NOAA Technical Memorandum NMFS

FEBRUARY 2008

A GUIDE TO CONSTRUCTING HYDROPHONES AND HYDROPHONE ARRAYS FOR MONITORING MARINE MAMMAL VOCALIZATIONS

Jay Barlow
Shannon Rankin
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NOAA-TM-NMFS-SWFSC-417

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Southwest Fisheries Science Center

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A Guide to Constructing Hydrophones and Hydrophone Arrays for Monitoring Marine Mammal Vocalizations

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This document provides a guide to building single hydrophones suitable for listening to and recording marine mammal vocalizations or linear hydrophone arrays in which several hydrophones are molded onto a single cable for localizing a sound source. This guide is intended for anyone with an interest in building hydrophones, and no special expertise is required. The hydrophones described below are based on an EC65 cylindrical hydrophone element (EDO Corporation Salt Lake City, Utah)[1] and a low-noise preamplifier. This combination has proven to be reliable, gives a very "clean" sound (up to approximately 40 kHz), and is excellent for receiving sounds from sperm whales, humpback whales, and several dolphin species.

The preamp incorporates a high-pass filter that reduces flow noise that occurs when towing the hydrophones. A very small modification can be made to remove this filter and extend the usable frequency response down to a few Hz. Note that even with this modification, the hydrophones are not linear in frequency response. An example calibration is provided. Some sound analysis software can compensate for a known frequency response to restore linearity.

The building process described here consists of many steps, none of which are difficult. Some steps, however, have little margin for error. Be sure you've had your coffee first. But not too much!

SUPPLIES

Pre-Amp

Chip: Analog Devices[1] AD743 Ultra-low Noise BiFET Op Amp
Resistors: 100Ω, 10kΩ and 20MΩ (metal film recommended for low noise)
Capacitors: 1µF, 2@4.7µF, 10µF, 2@0.1 µF (tantalum recommended for low noise)
Circuit board: Vector 8001 (cut as in diagram)
Wire
Header pins for splicing wires to pre-amp
Electrical tape & heat-shrink plastic tubing

[1] Mention of brand names throughout this document does not represent an endorsement of these products by NOAA or the National Marine Fisheries Service. Many other products may work equally well or better.

Cable
For a towed array, you need a specialized cable. The cable will be the major component of the array's cost. It needs to be kevlar reinforced and double jacketed. A kevlar core together with a kevlar braid between two polyurethane jackets will make a very durable cable. A shielded cable may be less vulnerable to sharks that are attracted to electrical currents. You will probably not find something suitable off-the-shelf. You may need to place a special order, which usually requires an order of many hundred meters. If you are not towing the array, you can get away with a lighter and cheaper off-the-shelf cable (e.g. TMB's kevlar-reinforced proplex ethernet cable). This type of cable is not double jacketed, however, and needs to the handled carefully. We recommend a polyurethane or neoprene jacket (not PVC).

Hydrophone Element
Cylindrical ceramic piezo element (EDO EC65) (0.997" OD X 0.117" wall x 0.505" length)
Silver soldering flux/solder
Cable ties

Hydrophone/Mold
Smooth-On ClearFlex 50 polyurethane (for mold)
Smooth-On ClearFlex 95 polyurethane (for hydrophone)
Release agent (Stoner E236 Urethane mold release or Smooth-on Universal mold release are excellent)
Rubber primer (Devcon FL-20 Primer)
Acetone (for cleaning)
Sandpaper (100 grit)
Measuring jug, metal or plastic mixing sick
Vacuum pump (very powerful) & chamber
Balance (accurate to 1g)
Funnel for mold

Tools required
Precision soldering iron
Side cutters
Pliers
Hacksaw or bandsaw (for cutting the circuit board)
Craft knife (or swiss-army knife)
Hobby vise
Heat gun
C-clamps
80cm Quick-grip clamp (the type with reversable jaws)
Hydrophone stretcher/frame (directions for building this provided below)
Safety gloves (latex/nitrile)
Safety goggles
Vacuum hood or respirator for volatile organic chemicals

Handy, but not required
Solder sucker
Swivel blade cable stripper (Ideal Industries 45-128)

multimeter
Signal generator
Oscilloscope

Preparation

You will need to build a hydrophone cable stretcher (Fig. 1). This is the frame you use to hold each hydrophone "node" while you are casting the polyurethane around the preamp and hydrophone element. The stretcher is made out of 2" x 4" lumber (25mm x 100mm) , hinged on the outside at the base, so it can splay outwards. It's helpful to have an adjustable strut holding one of the vertical arms. You need a stetcher to ensure that the element and electronics are in the middle of the urethane housing. Fasten it to the bench with C-clamps.

Figure 1. Hydrophone casting setup showing a stretcher frame that keeps the wire taut during the casting process.

You first need to make a mold. To do this, you must first make a blank, which is the exact shape and size you want each element to be (Fig.2). For towed hydrophones, this should be relatively long (50cm is good). For hydrophones used while stopped, it needs only be long enough to comfortably house the electronics.

The easiest way to make a blank is to make it from wood or PVC plastic, using a lathe. Using a metal-turning lathe will give much more precise control than using one intended for wood-turning. Make sure the “ends” of the blank are at least 10cm long and the same diameter (exactly) as your cable. Sand it so that it is very smooth, and seal with varnish or a spray clear acrylic, sanding between each coat.

Figure 2. Varnished wooden mold blank used for making a mold for hydrophone casting. The blank is exactly the finished size of the hydrophone and cable.

We use PVC plastic pipe to make the mold. It is easy to work with and cheap. Choose an inside diameter that is at least 10mm greater than your blank, otherwise the walls will be too thin. Cut the tube to length (allowing at least 20mm extra at each end to seal around the cable), and seal each end with endcaps (use PVC glue). When the glue is cured, cut the tube in half lengthways. Make indents for the cable, and on one of your halves, cut away one end (Fig. 3).

Figure 3. PVC form used for casting the hydrophone mold.

Organize a bench so that it is exactly level. You will need to make your mold in two halves, which will need two separate molding sessions. Spray the varnished blank with mold release, making sure to get none on where it contacts the tube ends. Likewise spray the inside of the tube.

Figure 4. Hydrophone mold making setup. The blank (Fig. 2) is secured within half of the PVC form (Fig. 3).

Settle the blank into the half mold (Fig. 4) and tape it in place firmly. Seal the ends where the “cable” ends of the blank go into the holes you made in the end caps. Hot-melt glue is great for this. Otherwise use caulking or Teflon pipe thread tape. Tape the blank down, so that it cannot float up when you pour in the urethane. Be thorough, or urethane will go everywhere.

Make sure everything is level. Mix urethane (Clear flex CF50) as per the instructions that came with it. Making the mold out of urethane that is more flexible than the stuff you’ll use for the hydrophone node makes it much easier to get the two apart. Degas the urethane in a vacuum chamber (wait until bubbles are almost gone, then release vacuum and degas again) and pour in urethane until it is exactly level with the top of the mold. Leave it for at least two days to cure. Heating the cast will speed the curing time. Do not remove the blank.

Spray the exposed side of your blank and the urethane half-mold with mold release, along with the inside of the other half of the tube mold. Tape the other half of the mold tube in place. Seal the bottom (hot-melt glue and tape) & seams very carefully. Be thorough. This has the potential to be very messy.

