UltraPole Project

Stage 2 Prototype Study Report

Issue 01

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Introduction

This report presents the findings of the work carried out within the scope of Stage 2 of the ‘UltraPole’ project.

As such this report constitutes the Stage 2 Prototype Study Report deliverable as defined in the ‘Detailed Proposal for Stage 2 Activities’ document.

Within the ‘Detailed Proposal for Stage 2 Activities’ document three activities were defined to be undertaken during Stage 2 of the project, i.e.

> ***Activity 1.***
>
> *The development of a device configuration that can facilitate the water or gel borne coupling of the ultrasonic energy into the wooden pole, in a form that meets the portability requirements of ‘in the field’ deployment.*
>
> ***Activity 2.***
>
> *The development of a scanning head arrangement to work within the above device configuration that will provide the scanning geometry – identified during Stage 1 - that is needed to image the entire volume of the pole.*
>
> ***Activity 3.***
>
> *The development of the initial processing and imaging SW required to, potentially, merge the images obtained from different circumferential points around the pole to provide the imagery required to enable the device operator to detect areas of rot or decay (i.e. abnormal ultrasonic regions within the pole)’*

The outcome of these three activities are presented in this report but not in the order shown above as it is probably easier to understand the nature of the device configuration (Activity 1) after gaining an understanding of the requirements for the scanning head arrangement (Activity 2).

Thus, in this report, the results of Activity 2 are presented in the two sections following the Executive Summary - that address the reconsideration of system operational configuration and the ramifications of this. Activity 1 is then considered in the following applicator design section, whilst the display SW development, defined under Activity 3, is reported on in the display SW subsection of the subsequent experimentation section.

The conclusions of this Stage 2 study are then presented in the final conclusions section.

Thus, in this manner, this report satisfies the objectives of the Stage 2 prototype study activities, in that it presents the information required to form the basis upon which the fabrication of an operationally deployable prototype UltraPole system could be undertaken during the envisaged Stage 3 of this project.

Executive Summary

The overarching conclusion of the Stage 2 prototype study activities, detailed in this report, is that it would seem to be completely feasible to develop a deployable, ultrasonic system that could facilitate the effective below-ground scanning of wooden poles for the presence of rot, etc.

To reach this conclusion, the work carried out within Stage 1 has been completely reappraised, leading to the identification of a totally new ultrasonic operational configuration, along with the design of an innovative adaptive applicator design - that is required to facilitate the new UltraPole operational configuration.

Without the new and innovative approaches identified in this report, the potential implementation of UltraPole as an effective, operational piece of equipment would not have been possible.

Reviewing the System Operational Configuration.

The work that was undertaken in Stage 1 was specifically designed to ascertain the viability and/or the risks involved in scaling up the equipment concept from the small-scale experimental ‘demonstrator’ to a full-scale, field deployable system.

In particular, this work focused on gaining a solid understanding of the relationship between the frequency of the ultrasonic sound and the manner in which this sound is absorbed as it propagates through the wood. As, whilst it was known that such absorption would be frequency dependent, the actual ‘quantification’ of the dependency was not known.

In order to quantify this frequency dependent absorption relationship, a combination of experimental and theoretical work was undertaken which produced the key finding as presented in Fig 1. (Originally Fig 7 in the Stage 1 Technology Assessment Report)

