POSSIBLE METHODS OF CAVE DETECTION

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CONTENTS

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Last year I published a rather journalistic article on this subject, but restricted to electrical methods. It is now my intention to extend the previous article, and to consider some different methods, with reference to the advantages and disadvantages of each.

All possible systems have one thing in common - they must be portable, since measurements must be made in the field. This condition immediately restricts the complexity of apparatus and its power requirements, since batteries tend to be heavy, and in general, the more complicated a piece of equipment, the larger and heavier it gets.

It is then required to construct some piece of equipment which will accurately delineate the interface between limestone and air. Across the interface there will be changes in conductivity, dielectric constant, magnetic susceptibility, elasticity, refractive index, and specific gravity i.e. density.

I shall below consider each of these changes for a feasible and practical method of cave detection.

MEASUREMENT OF CHANGES IN CONDUCTIVITY

The conductivity of any substance is a measure of the ease with which electricity flows through it. The first requirement for the use of this property then is some portable source of electric current and the means to apply it to the test area. Since there is no immediately obvious reason why direct current (d.c.) should not be used, we shall define our power source to be dry cell batteries. Dry cell because they are relatively small and light compared to accumulators, and because a check of conductivities shows that power requirements will be small, obviating the need for the extra energy of accumulators. To apply the current to the test zone, we shall drill small holes into the rock and affix contacts.

Having current passing through the rock (see Figure 1 for configuration), we must measure its magnitude. This will tell us the resistance of the test area, and hence its conductivity. Then the lower the conductivity, the larger the airspace. We therefore need electrical meters for measuring currents and voltages. Once a

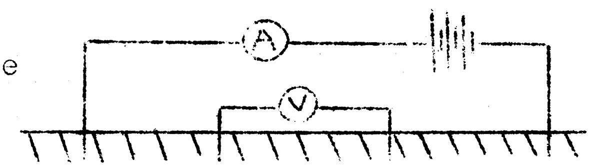


Figure 1
Four-electrode Method

measurement has been made, everything is moved to another spot and the process repeated.

Advantages of this system are that it is fairly simple and cheap to make, and that interpretation is relatively easy.

Disadvantages are that it is of low range in depth and that the area covered is very small.

We can increase the coverage area by extending the outer electrodes shown in Figure 1 on out of the page. Increasing the depth range can best be done by changing to the plotting of equipotential lines where deviation from parallel represents a change in conductivity. Lines converge into a cave, diverge from gold mines etc. This is the Equipotential Method of what is called Potentiometric Surveying.

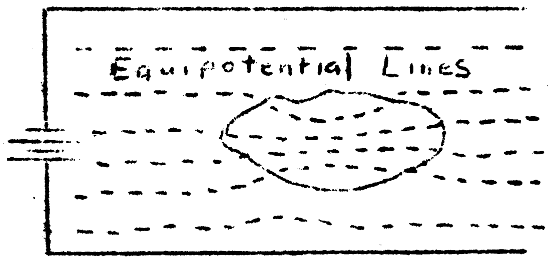


Figure 2 Equipotential or Parallel Wire Method.

Advantages of this system are that it is simple, coverage is good, with good depth range, and that it is accurate.

Disadvantages: Interpretation is harder than with the four-electrode method; it requires more equipment; power requirements are higher - it needs a minimum field strength of 0.25 volt/foot of wire separation (Experimental figure).

Comments on this section: Conductivity systems are simple and cheap, and reasonably accurate. However it is found that polarization of electrodes can occur, causing loss of efficiency. These can be annulled by the use of a.c., but apparatus then gets expensive and large. I have a power supply giving 200 volts peak to peak at 2 Kc/s, but its power requirements are enormous and its use is almost out of the question for field work, since packed for use it weighs almost 25 pounds.

MEASUREMENT OF CHANGES IN REFRACTIVE INDEX

The systems discussed below depend upon the fact that when electromagnetic radiation strikes a change of dielectric, part is transmitted and part reflected. This is best demonstrated by holding a sheet of plate glass to the light. Of course, rock is opaque to light waves. However it has been shown that limestone is virtually transparent to radiation at frequences of about 100 Kc/s.

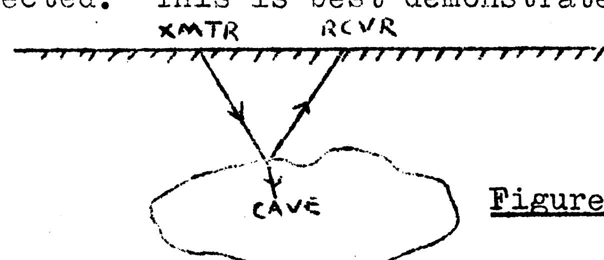


Figure 3

(At 100 Kc/s, the wavelength is 3 Kilometres). Therefore at any interface, there will be a certain amount of the signal reflected. Not much, but a sensitive receiver could detect it. We therefore need a 100 Kc/s transmitter and receiver, or, preferably many receivers. The next problem concerning us is the range between the transmitter and the interface. There are two feasible ways of doing this.