Set up tube mold and blank so it is vertical, with lots of old newspaper underneath. Now make up another batch of urethane (Clear Flex CF50), and pour into the top of the tube. If your taping job is not excellent, you will now discover that fact when polyurethane starts leaking everywhere. Leave for two days to cure, preferably somewhere warm.

De-mold carefully. If you use the mold release recommended above it should come apart easily. Keep the tube that you made the mold in. You’ll use the bottom half again when you pot up the hydrophone elements. The complete mold is shown in Figure 5. Remove the mold-release agent with acetone and tape along the bottom joint with duct tape. To allow air to escape and to improve the flow of urethane to the end of the mold, you can use a Dremel tool to cut an airhole from inside of the mold to the top.

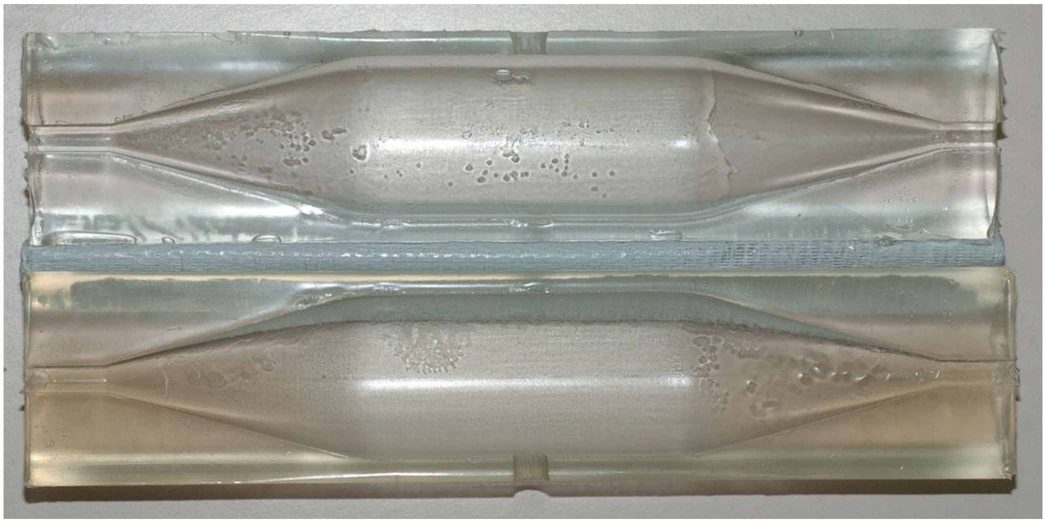


Figure 5. Completed mold after being removed from the PVC form.

Building the Electronics

Hydrophone elements never provide much output voltage, so you need to boost it with a pre-amplifier before it sending the signal up the cable. Our design (Fig. 6 & 7) provides 40dB (100x) amplification. Note that this design uses a double-side power supply, meaning that it needs +12v and –12v (Fig. 8). That means you need two batteries. Two 9v transistor batteries are fine for testing.

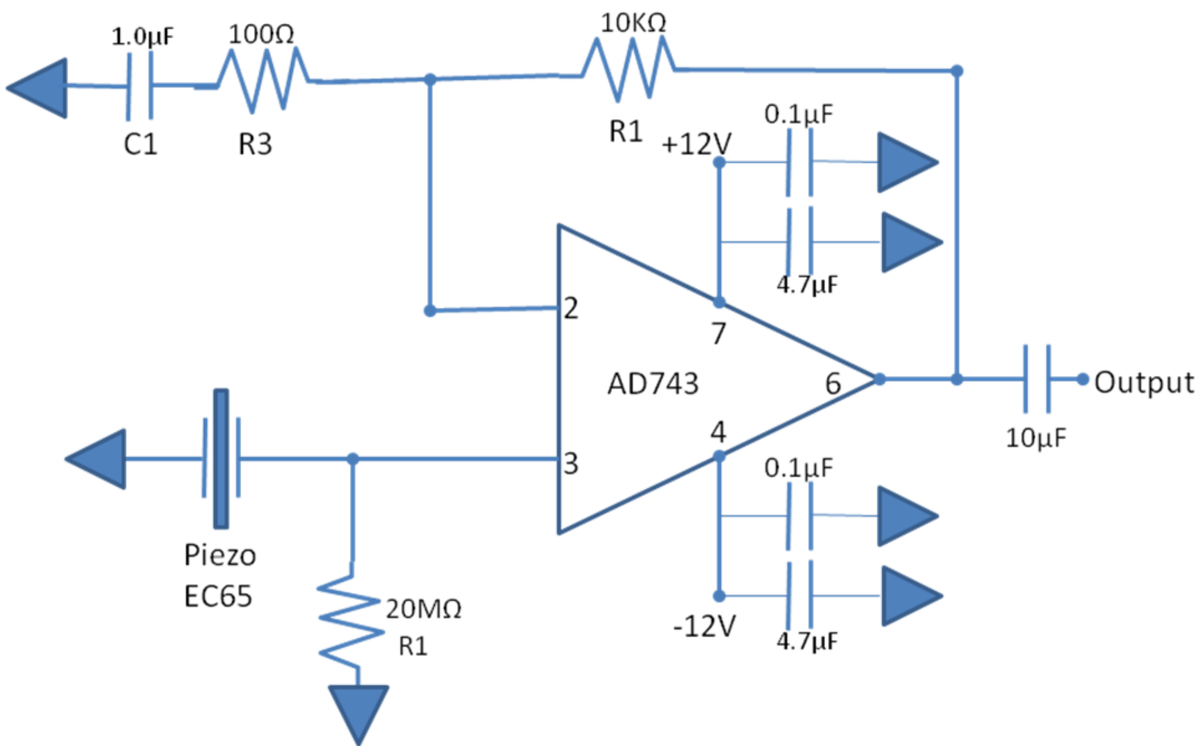
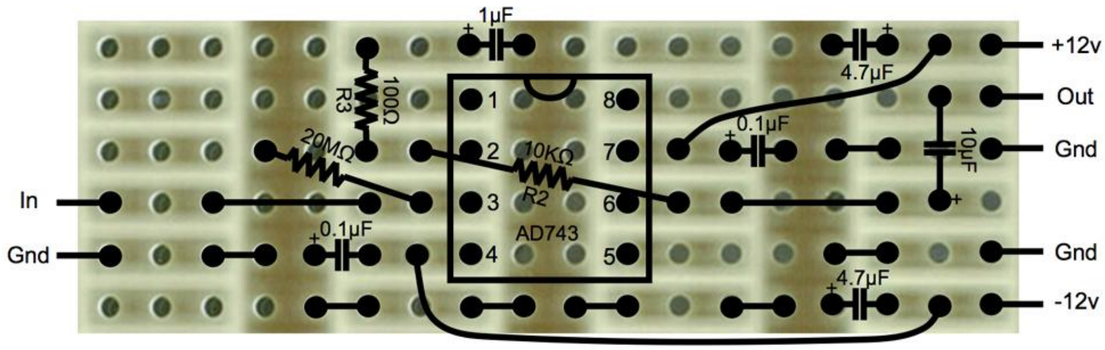


Figure 6. Schematic circuit diagram for a low-noise pre-amp built with an Analog Devices AD743 chip. For higher frequency response, an AD797 chip can be substituted.



