Using Dispersion to Measure Ground Conductivity

Several methods of remotely measuring ground conductivity are known, which depend on measuring the amplitude and phase of a received signal, relative to its transmitter. All of these methods require the separate transmission of a phase reference signal, with attendant difficulties. ***David Gibson*** *proposes that by transmitting a suitably constructed signal, a phase measurement may be made without the need for a separate reference. This is achieved by making use of the phenomenon of dispersion, in which the phase velocity of a wave depends on its frequency. A related technique that makes relative measurements of signal amplitude is also described.*

Geo-physicists and archaeologists are just two groups who have developed well-established methods of measuring the conductivity of the ground. Both direct 'contact' methods and 'remote sensing' methods of measuring ground conductivity are in common use and are well covered in geophysics textbooks. One that happens to be on my bookshelf, and which contains a comprehensive description of the techniques, is (Telford, Geldart, Sheriff and Keys, 1976).

Cavers have also used a variety of methods of measuring conductivity, usually with the aim of attempting to locate underground voids, although the technique can also be used to detect fault lines and, as has been speculated, cave passages and entrances. Another use by cavers has been to assess the performance of cave radio systems although, apart from a small amount of work in the USA, some years ago, there appears to have been no systematic study of ground conductivity with radio systems in mind.

Methods

In this short article there is not space to describe in any detail the methods in use, except to say that there are two basic classes of techniques – electrical resistance and electromagnetic.

Electrical resistance tomography (ERT; the construction of a 2D plan by making multiple measurements) has not yet successfully 'trickled down' into the world of caving – the mathematics and the computer processing being too advanced to be easily applied. An early description of a tomographic array and its use in detecting caves was given by (Noel and Xu, 1992). For a description of early attempts to use ERT for cave detection, see (Weymouth, 1994) and (Edwards, 1998). More recently in the CREG journal, the problems underlying ERT were described by (Bedford, 2012a; b).

There are several different types of electromagnetic method, and the only one I will describe here is where an induction loop receiver is used to measure changes to the fields from an induction loop transmitter, which occur due to changes in ground conductivity. This can manifest as problems with radio-location – see Ian Drummond's classic 1987 report, reproduced in (Drummond, 2002). It can also manifest as a distinct phase shift that can be detected with sensitive equipment – see (Drummond, 1989) and (Pease, 1991).

In my own field, ERT techniques are used to provide detailed maps of coal seams, in order to identify areas of 'washout' where the seam thins or contains intrusions. An established method is called the Radio Imaging Method (RIM) (Shope, 2010). This technique relies – like the method investigated by Drummond and Pease – on phase measurements and so the transmitter and receiver must be synchronised. (In Pease's case he used a very stable oscillator instead). This need for synchronisation is the topic I am going to discuss in this article.

Phase Synchronisation

One method of achieving synchronisation in a RIM application is to transmit a reference signal between the transmitter and receiver using a fibre-optic cable, but this is expensive and difficult to deploy because the cable has to run the entire length of a long-wall coalface. A copper cable cannot be used because of the danger that parasitic coupling would cause it to convey unwanted signals. The medium is usually 'sounded' at around 100kHz. A technique, described by (Stolarczyk, 2004), involves transmitting a reference signal on a 2.5kHz carrier, which is considered low enough not to be affected by the geological structure of the medium to the same extent as the 100kHz sounding signal. Although this method conveys some advantages, it still requires the deployment of a separate transmitter and receiver; and it would not work for caving applications, where we may need to sound the medium at only a few kHz.

I have proposed a technique that eliminates the need for phase synchronisation altogether. Essentially, a reference signal is still transmitted through the medium, as described above, but it is transmitted at the sounding frequency and is therefore subject to an unknown phase shift. The exercise amounts to one of transmitting sufficient signals to be able to eliminate the unknowns.

Elimination of a Synchronisation Channel

Propagation in a conducting medium does not lend itself to simple mathematical expressions. The super-position of the near and far fields is complex; and the secondary, induced fields that result from the conducting medium, even more so. In this brief article, I will give only a simple example based on how the technique would work in a pure far field. I must stress that this example is *not* a complete description of the technique.

