Thru-The-Earth 2-Way Voice Communication With Cave Divers
Equipment and Test Results

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4/5/03

Last fall, Wes Skiles asked if it was possible to modify some commercial diver-to-surface acoustic communication units to allow him to talk through the limestone to divers in Florida springs while we were tracking them from the surface with my 3496 Hz Radiolocation gear (the subject of another article). I said "probably yes" and borrowed two units for testing. I was able to design antennas for surface and diver use. Two months later I successfully tested the system at Wakulla Springs, Florida to a depth of 100 ft (30m) through the limestone and later to 200 ft (60m) at Alachua Sink. The most recent use was at Florida's Hart Springs Park where divers were tracked and directed to features visible from the surface and the tunnels were mapped by surveying the surface track.

Description of the Commercial Acoustic Equipment

The units were manufactured by *Ocean Technology Systems* and operate on Single Sideband voice. The basic operating frequency is 32.768 kHz upper sideband. Other manufacturers also use this frequency. The center of the sideband energy is near 34.5 kHz. The units can also be operated on lower sideband and optionally on other frequencies.

The Surface Unit, an STX-100 Buddy Phone

The surface unit is an STX-100 Buddy Phone built into a special Pelican box. It operates on 12V from either internal alkaline C-cells or external power and has a standard PTT microphone, and built-in loudspeaker. The acoustic transducer supplied with the STX-100 has a connector and enough cable to allow the sensor to dangle in the water below a boat. The unit turns on when the transducer is connected to the unit.

The Underwater Unit, an SSB-2010 with microphone, 2 earphones, and PTT Switch. The inboard end of the antenna with its matching network is visible.

The underwater unit is an SSB-2010. This DSP unit is voice-menu controlled via the PTT switch on the full-face mask, which also has a ceramic microphone and two 8-ohm dynamic earphones. The acoustic transducer attaches directly to the unit with a built-in connector. The 12V battery pack uses 8 alkaline AA cells.

Transmitter power for both units is about 2 watts.

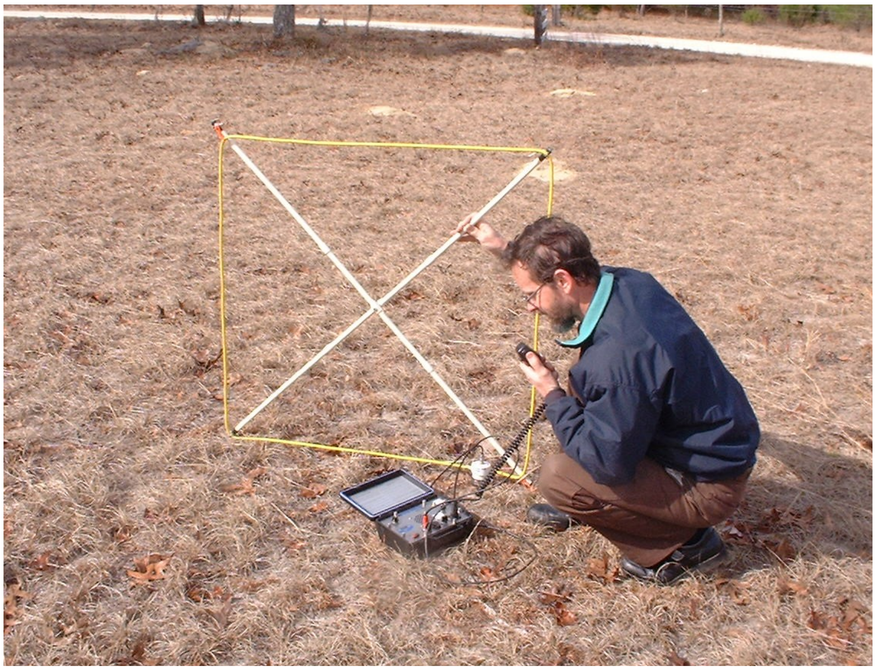
Antenna Design

This gear operates in the near field range using the magnetic fields generated by the antennas. There is very little true electromagnetic radiation.

