Radio Propagation in Standedge Tunnel

Back in 2003, CREG was invited by Network Rail to investigate radio propagation in Standedge tunnel. During these tests, some unexpected results were obtained. Various hypotheses were discussed, but the work was never followed up. ***David Gibson*** *asserts that a lack of 'experimenter's diligence' in the original work prevents us from drawing any useful conclusions, and he warns of the danger of making a 'wishful' hypothesis.*

Standedge Tunnel is a railway tunnel that runs under the Pennines of Northern England. At 4.9 km, this is the fourth longest railway tunnel in the UK and, in places, the overburden is around 190m.

The main purpose of the Standedge Tunnel experiments in 2003 was to look at VHF and UHF coverage by handheld radios but, at the same time, some brief tests were made with the UK's cave rescue radios of the time, known as HeyPhones. The HeyPhone is an 87kHz SSB radio that (usually) uses a grounded horizontal electric dipole antenna.

During these tests, some unexpected results were obtained. Although it was CREG's intention to investigate further, this did not happen, and there is therefore still an opportunity for further work to try to establish just what was happening. However, the salient point – as I will outline in this article – is that the experiments may have suffered from a lack of so-called 'experimenter's diligence' that is necessary in science.

The experiments were written up for the CREG Journal as (Bedford, 2003), together with some historical information about the tunnel. A subsequent article (Rabson, 2004) described further tests.

Reported Results

Although the main purpose of the articles was to report on VHF and UHF propagation along the tunnel, passing reference was made to some unexpected results of the HeyPhone tests. In summary it was found that, whilst the 190m of overburden precluded any through-rock communication with a HeyPhone, propagation along the tunnel itself suffered from very little attenuation. Since then, some informal discussion has failed to positively identify why this should have been the case, and a number of hypotheses have been suggested. Unfortunately it is impossible to properly evaluate the suggestions because the experimental data (as published in the CREG Journal) is incomplete. For example, although it was found that the HeyPhones did not communicate through the overburden; this could have been for the simple reason that the antennas (being horizontal grounded electric dipoles) did not make good contact with the ground. However, the experimental results do not report any measurement of antenna current, so it is impossible to make any firm deductions.

Through-Rock Propagation

So what *can* be deduced from the published data? The first article (Bedford, 2003) reported that...

> On our first trip into the Tunnel we achieved good communication only to 140m into the tunnel, which corresponded to a depth [i.e. vertical distance from surface] of 70m. By 260m (100m depth) the up-link was barely readable […] and at 560m (150m depth), although the signal was detectable no useful information could be passed in either direction. We came away from that first test with two possible explanations for the much reduced range.
>
> (1) Although we hadn't previously found geology that was significantly more attenuating than limestone at 87kHz, perhaps the gritstone of Standedge does fall into this category.
>
> (2) The floor of the tunnel was made of crushed limestone chippings to provide drainage. We found it very difficult to drive earth electrodes into the floor and, even when we did, the lack of mud or water would have resulted in a poor electrical contact.
>
> In the light of the second of these possible explanations, we constructed a very large single-turn tuned wire loop for the second set of tests. In order to provide the best coupling with an earth array on the surface, we arranged for the loop to be vertical by hanging it from support points along the wall of the tunnel. In this configuration it was roughly 48m long by 2m tall. The loop gave no substantial improvement over the poorly earthed ground array, so we were left with the geology as the most likely explanation for our failure.

That report raises a number of questions. Firstly, it is, of course, possible that the rock *was* significantly more conductive than usual. However, the conductivity of the ground was not measured and neither was there any objective measure of signal strength. Secondly, it is certainly conceivable that the transmitter – for some unknown reason – was not making good contact with the ground. But again, without a measurement of current, no such deduction can be made.

Rock Conductivity

Despite the lack of a detailed report, it does seem as if adverse geology might be the cause of the observations. Mike Bedford tells me that "local observations and scrutiny of the geological survey maps, [indicate] that the rock is alternating bands of gritstone/sandstone and shale. Both are a few orders of magnitude more conductive than limestone, the shale the most so".

It is worth noting that even if the ground were not of a high conductivity, there could still be problems with signal reception if merely the tunnel wall itself was highly conductive. Although 'engineering' bricks are non-porous, this is not true of 'ordinary' bricks, which could be saturated with water. And even if the bricks themselves were not conductive, there could be a build-up of water behind the brick lining.

