

Caveman Radio

With underground inductive transmission, 300 feet is almost DX.

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Magnetic-induction equipment which transmits signals through the ground is a valuable aid to cave-mapping and under-

ground rescue. Even more useful than its communication ability is its ability to accurately find a spot on the surface above an underground transmitter. It can also determine depth within a few percent, using field-geometry measurements.

It's legal! Magnetic induction is not real radio—it's simply very-loosely-coupled transformer action. The FCC does not define equipment operating below 10 kHz as "radio frequency devices."

How It Works

Inductive communication is a very old technique (see "Who Really Invented Radio?—The Twisted Tale of Nathan B. Stubblefield," 73, December, 1980). When amateur radio was banned during World War II, many hams communicated by "ground wave," i.e., magnetic induction and earth-current. ("Earth-current" is transmission of audio-frequency signals through the ground between pairs of widely-spaced ground rods connected to amplifiers.) Ranges greater than one mile were claimed.



120-foot-deep wells near Park City, Kentucky, penetrated cave within two feet of radio targets. Drill drift caused error. Pipes contain hydrological instrumentation. (Photo by Samuel S. Frushour)

Skin effect, which causes rf currents to travel only on the surfaces of conductors, normally prevents radio waves from penetrating ground or water more than a few feet. The depth of the "skin" increases as frequency is lowered; thus, submarines can receive transmissions from very powerful VLF stations. Experimenters have reported successful cave-to-surface communications on 160 meters. Others report positive but unpredictable results on higher frequencies.

Audio-frequency magnetic fields penetrate most geologic structures easily. There are methods for locating ore bodies, using magnetic-induction equipment as a sort of giant metal-detector (see *QST*, June, 1928).

Inductive communication is inherently short-range because magnetic dipole field strength decreases as the cube of the distance from the source, unlike radio waves which obey an inverse-square law. Conductive overburden will absorb the signal, but the inverse-cube attenuation is so predominant that absorption is rarely noticeable. Generating true radio (electromag-

netic) waves at audio frequencies would require enormous antennas.

E. R. Roeschlein suggested using the directional properties of magnetic fields to map caves in an article in *Electronics*, September 23, 1960. Cavers, notably William Mixon and Richard Blenz, refined the equipment and developed depth-measuring techniques which are independent of signal strength (several articles appear in *Speleo Digest*, 1964).

Equipment

It's easy to get 300-foot range with very simple equipment. Longer ranges are more challenging.

A transmitter is just an audio oscillator driving an amplifier which is driving a coil. Impedance matching is important for maximum coil current. Perhaps the most important part of the transmitter is the keyer—a circuit to make it go "beep... beep... beep." In addition to the advantage of saving battery power, a pulsed signal is much easier for the receiver operator to distinguish against a background of interference than is a steady tone.

A simple resonant coil connected to an audio am-



WB9TLH operates underground transmitter on 3500-Hz CW, using microswitch for telegraph key.

plifier will work for a receiver. Use crystal earphones, because magnetic phones will cause feedback.

The circuit of Fig. 1 is a Q-multiplier. The resonant circuit is in *negative feedback* instead of being simply connected to the amplifier's input. The Q (regeneration) control taps some of the output and feeds it back to the noninverting (+) input.

The amplifier forms a *negative resistance* which cancels the resistance of the coil. As the Q control is advanced, sensitivity and selectivity get higher and higher until the circuit goes into oscillation (infinite Q). Since it will oscillate, the circuit can also be used as a very-low-powered transmitter.