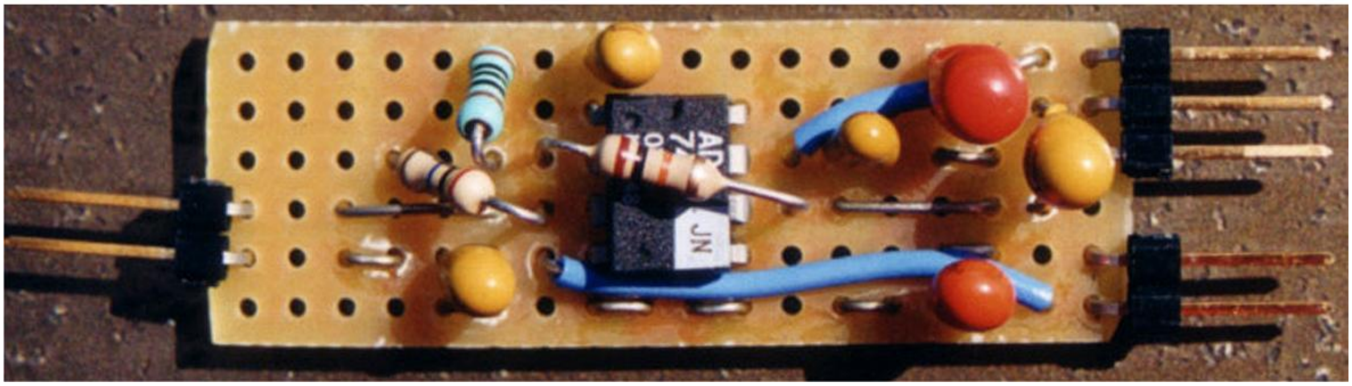


Figure 7. Layout of components on the circuit board. Note that all the soldering pads are on the underside and all the components are on the top.

The tantalum capacitors have a polarity, and have to go in the right away around. The positive pin is usually marked with + or a dot on the capacitor. The 1µF capacitor, C1, above pin 1 of the AD743 chip creates a a high-pass filter that gradually attentuates sound below a corner frequency of 1592Hz. This is excellent for a towed hydrophone, as it dramatically reduces flow noise. You can replace it with a direct wire link to remove the filtration, but this is a bad idea unless the hydrophone will only be used statically.

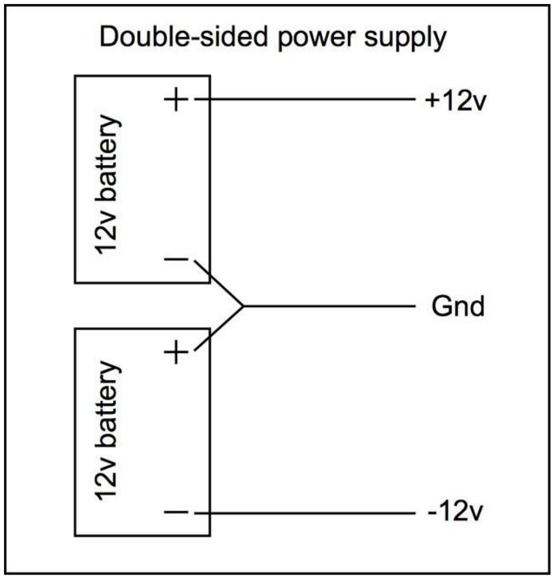
The gain of this pre-amp can be adjusted with the resistors R2 and R3:

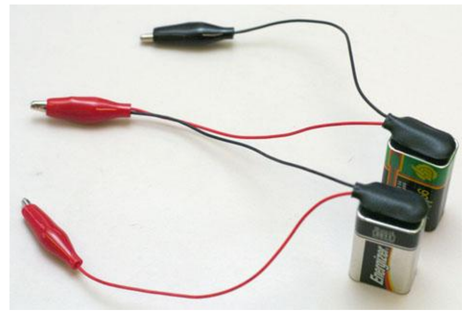
$$Gain \quad = \quad 1+\frac{R2}{R3} \quad \textit{or in this case} \quad 1+\frac{10k\Omega}{100\Omega} \quad = \quad 101 \approx \quad 40db$$

The corner frequency for the high-pass filter can be adjusted with the resistor R3 and adjacent capacitor C1:

$$HighPassCornerFreq \quad = \quad \frac{1}{2\cdot\pi\cdot C1\cdot R3} \quad = \quad \frac{1}{2\cdot\pi\cdot 10^{-6}F\cdot 100\Omega} \quad = \quad 1591\ Hz$$

Check all solder joints, test by plugging into two 9 volt Batteries and headphones. Make sure the polarity of the supply is right, or the preamp will fry. Consider using two rectifier diodes (not shown) as reverse polarity protection. Leave it plugged in overnight to make sure it stays working.





test supply

Figure 8. Setup for a double-sided power supply using two batteries (either 12 v or 9 v).

Solder wires (30 gauge stranded) to the hydrophone element

- Use clean pencil eraser to clean oxidation off surface of element for solder.
- Solder the black (ground) on the inside of the cylinder, and the red to the outside. (This standard is just for consistency. Reversing the wires will reverse the phase of the signal and in an array it is best to keep all signals in phase with each other.)
- Use silver solder with flux according to instructions
- Work quickly because too much heat will crack the ceramic piezo

Setting up the Hydrophone

For an array to localized dolphins or sperm whales, the hydrophone elements will typically be 3-5 m apart. Measure the desired separation and mark the location for all the elements (tape is ideal), and then slide the hydrophone element(s) onto the cable (after you've silver-soldered the wires on). Position the wire in the stretcher so that the desired location of the hydrophone element and the preamp will fall in the center of the mold. Carefully cut the jacket from the cable (the optional swivel cutter is excellent for this), exposing at least 50mm of wire on one side of the element. Cut back the shielding and remove, until you get to the twisted pairs underneath.

Wire Allocation (example using 8 wire configuration):

+12v	Brown	
Ground	White	← Common Ground
- 12 v	Blue	
Ground	White	← Common Ground
+ HP #1	Green	← Twisted pair
Grnd #1	White	← Twisted pair
+HP #2	Orange	← Twisted pair
Grnd #2	White	← Twisted pair
Extra HP	Orange	
Grnd Extra	White	

Fasten the cable on the stretcher with hose clamps, so that the de-jacketed part is in the middle (Fig. 9). Make sure you put tape over the cable jacket so that the clips do not cut into the jacket.

