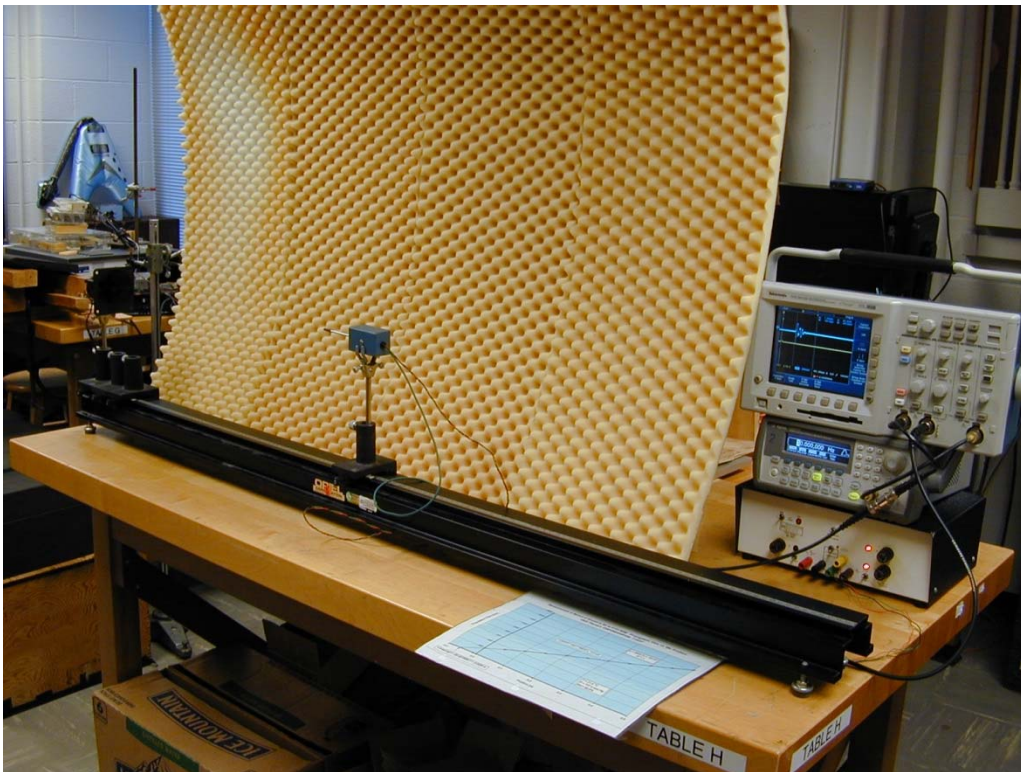


# Measurement of the Speed of Sound in “Free” Air

We have developed an experimental setup for the UIUC Physics of Music Lab that is specifically designed to measure the propagation speed of sound in “free” air – *i.e.* air that is not physically confined/constrained in any manner – *e.g.* sound propagation in {still} air in the great outdoors. Measurement of the speed of sound propagation in air inside a {large} room is an approximation to this ideal situation.