A 60-Hz notch filter will *not* get rid of power-line in-

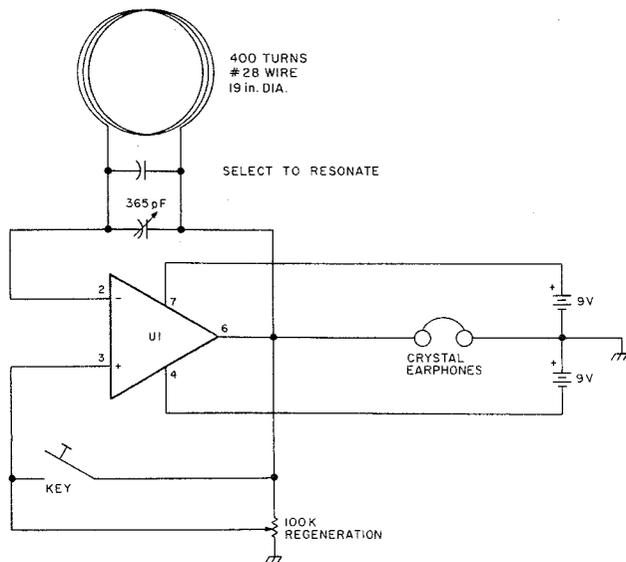


Fig. 1. One-chip transceiver uses Q-multiplier effect for high sensitivity and selectivity. Antenna needs no electrostatic shield. U1 is any 741-type op amp.

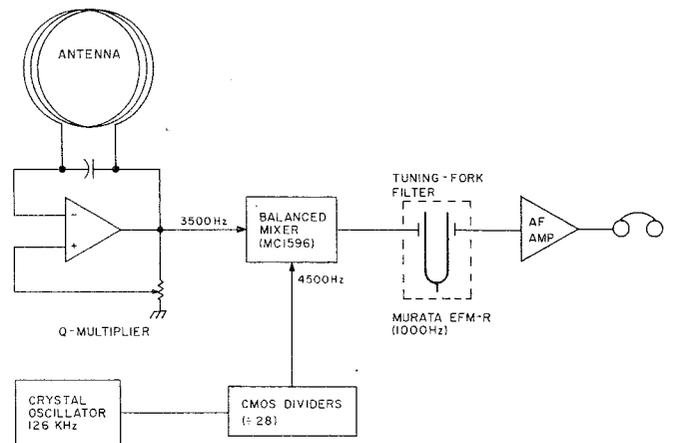


Fig. 2. Receiver with frequency conversion allows very high gain without feedback problems.

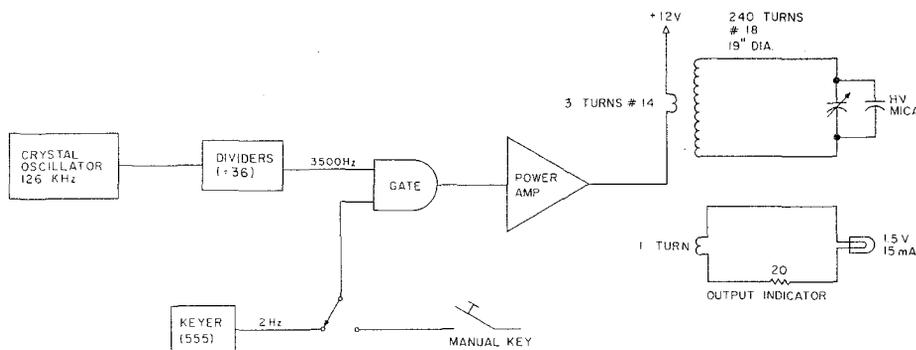


Fig. 3. A cave-radio transmitter. Precise frequency control is necessary if receiver uses very-narrow-bandwidth filters.

terference, which is not just 60 Hz but many harmonics. Don't use active filters indiscriminately. Very strong interference can *intermodulate* with the desired signal in an active filter, creating even worse interference.

Even with crystal earphones, receiver gain cannot be increased indefinitely. After a certain point, no amount of shielding and decoupling will prevent feedback. You can keep the antenna far from the amplifier,

but then it's not portable. A balanced mixer and local oscillator can convert the input frequency to some other frequency, which can then be filtered and greatly amplified without feedback problems. Fig. 2 is a block diagram of one such receiver.

