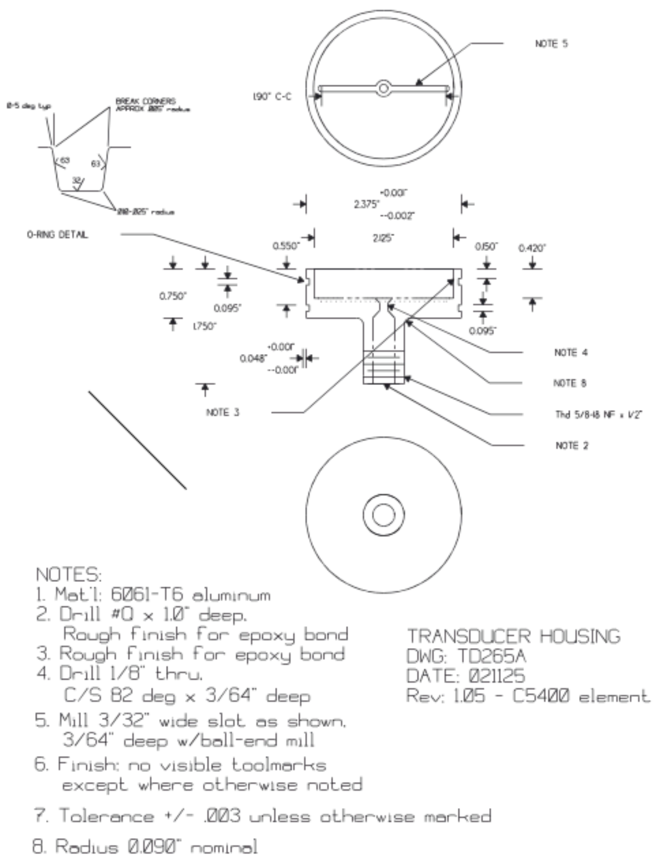
TAPS-6 TRANSDUCER DESIGN

The TAPS transducers are all basically similar in design. Each element is a Navy Type III ceramic element, housed in an anodized 6061-T6 aluminum housing (see the assembly drawing for the 265 kHz transducer, below). The ceramic was selected on the basis of insensitivity to changes in pressure and temperature, so that system sensitivity will be unaffected by changes in depth or water temperature.



Assembly is straight-forward. Briefly, the TAPS transducers are made from circular disk elements with electrodes on the large faces. Wires are soldered onto the electrodes. The elements are assembled into housings like the drawing above. A thin piece of Copaco -- a tradename for a paper insulator used in electrical motors -- is glued to the back side of the element and this assembly is then glued into the housing. The Copaco layer acts as a mechanical transformer for the back side of the ceramic element. The cavity is filled with epoxy to waterproof the assembly and to provide a matching layer from the ceramic to water. A cable is soldered to the wire leads from the ceramic element and the back cavity is filled with epoxy to waterproof the joints.

