!, Application Failed", errBuffer);

    if ((uirErr = hp8753x_close (instrHandle)) < 0) {
        hp8753x_errorMessage(VI_NULL, uirErr, errorMessage);
        Fmt (errBuffer, "%s<Application failed to close the Instrument Driver.\n\n"
            "%s\n\nExiting Application.", errorMessage);
        MessagePopup("ERROR!",errBuffer);
    }
    else
        MessagePopup("Application Aborted","Instrument Driver Closed, Exiting
Application.");

    QuitUserInterface (uirCode);
    exit (-1);

    return 0;
}

/*===========================================================================*/
/* Function: GetTemp                                                         */
/* Purpose:  This is a function used by the callback function of the button  */
/*                              DataRun on the panel Measure. It simlpy queries the
Yokogawa         */
/*                              UP550-01 controller for temperature data in degrees celsius
with*/
/*                              two decimal places.  Controller must be configured to
display  */
/*                              two decimal places.
                                                                    */
/*===========================================================================*/

float GetTemp(void)

{
char *hex;
const short int STX=0x02, ETX=0x03, CR=0x0D;
char *output, *input, *test;
int in_len_data = 12, yut_dev_addr = 1,x;
static unsigned char yut_out_buffer[256];
static char yut_in_buffer[256];
unsigned int z;
int calc;
float mtemp;

 Cls();
 OpenComConfig(2,"COM2", 9600,2,8,1,256,256);
 SetCTSMode (2,0);
 SetXMode(2,0);
                    /* Fmt (yut_out_buffer, "%c01010INF6%c%c",STX,ETX,CR);       IF
NEEDED TO VERIFY OPERATION*/
 yut_err=0;
 output=yut_out_buffer;
```

```
 input=yut_in_buffer;
 FlushOutQ(2);
 FlushInQ(2);

 Fmt (yut_out_buffer, "%c01010WRDD0003,01%c%c", STX, ETX, CR);
 output=yut_out_buffer;
 x=ComWrt(2,output, 19);

 x=ComRdTerm (2, input, 40, 13);
 input=yut_in_buffer + 7;
 /* printf("%s\n",yut_in_buffer); */
 Scan (input, "%s>%x4", &calc);       /*put 4 bytes of string (hex values) into decimal
*/
 if (calc > 32768)                                    /* if temp has gone below 0 degrees
C */
        calc = calc - 65536;
 mtemp=(calc/100.0);                                 /*change this to 10 if using one
decimal place on controller */
                      /*printf("The temperature is: %6.2f degrees Celcius.\n", mtemp);
*/

 yut_err=0;
 yut_close();
 return(mtemp);         /*return temperature in degrees celsius with 2 decimal places */
}

/*= End ==========================================================================*/
```

# APPENDIX B

# MATHCAD SIMULATION

Transducer - cube matrix model

This file finally has a mathematically correct model for the transducer. Some parameters can still be tweaked a bit, but everything is in the right order of magnitude. The assumption made, and supported by the references is that the acoustic port on the open end of the transducer is a zero in the matrix math, allowing the reduction of the 3x3 matrix to a 2x2. The assumption also made it that one acoustic ohm (kg/s) is equal to one electrical ohm. This version derives the material impedences from the material parameters. Note that the electrical port on the transducer is port 1. This revision furnishes smoothed data and pads frequency points down to near zero. Final version. Padding with first point down to zero and last point up to desired fmax.

Constants:

$c := 2.99 \cdot 10^{8} \cdot \frac{m}{s}$ $j := \sqrt{-1}$ $dB := 1$ $um := 10^{-6} \cdot m$ $f_0 := 10 \cdot MHz$ $ns := 10^{-9} \cdot s$

$\varepsilon_0 := 8.854 \cdot 10^{-12} \cdot \frac{farad}{m}$ $uH := 10^{-6} \cdot H$ $Z_0 := 50 \cdot ohm$ $us := 10^{-6} \cdot s$

Variables:

$k := .33$ Coupling coefficient used for transformer modelling of electrical port on transducer

A k value of .3 will produce an acceptable Zin graph, but k of .4 or so is what is expected.

$f_{start} := 1 \cdot MHz$ $f_{stop} := 19.0000000 \cdot MHz$ $w(f) := 2 \cdot \pi \cdot f$

$BW := f_{stop} - f_{start}$ $\Delta f := \frac{BW}{1600}$ $f := f_{start}, f_{start} + \Delta f .. f_{stop}$

$\Delta f =$

Frequency and material dependent variables:

$vlinb_L := 7315 \cdot \frac{m}{sec}$ $vlinb_{FS} := 4525 \cdot \frac{m}{sec}$

from Mauricio 36 degree Y cut from Mauricio 41 degree X cut

$v_{bond} := 2900 \cdot \frac{m}{sec}$ estimated by comparing simulation to measured data

material velocities below for LGT Velocities for LGT obtained from our results at room temperature; slow shear velocities are difficult to resolve.