From past experience I knew that the diver-to-surface uplink was the most difficult path because the surface receiver must contend with atmospheric (and manmade) noise while the diver's unit is shielded from most of the noise by the attenuation of the noise as it passes through the rock overhead. The voice signals are attenuated equally in both directions. The equation for plane wave attenuation is:

$$\text{Plane wave loss} = .01726\sqrt{(\text{Freq, kHz})(\sigma\text{, S/m})}\quad \text{dB/mtr}$$

For 34.5 kHz, and typical water-saturated Florida limestone with $\sigma = .02$ S/m, plane wave loss is 0.453 dB/mtr. For 100 ft (30m) depth the loss is 13.6 dB. If the diver's receiver was atmospherically noise limited at this depth (it is not quite, at least during daylight), then the signal to noise ratio of the downlink would be 13.6 dB greater than the uplink if both units had the same transmitted signal strength. For a symmetrical link, the diver's unit should transmit a much stronger signal than the surface unit. For this reason, I decided to use a long wire antenna underwater, which transmits a stronger signal than a small loop. The loop is an ideal antenna for a mobile surface operator.

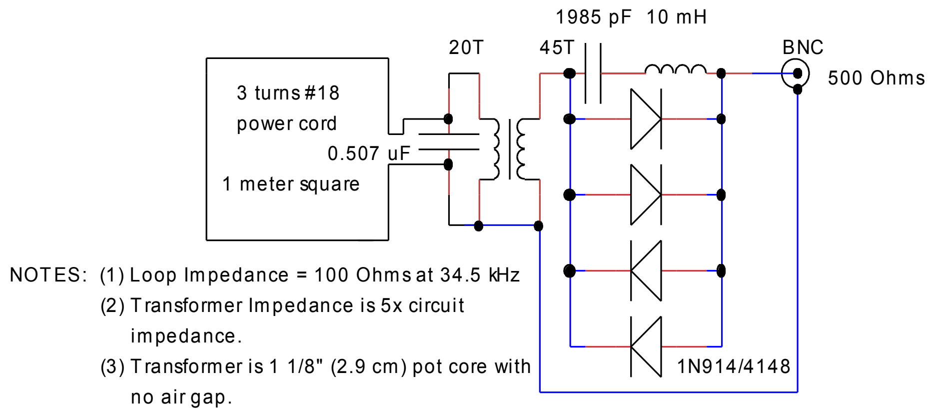


surface unit with 1-meter square antenna

I calculated the impedance of one of the acoustic transducers, using Ohm's Law, by inducing a known current through a resistance and measuring transducer voltage. The impedance was 440 ohms at 34.5 kHz.

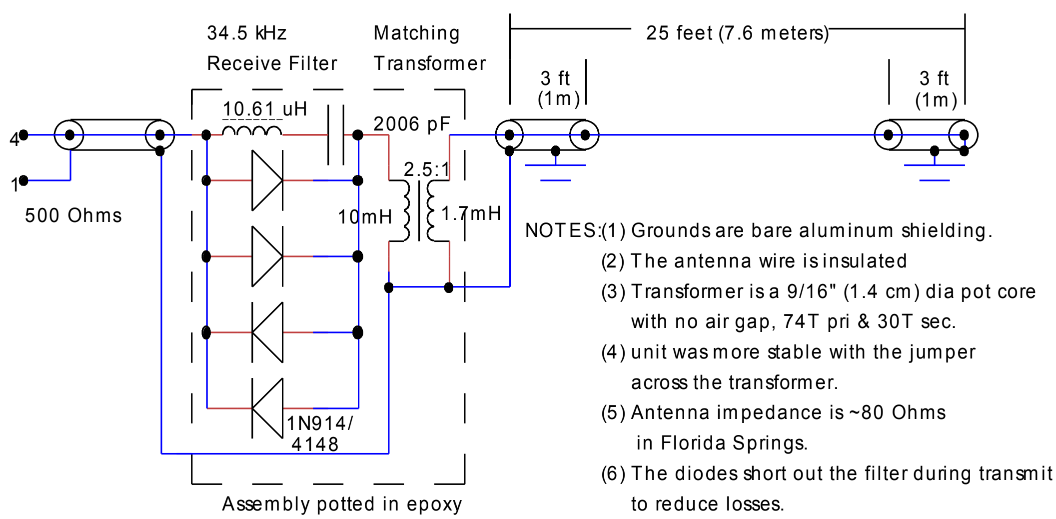
The input/output of the STX-100 is transformer coupled. In transmit, I loaded the output with resistance until the open circuit voltage was reduced 50%. Based on these measurements, I assumed that the output impedance was ~500 ohms. Using a similar technique, I found that the input impedance during receive was >1000 ohms.

