3496Hz Beacon Transmitter & Loop

by Brian Pease

A radio-location transmitter, receiver and associated loop are described in principle. Constructional details of the transmitter and loop are given. A unique feature of this design is the receiver (to be described in a follow-up article) allows depth to be determined by absolute field strength measurement.

General

This article gives the construction details of a simple continuous-carrier 3496Hz Cave Radio Beacon designed for use with a very sensitive surface receiver using a narrow-band (1Hz) "double-quadrature" detector of my design. The receiver can also phase-lock on the signal to allow a digital readout of field strength (mainly for quick depth measurement) with an apparent bandwidth of 0.1Hz or less. Detection of successful phase-lock can also set off an alarm to "wake up" the surface operator.

The receiver, which contains no inductors or expensive filters, will be described at the block diagram level in a subsequent article. Both units have been built and used in actual cave locating with excellent results. Changing to another frequency should not be difficult. Prototype PCBs for both the receiver and transmitter has been produced by Ian Drummond, but the receiver board has not been tested yet. My working units are hand wired using generic RS PCBs.

Loop Antenna Construction

The rigid loop consists of 19 turns of 12 gauge (2.053mm diameter) solid copper insulated "house" wire 24 inches in diameter. Loops with few turns like this one are rugged, have little shock hazard, and will even work submerged. It is not wound on a form but was simply bent to shape over a circle drawn on my basement floor, then wrapped tightly with plastic electrical tape to keep the inductance from changing. The loop is tapped 3 turns from the battery (Vcc) end.

A thin 0.5 inch wide piece of an epoxy-fibreglass sail batten was wrapped around the outside of the loop and attached with tie-wraps for added rigidity and protection. A separate bubble line-level is used for levelling. A 3-wire cable and plug connects the loop to the electronics, allowing all the capacitors and electronics to be carried in a waterproof container. The loop is resonated with 4µF of Radio Shack polyester capacitors which are a bit lossy but are small and cheap.

Table 1 gives the electrical parameters of both the resonant circuit and the loop alone. Appendix A gives the inductance formula I use.

Loop Parameter	Direct Lab Measurement	Comments
L_s	492µH	24 inch loop
X_l	10.8Ω	
R_{dc}	0.12Ω wire resistance	
C_{res}	4.198µF	polyester (mylar) caps
D_{cap}	.0072	cap dissipation factor
R_{3500Hz}	0.214Ω	loop AC series resistance
f	3501Hz	L-C resonance
Q	50	loop alone
Q_{res}	34.6	polyester caps
Bandwidth	104Hz	-3dB, includes cap loss
R_{res}	375Ω	L-C parallel resonance
R_{tap}	9Ω	L-C parallel resonance
weight	4lbs	complete loop

Table 1 : Electrical Parameters of Resonant Circuit & Loop

Transmitter Design

The so called class "E" mode of operation is used to make the transmitter simple and efficient. In class "E" a short pulse of specific duration (dependent on "Q") is applied to the resonant loop at a specific time during each carrier cycle. The loop then "coasts" through the rest of the cycle on its own. For beacon use a steady 3496Hz signal (derived from a 3.58MHz colour-burst crystal) is transmitted without modulation to allow the narrowest practical bandwidth to be used in the receiver during the search (1Hz). The receiver identifies the signal by its frequency, which is accurate to .05Hz or better when not phase-locked. CW (Morse Code) can be used for uplink communications using a broader bandwidth mode. Loop current (and voltage) is a reasonably clean sine wave.

Referring to the schematic (Figure 1), U1 contains an oscillator circuit using CMOS gates which drives a 14-stage binary (÷2) divider. AND gate U3A forms an 1/8 duty cycle positive pulse train at 6991.3Hz. When keyed, AND gate U3B feeds a 1/16 duty cycle 9V positive pulse train at 3495.65Hz to Q1. U3C doubles the drive current to Q1.