Interference

Power lines are the major source of interference, even in isolated areas. Harmonics of 60 Hz extend well into the ultrasonic frequencies. Pow-

er-line interference is usually directional and can be partially nulled out by the receiving antenna. To minimize interference, choose an operating frequency *in between* a pair of power-line harmonics and use a receiving filter narrow enough to reject the adjacent signals. Resonant-reed or tuning-fork filters of the type used in radio pagers can provide the necessary selectivity. Such extremely narrow bandwidths require precise frequency control and very slow CW speeds.

Atmospheric noise from distant thunderstorms can be a problem in summer. Daytime atmospheric noise is minimal around 3.5 kHz (*National Speleological Society Bulletin*, vol. 32, no. 1, January, 1970). The noise level increases appreciably after dark. Atmospheric noise is polarized such that it nulls when the receive coil is horizontal.

What's the best frequency to use? Mid-range audio frequencies work well, and the equipment is easy to

build. I use 3500 Hz. 3276.8 Hz would be a good frequency because it is easy to generate from a 32.768-kHz wristwatch crystal. 3276.8 Hz falls in between harmonics of both 50- and 60-Hz power lines, and so could be used in any country. At higher frequencies, ground absorption increases and audio amplifiers become less efficient. Some experimenters have tried SSB on ultrasonic frequencies, but have found no advantages to justify the complexity of the equipment. Below 2 kHz, atmospheric noise and power-line harmonics are very strong. Subaudible frequencies below 60 Hz have been used, with very complex receiving equipment.

The OMEGA navigation system transmits very strong signals on several frequencies between 10 and 14 kHz. OMEGA stations make good beacons for testing receivers. Each station transmits for one second in a sequence that repeats every ten seconds.

Antennas

For best performance, maximize the *magnetic moment* of the coils. Magnetic moment is Ampere-turns multiplied by the coil's area.

Doubling the range of an inductive system requires an eightfold increase in magnetic moment, other factors being constant. Self-resonance limits the number of turns a coil may have. An eightfold increase in current implies either much larger wire or a 64-fold power increase. It's easy to see that



Surface location and depth of transmitter are found by null-seeking with directional antenna and by measuring shape of magnetic field.

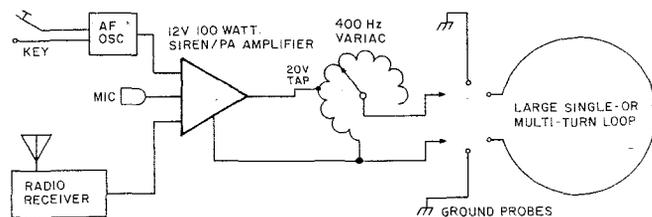


Fig. 4. Surface-to-cave transmitter uses large antenna and high power, so that underground equipment can be small. Surplus 400-Hz transformers are very cheap or free because there is little demand for them. (Caution—possible shock hazard between chassis and earth grounds if amplifier has no internal output transformer.)

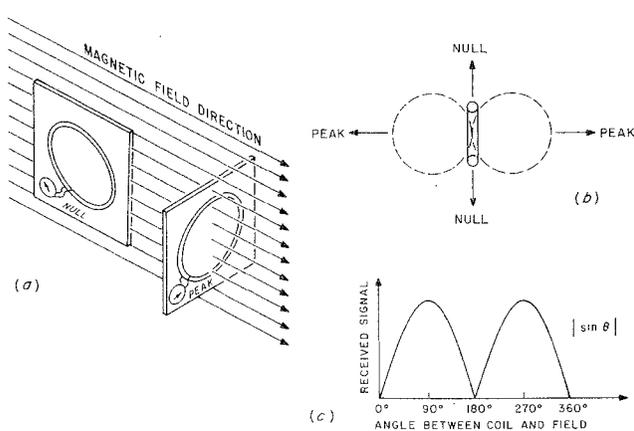


Fig. 5. (a) Received signal disappears when coil is parallel to magnetic field. (b) Note that magnetic-induction receiver coil's sensitivity pattern has null directions in the plane of the coil, unlike radio loop antennas. (c) Nulls are much sharper than peaks, but with very weak signals you may have to seek peaks instead of nulls.

the brute-force approach soon reaches limitations.