$vmx_{FS} := 3144 \cdot \frac{m}{sec}$ $vmy_{FS} := 2844 \cdot \frac{m}{sec}$ $vmz_{FS} := 2895 \cdot \frac{m}{sec}$ $vm45_{FS} := 3095 \cdot \frac{m}{sec}$

$vmx_{SS} := 3140 \cdot \frac{m}{sec}$ $vmy_{SS} := 2608 \cdot \frac{m}{sec}$ $vm45_{SS} := 3090 \cdot \frac{m}{sec}$

$vmx_L := 5601 \cdot \frac{m}{sec}$ $vmy_L := 5610 \cdot \frac{m}{sec}$ $vmz_L := 6587 \cdot \frac{m}{sec}$ $vm45_L := 6169 \cdot \frac{m}{sec}$

## Set transducer and cube velocities below:

$v_{tran} := vlinb_L$ $v_{cube} := vmx_L$

## Use material properties to find impedance of transducer:

$r_{tran} := .00165 \cdot m$ radius of active transducer electrode $\rho_{tran} := 4644 \cdot \frac{kg}{m^3}$ Mitch - Paper 1994 freq control

$r_{cap} := .00172 \cdot m$ use this radius to calculate capacitance of transducer (physical radius of active portion)

$A_{tran} := \pi \cdot r_{tran}^2$ $\eta_{tran} := .9 \cdot N \cdot \frac{s}{m^2}$ use .7 increase to get wider BW

$Zim_{01a} := j \cdot \left[ \sqrt{\left( w\left( f_0 \right) \cdot \eta_{tran} \right) \cdot \rho_{tran}} \cdot A_{tran} \right]$

$Z_{01a} := \left( A_{tran} \cdot \rho_{tran} \cdot v_{tran} \right) + Zim_{01a}$

$Z_{01} := Z_{01a} \cdot ohm \cdot \frac{s}{kg}$ $Z_{01a} = 290.552 + 4.383i \frac{kg}{s}$

## Use material properties to find impedance of bond:

$r_{bond} := .00160 \cdot m$ radius of active transducer electrode $\rho_{bond} := 2400 \cdot \frac{kg}{m^3}$ $\eta_{bond} := 4 \cdot N \cdot \frac{s}{m^2}$

$A_{bond} := \pi \cdot r_{bond}^2$

$Zim_{02a} := j \cdot \left[ \sqrt{\left( w\left( f_0 \right) \cdot \eta_{bond} \right) \cdot \rho_{bond}} \cdot A_{bond} \right]$

$Z_{02a} := \left( A_{bond} \cdot \rho_{bond} \cdot v_{bond} \right) + Zim_{02a}$ $A_{bond} = 8.042 \cdot 10^{-6} \, m^2$

$Z_{02} := Z_{02a} \cdot ohm \cdot \frac{s}{kg}$ $Z_{02} = 55.976 + 6.246i \, \Omega$

## Use material properties to find impedance of cube:

$r_{cube} := .00115 \cdot m$ effective radius after reflection $\rho_{cube} := 6150.4 \cdot \frac{kg}{m^3}$ our measurements of LGT

$\eta_{cube} := .41 \cdot N \cdot \frac{s}{m^2}$ .5 works here

$A_{cube} := \pi \cdot r_{cube}^2$

$$Zim_{03a} := j\cdot\left[\sqrt{\left(w\left(f_0\right)\cdot\eta_{cube}\right)\cdot\rho_{cube}}\cdot A_{cube}\right]$$

$Z_{03a} := \left(A_{cube}\cdot\rho_{cube}\cdot v_{cube}\right) + Zim_{03a}$

$A_{cube} = 4.155\cdot10^{-6}\ m^2$

$Z_{03} := Z_{03a}\cdot ohm\cdot\frac{s}{kg}$

$Z_{03a} = 143.125 + 1.654i\ \frac{kg}{s}$

$Z_{04} := 8\ ohm + j\cdot0\cdot ohm$ load resistor for cube

## Wavelength and length variables:

$\lambda_1(f) := \frac{v_{tran}}{f}$ wavelength of bulk wave in transducer $LiNbO_3$

$\lambda_1\left(f_0\right) = 0.029\cdot in$

$\lambda_2(f) := \frac{v_{bond}}{f}$ wavelength of bulk wave in bonding material

$\lambda_3(f) := \frac{v_{cube}}{f}$ wavelength of bulk wave in cube material - change above for mode of propagation

$l_1 := \frac{\lambda_1\left(f_0\right)}{2}$ propagation length in transducer-changes for shear or longitudinal

$l_1 = 0.014\cdot in$

$l_1 := .013\cdot in$ force to 13 mils from physical measurement

$l_2 := .5\cdot um$ propagation length in bonding material

$l_3 := 1.0\cdot cm$ propagation length in cube

Formulas:

$\beta_1(f) := \frac{2\cdot\pi}{\lambda_1(f)}$ $\beta_2(f) := \frac{2\cdot\pi}{\lambda_2(f)}$ $\beta_3(f) := \frac{2\cdot\pi}{\lambda_3(f)}$