(i) By time lag between transmission and reception

(ii) By the phase relation between the transmitted and the received signals.

This first method requires clocks capable of measuring in the microsecond to nanosecond range (10^{-6} to 10^{-9} seconds). These are triggered on by the transmitter and off by the receiver. Such timers are expensive and hard to come by. In addition, over the ranges in which we are interested, the triggering pulses would probably take as long to reach the clock as to traverse to the interface and back, thus introducing inaccuracies.

The other possibility, phase shift, depends upon the fact that the wavelength (3Km) is a good deal longer than the range we are interested in (0.01 to 0.1 Km).

Since at each point between the transmitter and the interface, the phase of the transmitted signal is different, knowing the phase at the interface is equivalent to knowing its range. Remembering that when electromagnetic radiation is reflected, an instantaneous phase shift of 180° results, we measure the phase angle at the receiver. Subtracting 180° gives the distance of the receiver from the transmitter in terms of radians. Knowing the wavelength in limestone, calculating the distance between the transmitter and receiver via the interface is a matter of simple geometry. This then leads to the cave depth in metres. The easiest method of phase detection is of course with the oscilloscope, which is, unfortunately, not really portable. Alternatively, a 100 Kc/s signal generator with a variable inductance or capacitance

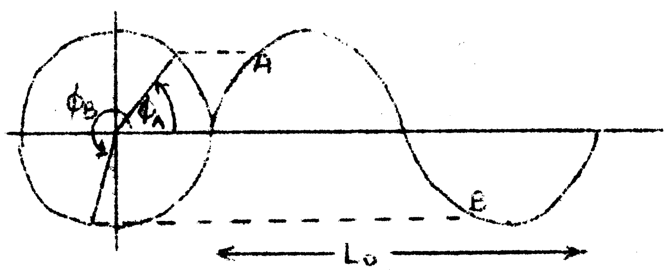


Figure 4

Phase Relationships

on the output calibrated in degrees of phase shift would do. After the detector and transmitter have been synchronised, the receiver and phase detector outputs are mixed, and the inductance tuned for maximum signal strength. The phase angle is then read off.

Example of Computation:

Suppose the phase detector reads 300° for maximum signal strength.
Subtracting 180° leads to a phase distance of 120° for XMTR - interface - RCVR.
120° is 0.667π radians.

Wavelength of 100 Kc/s in limestone is $\frac{L}{n}$ where n is given by the relationship $n = \frac{c}{v} = K^{\frac{1}{2}}$, so $L_1 = 1.03$ Km.

Whence 0.667π radians is equivalent to a distance of 0.343 Km. i.e. XMTR - interface distance is 172 metres.
Suppose angle of incidence to the interface is 45°, then perpendicular depth of cave is $172. \sin 45^{\circ}$ or 121 metres.

Advantages:

(i) Range is only limited by depth of limestone, power output of transmitter, and sensitivity of receiver.

(ii) One-frequency transmitters and receivers are fairly easy to construct.

Disadvantages:

(i) Owing to the long wavelength, the phase relationship degrees per metre is very small. Accordingly, a very sensitive and accurate phase detector (or else an oscilloscope) is needed to give accurate ranging.

(ii) The low coefficient of reflection requires that a very sensivitive receiver be used. However, note that as the angle of incidence increases, the coefficient of reflection increases. For low incident angles it increases slowly, then more rapidly as the angle increases to larger values, until the limit of one, when the angle of incidence is 90°. Consequently it may be possible to reduce the power requirements by increasing the angle of incidence to, say, 45°.

(i) and (ii) above require the use of directional antennae, which at these frequencies could well be large and cumbersome.