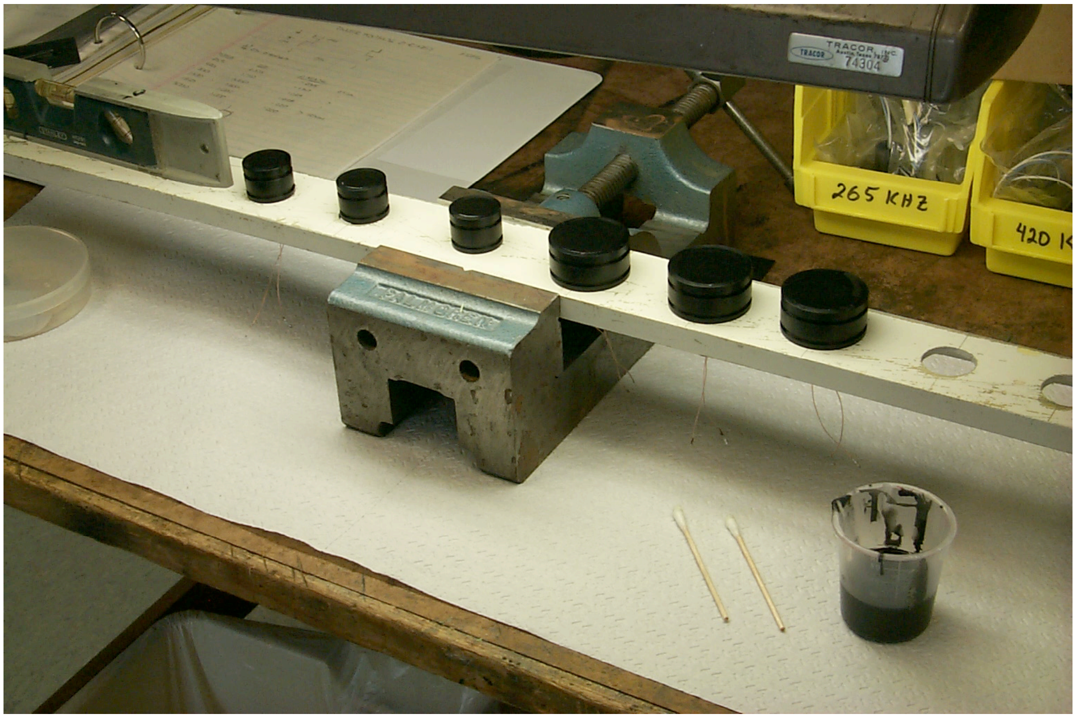
Typical construction begins with soldering a wire to the back electrode of the ceramic at the center. I prefer to attach the wire standing straight up from the electrode; the wire is tinned and clipped to obtain about 1/4 - 3/16" of tinned wire. This is then carefully soldered to the electrode, which has been tinned prior to soldering. This joint is tested for strength (gently), then cleaned with MEK and a small dab of 5-minute epoxy is applied to give the joint some mechanical strength.

A note on soldering to the metalized electrodes on the ceramic element: Too much heat will lift the electrode off the ceramic. You should start by mechanically cleaning the electrode surface -- I use an electric pencil eraser once used by draftsmen. Then clean the surface with a solvent (MEK works well on the electrode -- not so well on your lungs.) Place a large drop of solder flux on the spot to be tinned. Clean the soldering iron tip and load it with a bit of solder (I use SN62 fine solder). Place the tip on the fluxed electrode and transfer the solder -- this should happen almost immediately. Sometimes I dab at the spot with a little more solder while the iron is applied. Speed is important. No more than 1-2 seconds or you will lift the electrode.

When the 5-minute epoxy has cured, the back is spread with a thin layer of adhesive (Scotch-Weld 1838 two-part structural adhesive), the copaco backing (with a hole in the center) is threaded over the wire, and another thin layer of adhesive applied to the other side of the copaco. A second wire is threaded through the hole in the housing and along one of the machined channels in the transducer cavity, lapping over the side of the housing. Structural adhesive is applied to fill these channels and then the transducer assembly (element and copaco) is inserted with the attached wire fed through the hole with the other wire. The element is rotated and pressed downward to create a uniform thin layer of adhesive under the copaco. Extra adhesive that is extruded can be removed with a Q-tip.

I cure these assemblies overnight with a small weight pressing on the ceramic to ensure a thin joint. Use some sort of non-abrasive material between the ceramic and the weight to prevent damaging the upper electrode.

Next day, I inspect the transducer and then attach the second wire to the face electrode. I usually tin the wire and then flatten it with needlenose pliers before I solder it to the ceramic. Then I hook up the wires to an oscilloscope and thump the ceramic with the eraser end of a pencil. You should see 100-200 mV peaks on the response. The cavity is then filled with epoxy resin and left to cure (again, overnight). It is important that the top of the resin cover the element and that it be level with the edge of the housing. Keep things level! You might arrange a cover to keep dust from settling on the epoxy resin.