## Use transducer material properties to derive transformer turns ratio for electrical model:

$\varepsilon_s := 32 \cdot \varepsilon_0$ lithium niobate dielectric constant Mitch - paper in 1994 IEEE 32

$c_{esc} := v_{tran}^2 \cdot \rho_{tran}$

$c_{esc} = 2.485 \cdot 10^{11}\ Pa$

$e_{calc} := \sqrt{k^2 \cdot c_{esc} \cdot \varepsilon_s}$ lithium niobate piezoelectric constant

$e_{calc} = 2.769 \circ \frac{coul}{m^2}$

$A_t := \pi \cdot r_{cap}^2$ active area of transducer

$C_0 := \frac{\varepsilon_s \cdot A_t}{l_1}$ static capacitance of transducer

$C_0 = 7.975 \cdot 10^{-12}\ F$

$h := \frac{e_{calc}}{\varepsilon_s}$

8pF from our measured data

$nturns := h \cdot C_0$

$nturns = 0.078\ \frac{s \cdot A}{m}$

## Now to get impedances of materials

$n := nturns$

$Z_{0T} := 50 \cdot \frac{m \cdot kg}{s^2 \cdot A}$ convert acoustic ohms to electrical ohms

$n = 0.078\ \frac{s \cdot A}{m}$

$C_0 = 7.975 \cdot 10^{-12} \circ farad$

$Z_{01a} = 290.552 + 4.383i\ \frac{kg}{s}$

$Z_{0T} = 50\ \frac{s \cdot A}{m} \circ ohm$

**Use "t" style (Mason) model for transducer with transformer on bottom of center resistor:**

$$Z_{A1}(f) := j \cdot Z_{01} \cdot \tan\left(\frac{\beta_1(f) \cdot l_1}{2}\right) \qquad Z_{B1}(f) := -j \cdot Z_{01} \cdot \csc\left(\beta_1(f) \cdot l_1\right)$$

$$Z1_{11}(f) := j \cdot \left[\frac{(n)}{w(f) \cdot C_0}\right]^2 \cdot \frac{1}{Z_{01a} \cdot \cot\left(\beta_1(f) \cdot l_1\right)} - j \cdot \frac{1}{w(f) \cdot C_0}$$

$$Z1_{12}(f) := \left[\left(-j \cdot \frac{h}{w(f)}\right) + j \cdot \frac{h}{w(f)} \cdot \frac{\csc\left(\beta_1(f) \cdot l_1\right)}{\cot\left(\beta_1(f) \cdot l_1\right)}\right] \cdot \frac{m}{s \cdot A}$$

$$Z1_{21}(f) := Z1_{12}(f)$$

$$Z1_{22}(f) := \left(-j \cdot Z_{01} \cdot \cot\left(\beta_1(f) \cdot l_1\right)\right) + j \cdot Z_{01} \cdot \frac{\left(\csc\left(\beta_1(f) \cdot l_1\right)\right)^2}{\cot\left(\beta_1(f) \cdot l_1\right)}$$

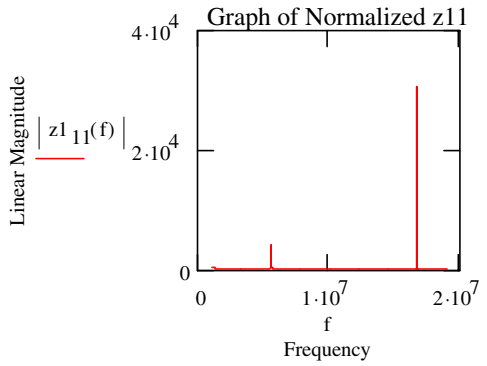
$$z1_{11}(f) := \frac{Z1_{11}(f)}{Z_0}$$

$$z1_{12}(f) := \frac{Z1_{12}(f)}{Z_0}$$

$$z1_{21}(f) := \frac{Z1_{21}(f)}{Z_0}$$

$$z1_{22}(f) := \frac{Z1_{22}(f)}{Z_0}$$

Graph and results below show low transducer impedance at center frequency




$$Z1_{11}(9.99 \cdot MHz) = -0.401 - 2.024i \cdot 10^3\ \Omega$$

$$Z1_{12}(9.99 \cdot MHz) = -319.096i \cdot ohm$$

$$Z1_{22}(9.99 \cdot MHz) = 1.395 - 92.493i\ \Omega$$

$$z1_{11}(9.99 \cdot MHz) = -8.011 \cdot 10^{-3} - 40.486i$$

$$z1_{12}(f_0) = -6.373i$$

$$z1_{21}(f_0) = -6.373i$$

$$z1_{22}(f_0) = 0.028 - 1.832i$$

## Calculate the reflection coefficient for transducer only, by making acoustic port2 equal to zero

$$Z_{tonly}(f) := Z1_{11}(f) - \frac{Z1_{21}(f) \cdot Z1_{12}(f)}{Z1_{22}(f)}$$

$$f_0 = 1 \cdot 10^7 \text{ Hz}$$

$$\text{Re}\left(Z_{tonly}(f_0)\right) = 16.323\ \Omega$$

$$Z_{tonly}(f_0) = 16.323 - 913.699i\ \Omega$$

$$z_{tonly}(f) := \frac{Z_{tonly}(f)}{Z_0}$$

$$Z1_{11}(f_0) = -0.396 - 2.022i \cdot 10^3\ \Omega$$

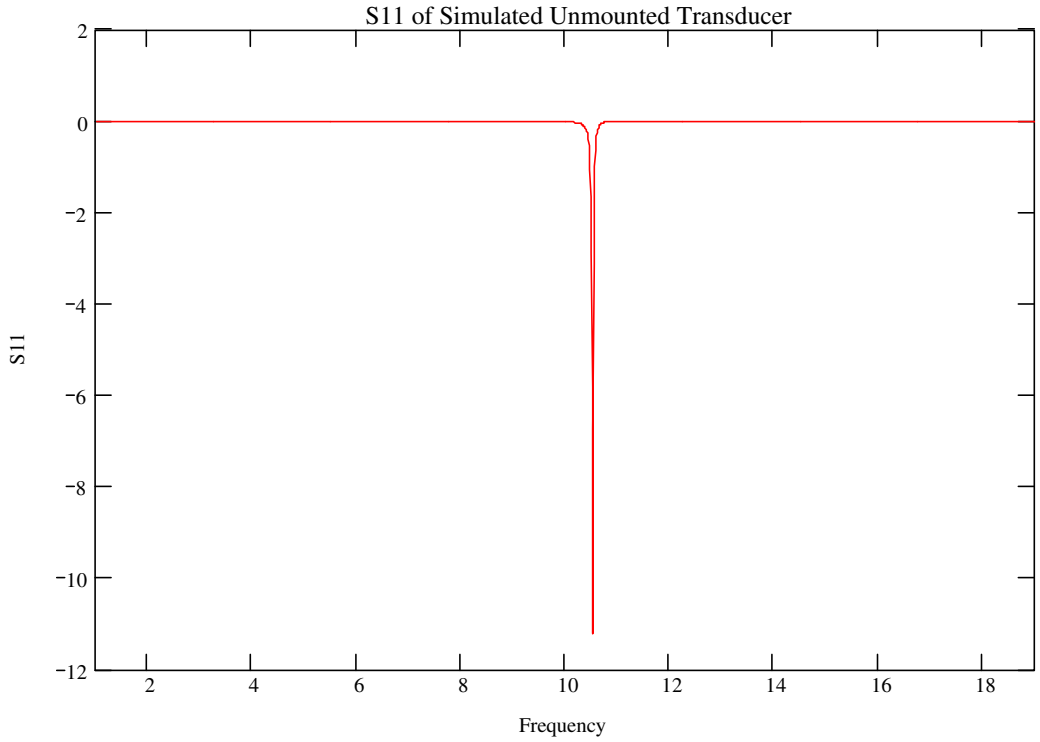
$$Z1_{12}(f_0) = -318.63i\ \Omega$$

$$S_{tonly11}(f) := \frac{z_{tonly}(f) - 1}{1 + z_{tonly}(f)}$$

$$Z1_{21}(f_0) = -318.63i\ \Omega$$

$$Z1_{22}(f_0) = 1.382 - 91.586i\ \Omega$$

$$S_{11g}(f) := 20 \cdot \log\left(\left|S_{tonly11}(f)\right|\right)$$




$$Q := \frac{\text{Im}\left(Z_{tonly}(9.46 \cdot \text{MHz})\right)}{\text{Re}\left(Z_{tonly}(9.46 \cdot \text{MHz})\right)}$$