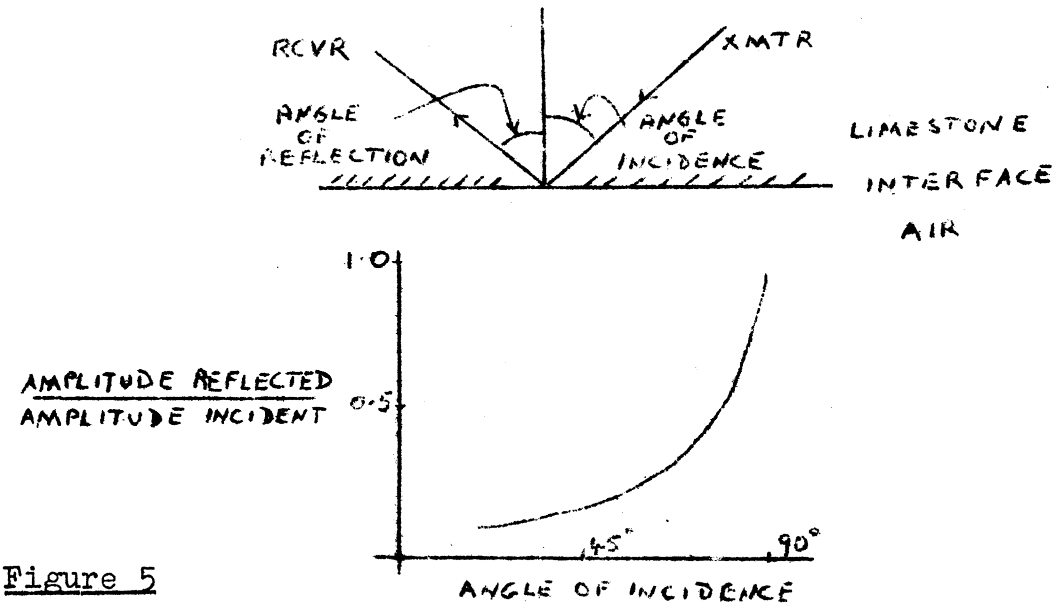


Figure 5

Comments on the above section: With the exception of the directional antennae, all the apparatus required could be made portable, although perhaps heavy. The greatest problem is the power supplies for the electronics. Valves would be preferable to transistors in the transmitter because of the larger signal voltage swing they can handle. This requires at least one 200v power sup, although the receivers could be transistorised. However, it is not strictly necessary that the transmitter be relocated once work has started. The receiver is portable, and can be moved instead, the shift of either being equivalent. So long as the transmitter - interface - receiver range does not exceed 0.5 Km ($\frac{1}{2}L_1$), no phase ambiguity can result.

MEASUREMENT OF CHANGES IN ELASTICITY

Under this section we shall consider such systems as use waves requiring a material medium for propagation. Of particular interest are sound and shock waves. These are bounced off the change of medium, or allowed through it and timed over a known distance.

In neither case, unfortunately, is it practicable to use phase detection for ranging, owing to the comparatively short wavelengths of sound waves (in limestone the audio range is approximately 0.2 metres to 50 metres; in air the wavelengths are approximately 0.1 of these).

When a sound wave is bounced off an interface, the coefficient of reflection is considerably higher than for radio waves, as the velocity changes are higher. Consequently the returning signal is easier to detect. If therefore we can design a unidirectional transducer for applying sound waves to the ground, we can work as in the previous section. Some form of narrow beam microphone and an amplifier is required to increase the intensity to a usable value. However such microphones are available, although expensive, and the design of high gain, low noise amplifiers is relatively easy (see at end of article).

Whether we bounce the signal, or time it over a given distance to detect the cave, we still need to know the time lapse between transmission and reception to know how deep the cave is.

Constructing a clock which works in milliseconds up is fairly simple. Owing to the low velocities involved it can be coupled to the transmitter by coaxial cable with only slight loss in accuracy, (over 100 metres, electrical pulses take 0.3 uS while sound waves in limestone take 25 mS, a loss in accuracy of only 0.001%).

Timing the signal through the cave requires that equipment be set up on opposite sides of a hill that the apparatus is strong enough to penetrate. That imposes a severe limitation on that method.

Furthermore, attenuation of the signal at the air-limestone interfaces will be such as to render it highly improbably that part of the signal will reach the receiver. However this effect would result in a zone of silence corresponding to the cross-sectional area of the cave, which could be used to determine the location of the cave and its vertical cross-section.