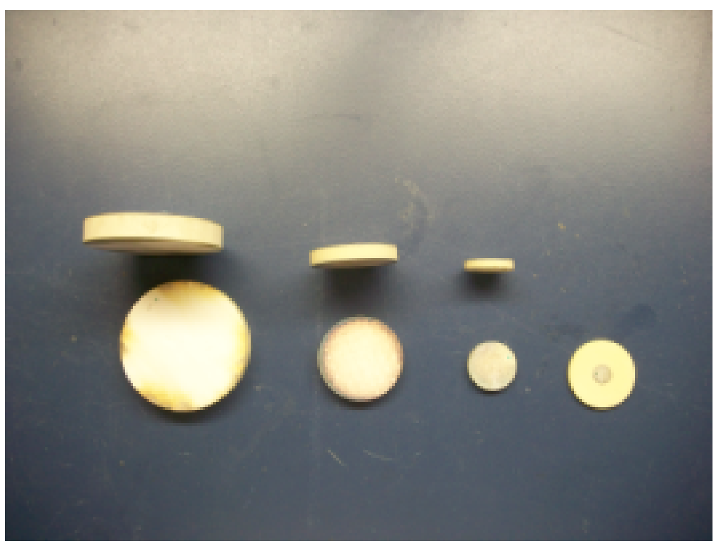


The epoxy resin we use has been selected to match, as nearly as possible, the thermal expansion rate of 6061-T6 aluminum. The current manufacturer is Lord Corporation of Erie PA; the epoxy is Circalok 6007 black encapsulant with 12% by weight of RT-7S hardener. This mixture needs to be thoroughly mixed in a glass beaker and then evacuated under low vacuum to remove as many air bubbles as possible. A good vacuum pump and bell jar are needed here. Failure to remove the bubbles will result in an acoustic window that blocks sound rather than transmitting it.

(An aside, I once purchased some thermistor assemblies from a reputable and well-known manufacturer that were rated for use at full ocean depth. One of them came apart at 3600 m depth (roughly 5300 psi), flooding the pressure case and destroying all the electronics inside. I discovered that these thermistors consisted of a stainless steel tube welded to a stainless steel fitting with the thermistor embedded in epoxy inside the tube. Pressure applied to the end of the tube was resisted by the shear adhesion forces along the inner wall of the tube. The thermistor that failed had a large bubble in the epoxy.)

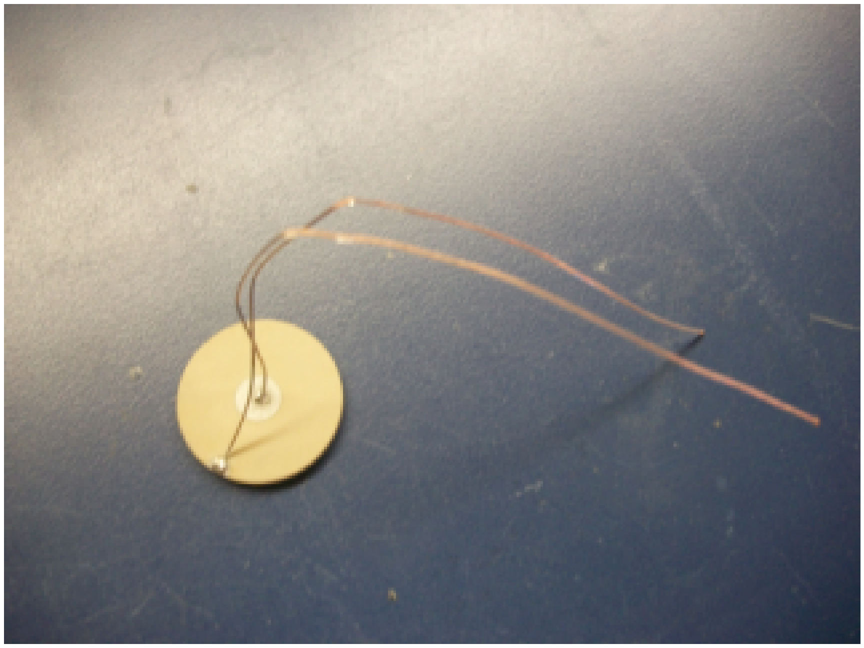
Day three has me attaching wires -- often RG-74 coax -- to the two wires coming out the back of the housing. I try to make a tidy joint that I can push into the housing and then seal with more epoxy resin. I evacuate this resin too, prior to filling the backs of the housings. Can't hurt.