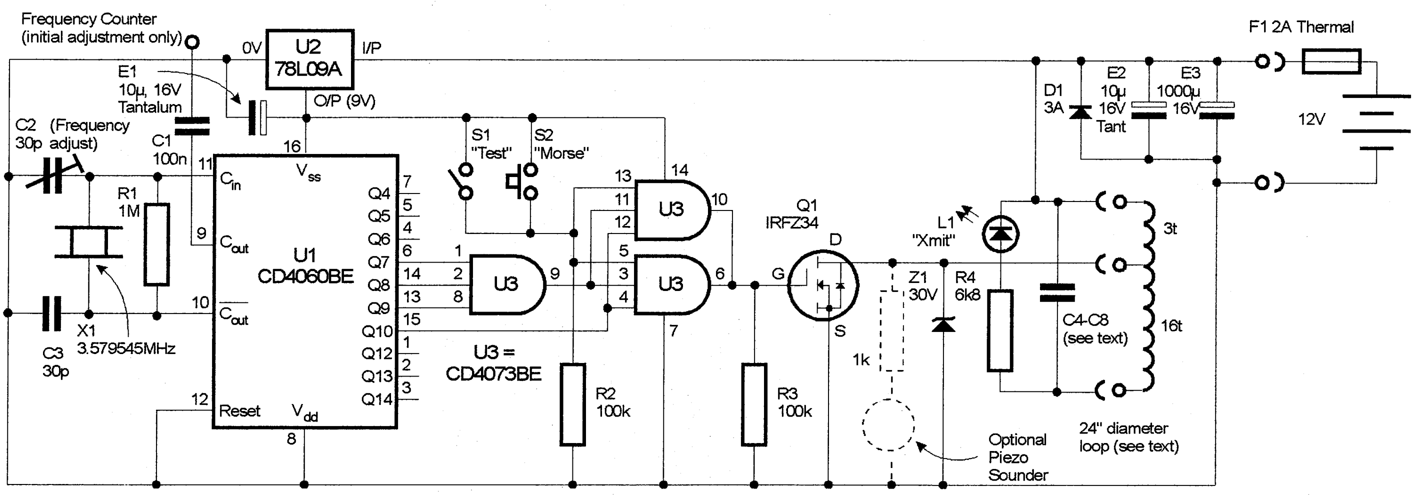
The primary attribute of Q1 is low "on" resistance (.05Ω). Any N-channel MOSFET with a rated voltage of 50V or 60V, a continuous current rating of 10A or more, and an "on" resistance of .05Ω or less should work. The International Rectifier IRLZ34 is a direct substitute. The IRFZ40, IRFZ42, IRFZ44, IRLZ44, or IRFZ46 should all work. Harris has the RFP45N06 and RFP25N06 and Phillips has some also. Switching losses are low due to the low frequency. Only a token heat sink is required. In my unit Q1 is bolted to about one square inch of the plated copper on a PCB.

When properly tuned, Q1 will turn on at the lowest voltage point of the sine wave. As shown in Figure 2, current in Q1 rises rapidly for 1/16 of each carrier cycle then suddenly drops to zero producing a large transient spike which is absorbed by Z1. The net effect is exactly like giving a small push on a child's swing each time it comes close except here we are causing a resonant circuit to "ring" resulting in a current of about 3.6A RMS in the loop.

For power I usually use a 12V 1.4 amp-hr Gel-Cell. These batteries seem to last indefinitely if they are kept charged when not in use (every few months) and never allowed to remain deeply discharged for more than a few hours. Table 2 gives the measured specifications of this beacon with the 24 inch loop but using an older MOSFET. L1 will only light when the loop is properly connected and actual transmission is occurring. An audio sidetone for CW can easily be added by connecting a pizeo-speaker element (RS 273-073) in series with a 1kΩ resistor between the drain of Q1 and ground. My unit is housed in a cheap blue plastic box (RS 270-221).

Tune-up

Tuning is a three step process. First construct the loop with its feedline then resonate it with capacitors C4-C7 before they are installed on the circuit board. It may be best to tune slightly above the operating frequency so that C8 can be used for final tuning. Next install C4-C7 and complete the beacon. Now simply find the value of C8 that gives minimum battery current. Fine-tuning can also be done by changing loop shape. This should be close to the point of maximum efficiency. Note that maximum



Notes: C2 should be replaced with a fixed capacitor once the correct value is found. Strictly speaking, the exact frequency is not important as long as it matches the receiver. If you have two transmitters, however, it is as well to standardise on a single frequency.

F1 and D1 are optional for reverse voltage protection.

S1 is a SPST switch to hold transmitter on for continuous measurements. S2 is a momentary action push-button for Morse code.

Figure 1 : Transmitter Circuit Diagram

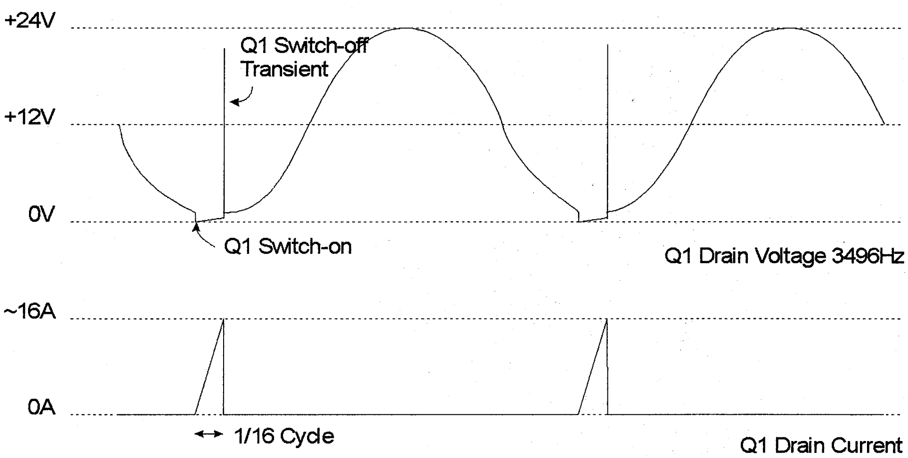


Figure 2 : Waveforms

output does *not* occur exactly at minimum current. To reduce current drain (and output) move the tap up the loop from 3 turns to 4 turns.