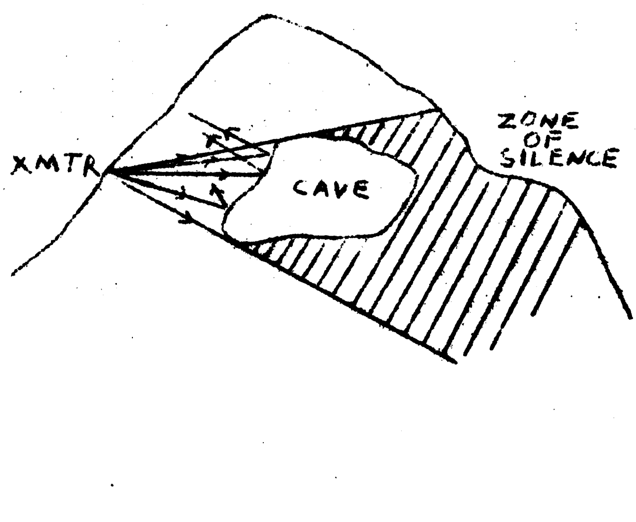


Figure 6

Zone of Silence

It would also be possible to carry out the above experiments using shock waves, detected by a seismograph. To increase the sensitivity of the seismograph, an interferometer system could be used. However, the use of shock waves would necessitate some form of shock pulse, such as that produced by explosives. Short pulse explosives (i.e. short rise and decay time of pulse) are essential to prevent masking of the shock front by the back of the pulse.

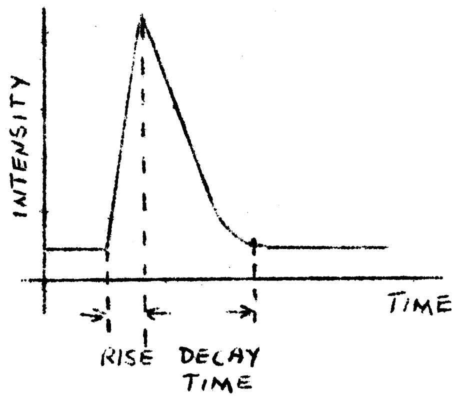


Figure 7

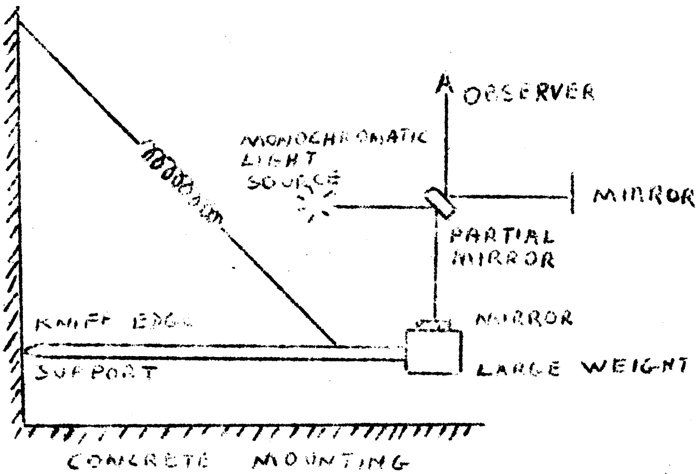


Figure 8
Simple Seismograph

Advantages:

(i) The clocks for these intervals are not too difficult to construct.

(ii) A good seismograph is relatively cheap and simple to make compared to a phase detector or a 100 Kc/s 1 watt transmitter. So too is the interferometer. The instant and magnitude of the shock front is determined by measuring the fringe shift as seen in the interferometer.

Disadvantages:

(i) Short pulse explosive have a very fast burning time. The fastest non-nuclear burning rate I know of is that of R.D.X. ($(CH_2N.NO_2)_3$) which is 8600 m/s. This is not available on the market and hence is expensive to obtain. The next is PETN with similar substances. Nitropril is both the cheapest and the easiest to make (in a concrete mixer is standard) but it has a long pulse compared with R.D.X. and PETN. Consequently the main disadvantage of seismic detection is that when explosives are available they are not satisfactory over short ranges, and those that are ideal are virtually impossible to obtain however the figures below

(Numerical Example:

Consider the use of shotgun cartridges. These have a charge approximately 1.5cm long, and a burning rate of about 500m/s. C onsequently the burning time is 3×10^{-5} seconds. With a velocity of sound in limestone of 3500 m/s, the shock pulse would have a length of 10 cm. Assuming that the length of the pulse is negligible provided it is less than about 5% of the total distance, a minimum range of about 2 metres is available)

show that if the energy output of these cartridges is sufficient, and if a suitable means of discharging them is available, they may be usable. I would be interested to learn if anyone has satisfactorily used these cartridges for seismic work.

(ii) Farmer Brown and Co. may not like ounce charges of R.D.X. going off on his property every hour or so.

(iii) Seismographs are heavy, since the inertial mass may easily be 20 or 30 Kilogrammes.

(iv) A sound transducer capable of putting high output into rock may be difficult to make.

Comments on this Section: The size and weight of the seismograph precludes the use of shock waves in cave detection. However, with a suitable transducer, the reflection method is a fairly simple one for use in the field.