The beam pattern of a disc transducer depends on the diameter of the disc and the frequency of operation. The higher the frequency or the larger the disc, the narrower the beam pattern. In order to obtain reasonably consistent beamwidths over the set of TAPS frequencies (265 - 3000 kHz), the higher frequency transducers need to be smaller in diameter. A couple of these transducers are fabricated using some special electrode patterns to obtain proper beamwidths from larger-diameter ceramics.



This figure shows the 265, 420, 700, and 1100 kHz TAPS elements (left to right). Note that the thickness decreases with frequency as does the diameter for these approximately-equal-beam-width transducer elements.

The 1100 kHz and 3000 kHz transducers are assembled using special-order ceramic elements with reduced-diameter electrodes on one surface. By selection of the size of one electrode (within certain bounds), a quasi-gaussian beam pattern can be produced from an otherwise narrow-beam transducer. These elements normally come with wire leads attached, as shown below.



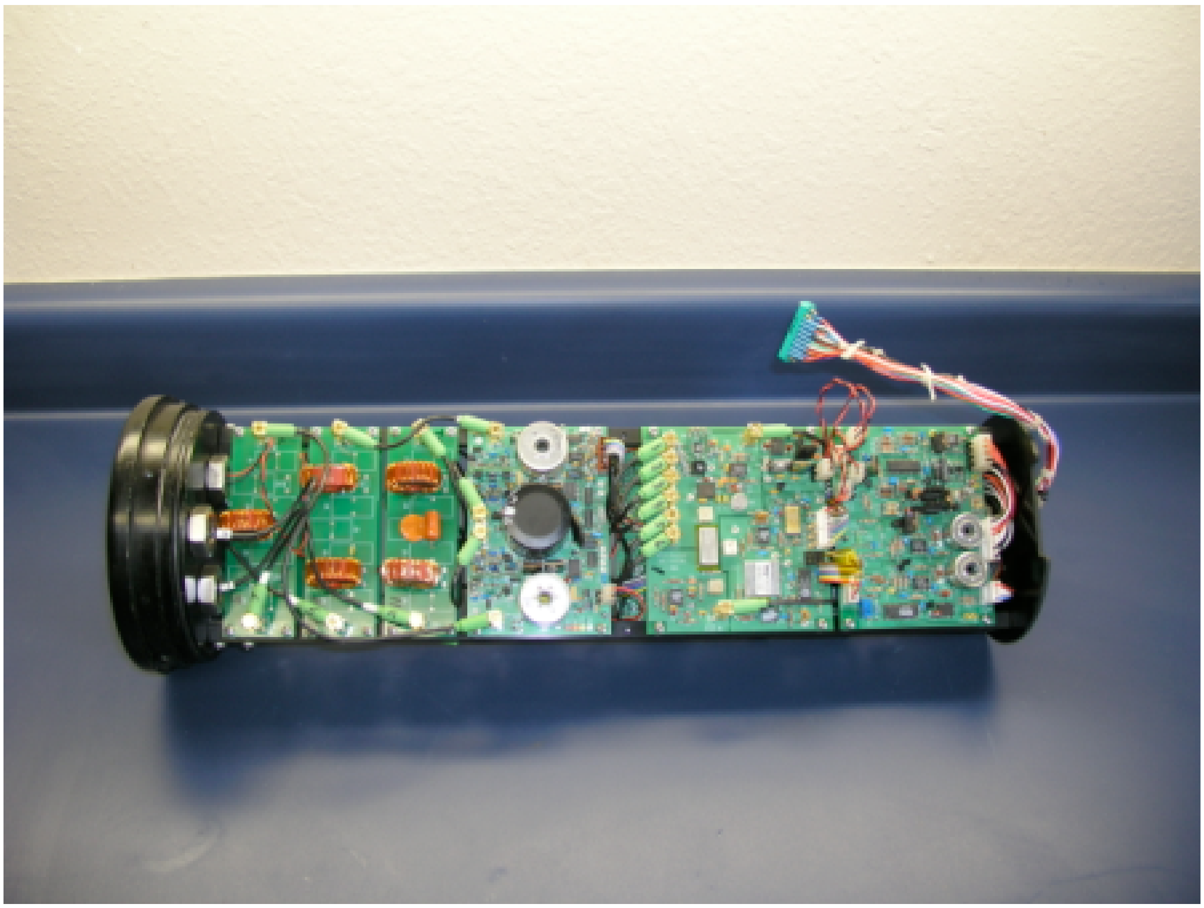
CASE DESIGN