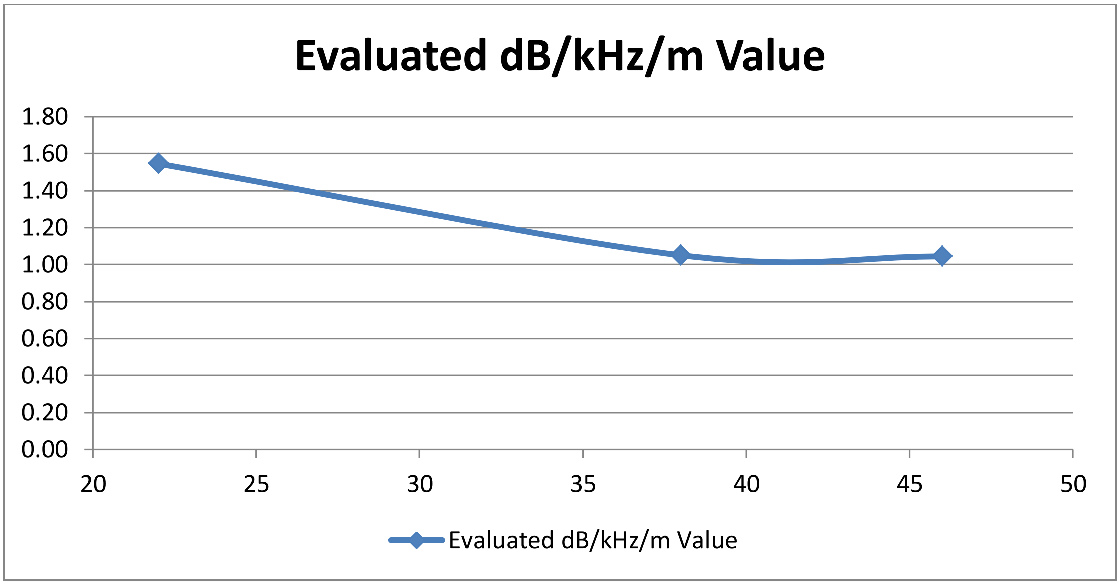

Fig 1 – Ultrasonic Absorption in Wood v Frequency (kHz)

These results suggested that there would seem to be a ‘sweet spot’ for ultrasonic transmission through such wood at around 40-45kHz, but that even in this sweet spot, and for a sample recognised to be likely to produce optimistic results, the lowest value evaluated is 1dB/kHz/m.

This key result led to the observation that, if two-way propagation is considered at 40kHz, then this loss value implies that the transmission loss through the wood actually gives rise to a total transmission loss of 80dB per metre of scanned pole length.

This expected level of loss per metre indicated that realistically an operational scanning range of say 1–1.5 metres could be achieved which it was suggested would facilitate a ‘down-pole’ scanning mode of operation that could scan down to about 0.5-1 metre below ground – which seemed to cover the real range of interest for such ground rot issues as, it was understood that, the rot that occurs at the base of the pole isn’t wet rot at the very end of the pole, but dry rot caused by fungus and bacteria that occurs just below the surface, i.e. where there is still enough air in the soil to allow such organisms to grow!

Nevertheless, it was clear from these key Stage 1 findings that the use of this potential scanning range would need to be carefully considered, and ways sought to both optimise its use, and to maximise its value, and this thought process led to a complete reconsideration of the system operational configuration!

Reconsideration of the System Operational Configuration.

In the original system configuration, probably because originally an 'up-pole' scanning mode of operation was primarily being considered, the idea had become established that the equipment would be sited on the pole say about 0.5 metres above ground level. However, in a consideration of other approaches to pole testing, it was discovered that the usage of other techniques required kit to be attached to the pole at heights significantly lower than this - at about 0.2 metres above ground level - so it was considered reasonable to suggest that the UltraPole equipment would now be sited at this lower installation height, in order to maximise the amount of the expected scanning range that would be available to scan the pole below ground level.

Secondly, in the original operational concept, the idea had been to fire the ultrasonic energy down the wall of the pole sitting directly below the transducer applicator point, in order to detect the presence of rot in this pole section. However, another finding from the Stage 1 experimentation work was the spread in the Speeds of Sound (SoSs) of wood that typified the different pole samples assessed during this Stage. This variation is the SoS of wood meant that, in practice, it was going to very difficult to design a piece of equipment that could fire an ultrasonic beam at just below the Total Internal Reflection (TIR) incident angle of the applicator/wood interface reliably regardless of the actual SoS of the wood in the pole under investigation.

Further, the Transmission/Reception (Tx/Rx) losses through the applicator/wood interface increase dramatically near to the TIR angle and thus, it was realised that operating in the near-TIR configuration originally considered would lead to a significant reduction in the scanning ranges available for inspecting the inside of the pole.

To overcome these interface Tx/Rx loss issues, a completely new system operation configuration was devised in which instead of the ultrasonic bean from an applicator point inspecting the section pole directly below it, this ultrasonic beam would now be directed down and across the pole so as to inspect the section of the pole diametrically opposite to the applicator position.