Assuming the usual complex time variation of $\exp(j\omega t)$ and that the propagation is in a 'good' conductor with negligible displacement current, i.e. $\sigma / j\omega >> 1$, the phase of a received signal at distance x is, following common convention,

$$\phi = -\omega\tau - \beta x \qquad (1)$$

where τ represents an arbitrary time origin, ϕ is the phase and β is the phase constant, equivalent to the reciprocal of the skin depth. The term βx is equivalent to T in the notation often used for through-rock propagation.

Our task is to derive β without knowing either τ or the absolute phase ϕ. Since this is a total of three unknowns, it requires three measurements, which we could make at frequencies ω and $\omega \pm \delta\omega$. The phases of the signals at the receiver are then

$$\left.\begin{aligned} \phi_0 &= -\omega\tau - \beta_0 x \\ \phi_1 &= -(\omega - \delta\omega)\tau - \beta_1 x \\ \phi_2 &= -(\omega + \delta\omega)\tau - \beta_2 x \end{aligned}\right\} \qquad (2)$$

from which we can obtain

$$(\phi_1 - \phi_0) + (\phi_2 - \phi_0) = -(\beta_1 + \beta_2 - 2\beta_0)x \quad (3)$$

The left side of this expression comprises two relative phase measurements. The right side contains x which we know, and the β term that depends on ω, δω, μ and σ. Because we are making *relative* phase measurements, we can declare them (without any loss of generality) to be made relative to ϕ_0, and so we can write the expression as

$$\tfrac{1}{2}(\bar{\phi}_1 + \bar{\phi}_2) = -\tfrac{1}{2}(\beta_1 + \beta_2 - 2\beta_0)x \quad (4)$$

where the bars denote that the phase is relative to ϕ_0.

If δω << ω, we have a signal comprising three closely-spaced frequencies, and it will be obvious to many readers that this is equivalent to a carrier that is either amplitude-modulated, or phase or frequency-modulated with a low deviation. The expression therefore relates the *mean* phase of the two sidebands (relative to the carrier), to the β term. From the standard definition of skin depth, and with the application of a binomial expansion, we can write this as

$$\tfrac{1}{2}(\bar{\phi}_1 + \bar{\phi}_2) \approx -\tfrac{1}{8}\beta_0 x\left(\frac{\delta\omega}{\omega}\right)^2 \quad (5)$$

from which we can derive the conductivity from β_0. To be strictly accurate, we must note the hitherto implicit assumption that there is no phase ambiguity. That is,

$$\tfrac{1}{8}\beta_0 x\left(\frac{\delta\omega}{\omega}\right)^2 << 2\pi \Rightarrow T << 16\pi\left(\frac{\omega}{\delta\omega}\right)^2 \quad (6)$$

which is clearly the case in all practical uses of this technique.

Implementation

There is not room in this brief article to discuss a practical implementation except to point out that an analogue 'decoder' would have a similar topology to that of a Costas Loop, used for detecting double-sideband suppressed carrier transmissions. The operation would be...

- Transmit an AM or NBFM signal with the modulation comprising a single LF tone.
- At the receiver, detect the carrier in a phase-locked loop and synchronously demodulate it.
- Feed the demodulated sideband signal into a Costas loop. The Costas loop will synchronise to the mean phase of the sidebands.
- The phase signal we require is therefore the phase difference between the Costas Loop's VCO and that of the initial synchronous demodulator.

Dispersion

The above derivation has shown that by measuring the mean phase shift of a pair of sidebands, relative to their carrier, we can deduce the ground conductivity, without the need for a separate phase reference. This derivation is possible because β is a function of frequency. Moreover, it is *only* possible because β is a *non-linear* function of frequency, which means that the group velocity (i.e. $d\omega/d\beta$) is not constant and so, according to established theory, the signal will undergo the phenomenon of dispersion. ***We are, in effect, utilising the dispersion of the signal to measure the phase constant.*** We use three frequencies, and rely on the fact that the dispersion of the first pair will be different to the dispersion of the second pair.