$$Q = -109.122$$

## Impedance for bond, using t-style model:

$$Z_{A2}(f) := j \cdot Z_{02} \cdot \tan\left(\frac{\beta_2(f) \cdot l_2}{2}\right) \qquad Z_{B2}(f) := -j \cdot Z_{02} \cdot \csc\left(\beta_2(f) \cdot l_2\right)$$

$$Z2_{11}(f) := Z_{A2}(f) + Z_{B2}(f)$$

$$Z2_{12}(f) := Z_{B2}(f)$$

$$Z2_{21}(f) := Z2_{12}(f)$$

$$Z2_{22}(f) := Z2_{11}(f)$$

$$z2_{11}(f) := \frac{Z2_{11}(f)}{Z_0}$$

$$z2_{12}(f) := \frac{Z2_{12}(f)}{Z_0}$$

$$z2_{21}(f) := \frac{Z2_{21}(f)}{Z_0}$$

$$z2_{22}(f) := \frac{Z2_{22}(f)}{Z_0}$$

$$z2_{11}(10 \cdot \text{MHz}) = 11.531 - 103.338i$$

$$z2_{12}(10 \cdot \text{MHz}) = 11.532 - 103.344i$$

## Impedance for cube, using t-style model:

$$Z_{A3}(f) := j \cdot Z_{03} \cdot \tan\left(\frac{\beta_3(f) \cdot l_3}{2}\right) \qquad Z_{B3}(f) := -j \cdot Z_{03} \cdot \csc\left(\beta_3(f) \cdot l_3\right)$$

$$Z3_{11}(f) := Z_{A3}(f) + Z_{B3}(f)$$

$$Z3_{12}(f) := Z_{B3}(f)$$

$$Z3_{21}(f) := Z3_{12}(f)$$

$$Z3_{22}(f) := Z3_{11}(f)$$

$$z3_{11}(f) := \frac{Z3_{11}(f)}{Z_0}$$

$$z3_{12}(f) := \frac{Z3_{12}(f)}{Z_0}$$

$$z3_{21}(f) := \frac{Z3_{21}(f)}{Z_0}$$

$$z3_{22}(f) := \frac{Z3_{22}(f)}{Z_0}$$

## change Z matrices to S matrices

$$\Delta_1(f) := \left(z1_{11}(f) + 1\right)\cdot\left(z1_{22}(f) + 1\right) - z1_{12}(f)\cdot z1_{21}(f)$$

$$\Delta_2(f) := \left(z2_{11}(f) + 1\right)\cdot\left(z2_{22}(f) + 1\right) - z2_{12}(f)\cdot z2_{21}(f)$$

$$\Delta_3(f) := \left(z3_{11}(f) + 1\right)\cdot\left(z3_{22}(f) + 1\right) - z3_{12}(f)\cdot z3_{21}(f)$$

$$\Delta_1(10\cdot\text{MHz}) = -32.444 - 43.374i$$

$$S1_{11}(f) := \frac{\left(z1_{11}(f) - 1\right)\cdot\left(z1_{22}(f) + 1\right) - z1_{12}(f)\cdot z1_{21}(f)}{\Delta_1(f)}$$

$$S1_{12}(f) := \frac{2\cdot z1_{12}(f)}{\Delta_1(f)}$$

$$S1_{21}(f) := \frac{2\cdot z1_{21}(f)}{\Delta_1(f)}$$

$$S1_{22}(f) := \frac{\left(z1_{11}(f) + 1\right)\cdot\left(z1_{22}(f) - 1\right) - z1_{12}(f)\cdot z1_{21}(f)}{\Delta_1(f)}$$

$$S1_{11}\left(2.0\cdot f_0\right) = 0.995 - 0.099i$$

this should be very close to 1

$$S2_{11}(f) := \frac{\left(z2_{11}(f) - 1\right)\cdot\left(z2_{22}(f) + 1\right) - z2_{12}(f)\cdot z2_{21}(f)}{\Delta_2(f)}$$

$$S2_{12}(f) := \frac{2\cdot z2_{12}(f)}{\Delta_2(f)}$$

$$S2_{21}(f) := \frac{2\cdot z2_{21}(f)}{\Delta_2(f)}$$

$$S2_{22}(f) := \frac{\left(z2_{11}(f) + 1\right)\cdot\left(z2_{22}(f) - 1\right) - z2_{12}(f)\cdot z2_{21}(f)}{\Delta_2(f)}$$

$$S3_{11}(f) := \frac{\left(z3_{11}(f) - 1\right)\cdot\left(z3_{22}(f) + 1\right) - z3_{12}(f)\cdot z3_{21}(f)}{\Delta_3(f)}$$

$$S3_{12}(f) := \frac{2\cdot z3_{12}(f)}{\Delta_3(f)}$$

$$S3_{21}(f) := \frac{2\cdot z3_{21}(f)}{\Delta_3(f)}$$

$$S3_{22}(f) := \frac{\left(z3_{11}(f) + 1\right)\cdot\left(z3_{22}(f) - 1\right) - z3_{12}(f)\cdot z3_{21}(f)}{\Delta_3(f)}$$

parallel load resistor:

$$Z_R := \frac{Z_{04}\cdot Z_0}{Z_{04} + Z_0}$$

This models a parallel resistor attached to the end of our t-line model.

$$S4_{11}(f) := \frac{Z_R - Z_0}{Z_R + Z_0}$$

$$S4_{12}(f) := \frac{2\cdot Z_R}{Z_0 + Z_R}$$

$$S4_{21}(f) := S4_{12}(f)$$

$$S4_{22}(f) := S4_{11}(f)$$

$$S1_{11}(10\cdot MHz) = 0.969 - 0.071i$$

$$S1_{12}(11\ MHz) = 0.193 - 0.15i$$

$$S1_{21}(10\ MHz) = 0.188 + 0.141i$$

$$S1_{22}(11\ MHz) = -0.265 + 0.93i$$

## Now convert to transmission (T) matrix:

$$M1(f) := \begin{bmatrix} \frac{1}{S1_{21}(f)} & -\frac{S1_{22}(f)}{S1_{21}(f)} \\ \frac{S1_{11}(f)}{S1_{21}(f)} & S1_{12}(f) - \frac{S1_{11}(f)\cdot S1_{22}(f)}{S1_{21}(f)} \end{bmatrix}$$