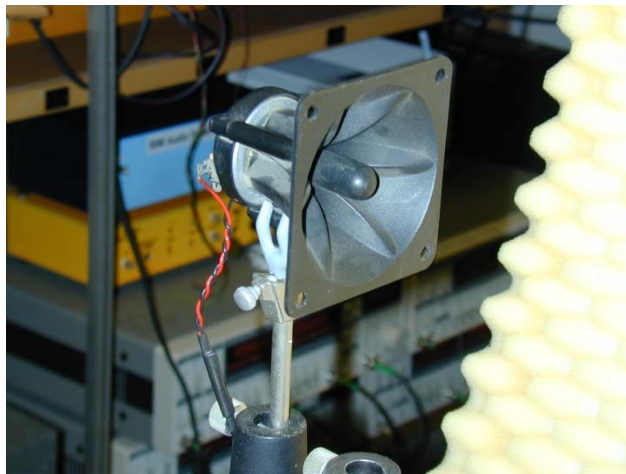
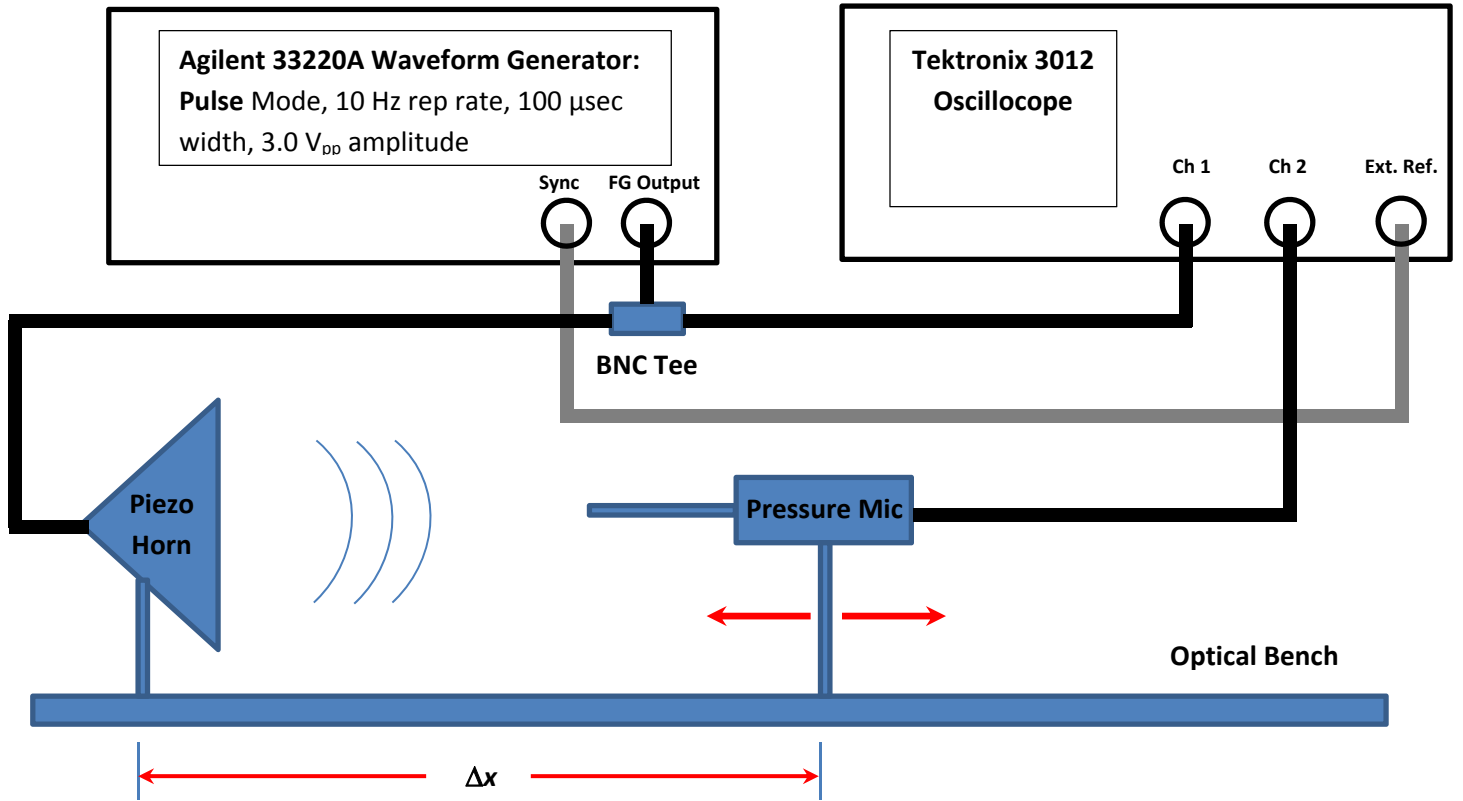
This experimental setup is shown in the pix below. The apparatus consists of using a narrow voltage pulse output from an Agilent 3320A Function Generator to excite a piezo-electric horn mounted at the LHS end of an optical bench. We use one of our specially-developed pressure microphones, also mounted on the optical bench, to detect the acoustic pulse output from the piezo horn, and a dual-channel Tektronix 3012 Oscilloscope to simultaneously display both the exciting voltage pulse signal output from the FG and the detected microphone signal. A  $\pm 15$  V<sub>DC</sub> power supply is used to power the microphone’s preamplifier circuit.



## Experimental Procedure:

A schematic diagram of the experimental setup is shown in the figure below. Switch on the 120V AC power to the Agilent 33220A FG, the Tektronix 3012 ‘Scope, and the  $\pm 15$  V<sub>DC</sub> power supply for the microphone preamplifier. Select the **Pulse** waveform mode for the FG, reduce the pulse repetition frequency *e.g.* to 10 Hz. A pulse width of 100  $\mu$ sec and amplitude of 3.0 V<sub>pp</sub> are adequate to excite the piezo horn. Don’t forget to press the **Output** {on} button on the FG!