For a given length of wire, the optimum antenna is a single huge circular turn. Very large loops are OK for fixed locations, but coils for direction-finding must be rigid, flat, and portable. Transmitting coils must be small enough to fit through tight cave passages. In any case, the easiest route to long range is with coils of the largest manageable diameter. Build a transmitter of a few Watts, carefully match it to the coil, and concentrate the rest of your effort on a good receiver.

Ferrite-core antennas should perform well if properly designed. Ferrite cores can introduce problems of temperature instability, microphonics, and magnetic saturation. Doug DeMaw's recent book, *Ferromagnetic-Core Design and Applications Handbook*, published by Prentice-Hall, is an excellent reference.

Nathan B. Stubblefield may have discovered the interesting interaction between the magnetic-induction and earth-current modes of communication: Current injected into the ground between a pair of widely-spaced rods flows around a large underground area, creating a large magnetic moment. An inductive

receiver will detect the signal. Likewise, a pair of ground probes can detect voltage induced by a distant current-carrying coil. Some cave-radio experimenters have built equipment which operates in either mode, allowing greater flexibility in varying conditions of ground conductivity.



Receiving antenna has inclinometer made from vernier radio dial and spirit-level for measuring vertical angles.

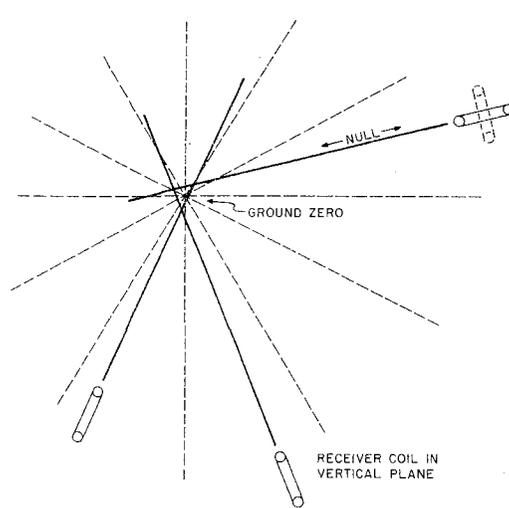


Fig. 6. Finding the approximate surface point above the transmitter (plan view).

Voice Operation

My own equipment was designed primarily for direction-finding and minimum weight. It can transmit from cave to surface by CW, but it does not transceive. Two-way communication is not essential for surveying operations, but it can be very useful. (People who don't know Morse code can usual-

ly send it intelligibly if provided with a code list and a few minutes of instruction on lengths of dots, dashes, spaces, letter and word spacing, and abbreviations.)

For a "downlink" I use a 12-volt-operated, 100-Watt police siren/PA amplifier driving either a large loop of wire lying on the surface or a pair of ground rods. A surplus 400-Hz variable auto-transformer matches the amplifier to different loads. The underground voice receiver has a ferrite-core coil connected to an audio amplifier through a high-pass LC filter which cuts off at 600 Hz, with 70 dB of rejection below 300 Hz. The filter rejects the strongest power-line harmonics. A band of voice energy called the *first formant* is lost, resulting in loss of the qualities that distinguish individuals' voices, but intelligibility remains. The female voice works best here.

Magnetic Direction-Finding

Someone must take the transmitter into the cave to the point of interest and turn it on at an appointed time. The transmit coil must be horizontal and very accurately level.