$$M1(10\cdot MHz) = \begin{bmatrix} 3.403 - 2.546i & 2.943 + 2.701i \\ 3.116 - 2.707i & 3.23 + 2.549i \end{bmatrix}$$

$$M2(f) := \begin{bmatrix} \frac{1}{S2_{21}(f)} & -\frac{S2_{22}(f)}{S2_{21}(f)} \\ \frac{S2_{11}(f)}{S2_{21}(f)} & S2_{12}(f) - \frac{S2_{11}(f)\cdot S2_{22}(f)}{S2_{21}(f)} \end{bmatrix}$$

$$M2(1\cdot MHz) = \begin{bmatrix} 1 + 1.084i\cdot 10^{-3} & 1.21\cdot 10^{-4} - 1.285i\cdot 10^{-4} \\ -1.21\cdot 10^{-4} + 1.285i\cdot 10^{-4} & 1 - 1.084i\cdot 10^{-3} \end{bmatrix}$$

$$M3(f) := \begin{bmatrix} \frac{1}{S3_{21}(f)} & -\frac{S3_{22}(f)}{S3_{21}(f)} \\ \frac{S3_{11}(f)}{S3_{21}(f)} & S3_{12}(f) - \frac{S3_{11}(f)\cdot S3_{22}(f)}{S3_{21}(f)} \end{bmatrix}$$

$$M4(f) := \begin{bmatrix} \frac{1}{S4_{21}(f)} & -\frac{S4_{22}(f)}{S4_{21}(f)} \\ \frac{S4_{11}(f)}{S4_{21}(f)} & S4_{12}(f) - \frac{S4_{11}(f)\cdot S4_{22}(f)}{S4_{21}(f)} \end{bmatrix}$$

$$M_{cascade}(f) := M1(f)\cdot M2(f)\cdot M3(f)\cdot M4(f)$$

$$M_{cascade}(10\cdot MHz) = \begin{bmatrix} 4.099 - 64.089i & 3.306 - 46.411i \\ 0.209 - 64.151i & 0.489 - 46.461i \end{bmatrix}$$

$$M_{cascade}(1\cdot MHz)_{0,1} = -135.912 + 1.714i\cdot 10^{3}$$

$$T_{11}(f) := M_{cascade}(f)_{0,0} \qquad T_{12}(f) := M_{cascade}(f)_{0,1}$$

$$T_{21}(f) := M_{cascade}(f)_{1,0} \qquad T_{22}(f) := M_{cascade}(f)_{1,1}$$

$$T_{11}(11\cdot MHz) = 0.611 - 62.249i$$

$$T_{12}(11\cdot MHz) = 0.063 - 45.096i$$

$$T_{21}(10\cdot MHz) = 0.209 - 64.151i$$

$$T_{22}(11\cdot MHz) = -1.913 - 45i$$

## Now convert from T matrix to S matrix parameters

$$S_{11}(f) := \frac{T_{21}(f)}{T_{11}(f)} \qquad S_{12}(f) := T_{22}(f) - \frac{T_{21}(f)\cdot T_{12}(f)}{T_{11}(f)}$$

$$S_{21}(f) := \frac{1}{T_{11}(f)} \qquad S_{22}(f) := -\frac{T_{12}(f)}{T_{11}(f)}$$

$$S_{11}(10\cdot MHz) = 0.997 - 0.061i \qquad S_{12}(10\cdot MHz) = 9.939\cdot 10^{-4} + 0.016i$$

$$S_{21}(10\cdot MHz) = 9.939\cdot 10^{-4} + 0.016i \qquad S_{22}(10\cdot MHz) = -0.725 - 5.252i\cdot 10^{-3}$$

$$l_2 = 0.5\cdot um$$

$$f := f_{start}, f_{start} + \Delta f .. f_{stop}$$

$$Z_{01} = 290.552 + 4.383i\ \Omega$$

$$Z_{02} = 55.976 + 6.246i\ \Omega$$

$$Z_{03} = 143.125 + 1.654i\ \Omega$$

$$Z_{04} = 8\ \Omega$$

$$C_0 = 7.975\cdot 10^{-12}\ F$$

$$Z_0 = 50\ \Omega$$

$$h = 9.773\cdot 10^{9}\ \frac{kg\cdot m}{s^3\cdot A}$$

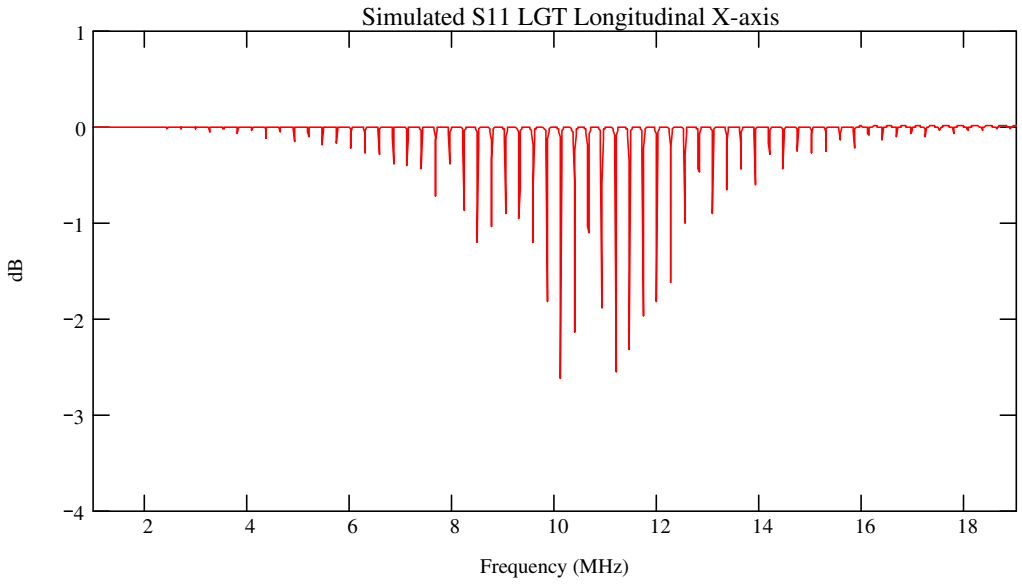
$$n = 0.078\ \frac{s\cdot A}{m}$$

transformer ratio

Graph of S11 for entire system

$S11graph(f) := 20 \cdot \log\left( \left| S_{11}(f) \right| \right)$

This graph takes two minutes to generate with 1600 pts.




## Put S11 data into an array format that mathcad will use. Simulates data taken from network analyzer

$numpoints := 1601$

$i := 0 .. numpoints - 1$

$freq_i := \left( f_{start} + i \cdot \Delta f \right)$ $\quad freq_0 = 1 \cdot 10^6 \text{ Hz}$

$(1600 \cdot \Delta f) = 1.8 \cdot 10^7 \text{ Hz}$

$cplxsig_i := S_{11}\left( freq_i \right)$

$freal_i := Re\left( cplxsig_i \right)$ $\quad fimag_i := Im\left( cplxsig_i \right)$

$Amp_i := \left| cplxsig_i \right|$ $\quad Ph_i := atan\left( \frac{fimag_i}{freal_i} \right)$

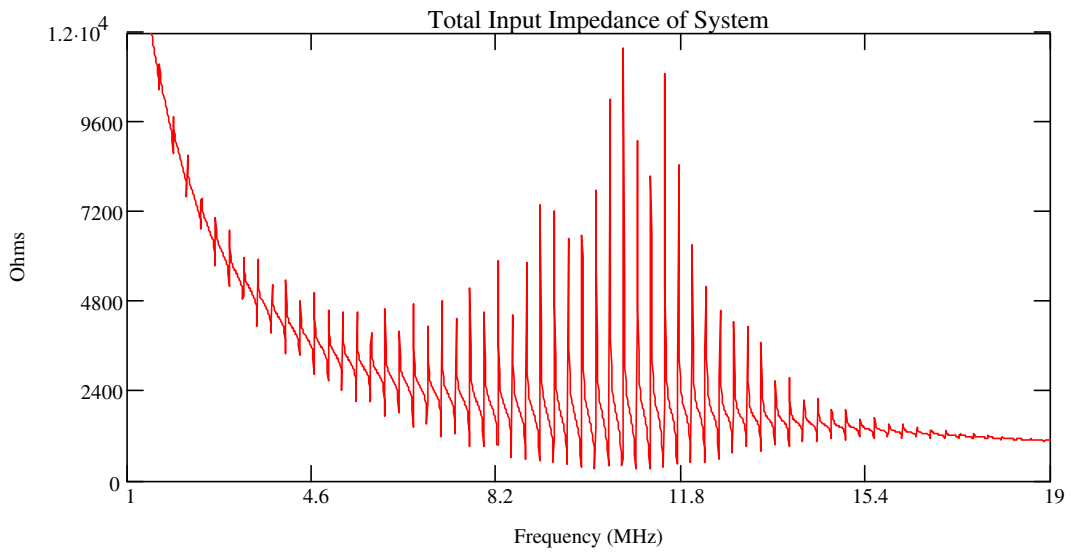
$f_i := Amp_i \cdot \exp\left( -j \cdot Ph_i \right)$ $\quad limit := max(freq)$

## Look at total input impedance

$f_{1001} = 0.975 - 0.012i$

$Z_{T_i} := Z_0 \cdot \frac{\left( 1 + f_i \right)}{\left( 1 - f_i \right)}$