Antenna Orientation

It was reported that a loop antenna was tried as the receiver. This is actually the 'correct' method of receiving a signal from an electric dipole transmitter, although it is not the one usually adopted by HeyPhone users. It is significant that there was no improvement in signal but, again, one can query the experimental technique – or at least the *reporting* of it. For example, a vertical loop would be in the correct orientation only if the surface transmitter was also correctly positioned. I assume that was the case, although it was not reported

LF Broadcast Station Survey

The article goes on to describe how the second hypothesis – that greater attenuation (probably due to greater rock conductivity) was the cause of the observed results – was tested by undertaking a further trip into the Standedge Tunnel to make measurements of the signal strengths of LF broadcast stations. It was reported that "the results of our tests at

Standedge were bizarre" and that the experimental technique may not have taken into account the fact that the signals from the various stations were arriving from different directions. In fact, I do not think that may have mattered much, because the (supposed) high conductivity of rock would have ensured, through refraction, that the signals were all propagating vertically downwards. The reported results do not indicate if any attempt was made to measure the polarisation of the signal. If it was *not* vertically downwards that might indicate a very non-uniform geology, which would make any predictions difficult and could certainly be cited as a possible cause of the strange behaviour.

Along-Tunnel Propagation

The experiments continued, and a further report was given in (Rabson, 2004). Again, the emphasis was on VHF/UHF, but some LF tests were also undertaken, viz...

> By changing from the vertical through-rock approach (surface station on the moor above the tunnel) to a surface station at Diggle portal, much better results were achieved on 87kHz. In fact, the achieved range of 1.5km (with signal strength still in hand) is better than we've achieved in limestone.

Unfortunately, apart from a brief additional mention in Tables 1 and 2 of the article, there is no other information reported. If I have understood correctly, a resonant loop receiver gave a range of 1100m in a tunnel with rails; and an earth current system gave a range of 1500m in a tunnel without rails laid. A mildly surprising result but, of course, these were *different* tunnels and *different* antenna systems, and a proper comparison is not possible without further information that was not given in the report.

Experimenter's Diligence and the Wishful Hypothesis

There is, perhaps, a lesson in basic experimental technique to be learned here. Too often, CREG experimenters have undertaken a simple practical equipment trial and cited it as experimental research. The former has its place, of course, but the latter requires the implementation of an 'experimenter's diligence' and the proper recording of data. It was, in part, the lack of diligence in the Standedge trials that lead to a list of guidelines for experimenters being published (Gibson and Gill, 2006).

To be fair, the Standedge trials did not set out with the aim of 'research' – and there was a limit to the amount of equipment that could be assembled and taken on these field visits. Thus, it was perhaps unfair of me to suggest, as I did above, that measurements of polarisation could have been taken. However, the lack of equipment (and time) to perform experiments should not excuse a lack of diligence in recording the basic experimental procedures, such as antenna orientation and antenna current – both of which are fundamental aspects of the experiments. The lack of this data makes it difficult to perform any meaningful analysis; and puts one in danger creating an unnecessary hypothesis.

One hypothesis, which arose in discussions about the Standedge results, was that the geology might have given rise to a transmission-line propagation along a stratum. (See box*: Waveguides and Transmission Lines*). This method of propagation is well-understood in coal mines and has been described in this Journal (Shope, 2010).

In the Standedge tunnel, transmission-line propagation would require a number of coincidences, not least the correct coupling of the antenna to the stratum. Being a transmission-line propagation, it requires both the electric and magnetic fields to be transverse, which means a particular orientation of the induction loop or earth current antenna. It seems unlikely that this would be the case, but it does hint that further experimentation with *recorded* antenna orientations, could be worthwhile. And, although there are various anecdotal reports of the antenna orientations, the fact remains that they were not recorded. If the best signal was obtained when the transmitter and receiver antenna *did not* line up that indicates a complex situation that would suggest 'all bets are off' on the geology; so it is an important point.

Until that is done, it is not (I assert) justified to make a seam-mode hypothesis since, due to the lack of experimenter's diligence, it is not in accordance with Occam's razor. We could describe it as a 'wishful' hypothesis – that is, one that appears to arise out of wishful thinking rather than genuine speculation. We have no business in invoking such a hypothesis until other, more obvious, methods of propagation have been discounted, at which point it ceases to be 'wishful' and becomes 'insightful'! (I should point out that the hypothesis in question was later withdrawn, during our discussions).

The *simplest* explanation for the long range is that the walls of the tunnel were conductive enough for there to be a TEM mode of propagation. Whether that is due to the inherent conductivity of the rock, or a property of the tunnel lining is something for investigation. With this in mind, the fact that the range was over 1500m is not the most useful of observations. What is required is an indication of the rate of attenuation, in dB/m, and a confirmation that this is uniform. Were we not all taught at school to plot graphs and find best line fits?