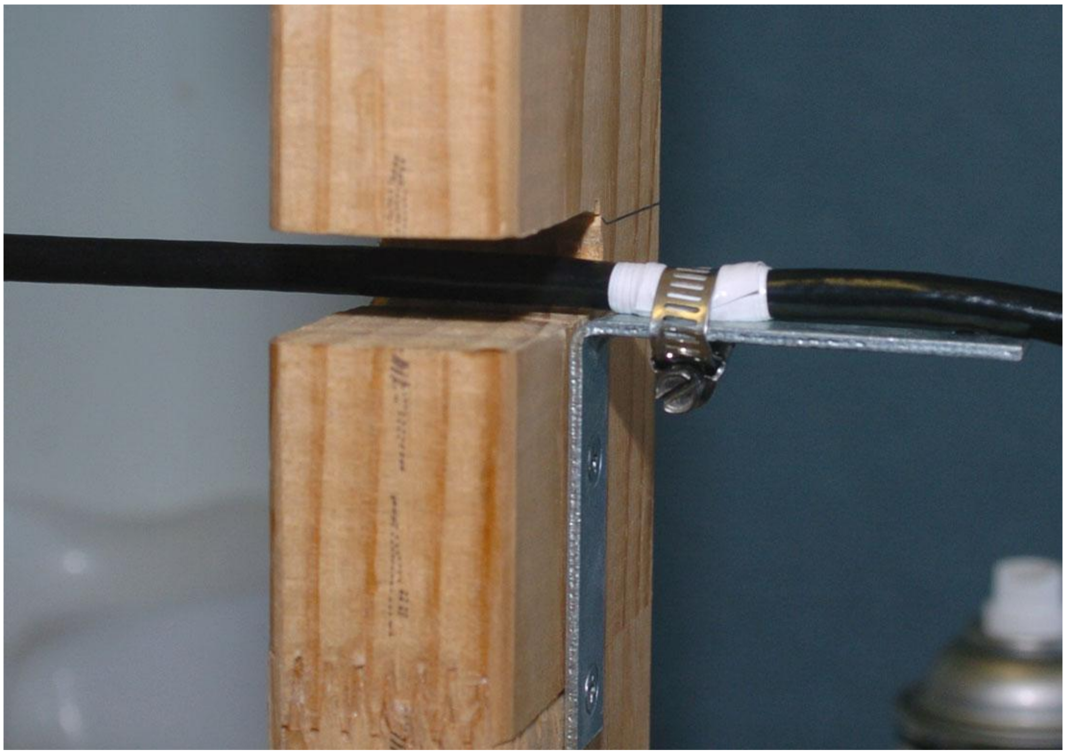


Figure 9. Attachment of the hydrophone cable to the stretcher frame with hose clamps.

It is important to remember that even if you are potting up a single hydrophone, or the last hydrophone in a line array, you need the cable to go entirely through the molded node. If you don't do this, and the node terminates the cable, when you tow it will oscillate and the flexing will eventually destroy the cable. So, make the cable go all the way through, leaving at least 2m at the end. Seal this end with urethane or epoxy and tie a 6-10m braided rope tail on the end.

Choose the wires that will be soldered onto the pre-amp. Whatever color combinations you use, write it down. Also be aware that while the preamp output wires do not need to continue down to the next hydrophone (which will use a different pair of wires), the power wires do. Hence you need to splice in extensions. Use heat-shrink tubing over each joint. It can be valuable to continue all the wires to the tail of the hydrophone element; this will allow you to cut off the tail and check for wire discontinuities (breaks) if anything goes wrong with your array, or if you wish to connect additional hydrophone nodes or other instrumentation at a later date.

Now you need to solder the wires onto the appropriate pins on the pre-amp. It is easiest if you bend the header pins away from each other to make more room (Fig. 10), and to start by soldering the innermost wires first. To get a really tidy join, strip ~6mm of the insulation off the wire you are using, slide a piece of heatshrink up the wire (as far from the soldering as possible), then form the bared wire strands around a paper clip or similar. Then slide this over the pin you need to connect to. Now solder it, using a minimum of solder. Finish by sliding the heat-shrink down over the soldered joint, and shrinking it with a heat gun. A loosely attached cable tie will stop things flopping around as you work. Repeat this with the remaining wires.

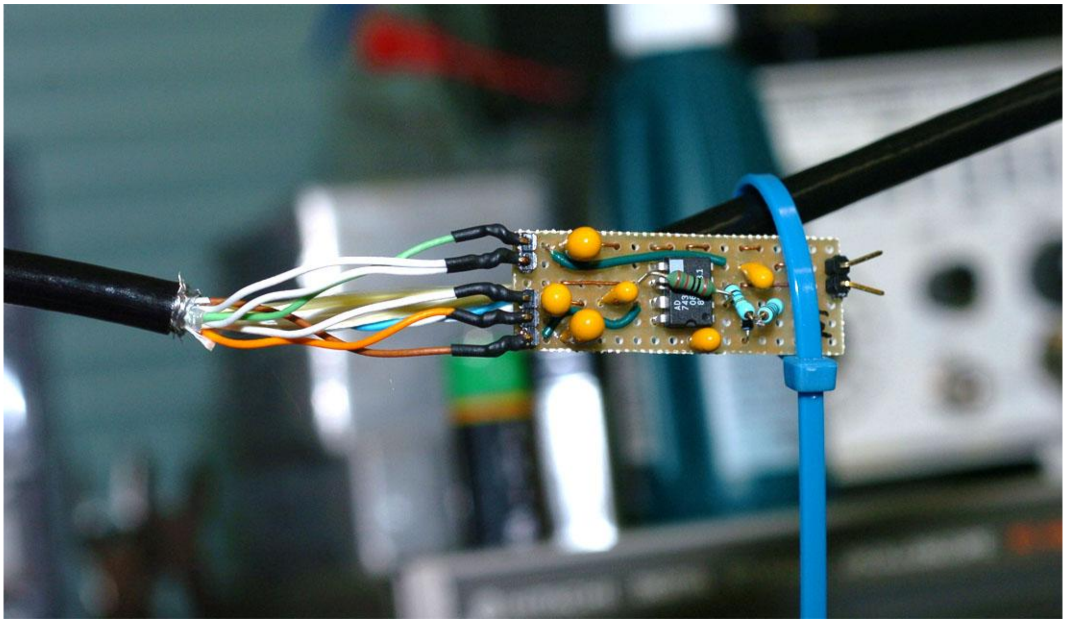


Figure 10. Position of the pre-amp along a section of the hydrophone cable where the jacket has been removed.

Now, put the hydrophone element in place (Fig. 11). It’s good to hold it in place and isolate it from cable noise by using a thin strip of sleeping mat foam or neoprene cork gasket material. Solder the hydrophone wires onto the pre-amp as described above, consistently connecting the outer (red) wire to the input pin and the inner wire to the ground pin.

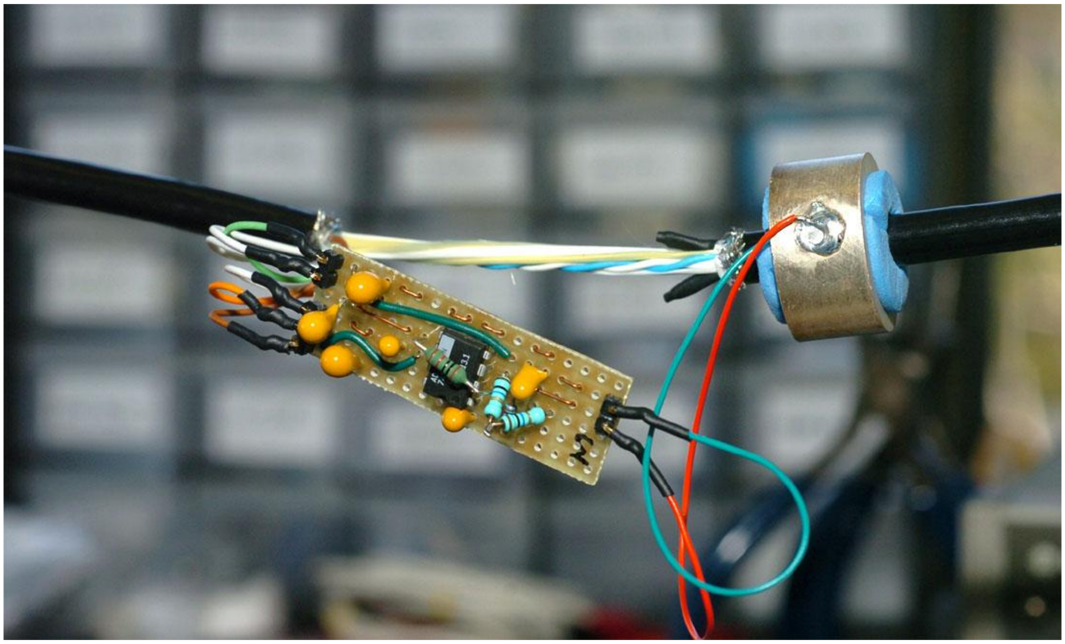


Figure 11. Position of the hydrophone element on the cable near the pre-amp.