This new operational configuration concept is presented schematically in Fig 2.

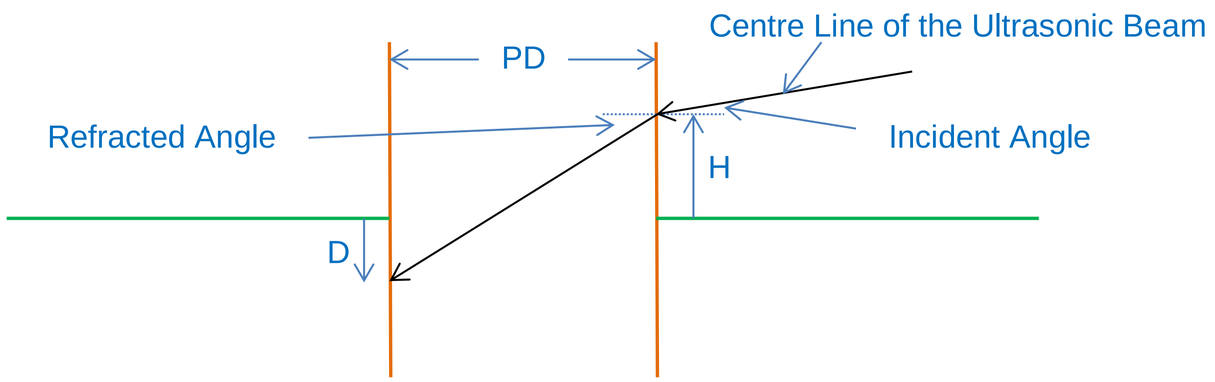

Fig 2 - New Operational Configuration Schematic

From this schematic it can now be seen that instead of operating at near-TIR incident angles, the system is now effectively operating at incident angles that are far less severe and are in fact near-normal incident angles. Thus this new mode of operation concept minimises the level of interface Tx/Rx loss and thus maximizes the amount of the expected scanning range available to scan the pole below ground level.

Ramifications of the reconsideration of the System Operational Configuration.

With the concept of the new operational configuration for the UltraPole system established, the question arose of ‘what were the ramifications on the practical implementation of the system resulting from this new mode of operation. Particularly in terms of:

- The applicator arrangement that would now be required to scan the entire cross-section of the pole.
- The operational approach required to try and ensure that very similar scanning geometries were undertaken in poles with different SoSs, and the ramifications of this approach on the applicator design and operation.

In order to address these issues, it is necessary to investigate the new configuration in a more quantitative manner based on the concept schematic presented in Fig 2.

As an exemplar, say the pole has a diameter (PD) of 30cm then if the scanning head is sited at a ‘height of the above ground’ (H) = 20cm and the ‘depth below ground that the centre of the ultrasonic bean impacts on the far side of the pole’ (D) = 10cm, then a refracted angle inside the wood of just 45^o is required. Assuming a nominal SoS for wood = 4000m/s and a nominal SoS for the coupling applicator = 1500m/s, i.e. that of water, then this implies that an off-normal incident angle of just ~15^o would achieve this configuration. Which, as noted above, is very important because this implies that a lot more energy will be coupled into the pole at this incident angle, as opposed to operating at near-TIR incident angles.

Using this configuration also minimises the path lengths that the acoustic energy needs to propagate over. For instance the configuration above implies a boresight, i.e. beam centre, two-way path length (inside the wood) of ~85cm giving rise to a propagation loss, at 40kHz, of ~34dB (based on the 1dB/kHz/m value derived in the Stage 1 work).

In operation the detection of rot etc. in the section of the pole being scanned would be facilitated by the fact that in a good pole the ultrasonic energy transiting through this section and then incident on the side wall will simply bounce back travelling further down the pole being ultimately absorbed in the wood, whereas the presence of a rot inclusion would produce a monostatic backscatter detectable by the UltraPole equipment.

The transducer also has a finite beamwidth and, based on a transducer diameter of 40mm and a 40kHz propagation through water, the 3dB beamwidth is calculable at about 29^o, i.e. boresight +/- 14.5^o.