The Unscientific Method

Whilst I was writing this article, I happened to come across an article in New Scientist reporting on the poor quality of reported research in certain fields (van Gilder Cooke, 2016) and just how irreproducible some experiments are. Two of the problems were cited as experimenter bias caused by 'wishful thinking', and the creation of 'unnecessary hypotheses'!

I am not suggesting that the CREG experiments were flawed to the same extent as those reported by van Gilder Cooke, but it was interesting to see that I was not the only one to describe hypotheses as being 'wishful' or 'unnecessary'! Neither do these CREG experiments suffer from the Doctrine of Naïve Analogy, that I described in (Gibson, 2013).

The point is simply that there was probably some confusion between an *experiment* and a *field trial* and that the exercise of applying experimenter's diligence to record all possibly relevant data was not fully undertaken.

Several processes give rise to an exponential attenuation (i.e. one that is linear in dB/m) and the value of the attenuation would be an indication of the process involved. Making a wild guess at the AGC range of a HeyPhone, it is possible to surmise that the attenuation could have been of the order of 0.05–0.1dB/m. It can also be expressed in the form $\exp(-\delta/d)$ where δ is, in this case, a figure of merit of, say, 85–170m and d is distance. This figure for δ is too high for it to represent an evanescent wave and possibly also too high (depending on the rock conductivity) for it to represent through-rock transmission. Thus the questions boil down to a) is this a suitable figure to represent the conductivity of the tunnel wall?, b) was the orientation of the transmitter conducive to a TEM mode of propagation?, and c) is there anything else we can dream up, when applying experimenter's diligence. For example, could the signal have been coupled to a rail in the parallel bore? This could be investigated by placing a search coil next to the rail. (Although, since the parallel bore was not actually adjacent, the chance of this being likely is probably extremely low).

In an attempt to make sense of the reported results, I initially thought that the situation could be modelled by conduction along the walls. One could imagine 'un-rolling' the tunnel's topology and treating it as a flat surface with current injection at two points, and voltage detection at a further two points. Due to the symmetries of the topology, this is a straightforward task. However, after thinking about it, I reached the conclusion that I had almost been fooled, myself, by

Waveguides and Transmission Lines

Waveguides

Consider a highly-conducting metal pipe with a beam of radio waves directed down the inside. The waves will reflect off the walls and bounce to-and-fro down the pipe. This is a **waveguide**.

If the wavelength of the waves is much smaller than the diameter of the pipe, then the 'ray' analogy is quite a good one. If the pipe is smaller, or has rough walls, then the analogy is less good, and it makes more sense to imagine a wave front advancing uniformly down the pipe. It can be shown (but the maths is complicated for a pipe; it is easier for a pair of parallel plates) that if the frequency drops below a certain value (called the cut-off frequency), then whatever the orientation of the beam of waves, they will eventually meet with a wave in anti-phase and so cancel out. This does not happen instantaneously, of course, because the waves are bouncing back and forth. The result is that the wave is attenuated exponentially with distance – it is known as an *evanescent* wave. Broadly-speaking, the attenuation coefficient is such that the wave behaves as if the skin depth was equal to the diameter of the pipe (give or take some 2s and a π, and various constants that describe shape of the waveguide), which is quite a severe attenuation, of course.

Waveguide 'modes', as they are known, require that either the electric or magnetic field is transverse to the direction of propagation and are known as TE (transverse electric) and TM (transverse magnetic) modes. Additionally, as noted above, there is a cut-off frequency.

Transmission Lines

Now consider an electric cable – either a co-axial cable, or a length of bell-wire or a flat VHF antenna cable, or two parallel strips of metal on either side of a printed circuit board. Each of these configurations can be used to transmit power, by the simple expedient of connecting a voltage source to one end of the pair of wires and a load to the other end. This is a **transmission line**.

At low frequencies, it is sufficient to think of it as a pair of wires. At higher frequencies, the analysis can be simpler if, instead of thinking of the current flowing in the conductors, we consider the electric and magnetic fields that are set up in the space between the conductors and *bounded* by them. It is straightforward to see that, in this situation, both the electric and magnetic field lines are transverse to the direction of propagation of the power.

So, although we can analyse this like a waveguide, by looking at the fields rather than the currents, it is ***not*** actually a waveguide mode, because ***both*** fields are transverse. It is known as a TEM (transverse electromagnetic) mode. With this mode, there is ***no*** cut-off frequency.