**Experimental Setup for the Measurement of the Propagation of Speed of Sound in “Free” Air:**



Piezoelectric Horn



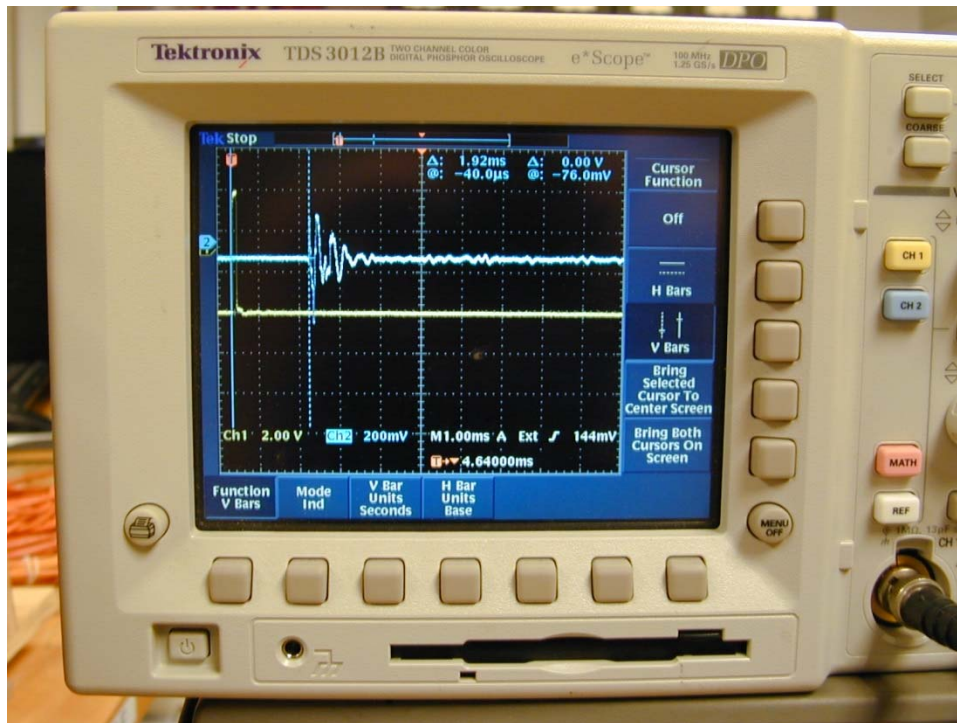
Pressure Microphone + Preamplifier

The pulse output from the FG and the microphone signal should appear on Ch1 (Ch2) of the ‘Scope – yellow (blue) traces respectively. Depending on whomever last used the experimental apparatus, the individual Ch1/Ch2 input sensitivities, the ‘Scope’s horizontal time base and trigger threshold, *etc.* may need to be adjusted to properly display these waveforms. If any difficulties are encountered here, don’t hesitate to ask a POM TA for help/assistance!

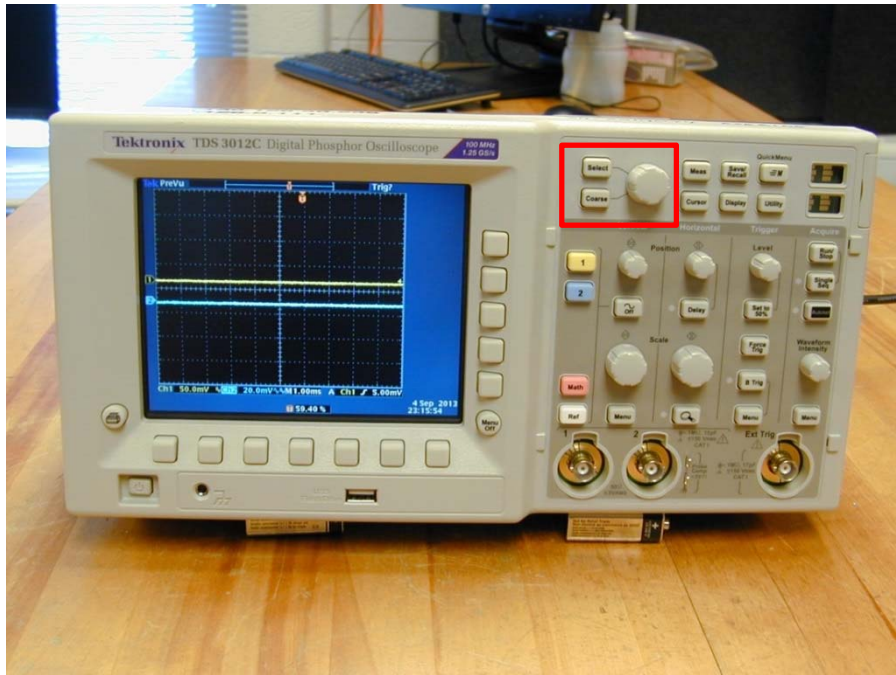
Slide the microphone towards/away from the piezo horn – observe the time *difference* between the piezo horn pulse and the microphone signal. For “free” air, the speed of propagation  $v$  is a constant, hence the time  $\Delta t$  that it takes sound to propagate a distance  $\Delta x$  is simply given by the formula  $\Delta t = \Delta x/v = \frac{1}{v} \Delta x$ . The linear relationship between  $\Delta t$  and  $\Delta x$  is a straight line  $\{y = mx + b\}$  on a piece of graph paper, with positive slope  $m = 1/v$ . Hence if a series of  $i = 1:N$  measurements of data point pairs  $\{\Delta x_i, \Delta t_i\}$  are plotted up on graph paper, the reciprocal of the slope of a straight-line fit to the data gives the best-fit speed of propagation of sound in “free” air.