This means that this 3dB beamwidth scans a section of the pole side wall with both a vertical and circumferential extent. In the geometry exemplar defined above, with the boresight impacting on the side wall some 10cm below ground level, the upper beamwidth point impacts on the side wall at ~19cm above ground level (allowing for the refraction of this ray path inside the pole). The lower beamwidth ray path incident angle is actually greater than the TIR angle and so, in theory, this lower part of the beam scans down to the bottom of the pole.

The upper path length is ~60cm (Path Loss ~24dB), whilst the lower path length and Loss is determined by the length of the pole buried below the ground. Thus operating in this configuration effectively scans the pole from almost the sensor height down to, in theory, the bottom of the pole – though in practice the absorption within the wood will ultimately limit this.

Circumferentially, it may be seen from the schematic in Fig 3 below that in order to scan a 90^o sector of the side wall (or one-quarter of the circumference) a 45^o angle is required at the opposing side wall.

Now, if the sensor boresight is orientated diametrically across the pole then, to a first order (local tangent) approximation, the refracted beamwidth inside the wood will scan ~+/- 45^{o} around this boresight. However, in practice with a round pole, the angular extent of this scanning will be limited by the Tx power loss that will be experienced at increasingly large incident angles. So it's probably best to assume that an individual sensor will effectively scan the opposing 90^{o} sector of the pole, i.e. the opposing one-quarter of the circumference.

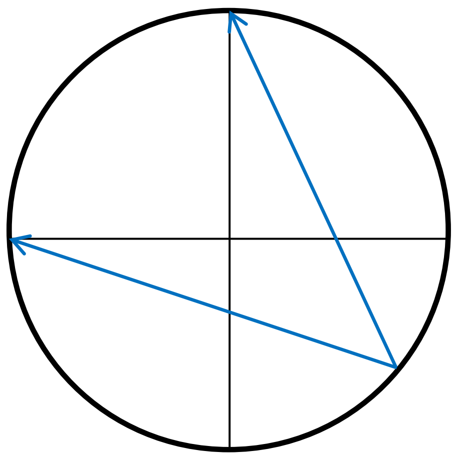

Fig 3 – Circumferential Coverage Schematic

So to achieve a full 360^{o} scan of the inside of the side wall, a single sensor that moves around the pole could be used or, more realistically, four fixed sensors on applicators situated 90^{o} apart around the pole circumference.

Now whilst the geometry exemplar noted above is just that – an exemplar – and more work – both theoretical and experimental – will be required in Stage 3 to identify the exact sensor incident angle geometry to be utilised in practice. Nevertheless, it is clear that the refraction that is being exploited to achieve this scanning operation will be contingent on the specific SoS of the wood within the pole being scanned.

Now, from the Stage 1 work it is known that the SoS of wood will vary from pole to pole and thus, if it is an operational requirement to ensure that very similar scanning geometries were undertaken in poles with different SoSs, i.e. that the same 'optimal' refraction geometry is achieved within every pole, then this implies that the applicator will need to accommodate slightly different transducer boresight incident angles in order to achieve the same internal refracted angle in the presence of the different wood SoSs!

This can be seen from the following equation that defines the incident angle required to achieve the exemplar geometry above for a given value of SoS_{wood}.

$$\mathrm{Sin(Req\ Incident\ Angle)} = [SoS_{applicator}/SoS_{wood}] \times \mathrm{Sin(ArcTan\{[H+D]/PD\})} \qquad \text{……(Eq1)}$$

Thus for a fixed set of H, D and PD values, varying the value of SoS_{wood} will produce a variation in the required incident angle, and this requirement for an applicator design that can accommodate such a variable incident angle geometry requirement is considered in detail the following section.

Nevertheless before moving onto that, it is worth noting that near the start of the preceding section the driver for the reconsideration of the system operational configuration was stated as 'that the use of this potential scanning range would need to be carefully considered, and ways sought to both optimise its use, and to maximise its value'.

And whilst the system architecture will not be fully finalized until Stage 3, it is clear from the following points that the new operational configuration for UltraPole has found ways to significantly maximise and thus optimise the use of the potential scanning range by keeping the operational Tx/Rx and propagation losses as low as possible:

- Minimising the propagation losses – by keeping the path lengths down to the absolute minimum.
- Minimising the additional Tx/Rx losses due to non-normal incidence – by using a configuration that seeks to keep the incident angles as near-normal as possible.