The TAPS-6 transducers were designed as replaceable units that insert into the endcap of the TAPS. These designs can be used with minor modifications for external transducers. For example, the threads on the back could be extended up the shank to permit inserting the transducer through a hole in a mounting plate and securing it with a nut on the back. A larger diameter back shank would permit molding a larger cable into the case. A 1.0" OD shank would permit the securing nut to pass over a 2-pin or coax connector backshell.

The case material should not be changed unless a change in the potting material is also made. In which case, you would need to construct sample coupons of the epoxy to measure sound speed and density. These values are needed to compute the proper window thickness for the transducer.

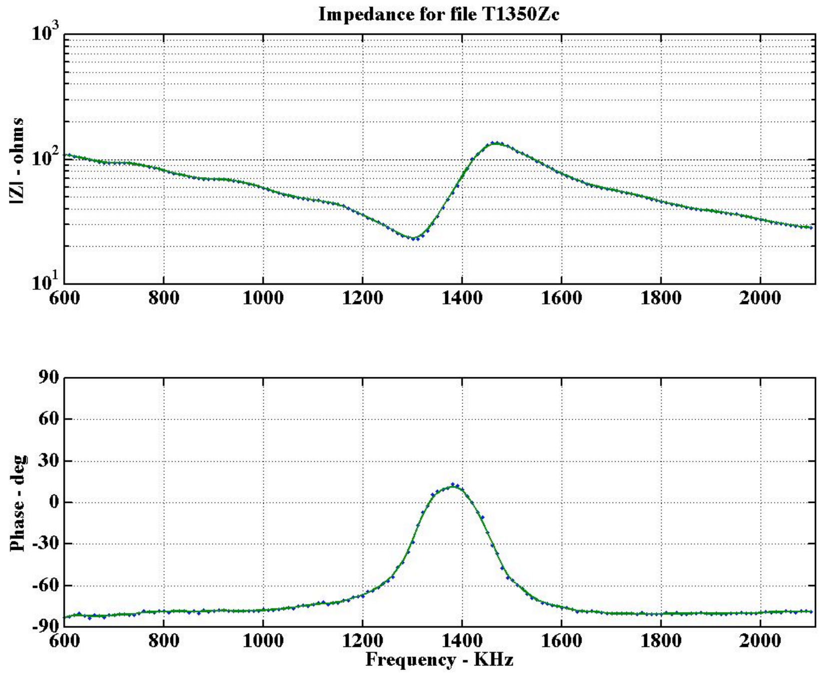
TUNING THE TRANSDUCER

A transducer displays a frequency-dependent impedance: the resistive part as well as the reactance vary with frequency in a complex way. Dealing with this can be tricky. Since power amplifiers are designed to operate into a fixed resistance, driving a complex (reactive) load requires insertion of a tuning network between the amplifier and the transducer. In the figure below, the three boards on the left are tuning networks for three of the six TAPS-6 transducers.