The optical bench has a {metric} ruler on its side, with position markers on the base of the piezo horn and mic holders/stands. Hence, measurement of the position differences  $\Delta x_i$  between the piezo horn and the microphone for each mic location is straightforward. Note that the position *offset* between the microphone element relative to the marker on the mic holder base (and likewise for the location of the piezo disc inside the piezo horn relative to its marker on the piezo horn holder base) simply manifest themselves as a non-zero  $y$ -intercept/offset,  $b$  in the above linear relation. The  $x$ -intercept ( $@ y = \Delta t = 0$ ) gives the above position offset between the piezo element and mic position.

The measurement of the time differences  $\Delta t_i = (t^{pulse} - t^{p-mic})_i$  can be accomplished e.g. by using the {vertical} cursors of the ‘Scope, positioning one cursor at the leading edge of the FG pulse and then positioning the 2<sup>nd</sup> cursor at the leading edge of the microphone signal, as shown in the pix below:



The {vertical} cursor option(s) on the ‘Scope can be selected by first pressing the **Cursor** button at the top ~ center of the ‘Scope as shown in the pix below:



The **Cursor Menu Option(s)** can be selected from the buttons located at the bottom and right-hand side of the ‘Scope’s display screen. Press the **Select** button (immediately above the **Cursor** button) to select the 1<sup>st</sup> (leading) or 2<sup>nd</sup> (trailing) vertical cursor, then use the large round knob immediately next to these buttons to carefully/accurately position that cursor at the **leading** edge of the waveform. Do the same for the 2<sup>nd</sup> waveform. The time difference between the two vertical cursors (representing the time difference between the leading edges of the two waveforms) appears on the upper right-hand side of the scope display screen as the quantity  $\Delta$ .

Note that for improved experimental accuracy in measuring the FG pulse – mic signal time difference, it is useful to first change/expand the ‘Scope’s timebase and use the ‘Scope’s horizontal position knob to position the FG pulse near the RHS of the screen and the mic signal near the LHS of the screen – *i.e.* as wide apart on the ‘Scope screen as possible.

### **Data Analysis:**

We encourage you to plot up your data point pairs  $\{\Delta x_i, \Delta t_i\}$  as you carry out the experiment on a piece of graph paper {we have graph paper in the POM Lab – ask a POM TA for some if you need a sheet or two}. Using graphical methods (*i.e.* pencil & ruler), a “best fit” straight line through your  $\{\Delta x_i, \Delta t_i\}$  data points can be drawn, from which the slope  $m = \text{rise}/\text{run} = \Delta y/\Delta x$  can be determined, and hence an experimental determination of the speed of propagation  $v = 1/m$  in free air extracted.

We also encourage you to make efforts to obtain reasonable estimates of the uncertainties associated with the  $\Delta x_i$  and  $\Delta t_i$  measurements – *i.e.* how accurately (and/or reproducibly) can the  $\Delta x_i$  and  $\Delta t_i$  measurements be made? Is a 1 standard deviation uncertainty on  $\Delta x_i$  of  $\sigma_{\Delta x} \sim 1 \text{ mm}$  achievable/realistic? Is it possible to do better than this? Is a 1 standard deviation uncertainty on  $\Delta t_i$  of  $\sigma_{\Delta t} \sim 10 \mu\text{s}$  achievable/realistic? Is it possible to do better than this?

Finally, we encourage you to carry out a linear least squares fit  $\{y = mx + b\}$  of your experimental data  $\{\Delta x_i, \Delta t_i\}$ , to obtain a “best fit” estimate of the slope,  $m$  and hence of  $v = 1/m$ . Simple-minded least-squares straight line fits can be carried out *e.g.* using Excel, or Origin. We also have the capability of carrying out more sophisticated least-squares fits to a straight line relation, taking into account uncertainties in both  $x$  and  $y$  variables, using either a Matlab based script or a LabWindows/CVI based program – both software packages functionally carry out the same algorithm. Ask one of the POM TA’s about using these analysis software packages, if interested.

The two figures shown below show the results of carrying out a simple least-squares fit (using Excel). The 2<sup>nd</sup> plot shows the fit residuals. The fitted value of  $v$  has an uncertainty of  $\sim 0.3\%$ . We did not go to extraordinary lengths to obtain super-accurate data. We simply wanted to see how well the apparatus worked if we went to a “reasonable” effort to obtain decent-quality measurements.