Caveats

There are two obvious difficulties with this proposed technique. Firstly, since δω << ω the phase shift is very small – a second-order effect. Secondly, the phase will be distorted considerably by the use of a tuned antenna; not only because of the tuning itself, but also due to the temperature-dependent properties of the tuning capacitor, which may have to dissipate significant power.

The very small phase shift is not, in itself, necessarily a problem because phase is maintained during demodulation, effectively expanding it in time. Looked at another way, the phase-locked loops amount to low-pass filters, which remove noise from the measurement.

However, in a digitally-implemented decoder, where it may be tempting to take short-cuts and to measure the phase directly (e.g. by timing the various zero-crossings), there could be considerable signal/noise issues. These would be eliminated by integration, achieving much the same effect as the analogue phase-locked loops. In fact, it may well be simpler, overall, to approach a digital design from the point of view of simulating a traditional phase-locked loop design. One important point to bear in mind is that the digitisation of the signal should be synchronised to the carrier. An asynchronous sampler essentially introduces another 'random' phase shift into the system.

Amplitude Measurements

As an alternative to measuring the relative phase, we could measure the relative amplitude of the sidebands. Adopting, for clarity of explanation, a simple plane-wave far-field model as used above, the magnitude of the field strength at the receiver is proportional to exp(–T). If two signals are transmitted at closely spaced frequencies ω ± δω, the resulting ratio of attenuation at the two frequencies can be written, using an expansion of the exponential term, as

$$\frac{H_{\omega+}}{H_{\omega-}} \approx 1 - T_0\frac{\delta\omega}{\omega} \quad (7)$$

Note that whereas the phase measurement involved a second-order term in the binomial expansion, the amplitude measurement is a first-order expression – it is larger in magnitude and does not depend on dispersion. It could therefore be conjectured that, in a practical system, it could be responsive to different geological conditions. In fact, it is known with the RIM technique that certain anomalies cause phase discrepancies whereas others cause amplitude discrepancies.

Interpretation of Results

I have described how, by transmitting a suitably designed signal, it can be decoded at the receiver *without* the need for a phase reference, to give a parameter which is *assumed* to be related to the bulk conductivity of the ground. This could be a significant advantage in remote sensing methods. However, there are two points to bear in mind.

Firstly, in this brief article, I have made a significant approximation by considering only the far field. In fact, because the technique depends on dispersion it will not work in a 'pure' near field because the signal does not disperse in that situation. This is not a problem because a 'pure' near field is only a theoretical approximation. In the real world, we will be working in the transition zone where near and far field components are both present. Unfortunately, the maths is rather complicated, and it should be noted that, in the transition zone, the amount of dispersion depends on the direction of the field point.

However the second point is that it does not really matter if we cannot easily derive the conductivity 'as such'. Even a single electrical resistance measurement does not give us an unambiguous conductivity, since this term is not possible to define in a non-homogenous earth. In any case, tomographic techniques do not depend on an accurate knowledge of how the signals relate to conductivity. The simpler tomographic algorithms, for example, assume that the fields propagate as rays, which is certainly not the case. The more advanced algorithms allow for the spreading of the field without needing to know the exact process.

What I have described amounts to a new technique, which provides two 'figures of merit' for through-rock propagation – one based on phase and one on amplitude. It does not matter exactly *what* is being measured – they are just two more sets of data that can be collected and, hopefully, interpreted.

Passive Measurements

I have described how the sounding signal can be considered to be an AM (or narrow-band FM) transmission. This suggests that

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we could consider using an existing broadcast transmission as the source. The technique of prospecting by using a radio receiver on the surface to detect the polarisation of a broadcast transmitter is well known – see, for example, (Phillips and Richards, 1975). The polarisation is affected by secondary fields, and it changes near to cavities, mineralised areas, fault lines and so on. Detecting the relative phase shift of the sidebands of a broadcast signal may be more practical than detecting a change in polarisation (although the circuitry is more complicated and there are points to be aware of, concerning antenna phase shift, as noted above). The new technique may not detect exactly the same anomalies as earlier techniques but, nevertheless, here are two new parameters to measure, which may give rise to some interesting results when used as passive prospecting tools.