Thus the ramification of the identification the new UltraPole operational concept is that the use of this new operational configuration suggests that it is completely feasible to design a deployable, ultrasonic system that could facilitate the effective below-ground scanning of wooden poles for the presence of rot, etc., providing that a loss efficient applicator design can be achieved.

Applicator Design

Incident Angle Range Requirements

Given the requirement, derived in the previous section, that the applicator design must be able to accommodate a variable incident angle geometry requirement, it is first important to understand this requirement in more detail.

As has already been noted, the new mode of operation for the envisaged UltraPole system requires that the ultrasonic energy is transmitted at near-normal angles into the pole surface. In the geometric exemplar noted earlier it was shown that, for typical SoS's for wood, an incident angle of ~15^o produces the level of internally reflected angle, ~45^o, required for this application. Moreover the same 'Snell's Law' calculation indicates that the critical TIR incident angle lies at ~22^o, which provides an upper bound for the required variable incident angle geometry.

For reasons that will be covered when the overall concept of operation of the envisaged UltraPole equipment is discussed later, there is also a requirement for the applicator to facilitate the firing of the transducer normally into the wood. So in summary the required incident angle range to be accommodated by the applicator design lies between 0^o and ~22^o.

Gel Based Applicator

Now in other applications in which a variable incident angle geometry is required, e.g. foetus scanning for pregnant women, a water based gel is used as the agent to couple the ultrasonic energy into the skin surface. And, as this approach is also used in other applications, transducers are available – though not at the frequencies applicable to UltraPole – that are 'self-gelling', i.e. they have a gel dispenser as part of their integral design that dispenses a 'blob' of gel onto the transducer surface whenever the transducer is pressed against a surface.

Now accepting that there might well be operational reasons that such an approach may be unacceptable - perhaps because it would leave a gel residue on the pole surface - nevertheless, because this is an available, 'off the shelf' technology, its applicability to the specific UltraPole application was investigated experimentally.

The problem with this approach, that this investigation uncovered, is that such a coupling using a water based gel actually introduces some very large losses into this coupling process. To put this into context, whilst coupling the ultrasonic energy into and out of a wood surface using a water bath might introduce a total Tx/Rx coupling loss of ~ 4-5 dB – for a normal incident angle – the use of a gel to enable this coupling raised this Tx/Rx coupling loss to ~31-38dB! So typically, using such a gel based coupling approach would introduce an additional ~30dB of loss into the ultrasonic propagation equation.

Now why the use of a gel introduces such a large additional Tx/Rx coupling loss is one question, and the thinking is that as the gel layer itself is 'unbounded' around its edge then it is free to expand parallel to the wood surface, and so the theory is that a significant percentage of the pressure applied by the transducer face to gel 'escapes' out of the side of the gel layer rather than being transmitted on into the wood surface, as this side-away expansion offers the path of least resistance!

Nevertheless, whatever the actual mechanism, to put this additional loss into context it was noted earlier that if two-way propagation is considered at 40kHz, then the transmission loss through the wood gives rise to a total transmission loss of 80dB per metre of scanned pole length. So incurring an extra 30dB of Tx/Rx coupling loss by using a gel coupling agent would reduce the operational 'in-pole' scanning range of UltraPole by about 40cm – and it was considered that such a range reduction would impact too heavily on the operational usefulness of UltraPole for the use of a gel based coupling agent to be considered further.

Fixed Wedge Based Applicator

Now, in theory, the required variable incident angle geometry could be achieved by having a set of pre-formed ‘wedges’ available to provide a range of such incident angles. And, in order to test the applicability of a certain type of coupling materials, a set of such wedges was made. Now the coupling materials investigated using this approach are known as ‘Rho C’ materials, because their physical properties – particularly their SoSs – are close to the SoS of water (for which the notation ρ_c ‘Rho C’ is used in Defence - where the use of such materials has been extensively studied and exploited – hence the term used to identify them).