Ok, now test it by hooking up the headphones to the correct wires at the end, and attaching batteries to the power wires. Make sure you get the polarity right. It should sound very sensitive to touching the element, and will almost certainly pick up lots of 50 or 60 Hz hum from your building’s wiring. This is normal, and not a problem underwater.

Wrap the wires and kelvar strands with electrical tape, and nestle the preamp into place. Now you can use cable ties to tie everything down (Fig. 12).

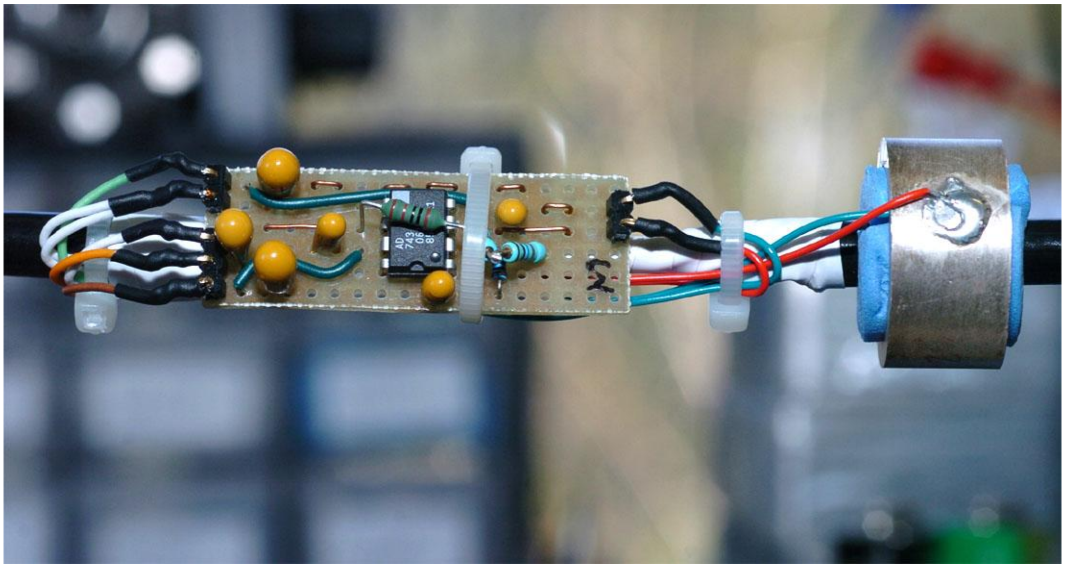


Figure 12. Final configuration of the pre-amp and hydrophone element. Use cable ties to secure all loose wires. It’s good to keep things as tidy as you can

Now thoroughly buff the cable that will contact the urethane with sandpaper (Fig. 13), and paint with the Devcon FL20 primer. This will ensure maximum adhesion to the cable. Do not touch after priming. The primer fumes are toxic so be sure to use a respirator mask.

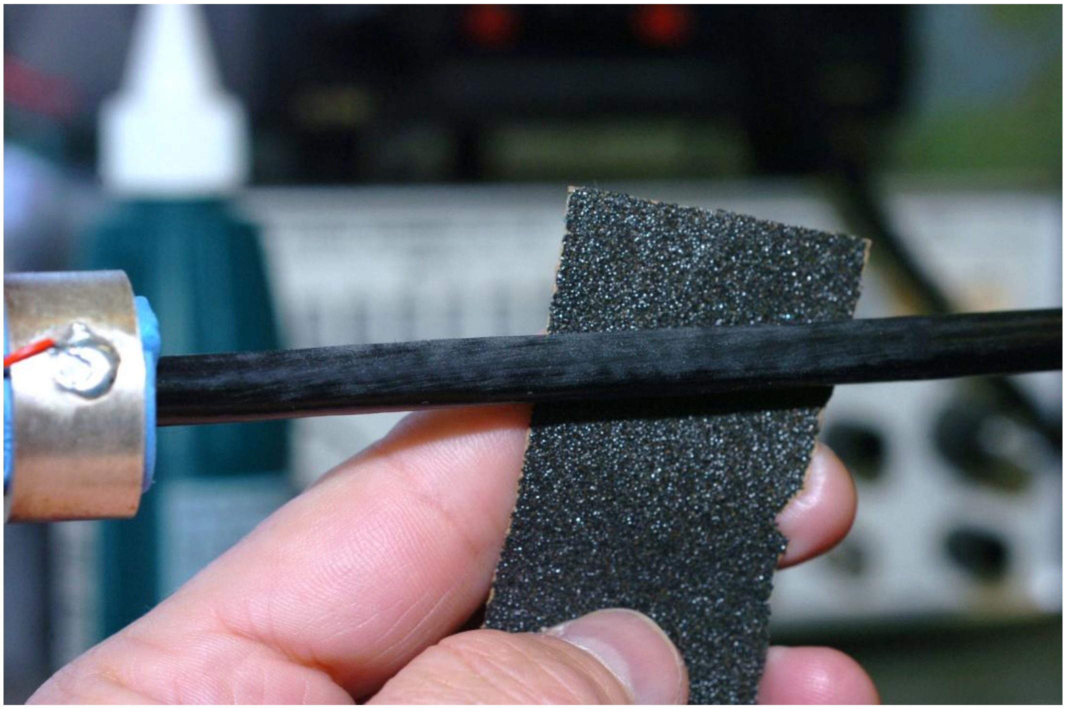


Figure 13. Buff the cable with sand paper and clean thoroughly with acetone to ensure a good bond between the polyurethane and the cable.

Preparing the urethane

The urethane is a two part mix, and the exact details will vary depending on which kind you use. These instructions are be for Smooth-On CF95. This is a harder urethane than we used for the mold. It has a gelled density (1.04 g/cc) that is very close to seawater.

Clean all mixing and pouring materials and spray with mold release (including your mixing jug). Let the release agent sit for 20 to 30 minutes

Set up the hydrophone on the stretcher. Make taut with the clamp. Place the mold over the hydrophone element (with the funnel hole over the pre-amp), and tape the ends very snugly with electrical tape (leaving space for the airholes) (Fig. 14).