MEASUREMENT OF CHANGES IN SPECIFIC GRAVITY

Basically the mean specific gravity of an area determines the local acceleration due to gravity, g.

Neglecting local changes due to inhomogeneities in the crust, the acceleration at any latitude L, and height h in metres above sea level is given by:

$$g = 980.616 - 2.5928\cos 2L + 0.0069\cos^2 2L - 0.0003h \text{ cm/s}^2$$

However slight alterations are induced by the presence of air spaces in the rock. An instrument to detect these small changes is called a gravitometer. One such, suitable for amateur construction, is the Cavendish Pendulum. In view of the size, weight and complexity, and hence price, of this and similar instruments, they are not really suitable for use in detection by speleological societies, and consequently I shall not cover them any more fully in this paper. Any person considering experimenting in this field is recommended to read the article on the Cavendish Pendulum in the "Scientific American" for September 1963, pages 267-280.

MEASUREMENT OF CHANGES IN MAGNETIC SUSCEPTIBILITY

In this section we shall consider the effects on the Earth's magnetic of a body of limestone and air. Now air is paramagnetic, limestone is diamagnetic, consequently there will be a slight bunching of the natural field lines about a cavity, a slight rarefaction about solid rock. Any caves will therefore show themselves by an intensification of the Earth's local magnetic field.

An instrument which will detect such changes in magnetic fields can be constructed about the Hall Effect. This is the name given to a phenomenon which occurs when a current flows through a thin strip of conductor in the presence of a perpendicular magnetic field: a potential drop is observed perpendicular to both the applied e.m.f. and the magnetic field. E.H. Hall carried out his original experiments in 1879 using copper strips, finding a perpendicular potential drop of less than 1 microvolt. It has recently been found, however, that this can be augmented by a factor of up to 10^5 by using semiconductors instead of copper.

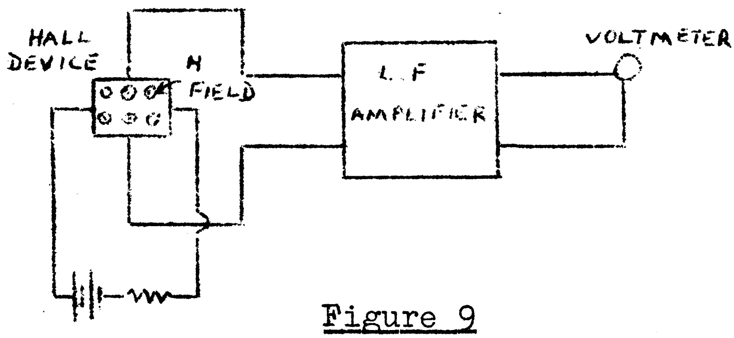


Figure 9

Hall Device as Fluxmeter

Especially suitable are alloys of indium and arsenic.

The transverse current depends upon the normal current flow in the strip and on the field strength, while the transverse potential depends inversely upon the thickness of the strip. It is common then to make Hall Devices only a few thousandths of an inch thick.

In Figure 10, a suitable amplifier for the fluxmeter is shown. The potentiometer R is used to adjust the output to zero in any given field. Changes in the field strength then show as positive or negative changes on the voltmeter of Figure 9 - positive for para changes, negative for dia changes.