Surface Antenna: I estimated that a square loop 1 meter on each side with 3 turns of #18 wire would have a bandwidth wide enough to pass voice. I constructed the loop with a folding, shock-corded frame, and waterproof matching network case, exactly like the antennas used with my 185 kHz transverters.



Surface Loop for STX-100

The loop resonates with 0.485 µF of low-loss polypropylene capacitance. The bandwidth is 5.2 kHz with a resonant impedance of 100 ohms at 34.5 kHz. I built a 100/500 ohm matching transformer using a 1" (2.5 cm) pot core with no air gap, 20/35 turns ratio, and winding reactance of 5x the circuit impedance. I also added a simple series-resonant filter to improve the front-end selectivity of the receiver, which was not designed for RF.



Diver's Trailing Wire Antenna for the SSB-2010

Underwater Antenna: I realized that a loop antenna similar to the surface design was impractical underwater. A compact ferrite rod antenna with voice bandwidth would not have sufficient range. I settled on a "trailing wire" antenna similar to the ones used by nuclear submarines to receive ELF and VLF broadcasts. I chose 25 feet (7.6m) as the longest practical length (longer is better). The antenna has two grounding electrodes; one at the tip, and the other near the unit. The transmit current flows through the water between the electrodes, creating the electromagnetic fields. The magnetic field pattern is essentially the same as that of a vertical loop oriented parallel to the wire. The antenna efficiency is determined by its impedance (the lower the better), which is mostly just the resistance between the electrodes through the water, calculated from Dave Gibson's equation below with R = resistance between two electrodes in Ohms; ln = natural log; L = electrode length in meters; d = electrode diameter in meters; σ = conductivity of earth (or water) in Siemens/mtr.

$$R = \frac{\ln(4L/d)}{\pi \bullet \sigma \bullet L} \text{ Ohms}$$

With my trailing wire electrodes, the antenna impedance in typical Florida spring water (conductivity=.028 S/m) is 80 Ohms calculated. This has been checked by actual measurement. The 2.5:1 turns ratio of the transformer matches the 500-ohm output of the SSB-2010. Unlike the surface loop, the trailing wire antenna is broadband and non-resonant. For this reason I included a simple 34.5 kHz bandpass filter to provide some selectivity.

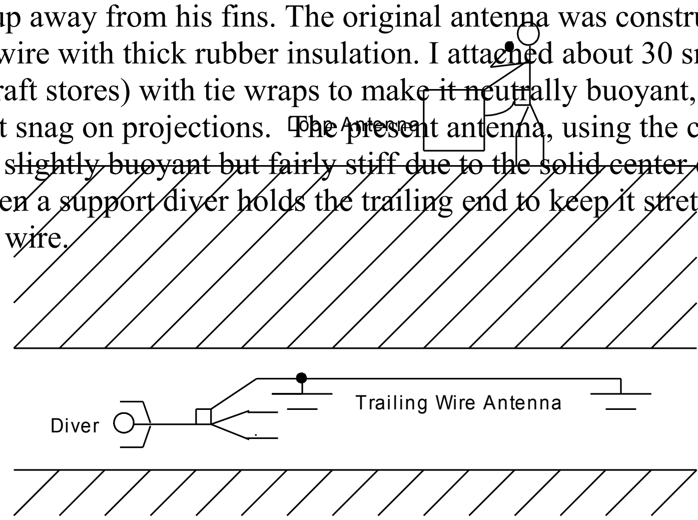
Important Note: *This underwater antenna is optimized for Florida springs water. It should work in most water filled limestone caves, and also sumps in dry caves. For waters of drastically different conductivity, the transformer turns ratio must be changed.*

The wire antenna could be used in dry caves if the grounds can be submerged in a cave stream or in pools. A longer wire and large grounds could be used.

For fresh water lakes and streams, and non-karst springs and caves where the conductivity is very low, the antenna impedance will become quite high. The transformer can be eliminated, or changed to step the antenna impedance down to 500 Ohms. There is a possible shock hazard to divers from the high transmit voltage developed between the electrodes. I suppose that divers in open water could use the 1-meter loop. The optimum frequency will be much higher, probably in the low MHz range, where a tuned (loaded) insulated antenna can be used.

In seawater, the range will be very limited despite the low impedance between the electrodes, even with a proper impedance match. The optimum frequency is much lower. I don't recommend use in seawater. Let me know of any successful results!