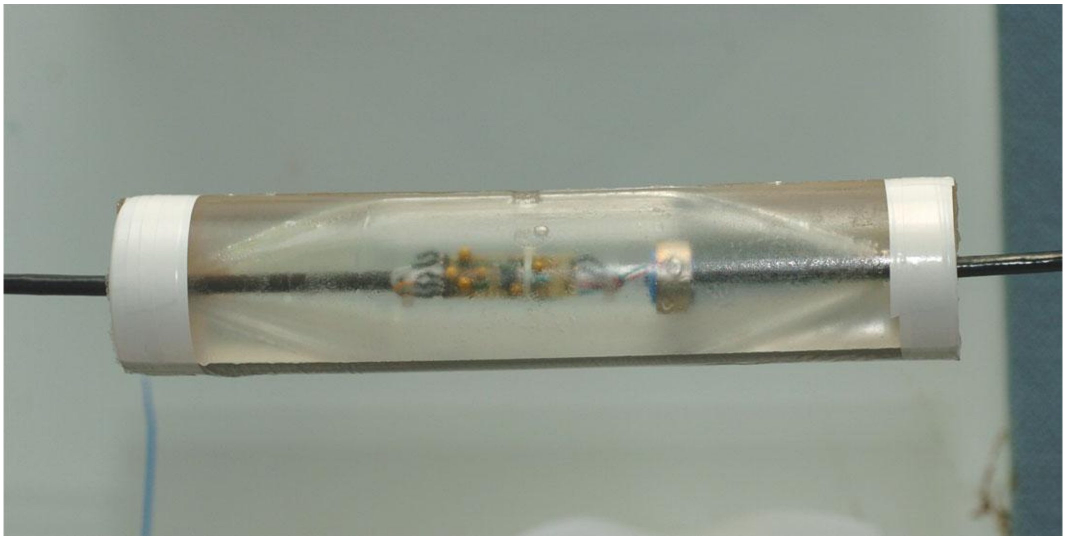


Figure 14. Position of the mold around the pre-amp and hydrophone element prior to casting.

Put the PVC cylinder underneath the mold, and tape it up to the stretcher clamp (Fig. 15). Make sure that the join in the mold is vertical (so that the airbubbles will escape). Put the funnel in its place. Give the preamp one more test to ensure that all is well.

Figure 15. Setup for casting a hydrophone node onto a cable.

Measure the volume of urethane that you need by measuring the volume of your hydrophone blank. Add 10% at least for spillage and shrinkage.

Before mixing anything, read the smooth-on instructions carefully. It is critical that you throughly stir part A before using. You can do this by shaking Part A container (before opeing it!). Pour both parts of polyurethane into the mixing bucket, and stir thoroughly for 3 minutes. Once mixed you have 20-30 minutes until the urethane starts getting thick.

After mixing, degas with the vacuum pump (see earlier description and Fig. 16). Completely pump out gas bubbles twice.

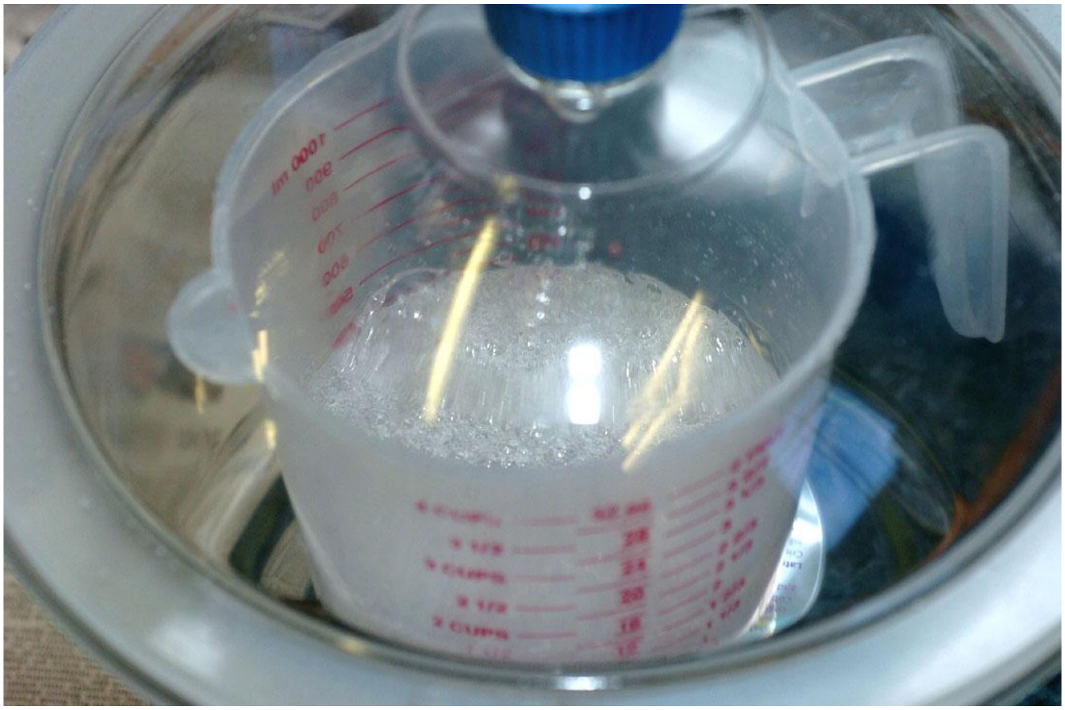


Figure 16. Degassing the urethane mix using a vacuum chamber.

Pour the urethane mix into the mold. Don’t hesitate, it will flow more smoothly when it is still very fluid. After it is full, continue to add more slowly to the funnel as it seeps out. Keep doing this until the polyurethane is very viscous and not oozing out. As the urethane sets it tends to shrink, and it will tend to suck in air bubbles at this time. That’s why it is important to keep adding urethane, even when it seems that nothing is happening.

While you are at it, seal the terminal (deep) end of the cable. You can do this with Epoxy or urethane. Figure 17 shows a setup for using urethane. The glass tube has been sprayed with mold release, and slips off easily when the urethane has cured.