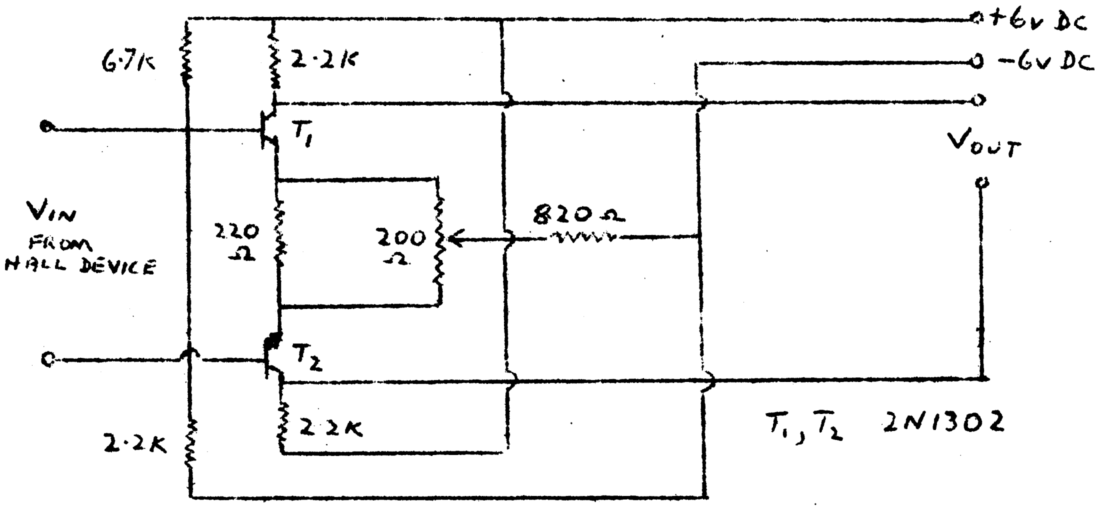


Figure 10
Amplifier for Hall Device as Fluxmeter

The magnetic field in the Hall Device may be intensified by using ferromagnetic strips overlapping over and under the semiconductor strip as in Figure 11.

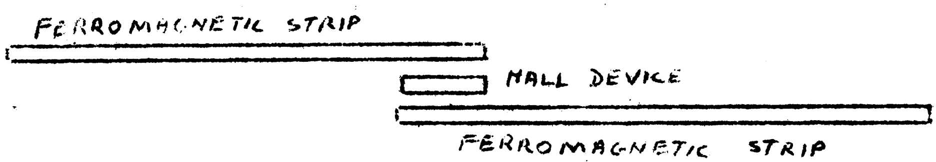


Figure 11
Flux Amplifier for Hall Fluxmeter

The probe can be "supersensitized" by the following steps:

(i) Adjust R for peak response as the probe is reversed in the Earth's field, and rotate to the null-position.

(ii) Adjust zero controls so that two peaks are equal in amplitude.

(iii) Rotate probe to null point.

(iv) Increase gain of amplifier until null potential is 5mV.

(v) Energise Hall Device with a.c. of 400 c/s, then increase current in Hall Device to 200 mA.

The sensitivity of the instrument at this stage is 2×10^{-4} gauss, or 0.1% of the Earth's magnetic field.

(The above figures are for the BH700 Hall Device, marketed by F.W. Bell, Inc., 1356 Norton Avenue, Columbus, Ohio 43212, U.S.A.).

With the ferrite intensifier described above, the field is applied along the long axis of the strips. The probe is aligned for use with the Earth's magnetic field and flux measurements made across a grid over the test locality.

To align the probe with the field lines, rotate it in horizontal and vertical axes until the maximum flux reading is obtained for the test point.

To minimize magnetic effects in the mounting, an aluminium theodolite mount would be suitable.

The <u>advantage</u> of this system is that apart from the expense of the circuitry it is very simple and cheap. The electronics can be built into a box 6" x 6" x 8" with a milliammeter at one end and weighing perhaps 5 pounds. Hence it is easily portable.

The <u>disadvantage</u> is that Hall Devices are at present unobtainable in Australia, and must be imported from the U.S., making them expensive.

<u>Comments on this section</u>: If a Hall Device such as the BH700 can be obtained, the above represents probably the simplest method of detecting and mapping caves from the surface possible.

It is however impossible to determine the depth with this system, so other methods must be resorted to for that.

MEASUREMENT OF CHANGES IN DIELECTRIC CONSTANT

The main use of dielectric constant is the measurement of capacitance. It is therefore feasible to use the test zone as an element of tuned circuit in an oscillator.

Figure 12 shows a Colpitt's Oscillator, for which the frequency of oscillation f is:-

$$f = \frac{1}{2\pi}\left(\frac{1}{LC_1} + \frac{1 + R/R_a}{LC_2}\right)^{\frac{1}{2}}$$

Suppose C_1 were formed of two long parallel wires strung across the test zone. A measurement of the resonant frequency is then a direct measurement of the capacitance, and hence dielectric constant of the area.

The advantages of this system are that it is physically very simple, merely requiring a Colpitt's Oscillator, several yards of wire, and a 200 volt d.c. power supply.

The disadvantage is that mathematically it is very complicated, and determining the difference in K between limestone (8.5) and air (1.0006) may be extremely difficult.

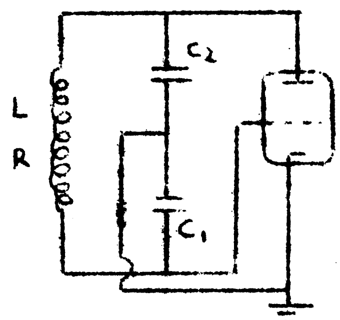


Figure 12
Colpitt's Oscillator

SUMMARY

Over the previous pages we have considered **ten** feasible methods for detecting either caves themselves or the more general case of an interface between changes of medium. Of these ten, the simplest is that using the Hall Effect to detect changes of magnetic susceptibility. This is not to say it is the most convenient - that is probably the parallel wire method under "Conductivity". The parallel wire method can accurately detect and map caves over an area only limited by the experimenter's power supply, and measures the depth simultaneously.