The figure on the next page shows a typical (assembled) transducer impedance. This figure displays the modulus (or magnitude, |Z|) of the impedance and the phase versus frequency. Note the fairly rapid change in |Z| around 1300-1450 kHz. The maximum in |Z| occurs near the mechanical resonance (parallel resonance) of the ceramic. This frequency depends on the bulk sound speed of the ceramic. The minimum in |Z| occurs near the series resonance, which depends on the motional reactance of the poled ceramic. Note that the phase is capacitive (negative) for all but a small region around these resonances. Typical of most assembled transducers, the impedance changes rather smoothly over frequency.

Typically, maximal transmitting efficiency is found near the series resonance (impedance minimum or conductance maximum). Maximal receiving response is found at the parallel or mechanical resonance. I have usually selected ceramics to place the desired operating frequency between these two resonances.



Measuring the impedance of transducers is the first step in designing a tuning network. In principle, this is simple. Drive the transducer (in water) with a signal generator. Measure the drive voltage, the drive current (with a current probe), and the phase difference between the voltage and current. Then compute |Z| = V / I.

The complex impedance can be computed from these data as:

$$Z = |Z|\cos(\theta) + j\,|Z|\sin(\theta)$$

$$or$$

$$Z = R + jX$$

where R is the resistance and X the reactance of the transducer. It is important to measure the impedance at enough frequencies to characterize the behavior in the resonance region of the transducer. However, some heavily-loaded transducers (such as some commercial units) may not show marked changes in the resonance region.

If the transducer is to be used at a single frequency (such as TAPS-NG), then it is only necessary to "tune" the transducer at this frequency. This can be done by following the steps in the document, **TUNING TAPS**

TRANSDUCERS. Note that this tuning requires further measurement and thus should be done in the test tank where the impedance was measured.

A note on measuring impedance: It is almost always necessary to measure the impedance of the transducer with the face loaded with water. (Try measuring both in water and air and see.) The size of the tank of water is of some importance because strong reflections arriving back at the transducer face will cause changes in the apparent impedance. This is normally seen as regular oscillations in the impedance curves. Drive voltages on the order of 10-30 V_{pp} are low enough that reflections in a modest-size tank will usually be negligible.

CALIBRATING THE TRANSDUCER

Calibration consists of transmitting from the test transducer to a calibrated standard transducer and vice versa. Simple. Of course, there are some practical issues to pay attention to.

You need a tank of water. The larger the tank, generally speaking, the better. Two issues arise here. First, transducers (like antennas) have a near-field, a region where amplitudes vary rather quickly with range and sometimes go up and down. For most common transducer shapes, minimal errors arise when the distance to the measurement point, Rp, obeys