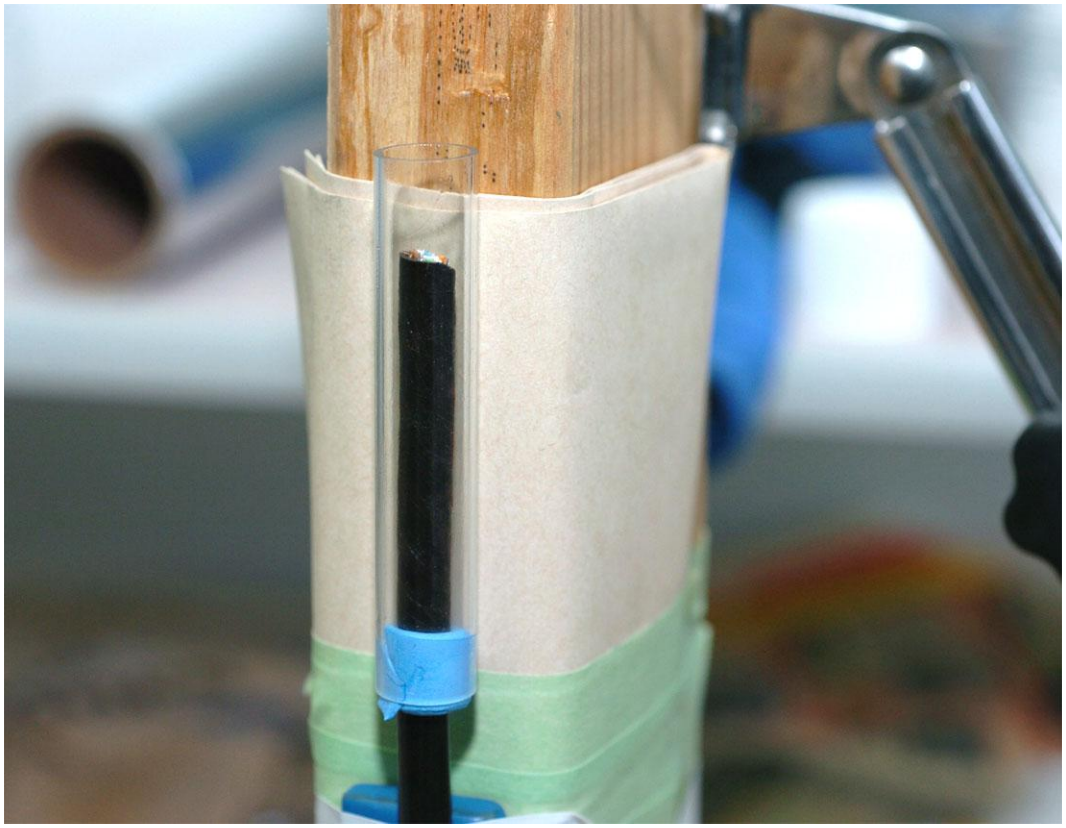


Figure 17. Casting form to seal the end of the cable.

Let stand, but check on it occasionally for the next two hours to make sure all is well. Leave for two days before removing the mold. Otherwise, it tends to sag and deform.

Test again and celebrate (if it works!).

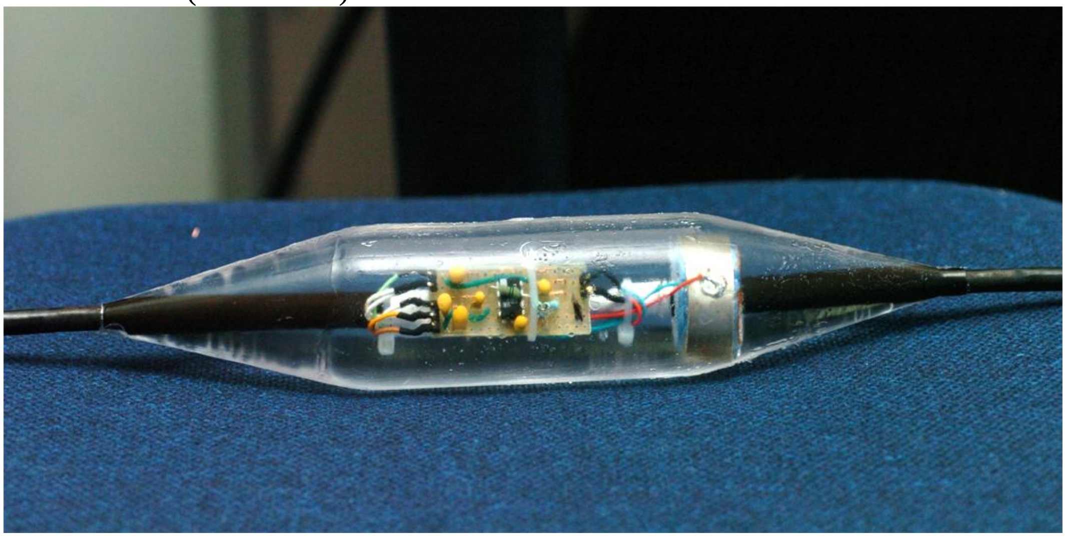


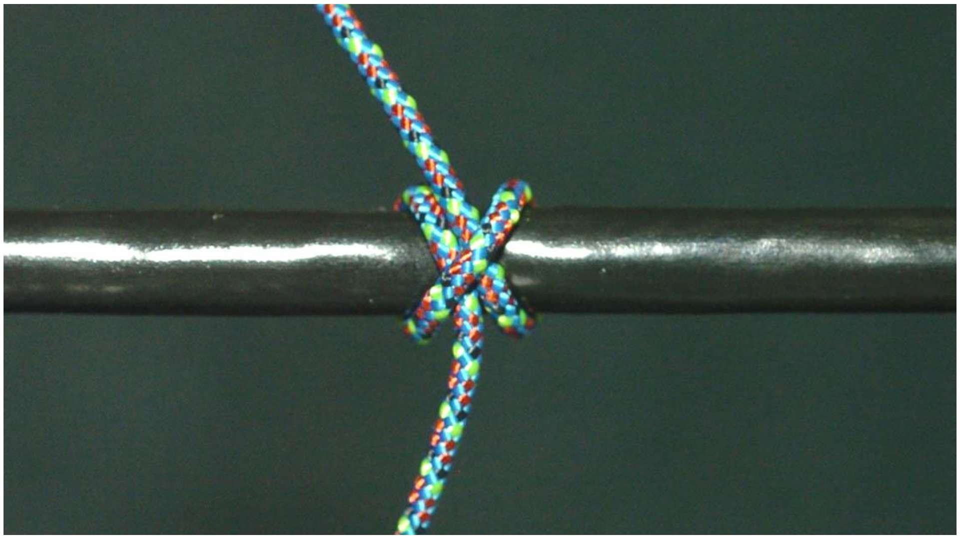
Figure 18. Finished hydrophone after being removed from the mold. Note that this hydrophone will be used statically. A longer hydrophone node would be quieter in a towed hydrophone.

Don’t worry about minor bubbles near the surface. You can open these up with a sharp knife, and fill them with a new urethane mix. Because the urethane shrinks when it cures, the ends of the hydrophone may need to be supplemented with additional urethane after the initial casting is complete. An easy way to fill them is to mix a small amount of urethane and let it harden until it is just tacky. Fill the ends with the tacky urethane using a flathead screwdriver until they are overflowing. Tape over the ends with insulation tape and let stand for a day. Wet sand the ends until they are streamlined and smooth. Special attention to the hydrophone ends is necessary because in a towed array they are the most likely point of failure. After several days, you can wet sand the hydrophone node smooth. This will ensure that it tows as quietly as possible.

The ends

Be sure to terminate the boat end of the array with a connector that can be plugged in only one way. The polarity of the power supply is critical. Reversing it by accident (e.g. while reconnecting the batteries after charging) will be fatal to the preamps, which when potted up, are not repairable.

The far end of the array needs to have a rope tail to ensure it tows straight, and to give pelagic predators something to bite that does not matter. Use braided line, and a strain-relief weave (Fig. 19) to tie on the rope. This will ensure the cable tows well. Start with a clove hitch



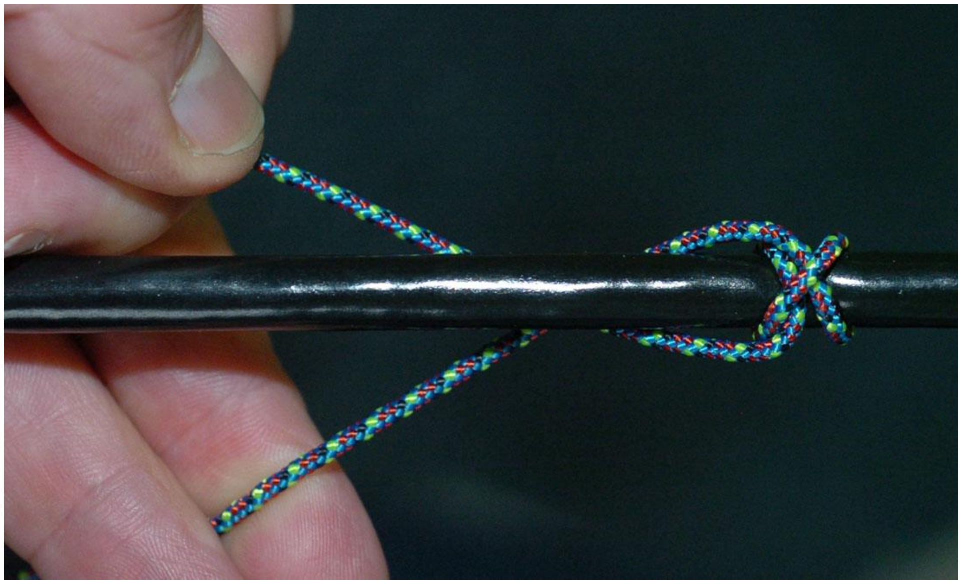


Figure 19. Beginning a strain-relief weave on the end of a hydrophone cable.