Improvements

3496Hz is OK for countries having 60Hz power, with the nearest harmonic being 17Hz away, but is a poor choice for the UK with the nearest harmonic of 50Hz only 4Hz away at 3500Hz. 2-4kHz is an atmospheric noise null. A 3MHz crystal will give 2930Hz which is acceptable for 50Hz areas with the nearest harmonic 20Hz away.

For those looking for the ultimate beacon the following comments are offered:

A) Appendix B gives both the general design equations for the beacon and the theoretical design for a larger folding loop that could be used with or without a frame.

B) A single layer loop winding would increase "Q" and magnetic moment.

C) Shortening or eliminating the loop's feedline completely would also increase "Q". Mine is 5 feet of 16 gauge 3-conductor wire.

D) Aluminium wire is acceptable for weight reduction in a rigid loop.

E) Installing the tuning capacitors at the loop end of the feedline helps "Q" and allows a 2-wire cable to be used. This is also a good idea if interchangeable loops of different sizes are planned.

F) Use polypropylene capacitors which have 1/10 the loss of polyester units, but are much larger and more expensive.

Note: All loop and beacon parameters are defined in Appendix A or B

Beacon Parameter	Measured Value (at Home)	Comments
V_{loop}	38.9V RMS	24 inch loop
I_{loop}	3.6A RMS	
I_d	13A peak	
Magnetic Moment	19.8 a-t-m squared	
I_{cc}	.405A	Battery current
P_{in}	4.86W	Battery power
P_{out}	4.0W	Includes cap loss
E_{eff}	.82 (82%)	Based on older MOSFET with R_{on}= 0.15Ω
MOSFET heat loss	0.9W	New MOSFET would be 0.3W and E_{eff}= 94%

Table 2 : Measured Specification of Beacon with 24" Loop and Older MOSFET

Appendix A

My favourite loop inductance formula works with any antenna from skinny one-turn loops to fat "donuts". The "c" and "l" dimensions are the approximate cross-section of the actual winding. Note that it is not necessary to know the wire gauge. The inductance will change (increase) if the winding is tightly taped after construction. A single layer or any widely spaced winding will give higher "Q" due to reduced proximity effect, but they are harder to build. L_s = series inductance in µH.

$$L_s = \frac{aN^2}{13.5} \cdot \log\left(\frac{4.9a}{\ell + c}\right) \quad ,\mu\text{H}$$

$$\text{or } N = \sqrt{\frac{13.5L_s}{a\ \log(4.9a/\ell + c)}} \quad ,\text{turns}$$

where N = number of turns, ℓ = winding width in inches, c = winding thickness in inches, a = winding radius to centre of cross-section in inches, and Log = base 10. The dimensions a, c and ℓ are identified in Figure A.1.

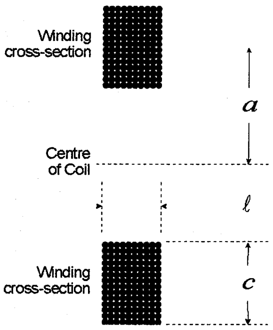


Figure A.1 : Identification of Loop Dimensions a, c and l

Appendix B

For those wishing to design their own class-E beacons for different loops, frequencies, or power levels, the following procedure was extracted from a paper by N. Sokal entitled "Class E Power Amplifier With Just One L and One C -Approximate Analysis" in the *IEEE Journal of Solid State Circuits*, Aug. '81 (Vol. 16).

The general procedure is to build the loop ***first*** and determine its parallel resonant Q (Q_{res}) and impedance (R_{res}) with the capacitors you will actually use (C_{res}). Q_{res} can be determined by measuring the -3dB bandwidth. R_{res} is the product of Q_{res} and the inductive (X_l) or capacitive (X_c) reactance. The following equations then tell you the optimum MOSFET duty cycle (duty ratio D) and where to place your tap on the loop for your chosen battery voltage (V_{cc}) and the average battery current (I_{cc}) that you want.

$$Q_{res} = \frac{f}{\textit{bandwidth of loop}}$$

where f = carrier frequency in Hz, and Q_{res} = loaded Q of tuned circuit.

$$R_{res} = Q 2\pi f L_s$$

$$\text{or } \frac{Q}{2\pi f C_{res}} \quad ,\Omega$$

where L_s = loop inductance in H, and C_{res} = resonating capacitor in F.

$$X = 2\pi\ Q_{res} \quad ,\text{dimensionless}$$

$$D = \frac{1}{1+\sqrt{X}} \quad ,\text{approx.}$$

where D = on/off duty ratio of MOSFET.