$$R_p > \frac{D^2}{\lambda}$$

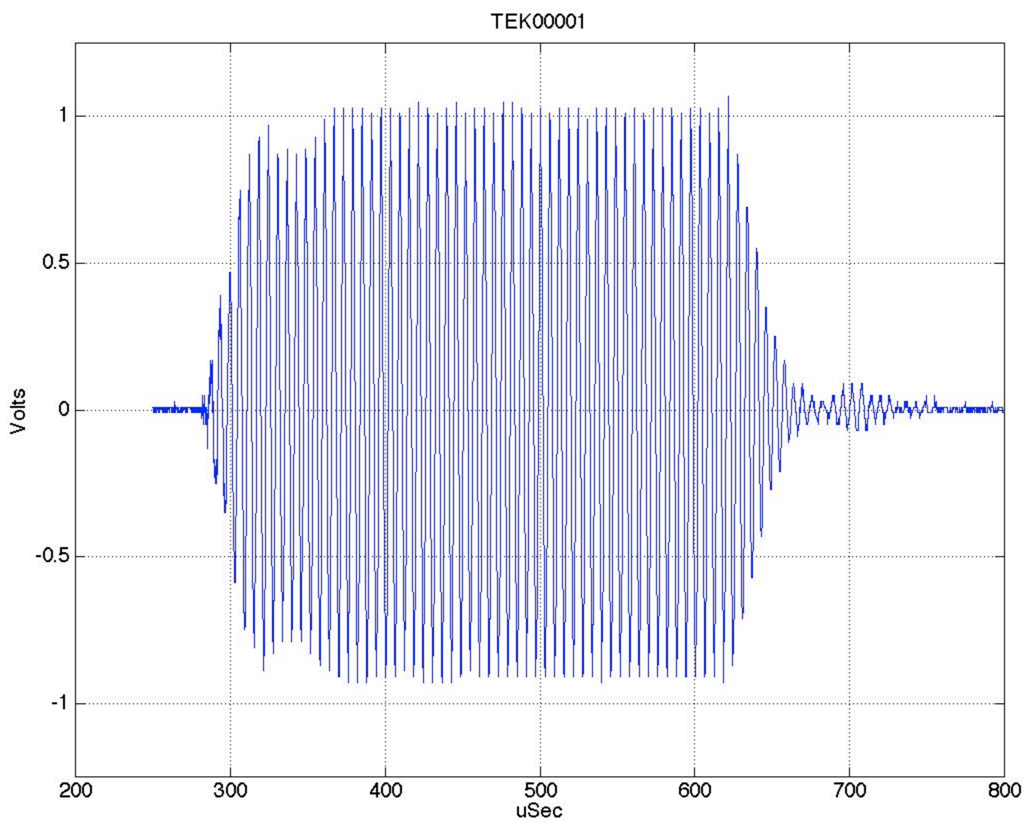
where D is the diameter or major dimension of the transducer and λ is the wavelength (λ = c / f, where c is the speed of sound in water and f is the frequency). If the standard transducer is not a point, then this equation is modified to

$$R_P = \frac{(D_1 + D_2)^2}{\lambda}$$

where D_1 is the diameter of one transducer and D_2 is the diameter of the other. If feasible, larger measurement distances are usually preferable.

Second, tanks have boundaries. Sound bounces off of boundaries (particularly the water surface). At long ranges, the distance from source to boundary to receiver can be very close to the direct-path distance between the source and receiver. This can cause interference between the signal you wish to measure (direct path) and the boundary reflections. Clearly, you need to use pulsed signals to allow you to discriminate between direct and boundary signals. Depending upon the geometry and size of the tank, this may require rather short pulse lengths.

Which can be a problem in it's own right. Transducers are damped resonant systems. This means that the transducer is somewhat slow to respond when a pulsed CW signal is first applied, taking several to many cycles before the output reaches the so-called steady-state value. One hopes this state is reached before interfering signals begin to arrive at the receiver. The example below is fairly benign; measurements after about 375 μSec should be indicative of the steady state.