A material that is readily, commercially available that is a pretty good Rho C material is silicone rubber, and as this material is easily worked with to produce different shapes, it was used to form the range of wedges shown in Fig 4.

Fig 4 - Silicone Rubber Wedges

These wedges were used experimentally to both proof that the use of such Rho C materials can result in Tx/Rx coupling losses very similar to those obtained using a water in a water bath, and to investigate the level of increase in such losses to be expected when such materials are used to produce the near-normal range of incident angles required by UltraPole.

This variation is shown in the plot in Fig 5.

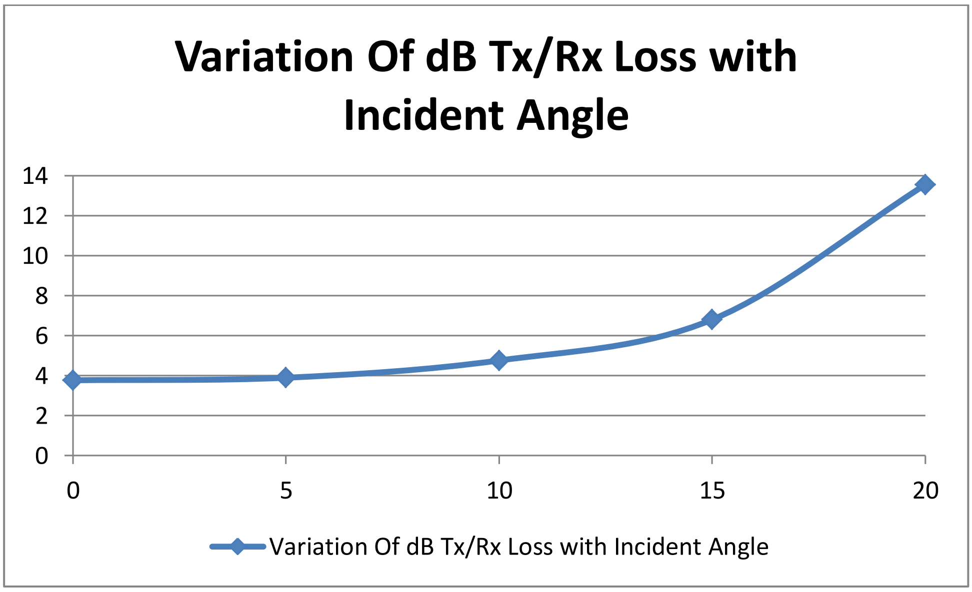

Fig 5 – Variation of Tx/Rx loss with Incident Angle

What this plot shows is that at the ~15^o incident angles, expected to be utilised in the envisaged UltraPole operation, the Tx/Rx losses are only about 3dB higher than that expected at 0^o (normal) operation. This plot also shows how the loss ramps up very rapidly as the incident angle approaches the critical, TIR angle at just over 22^o – in fact at 22^o the loss is ~47dB but this point hasn't been included on the plot in order to emphasise the variation at lower incident angles.

Nevertheless, the point to be remembered here is that the original UltraPole concept required that the system operated at such near-TIR incident angles, and it is the ~40dB+ reduction in these Tx/Rx losses, arising from the near-normal operation introduced by the new UltraPole operational concept, that results in the scanning ranges that enable the new UltraPole configuration to provide a useable operational performance.

So, what the results in Fig 5 show clearly is that the use of a set of Rho C wedges could be used to produce the variable incident angle geometry applicator required by UltraPole. However, for a field deployable system this solution would not seem optimal as it would require a set of wedges to be available say spanning an incident angle range of 10^o – 20^o, at say a 1^o increment, plus a 0^o normal incident coupler, with four wedges provided for each setting, to cover the four applicators required to circumferentially scan the pole. So maybe a set of about 48 wedges, without carrying any spares!

And then this would require the operator to be selecting the right wedges and swapping them over, introducing the potential for operator error etc. With this in mind, probably a more practical idea is to conceptually make an applicator with an adaptive wedge angle!

Adaptive Wedge Based Applicator

In this concept the applicator is shaped like a small flexible bag of water – think of the 'liquid detergent capsules' used in washing machines – but filled with water and with an outer skin made from a flexible Rho C material. Also perhaps with a moulded collar on them that would allow them to be attached to end to the transducer – as shown in the schematic in Fig 6.