$mmm := 1000, 1001 .. 1040$




**Now pad data with "zeros" so that fpoints are obtained. Pad down to near 0Hz and up to where fpoints are obtained.**

fpoints := 32768 endsm := 70

$LBW := f_{start} - 0 \cdot Hz$ $Lpts := \frac{LBW}{\Delta f}$ ILpts := trunc(Lpts)

$\Delta f = 1.125 \cdot 10^4$ Hz

ILpts = 88

numpoints = $1.601 \cdot 10^3$

k := 0, 1 .. ILpts − 1 $nfreq_k := \left[ f_{start} - \Delta f \cdot (ILpts - k) \right]$

kk := ILpts, ILpts + 1 .. numpoints + ILpts − 1 $nfreq_{kk} := \left[ f_{start} + (kk - ILpts) \cdot \Delta f \right]$

kkk := numpoints + ILpts, numpoints + ILpts + 1 .. fpoints − 1

$nfreq_{kkk} := f_{stop} + \Delta f \cdot (kkk - (numpoints + ILpts - 1))$

lkk := ILpts − endsm, ILpts − (endsm − 1) .. ILpts − 1

hkk := numpoints + ILpts, numpoints + ILpts + 1 .. numpoints + ILpts + (endsm − 1)

$$Ampv := \left| S_{11}\left(f_{stop}\right) \right| \qquad Phv := \operatorname{atan}\left(\frac{\operatorname{Im}\left(S_{11}\left(f_{stop}\right)\right)}{\operatorname{Re}\left(S_{11}\left(f_{stop}\right)\right)}\right)$$

$$kksm := ILpts - endsm,\ ILpts - (endsm - 1) \ldots numpoints + ILpts + (endsm - 1)$$

$$Ampu := \left| S_{11}\left(f_{start}\right) \right| \qquad Phu := \operatorname{atan}\left(\frac{\operatorname{Im}\left(S_{11}\left(f_{start}\right)\right)}{\operatorname{Re}\left(S_{11}\left(f_{start}\right)\right)}\right)$$

$$cplxsig_{kk} := S_{11}\left(nfreq_{kk}\right)$$

$$cplxsig_{nkk} := S_{11}\left(nfreq_{ILpts}\right) \qquad cplxsig_{nkk} := S_{11}\left(nfreq_{numpoints + ILpts - 1}\right)$$

$$freal_{kksm} := \operatorname{Re}\left(cplxsig_{kksm}\right) \qquad fimag_{kksm} := \operatorname{Im}\left(cplxsig_{kksm}\right)$$

$$Amp_k := Ampu \qquad Amp_{kk} := \left| cplxsig_{kk} \right| \qquad Amp_{kkk} := Ampv$$

$$Ph_k := Phu \qquad Ph_{kk} := \operatorname{atan}\left(\frac{fimag_{kk}}{freal_{kk}}\right) \qquad Ph_{kkk} := Phv$$

$$f_k := Ampu \cdot \exp(-j \cdot Phu) \qquad f_{kk} := Amp_{kk} \cdot \exp\left(-j \cdot Ph_{kk}\right) \qquad f_{kkk} := Ampv \cdot \exp(-j \cdot Phv)$$

$$f_{32767} = 0.996 + 0.093i$$

$$\left| f_{32767} \right| = 1$$

$$f_0 = 1 + 5.707i \cdot 10^{-3}$$

$$n := 0 \ldots fpoints - 1$$

## Now Smooth the data which, in effect, removes the cube reflections

$$nsmooth := 171$$

$$sAmp_k := Ampu \qquad sAmp_{kkk} := Ampv$$

$$sPh_k := Phu \qquad sPh_{kkk} := Phv$$

$$sf_k := Ampu \cdot \exp(-j \cdot Phu) \qquad sf_{kkk} := Ampv \cdot \exp(-j \cdot Phv)$$

$$sRes_k := 20 \cdot \log(Ampu) \qquad sRes_{kkk} := 20 \cdot \log(Ampv)$$

$sreal := medsmooth(freal, nsmooth)$ $simag := medsmooth(fimag\ nsmooth)$

$sAmp_{kksm} := \sqrt{(sreal_{kksm})^2 + (simag_{kksm})^2}$ $sPh_{kksm} := atan\left(\frac{simag_{kksm}}{sreal_{kksm}}\right)$

$sf_{kksm} := sAmp_{kksm} \cdot exp(-j \cdot sPh_{kksm})$ $sRes_{kksm} := 20 \cdot log(sAmp_{kksm})$

$f_{lkk} := sAmp_{lkk} \cdot exp(-j \cdot sPh_{lkk})$ $f_{hkk} := sAmp_{hkk} \cdot exp(-j \cdot sPh_{hkk})$

$t := icff(f)$

## Substract the smooth function from the measured response yielding only the acoustic reflections :

$Netf_{kkk} := NetAmp_{numpoints + ILpts - 1} \cdot exp(-j \cdot NetPh_{numpoints + ILpts - 1})$

$Netf_{kkk} := 10^{-25}$ $Netf_k := NetAmp_{ILpts} \cdot exp(-j \cdot NetPh_{ILpts})$

$Netf_k := 10^{-25}$ difference here is actually set to near zero. NetAmp is not used in this simulation.