Acknowledgement

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Letters and Notes

*Please send contributions to the editor at **creg-editor@bcra.org.uk***

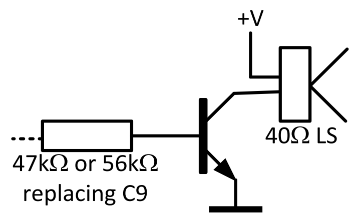
Bat Detector Loudspeaker

Having decided to build the bat detector featured in CREGJ84, (Messina, 2013) it seemed, though practical and simple, slightly selfish to only have a single earpiece.

On a bat-walk often organised by local groups, nature reserves or cavers down a cave, one is surrounded by other folk who might like to hear the sounds from the bat detector.

Adding a small loudspeaker permits a friendlier gathering; the simplest circuit here suggested having only three components, shouldn't tax one's initiative. One transistor, almost any NPN, (I chose a BC548) and one resistor, 47k or 56k, allow a 40Ω loudspeaker to be driven directly. Alternatively you could use an old telephone earpiece, though this may be more difficult to mount.

From RV1, omit C9, replacing it with the resistor.



It should be noted that a small on/off switch will now be needed.

John Hey

Reference

Messina, Tony (2013) *The 'Simple' Approach to Detecting and Logging Bats*, CREGJ **84**, pp 10-13

Rob Gill adds:

Thanks for a useful idea, John. John notes that PCBs for the Simple Bat Detector are available in the UK from Lee Rogers, with contact details on Tony Messina's web site; **home.earthlink.net/~bat-detector**.

Tony Messina points out that for larger group listening or greater flexibility, it is possible to use a small amplified loudspeaker. He discusses this at **home.earthlink.net/~bat-detector/BatAmp.html**

Radiolocation Kits

I have just acquired a few PC boards for my high-performance radiolocation receiver and Class-E beacon transmitter. I sell at cost, which is $31.00 plus shipping for a 3-board set with receiver main board, RF amp, and a Class-E beacon board with special toroid and the wire to wind it. I will sell a beacon with toroid and wire for $9.00 plus shipping. See **radiolocation.tripod.com** for more details.

Also on my website, have some simple, lower performance, shorter range, straight-audio radiolocation transceivers that I am offering as *complete kits*, at cost. You just supply the loop frame and wire. They are the Basic-1 and Basic-2. The underground and surface units are identical (including loops) as each unit is both a beacon and a receiver. This also allows two-way Morse code communications. They will run all day on a single 9V internal battery.

These were intended mainly for education and fun, but recently a Basic-2 set was used for a real location in Mammoth Cave, Kentucky!

Brian Pease

Reference

Pease, Brian (2011) *The Simplest Radiolocator,* CREGJ **76**, pp 6-10

Web Watch

*A brief selection of links from **Peter Ludwig.***

A very compact hand-held thermal image: **flir.com/cs/emea/en/view/?id=60477** with either 480x320 or 240x160 resolution according to model (and price!). These seem to be aimed at the boating fraternity, but there must be uses on the hills…

Marketed as an App (isn't almost everything these days?) this system only actually uses the App for display and control. **vexilar.com/info/sonarphone-mobile-depth-sounder-app** actually relies on a smart depth-sounder unit that includes a wifi hotspot to communicate with an Android or Apple device. Could this be useful for characterising the hidden depths of large bodies of underground water?

Finally, a link for the UCAT robotic turtle, featured in Mike Bedford's *We Hear* column on page 16 of this issue: **treehugger.com/gadgets/robotic-sea-turtle-will-dive-explore-ship-wrecks.html** – looks fun!

Greetings from Austria!