My own opinion is for the parallel wire method, followed by the Hall Effect method and radio reflection with phase detection ranging.

I would welcome comments from persons interested in this field who can reach me care of the National University Caving Club, P.O. Box 4, Canberra, A.C.T., 2600.

SOURCES OF INFORMATION

J.B. Clark	Physical & Mathematical Tables.
F.W. Constant	Theoretical Physics.
A.J. Dekker	Solid State Physics.
Encyclopaedia Britannica	
G.P. Harnwell	Principles of Electricity and Magnetism.
E. Norman Lurch	Fundamentals of Electronics.
Scientific American	September 1963 and July 1965.

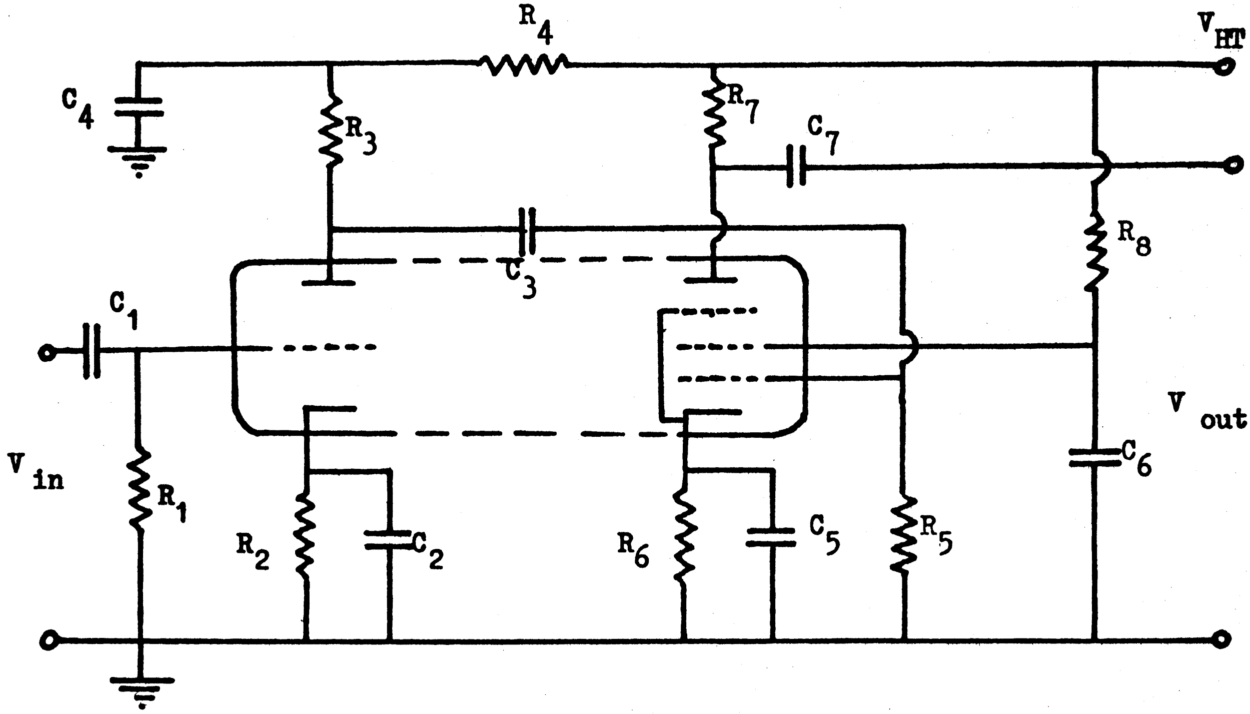
APPENDIX A

NUMERICAL DATA APPLICABLE TO THE ABOVE

Property	Limestone	Air	Units
Specific gravity	2.6	1.29×10^{-3}	grammes/cm^3
Refractive index at 100 Kc/s. (n)	2.92	1.00	
Coefficient of reflection at 100 Kc/s. (r)	0.24		
Resistivity (p)	$4 \times 10^4 - 7 \times 10^4$	10^{12}	ohm-cm.
Conductivity (σ)	2×10^{-5}	10^{-12}	mho/cm.
Dielectric constant at 100 Kc/s. (K)	8.5	1.0006	
Magnetic susceptibility at 100 Kc/s. (X_m)	-10^{-5}	3.65×10^{-7}	emu/gm.
Velocity of sound at 0°C.	3500 11480	331 1087	metres/sec. feet /sec.
Wavelength of 100 Kc/s	1.03 (L_1)	3.00 (L_o)	kilometres.