Received signal strength depends on how much magnetic flux passes through the coil. With the plane of the coil parallel to the field, no

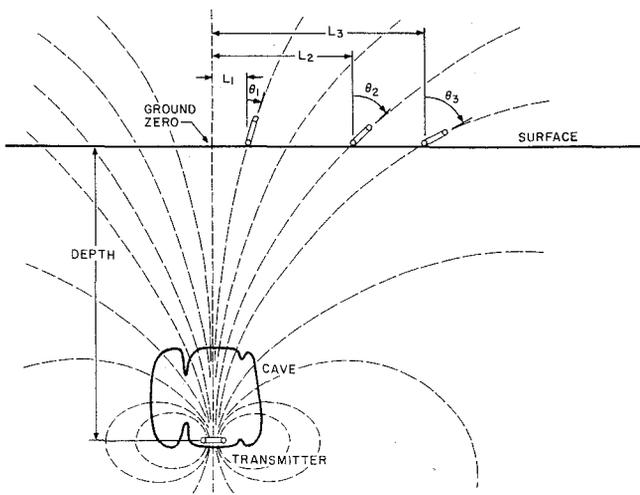


Fig. 7. Ground zero is pinpointed by finding the spot where the field is vertical. Then, distances (L) and vertical angles (θ) are used in calculating depth of transmitter.

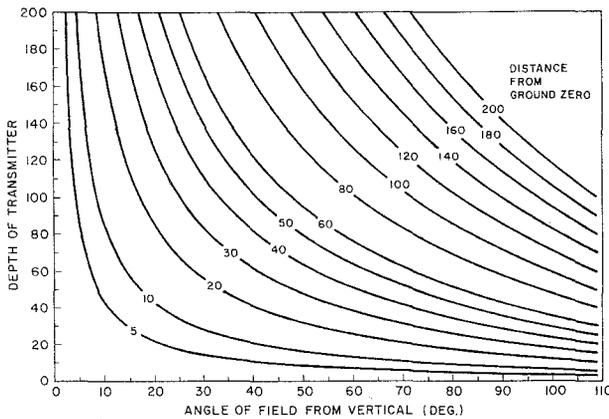


Fig. 8. Cave Radio Depth Chart (after W. Mixon). Each curve is depth vs. field angle for a different horizontal distance from ground zero. Use any distance units: feet, meters, etc. Example: For distance 50' and angle 40°, depth is 102'. Thanks to Robert F. Blakely for providing this HP-85 computer plot.

flux passes through the center and the signal disappears in a very sharp null (Fig. 5).

Viewed from above, the field of the transmit coil looks like straight lines radiating from the center (Fig. 6). The receiver operator can home in on the area of the underground transmitter by a technique similar to that of normal hidden-transmitter hunting: Hold the coil in a vertical plane and rotate to find the null direction, then "triangulate."

Once the approximate site has been found by horizontal nulls, the location can be refined to within a few inches, using vertical nulls. Fig. 7 shows a side

view of the curved shape of the field. Point the coil toward maximum signal, then tilt it back and forth to find a null which indicates the direction of the field coming up out of the ground. Move in the direction of decreasing vertical angle to find a place where the null direction is straight down. Turn 90° horizontally and repeat the procedure, getting closer to the center of the field each time. "Ground zero" is the point where the vertical null is straight down, no matter what horizontal direction you point the coil's axis. An experienced operator can usually find ground zero in about ten minutes and de-

CALCULATOR METHOD

Finding depth by calculator is fast, easy, eliminates plotting errors, and provides wider range than the graph. (The graph still has the advantages of low cost and easier error detection.) A programmable pocket calculator with nonvolatile memory, such as the Hewlett-Packard HP-29C, is ideal for calculating depth while on location.