$Netreal_{kksm} := freal_{kksm} - sreal_{kksm}$ $Netimag_{kksm} := fimag_{kksm} - simag_{kksm}$

$Netreal_{kksm} := if(Netreal_{kksm} = 0, 10^{-25}, Netreal_{kksm})$

$NetAmp_{kksm} := \sqrt{(Netreal_{kksm})^2 + (Netimag_{kksm})^2}$ $NetPh_{kksm} := atan\left(\frac{Netimag_{kksm}}{Netreal_{kksm}}\right)$

$Netf_{kksm} := NetAmp_{kksm} \cdot exp(-j \cdot NetPh_{kksm})$

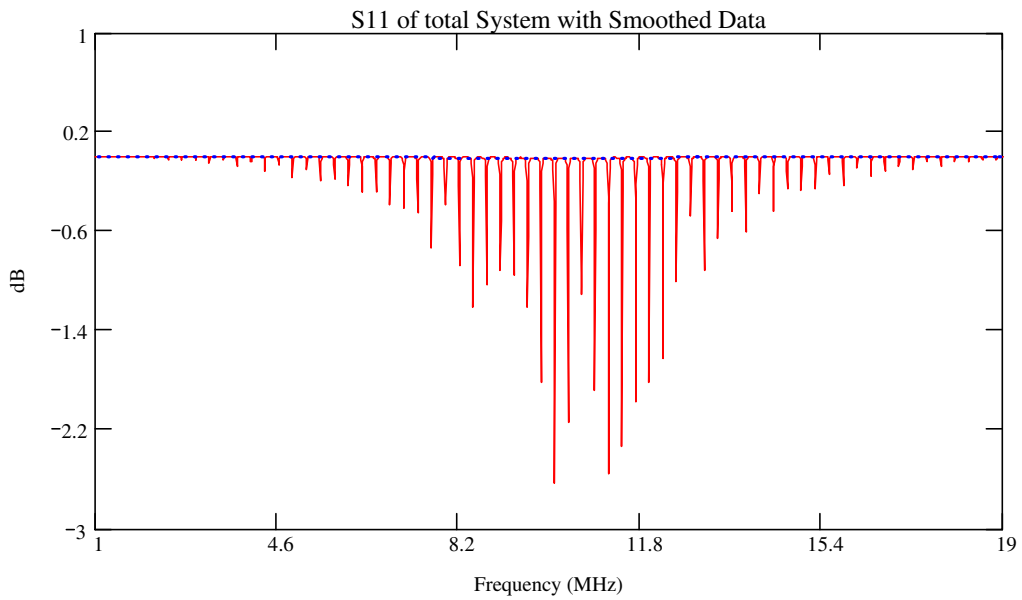
$NetRes_n := 20 \cdot log(|Netf_n|)$

## Smooth frequency response :

$st := icff(sf)$ $difreal := Re(t) - Re(st)$ $difimag = Im(t) - Im(st)$

$magdif_n := \left|\sqrt{(difreal_n)^2 + (difimag_n)^2}\right|$ $P_n := atan\left(\frac{Im(t_n)}{Re(t_n)}\right)$ $sP_n := atan\left(\frac{Im(st_n)}{Re(st_n)}\right)$

$difP_n := P_n - sP_n$ $divP_n := \frac{P_n - sP_n}{sP_n}$




In the graph above, the dotted line is the smoothed data, and the solid line is the simulate S11 data.

These are the values used after S11 data is padded with "zeros."

$$\max(nfreq) = 3.686 \cdot 10^{8}\ \text{Hz} \qquad \min(nfreq) = 1 \cdot 10^{4}\ \text{Hz}$$

## Re-calculate the sampling rate dt. dt = (max(freq) - min(freq)) / # of total points-1

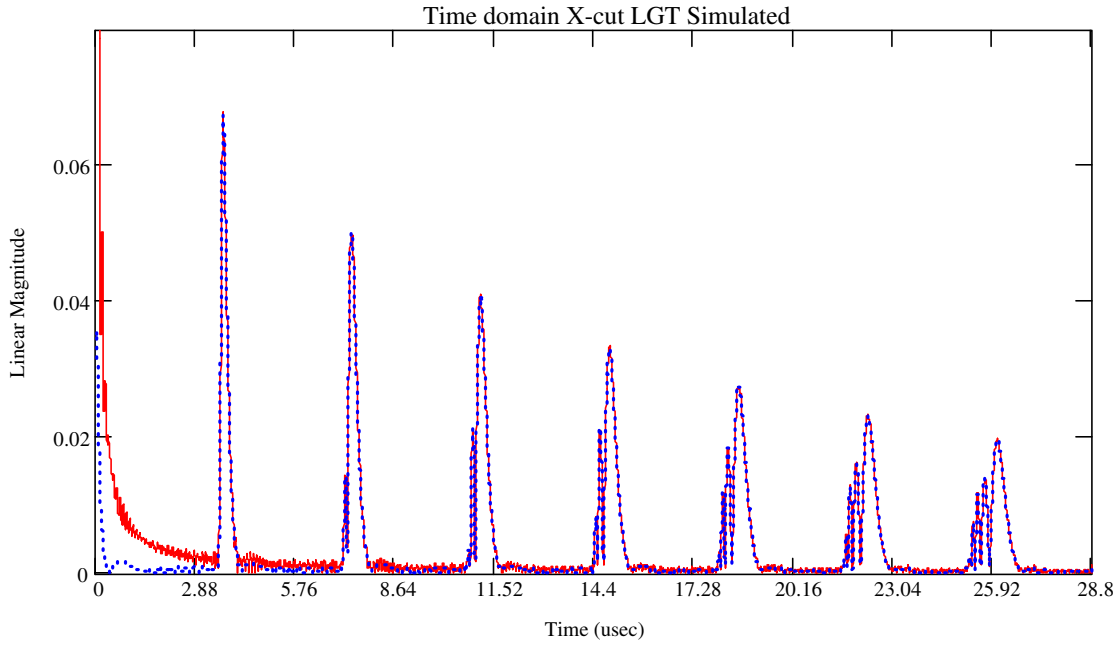
$BW := (\max(nfreq) - \min(nfreq))$ $\quad df := \frac{BW}{fpoints - 1}$ $\quad dt := \frac{1}{BW}$ $\quad t_n := |t_n|$

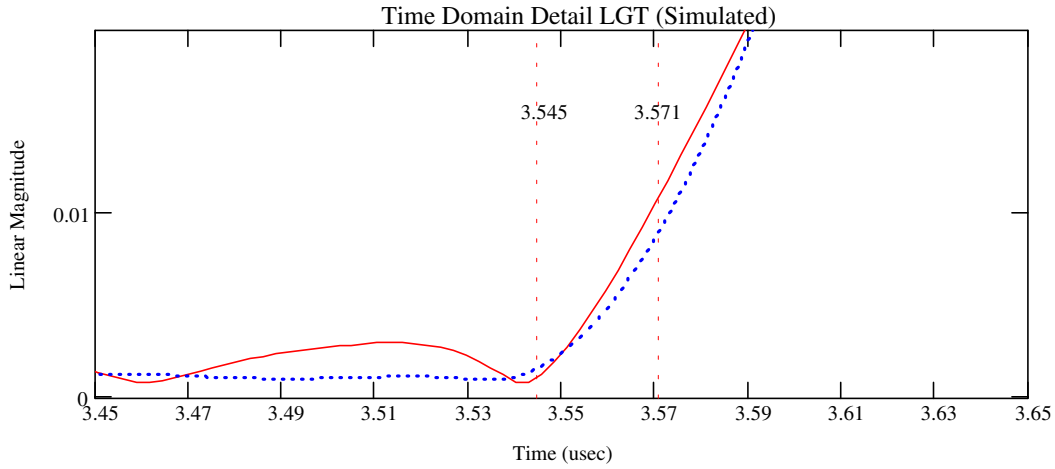
$BW = 3.686 \cdot 10^{8}$ Hz