APPENDIX B

A SIMPLE HIGH GAIN AMPLIFIER



C_1	0.1	μF	R_1	12	Kohm
C_2	10	μF	R_2	680	ohm
C_3	5000	pF	R_3	68	Kohm
C_4	16	μF	R_4	8.2	Kohm
C_5	50	μF	R_5	680	Kohm
C_6	16	μF	R_6	47	ohm
C_7	0.1	μF	R_7	2.5	Kohm (10 Watt)
			R_8	6.8	Kohm

Valve is a 6GW8 triode-pentode

V_{HT} = 300v d.c.

V_{in} = 0.1v p-p

Maximum V_{in} for no distortion = 0.6v p-p

Normal V_{out} = 150v p-p

Normal gain = 63.5 dB

APPENDIX C

THE TRANSMISSION OF RADIO WAVES IN LIMESTONE

When electromagnetic radiation passes through a medium of finite conductivity it is attenuated. A measure of this loss of amplitude is given by a factor called the skin depth which is constant for any given material, and is defined as the distance in which the amplitude of the wave is attenuated to e^{-1} (0.378) of its initial value, and hence in which the intensity (actually measured by the receiver) falls to e^{-2} (0.136).

$$D = \frac{1}{(\sigma \pi u f)^{\frac{1}{2}}}$$

D is skin depth.
u is permeability of free space, i.e. $4\pi . 10^{-7}$
f is frequency in cycles per second.

Consequently, in limestone the following values apply:-

f	D
27 Mc/s	2.38 metres
8.5 Mc/s	3.84 metres
3.7 Mc/s	5.86 metres
100 Kc/s	35.6 metres
10 Kc/s	112.8 metres
1 Kc/s	356 metres

Therefore, at high frequencies, any signal received over a distance in excess of a few metres has almost certainly been preferentially transmitted through minor cracks and fissures in the rock, and, although the results will be consistent and reproducible, they will only be accurate, or even predictive, when the direction of the fissuring within the limestone is precisely known.

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ADDITIONAL COMMENTS BY AUTHOR

CHANGES IN CONDUCTIVITY:

1. The depth coverage using the equipotential method is usually about 10% less than wire spacing.

2. The field strength used should not be greater than 2.5 volts per foot of wire separation.

3. For measuring the equipotential line I have been using a Model 8 Avo with a sensitivity of 50 micro-amps.

4. The way you take the measurements is to have the meter connected between two movable pegs, put one of the pegs in the ground between the two wires and then search for a position with the other peg so that the meter gives a zero reading i.e. both pegs are now on a equipotential line. The next step is to shift the rear peg out beyond the front one to locate the next equipotential point. And so it goes on till the whole of that equipotential line between the two wires has been found. The succeeding positions of the pegs are of course surveyed so that the equipotential line can be plotted on the map. The pegs are then moved across a reasonable distance and the next equipotential line plotted in a similar way. Polarisation of the pegs is not usually a problem with this method because the leap-frogging method of moving the pegs tends to cancel its effect out.

5. Working with wet soil is usually a problem because it effectively shorts the circuit and you can't get underneath it to get reliable readings.

6. The easiest way to attach the two outside wires to the ground is of course to put in tent pegs every ten feet or so and just tie the wire to them. However if you're in straight out limestone outcrop I've found it best to actually tape the wire straight to the rock. It's still better to get them into soil if you can so even if you have a pocket of soil in the rock then so long as the soil is not separated from the rock, put the peg into this.

7. The traces I have generally been working on are just over 300 feet in length and 180 to 250 feet in width, giving a depth maximum of between 150 to 220 feet.

8. A further experimental figure is that to get straight equipotential lines in homogeneous rock. To achieve this the test length should be at least 1½ times the test width. Otherwise the equipotential lines tend to curve as if the outer wires were more like point sources.

9. The average spacing between successive peg readings would be about 20 feet.

10. To avoid interferance from a water-table, the depth of penetration should be reduced by bringing the two wires closer together.

11. If one looks at a section of the rock end on to the two wires then the area of rock traversed by the current turns out to be approximately a square with rounded corners so that the depth penetration is about 10% less than the separation between the two wires. It also means that you can plot equipotential lines as close to the wires as about 5% of the separation.

12. The smallest cave you can detect gets larger as you go down because of bias towards the surface. The smallest cave I have been able to detect about 30 feet from the surface has been about 2 feet across. I think that at about 100 feet the smallest cave would be maybe 5 to 10 feet across and deeper than 300 feet you definitely wouldn't see anything less than 10 feet across.

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