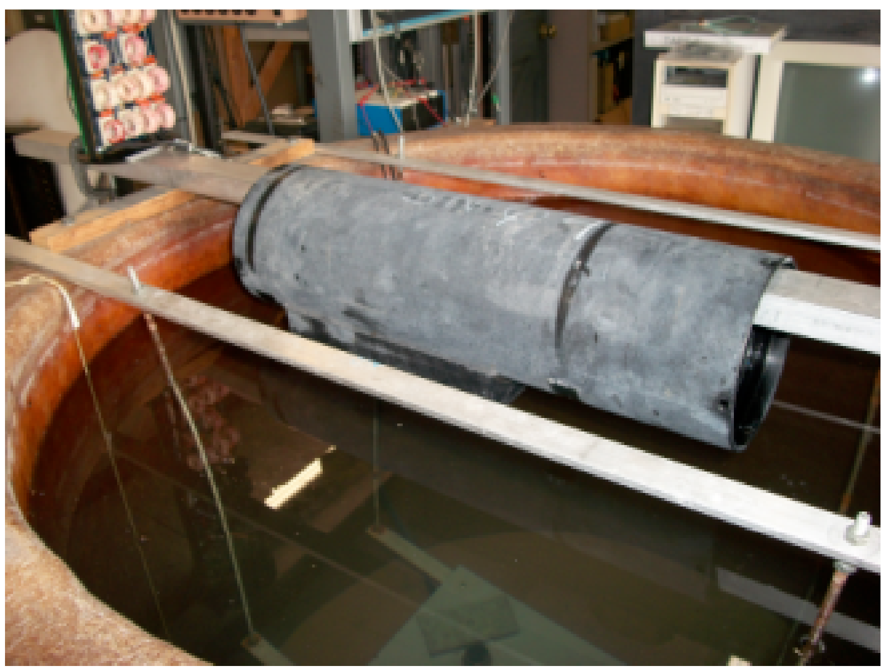


You also need a calibrated standard transducer. These are available (to government and universities) from USRD at the Naval Research Laboratory. These are accurate standards but it is difficult to impossible to obtain usable standards much over 1-2 MHz.

I have had good luck using NDTE transducers from Panametrics for this purpose and calibrating them myself. These are highly-damped transducers with relatively low sensitivities but with very broad frequency response. Two units (one resonant at 0.5 MHz and one resonant at 2.25 MHz) serve as calibration standards from below 100 kHz to well above 3 MHz. The methodology for calibrating one of these transducers for use as a standard is given in a separate document.

Then there is the problem of aligning two directional transducers. The ideal is to have a huge tank with rigid alignment columns that can be raised, lowered, and rotated to point two transducers at one another.

Practicality suggests that a more modest approach be taken. For systems like the TAPS-8, an arrangement like that below works well.



The key in any arrangement is control of the separation distance and the boundaries. Keep these in hand and the calibration data should be accurate.

Something to keep in mind. If your alignment is accurate, then the separation distance can be fudged a bit if necessary. There are theoretical corrections available for the case of two piston transducers at marginal distances (Sabin, 1964; JASA 36, pp 168-173).

So what does a calibration consist of? Basically, you transmit from the TAPS to your standard transducer and note the voltage of the received signal and the range. The sonar equation (Urick 1967) for this situation is,

$$\hat{V} = SL + RS - 20Log(R)\ V$$

where $\hat{V}$ is shorthand for 20 Log (V_{rms}), SL is the source level of the transmitting transducer (in dB//μPa/m), RS is the receiving sensitivity of the receiving transducer (in dB//V_{rms}/μPa), and R is the range. Note that RMS (root-mean-square) values are used here. The simplest measurement to make on an oscilloscope is the peak-to-peak voltage of a waveform. The RMS value of a sine wave can be obtained by dividing this value by $\sqrt{8}$ = 2.83.

Now, knowing RS and R and measuring $\hat{V}$, we can rearrange that equation to solve for SL. We expect numbers around 210 dB or so for most TAPS frequencies. Note that RS values are going to be on the order of -200 dB; keep the sign straight when you do the algebra.

Switching names a little, the same equation could work for measuring the receiving sensitivity of TAPS. However, the useful number is not just the sensitivity of the transducer but of the whole receiving chain: transducer, T/R switch and preamp, amplifier, and detector. So the voltage we would measure is the envelope of the received signal, amplified and converted to an Intermediate Frequency and detected. The amplitude of this signal is proportional to the RMS value of the AC signal. So we would use this amplitude as-is for $\hat{V}$.

Additional complications arise from the architecture of the receiver. A special Controller mode is required to set the TVG to a gain value corresponding to a range of 1 m. Manual opening of the T/R switch (install a 2-pin jumper) is required. These do not affect the basics of the calibration, however.