I have not yet found a good wire for this trailing antenna. I think that the antenna should be very flexible and float on its own, or be neutrally buoyant with a float close to the diver to hold it up away from his fins. The original antenna was constructed with very flexible "test lead" wire with thick rubber insulation. I attached about 30 small Styrofoam balls (available at craft stores) with tie wraps to make it neutrally buoyant, which was ok for testing but might snag on projections. The present antenna, using the core of 75-Ohm RG-6 foam coax, is slightly buoyant but fairly stiff due to the solid center conductor. It works well only when a support diver holds the trailing end to keep it stretched out. I may try a "sinking" wire.



Optimum Orientation and Position of the Antennas

Test Results

The first test was conducted at the entrance to Wakulla Springs in north Florida. The antenna with Styrofoam balls was used, with no one holding the wire straight-out underwater. The diver swam deeper while I stayed on the "beach". We still had 2-way voice communications at the 100-ft (30m) limit of the dive. Atmospheric noise was low, but EMI from digital and video still cameras was severe at a range of less than 10 feet (3m). Visit http://www.floridasprings.org/expedition/dispatch2 to see photos, video, and audio clips from this test.

The second test was conducted further south at Alachua Sink, where successful comms were maintained at ~200 ft (60m) depth (160 ft of rock plus 40 ft of overburden). The diver used the improved trailing antenna built from RG-8 foam coax. A support diver kept the antenna stretched out. I tracked the divers with 3500 Hz Radiolocation gear while a second person followed me with the voice unit. The optimum orientation for the vertical surface voice loop is parallel to the diver's direction of travel, with the strongest signal directly overhead. The tunnel passed under a busy 4-lane highway. The surface voice operator was forced to orient his loop to null out interference from the high tension power lines that ran along both sides of the road, but was able to maintain comms even in the median.

The final trial involved some real work at Florida's Hart Springs Park. I tracked the divers carefully at modest depths ~65 ft (20m), while a second person on the surface used the voice unit to direct the divers to swim under certain surface features to inspect blockages from underneath. My path was marked with flags, while the divers reported depths. They could also have reported passage crossections and other details instead of writing them down. We later surveyed the path with compass, clino, and tape; in effect surveying the tunnels from the surface.

Conclusions

Thru-the-earth voice communications with divers is both possible and useful. The system described here is easy to assemble, because only the antennas need to be constructed. Other brands of underwater acoustic gear could probably be modified in a similar way.

The range of my system is adequate for its intended use, but is not enough for 250-300 ft (90m) depths, or when used by itself without seperate diver tracking. Due to the shape of the trailing wire's magnetic field, it is not possible to track the diver closely, in real time. All one could do is to run around on the surface hunting for the best signal. The best solution to increase range may be to increase transmit power. Orcatron.com has several acoustic SSB units that operate on 32.768 kHz USB, and also long range 8 and 16 kHz units with 50 watts output.

A longer trailing wire and/or larger grounds (with proper impedance matching) will improve the link in both directions, as the diver's receiver is typically not atmospheric noise limited.

A better surface loop will improve the downlink s/n, but not the uplink, which is usually atmospherically noise limited. Changing the loop to #16 wire should narrow its bandwidth to about 3kHZ, the highest practical Q. The transformer ratio would have to be changed to reflect the higher impedance. The largest mobile surface loop is probably 1.5 meters square and might be worth trying.

A long grounded wire can be deployed along the surface over known passage. This should provide comms throughout the dive. The surface operator can then remain at the entrance. Since good grounding is very difficult in dry earth, it would be far better to run the wire between two water-filled sinkhole entrances. It can be matched like the diver's antenna, using the impedance equation. Most likely a multi-pole bandpass filter will be necessary to reduce interference from out of band signals.

This voice system could be used in dry caves if the trailing wire grounds were submerged in a cave stream or pools. It would not be mobile unless the operator was wading in a cave stream. The SSB-2010 diver unit is about as "caver-proof" as electronics can get. An SSB-2010 could be used, with a headset/mike, on the surface in place of the STX-100 for improved waterproofness and portability.

References

Gibson, David, *The Resistance of Ground-Electrode Arrays*, CREGJ 29, pp 26-27, Sept 1997

Ocean Technology Systems (SSB-2010 & STX-100):
http://www.oceantechnologysystems.com

Orcatron Communications Ltd (High Power gear):
http://www.orcatron.com

Florida Springs website (Voice and Tracking demo at Wakulla Springs):
http://www.floridasprings.org/expedition/dispatch2

Thru-the-Earth Radiolocation & Voice construction and use (author's Website):
http://Radiolocation.tripod.com