Now just pick the closest binary ratio as I did (1/16, 1/32, etc.) or use a monostable to get the exact value. D' = ratio you will actually use.

$$R_{tap} = \left(V_{cc} - I_{d\ peak} R_{on}\right) \frac{\sqrt{X}}{I_{d\ peak}} \quad ,\Omega$$

where $I_{d\ peak}$ = peak MOSFET drain current = approximately $2I_{cc}/D'$ A, R_{on} = "on" resistance of MOSFET from spec sheet in Ω R_{tap} = resonant impedance at loop tap (from V_{cc} end).

Now the number of turns to the tap can be found:

$$N_{tap} = N\sqrt{\frac{R_{tap}}{R_{res}}}$$

where N = total loop turns, and N_{tap} = number of turns from V_{cc} end to tap.

The following equations will estimate the AC loop current:

$$E_{eff} = 1 - \frac{I_{d\ peak} R_{on}}{Vcc} \quad ,\text{approx.}$$

$$P_{out} = E_{eff} I_{cc} V_{cc} \quad ,\text{W}$$

$$I_{loop} = \sqrt{\frac{QP_{out}}{2\pi f L_s}} \quad ,A$$

$$V_{loop} = I_{loop}\, 2\pi f L_s \quad ,\text{V}$$

where E_{eff} = proportion of battery power delivered to the load (loop+caps), P_{out} = power delivered to load (loop+caps) in W, I_{loop} = RMS current flowing in loop (for magnetic moment) in A, Magnetic Moment = I_{loop} N (area of loop) in a-t-m squared, V_{loop} = RMS voltage across loop (for voltage of capacitors) in volts.

Example

Using the above equations, plus a little guesswork, I designed a 48 inch diameter flexible (frameless) loop intended to be stuffed in a cave pack and dragged to remote areas. It consists of 18 turns of no.14 stranded wire (about 1.84mm dia.) tapped 2 turns from the V_{cc} end, about 3.5lbs weight. The following values are calculated. L=1193µH, Q=36.4 approximately for loop alone or 26.9 with mylar capacitors, C=1.74µF, optimum duty cycle 1/14, but 1/16 should be fine. With a 12V battery I_{cc} = 0.5A, I_{loop} = 1.9A RMS which gives a magnetic moment of about 40 amp-turns-metres squared. V_{loop} = 50V RMS. Note that I have ***not*** built this loop yet.

Editorial Note

The RS numbers quoted for some components refer to Radio Shack (USA), not RS Components (UK).

The G3TDZ Loop Antenna

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Construction

Star-shaped 1" × ¼" wooden supports hold the loop in a rough circle. On the "upstairs" version, the loop is anchored with P-clips, and the capacitors are mounted on a small PCB screwed to the support. Small P-clips secure the coax cable.

On the cave loop, the P-clips are replace by Terry clips, enabling the loop to be folded up for transporting. On this, the capacitor board is attached by P-clips to the loop.

Figure 1 provides mechanical details.

Field Strength Measurement

The field strength meter was connected to a single turn untuned 1m diameter loop of hard-drawn copper wire. The graph in Figure 2 shows signal levels at the receiver input terminal, using a similar loop to the transmitter. It should be pointed out that these impressive results are measured with a full power continuous sine wave. SSB speech will typically result in half the range.

Rule of Thumb Design

1. From Hey's formula for medium Q circuits, choose C:

$$C = \frac{750}{f} \tag{1}$$

where C is in pF and f in Hz.

As high performance capacitors only come in a few values, choose the nearest e.g. 10n.

2. Find the inductance:

$$L = \frac{25330}{f^2 C} \tag{2}$$

where L is in µH.

3. Find the number of turns:

$$t = 0.6\sqrt{\frac{L}{d}} \tag{3}$$

where d is the loop diameter in metres.

Fine tuning can be achieved by altering the feeder length, as this forms part of the series circuit.

Results of further field trials are likely to be reported in due course.

References

Gibson, David (1995a) *Losses in Tuning Capacitors*, JCREG **19**, pp 12-15.

Gibson, David (1995b) *A Design Procedure for Transmitting Loop Antennas*, JCREG **21**, pp 14-18.

Hey, John (1995) *The G3TDZ Cave Radio*, JCREG **22**, pp 12-16.