## Calculate the time range for determining the exact travel time.

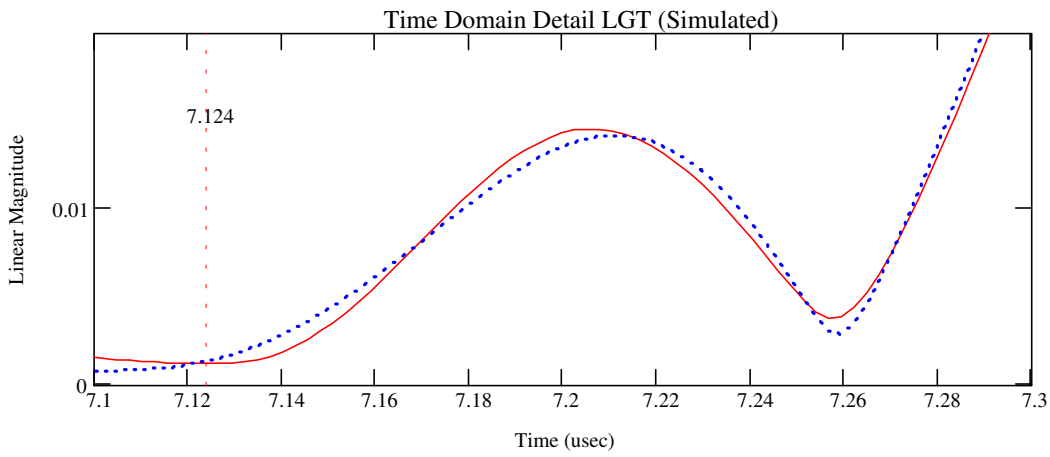
$time_n := (n) \cdot dt$ $\quad tmax := (fpoints - 1) \cdot dt$ $\quad tmax = 8.889 \cdot 10^{-5}$ s

$dt = 2.713$ ns $\quad df = 1.125 \cdot 10^{4}$ Hz

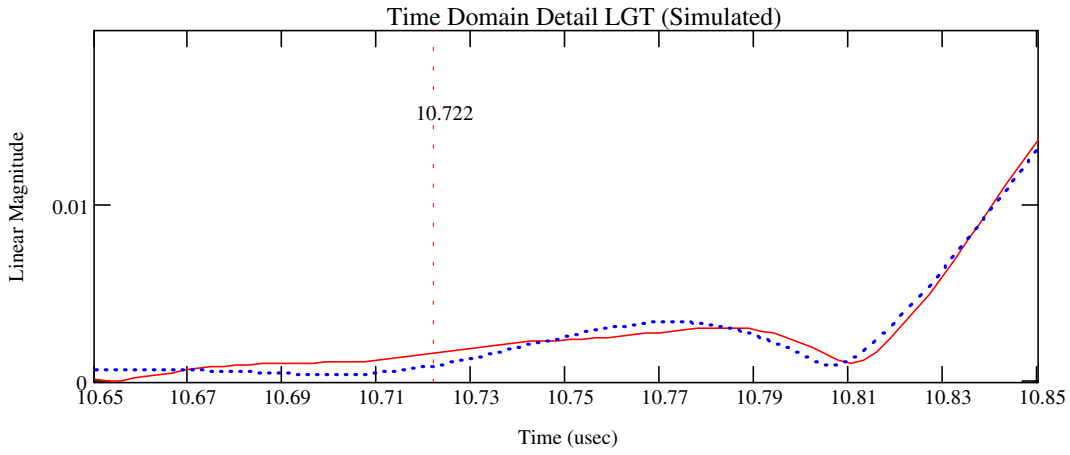



$tt1 := 3.545$




tt2 := 7.124




tt3 := 10.722

$$velocity := \frac{2 \cdot cm}{3.571 \cdot us} \qquad velocity = 5.601 \cdot 10^{3} \frac{m}{s} \qquad l_2 = 5 \cdot 10^{-7}\ m$$

Reflection times using input velocity:

$$velocity := \frac{2 \cdot cm}{3.571 \cdot us}$$

$$velocity = 5.601 \cdot 10^{3} \frac{m}{s}$$

$$velocity := \frac{4 \cdot cm}{7.142 \cdot us}$$

$$velocity = 5.601 \cdot 10^{3} \frac{m}{s}$$

$$velocity := \frac{6 \cdot cm}{10.713 \cdot us}$$

$$velocity = 5.601 \cdot 10^{3} \frac{m}{s}$$

Measured reflection times and resultant velocities:

$$vactual := \frac{2 \cdot cm}{tt1 \cdot us}$$

$$vactual = 5.642 \cdot 10^{3} \frac{m}{s}$$

$$vactual := \frac{4 \cdot cm}{tt2 \cdot us}$$

$$vactual = 5.615 \cdot 10^{3} \frac{m}{s}$$

$$vactual := \frac{6 \cdot cm}{tt3 \cdot us}$$

$$vactual = 5.596 \cdot 10^{3} \frac{m}{s}$$

# REFERENCES


[1] B. J. James, Thesis, "Determination of the Elastic and Dielectric Properties of Quartz," Royal Holloway and Bedford New College, London Univ., Spring 1987.

[2] B.J. James, "A New Measurement of the Basic Elastic and Dielectric Constants of Quartz," *42nd Annual Frequency Control Symposium*, pp. 146-154.

[3] G. L. Petersen, B. Chick, W. Junker, "Error Correction Methods in Gated Amplifier Absolute Velocity Measurements and Comparison with the Pulse-Echo-Overlap Technique," *IEEE Ultrasonics Symp. Proc. 1975*.

[4] W. Soluch, "Measurements of Elastic and Piezoelectric Constants of $Li_2B_4O_7$ Crystal," *11th European Frequency and Time Forum*, Neuchatel, Mar. 1997, pp. 382-385.

[5] M.A. Breazeale, J.H. Cantrell Jr., J.S. Heyman, "Ultrasonic Wave Velocity and Attenuation Measurements," *Methods of Experimental Physics*, *vol. 19,* Academic Press, Inc., 1981, pp. 67-135.

[6] B. A. Auld, *Acoustic Fields and Waves in Solids,"* Second edition. Malbar, FL: Robert E. Krieger Publishing Company, 1990.

[7] J. C. Brice, "Crystals for Quartz Resonators," *Reviews of Modern Physics,* vol. 57, no. 1, pp.105-146, Jan. 1985.

[8] D. Salt, *Hy-Q Handbook of Quartz Crystal Devices*. Berkshire, England: Van Nostrand Reinhold Co. Ltd., 1987.

[9] S. Datta, *Surface Acoustic Wave Devices*. Englewood Cliffs, NJ: Prentice-Hall, 1986.

[10] G. Gonzalez, *Microwave Transistor Amplifiers Analysis and Design,* Second Edition. Upper Saddle River, NJ: Prentice Hall, 1997.

[11] V. M. Ristic, *Principles of Acoustic Devices.* New York, NY: John Wiley and Sons, Inc., 1983.

[12] A. Ballato, "Bulk and Surface Acoustic Wave Excitation and Network Representation," *Proc. of the 28$^{th}$ Annual Frequency Control Symp.,* 1974, pp. 270-279.

[13] Y. V. Pisarevsky, P.A. Senyushenkow, B.V. Mill, N. A. Moiseeva, "Elastic, Piezoelectric, Dielectric Properties of $La_3Ga_{5.5}Ta_{0.5}O_{14}$ Single Crystals," *Proc. 1998 IEEE International Frequency Control Symp.,* 1998, pp. 742-747.