HP-29C Program for Depth of Cave Radio

Equation solved for depth:

$$D = \frac{L(3 + \sqrt{9 + 8 \tan^2 \theta})}{4 \tan \theta}$$

$$0^\circ < \theta < 90^\circ$$

01	15	13	00	g	LBL	0
02		15	34	g	DEG	
03		14	54	f	TAN	
04			31		ENTER	
05		15	63	g	x ²	
06			08		8	
07			61		X	
08			09		9	
09			51		+	
10		14	63	f	√x	
11			03		3	
12			51		+	
13			21		x ² y	
14			04		4	
15			61		X	
16			71		÷	
17			61		X	
18		15	12	g	RTN	

To use: Key in L.

ENTER

Key in θ (in degrees).

GSB 0

Example: $L = 50'$, $\theta = 45^\circ$: Depth = 89.04'

termine depth in another ten.

Finding Depth

The receiver antenna should be mounted on a rigid, flat board or framework and must be equipped with some type of inclinometer, such as a carpenter's protractor. Estimate vertical angles to the nearest 1/10 degree when taking data for depth.

Mark ground zero with a stake or rock. Stretch a measuring tape horizontally away from ground zero and measure the vertical angle of the field at several different distances away. Use the distance-and-angle data in the calculator formula above or plot the data on the fami-

ly of curves in Fig. 8. Average the results of several pairs of data. The depths should be consistent, falling near the average value and randomly either side of the average. An increasing or decreasing trend indicates an error in ground zero location or an unlevel transmit coil. Most of the error can be recovered by taking another set of data in the opposite direction away from ground zero and averaging the results of both sets.

Note that the slope of the depth function (Fig. 8) is very steep for small angles, i.e., a small error in measuring the angle will produce a large depth error. For best results, use only angles between 12° and 75°. (At vertical angles

near and greater than 90°, the null is less distinct and, of course, the signal is weaker at greater distances from ground zero.)

The depth chart (Fig. 8) derives from the formula: $\tan \theta = 3LD/(2D^2 - L^2)$, where: θ = angle of field (measured from vertical = 0°), L = horizontal distance from ground zero, and D = depth. The formula is an approximation which assumes that the transmit coil is very small relative to depth.

Note that the closed curves of the magnetic field are ellipses, not circles. Simple triangulation cannot be used to determine depth (D = L when $\theta = 71.57^\circ$, not 90°). An 8 1/2" x 11" working copy of the depth chart is available from the author for an SASE.

The Future

Extending the range of underground communication makes a fine project for

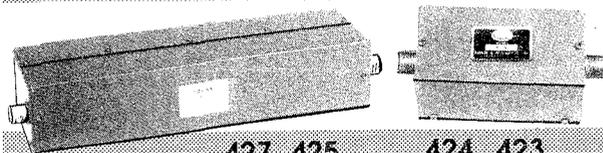
hams, especially VLF enthusiasts. Experiments on 1750 meters should be especially interesting.

Correlation, signal-averaging, and other sophisticated techniques for weak-signal recovery are becoming increasingly attractive to amateurs with new developments in integrated circuits. Very-long-range cave radio could, of course, be accomplished by interfacing short-range cave-to-surface links with conventional amateur radio equipment. Future technology may allow communication through the entire Earth on modulated beams of neutrinos! ■

The National Speleological Society is an organization promoting safety and conservation in the sport and science of cave exploring. Their address is Cave Avenue, Huntsville, Alabama 35810.

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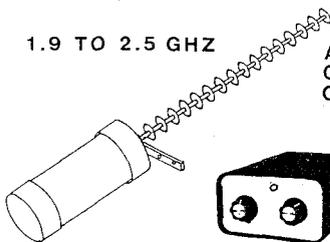
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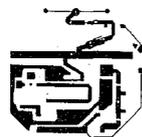
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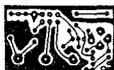
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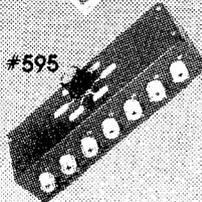
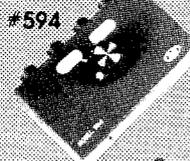
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