Fields v. Currents

The principle – that different methods of analysis may be appropriate in different situations – can apply to a number of situations. In the main text I described how it applied to the tunnel wall problem itself. We can note that it is also applicable to earth-current transmission. A grounded horizontal electric dipole (G-HED), as used by the HeyPhone, can (Gibson, 2014) be modelled as an electric dipole, without any need to think about the current flowing in the ground. A model that invoked ground currents would *have* to give the same answer, but is not as simple to analyse as the dipole model.

Tunnel Modes

So, where does this discussion leave us?

Clearly, at high frequencies, some type of waveguide mode will be in operation – but only provided that the conductivity of the tunnel wall is high enough for the skin depth to be a small fraction of the tunnel width. If that is not so, then the mode would be so lossy that it would probably not be recognisable as a waveguide mode.

As the frequency drops we will reach a cut-off point, below which we have the characteristic that the attenuation coefficient along the tunnel is similar to that which would arise from through-rock transmission with a skin depth similar to the tunnel's diameter. Of course, if the skin depth really is as high as that then, once again, the mode would be too lossy to properly distinguish.

As the frequency drops still further then (provided the antenna is in the correct orientation and the strata is suitable), we may achieve a TEM mode. This is typical in coal seams where the top and bottom strata act as the two plates of a transmission line.

It is important to note that neither a flat-plate nor a coaxial geometry is *necessary* for a TEM mode. A conductive pipe can support a TEM mode if the signal is correctly applied. It will be a lossy transmission, but TEM nevertheless.

This leads to the interesting point that – just below cut-off – the tunnel itself could support either a TEM mode or an evanescent waveguide mode. These might be distinguishable (apart from the field orientation) by the attenuation rate, although the situation is made complicated by the problem of the tunnel wall conductivity, which I am guessing will favour a TEM mode over a waveguide mode.

the doctrine of Naive Analogy. The basic scientific tenet is *quod supplantandum prius bene sciendum*. That is, you need to understand what you are doing, or you will just be talking nonsense. The reason why a special 'tunnel wall conduction' hypothesis is questionable is because *all* waveguide modes, including evanescent and TEM waves are supported by currents circulating in the walls of the tunnel! Whether one explicitly works with the flow of current in the walls, or uses the concept of an electromagnetic wave, bounded by the walls, one *must* end up with the same answer (See *Fields v. Currents* in the Box above).

If the tunnel wall were highly conductive, then a TEM mode is likely, but the first step in pursing this hypothesis must be to investigate the tunnel wall conductivity. Certainly, there is no room here for some 'wishful' new propagation mode.

Concluding Remarks

Experiments in Standedge Tunnel gave rise to some unexpected results. My assertion is that some of the hypotheses that were created to account for the results were merely 'wishful' and were not based on a sound analysis of the results. There is no evidence, at this stage, that any new or uncommon propagation mode is responsible.

However, a detailed analysis of the published results is not possible because the experiments were only briefly reported with many salient facts missing entirely. I infer that the experiments were not carried out with sufficient 'experimenter's diligence' and that a proper experimental procedure should be a priority in any future work.

Whilst there is certainly a place for 'equipment trials', these must not be confused with 'research'; and it seems as if there is some interesting further work that could be done to investigate both LF broadcast reception and LF tunnel propagation.

Acknowledgements

I would like to thank Mike Bedford for making some detailed and helpful comments on an early draft of this text.

References

Bedford, M. (2003*). Communication in Standedge Tunnel*. CREGJ **54**, pp4-8. Available at **bcra.org.uk/cregj/?j=54**.

Gibson, D. and R. Gill (2006*). How to Report Experiments*. CREGJ **65**, p19. Available at **bcra.org.uk/cregj/?j=65**.

Gibson, David (2013). *Letters: Dowsing and the 'Doctrine of Naive Analogy'*. CREGJ **82**, p20. Available at **bcra.org.uk/cregj/?j=82**

Gibson, David (2014). *How Earth-Current Antennas Really Work*. CREGJ **88**, pp13-14. Available at **bcra.org.uk/cregj/?j=88.**

Rabson, J. (2004*). Improved Communications in the Standedge Tunnels*. CREGJ **57**, pp26-27. Available at **bcra.org.uk/cregj/?j=57**.

Shope, Steven (2010). *Seam Wave Propagation and its Possible Application to Cave Radio*. CREGJ **73**, pp6-9. Available at **bcra.org.uk/cregj/?j=73**.

van Gilder Cooke, Sonia (2016). *The Unscientific Method.* New Scientist **230**(3069), pp38-41. 13 April 2016. Available at **ScienceDirect.com**. DOI: **dx.doi.org/10.1016/S0262-4079(16)30667-4**

CREG