The cross them alternately behind and in front of the cable. Continue this to the end of the cable (Fig. 20). For a towed array, this braided knot should be reasonably long (1m at least) to ensure the strain is spread out.

Figure 20. Completed strain-relief weave on the end of a hydrophone cable.

Tie this to a swivel, and tie a thicker braided rope tail (~6mm) to that. Use braided, rather than laid rope. The latter will cause the array to twist. Use the same knot on the boat end of the cable, to tie the cable to something solid on the boat.

Managing a small array (say 100m or so), so long as it is on relatively light cable, is easiest on a garden hose reel. Most of these have an axle that rotates that can take a waterproof connector glued into the hub. Remember to disconnect the cable from your recorder to the reel before winding the handle!

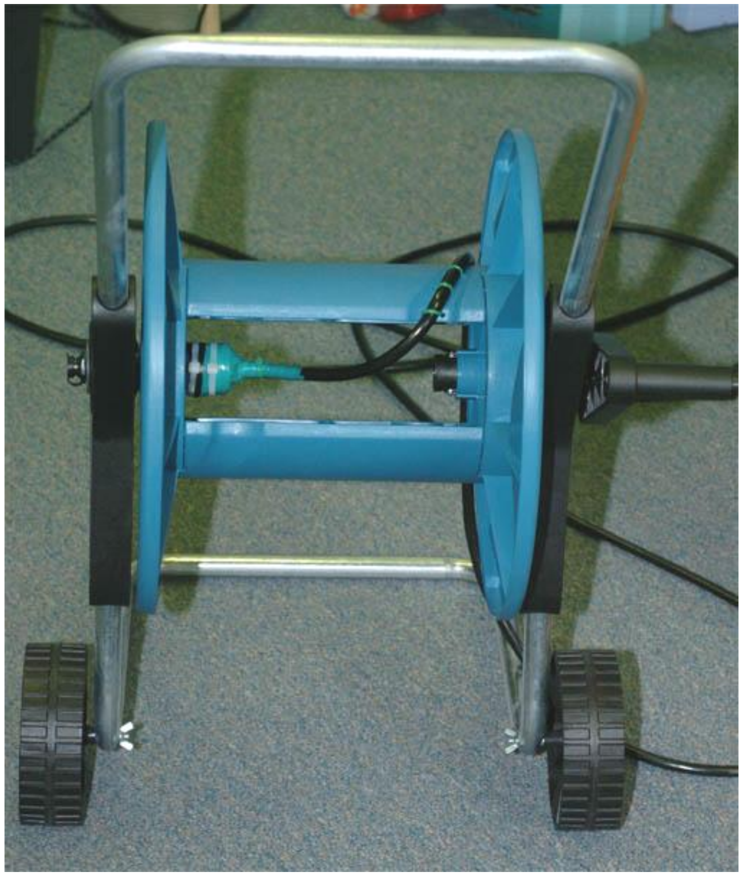


Figure 21. Garden hose reel modified for use as a hydrophone cable reel. Ensure that the hose reel *and bolts* are made of marine grade stainless steel, or aluminium. An endcap on the connector is important to protect from splashes and allows easy rinsing and cleaning at the end of the day.

Calibration

Determining the frequency response of a hydrophone requires calibrated equipment and is typically done in a specialized tank under carefully controlled conditions. This is likely to cost much more than the material costs of making a hydrophone. Nonetheless, it is a necessary step if you plan to make measurements of sound pressure levels produced by marine mammals or of the relative amplitudes produced at different frequencies. Figure 22 shows a calibration curve of one hydrophone element based on the design described in this report.

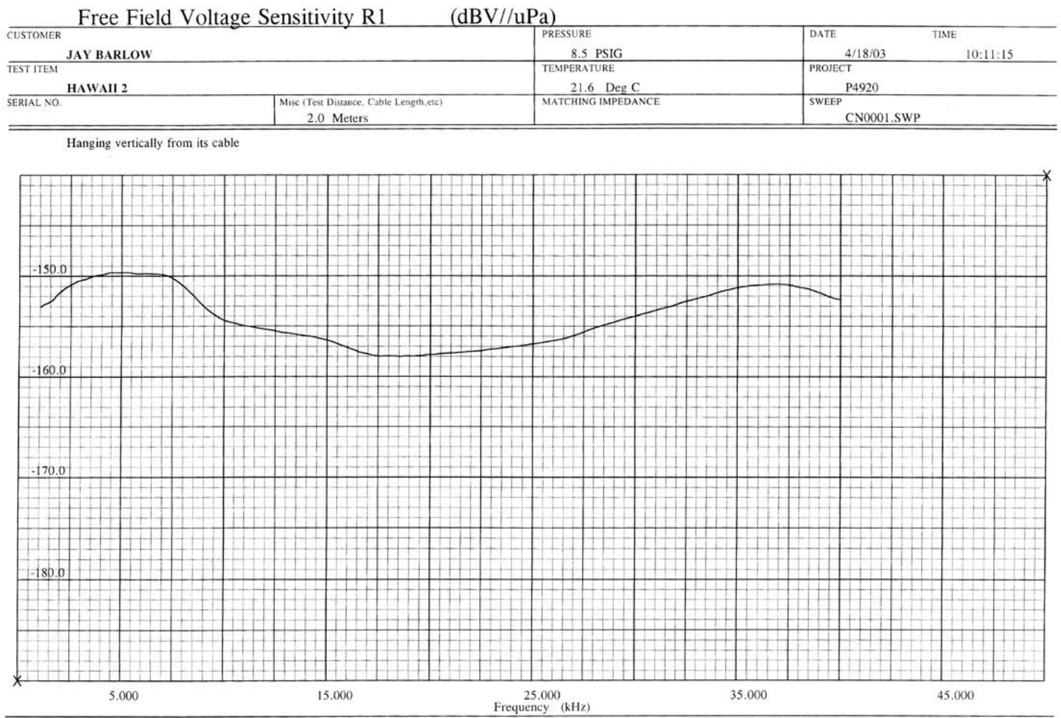


Figure 22. Calibration curve of a hydrophone built using the methods outlined here over a frequency range of 2 to 40 kHz. Sensitivity is measured in dB-V//μPa. Note that each hydrophone will vary slightly.

Acknowledgments

We gratefully acknowledge the many helpful comments from Brian Miller and Tom Norris on earlier drafts of this report.

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