Fig 6 – Adaptive Wedge Angle Applicator

Then when the applicator is pressed against the pole it forms a 'wedge' with one edge formed by the pole wall and the other formed by the transducer face – obviously with more rounded 'corners' than in the simple diagram below – but nevertheless with a wedge angle defined by the orientation to the transducer face relative to the wall of the pole, see Fig 7.

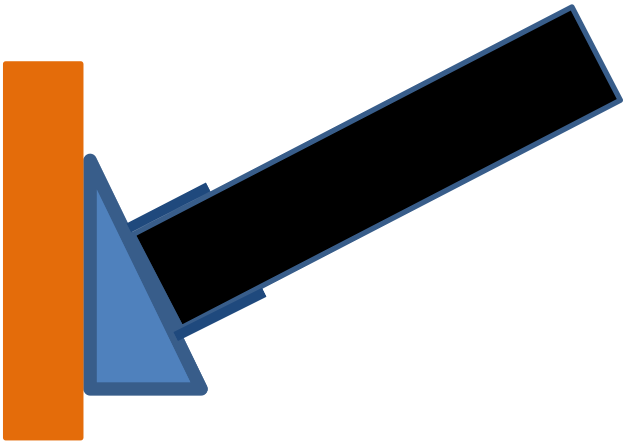

Fig 7 – Adaptive Wedge Configuration

Thus a flexible applicator head like this would allow the incident angle to be varied to any angle – not just one selected from a pre-defined set – also the flexibility of the applicator should also allow it to mould itself circumferentially around the pole to facilitate a better horizontal refracted beamwidth and thus a better circumferential scanning of the pole cross-section.

Further, using such an adaptive applicator head would mean that the head would be permanently attached to the transducer and thus only would be needed. Obviously spares could also be carried, but fitting these in the field would be quite simple and silicone rubber itself is quite a durable material and so it would be hoped that such an applicator head would prove to be long-lasting in service.

Now this is not to say that silicone rubber is definitely the outer material that will be used in the actual equipment, think of it more as a 'proof of concept' material, and in Stage 3 a survey of more specialised Rho C materials will be undertaken to perhaps select a material that is capable of even better and/or more durable deployed performance.

Incident Angle Variation Mechanism

The development of the concept of an applicator with an adaptive wedge angle also opens up the opportunity for a completely automated ultrasonic scanning process providing that a mechanism is introduced into the applicator design to facilitate the automatic variation of the incident angle. In order to operate successfully this mechanism needs to keep the applicator head pivoting around a fixed point on the pole whilst rotating the back of the transducer up and down to achieve the desired incident angle. Thus a mechanism something like that shown in Fig 8 would be required.

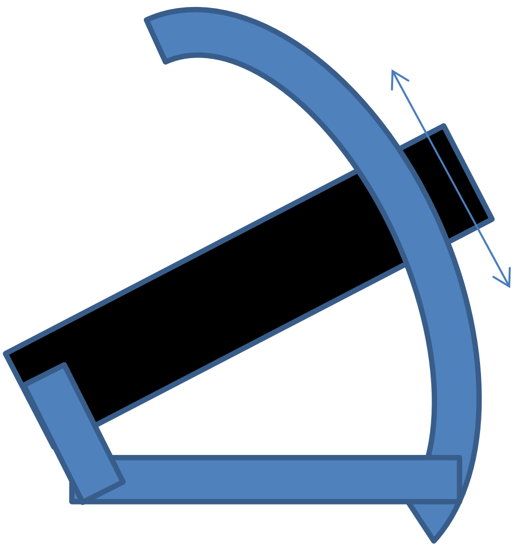

Fig 8 – Incident Angle Variation Mechanism

Obviously, again in Stage 3, the design for this mechanism would be revisited and firmed up, Nevertheless, even from its conceptual design, this new adaptive head applicator can also be seen to further contribute to the overall design aim of significantly maximising and thus optimising the use of the potential UltraPole scanning range by keeping the operational Tx/Rx and propagation losses as low as possible, by:

- Minimising the additional Tx/Rx losses due to additional coupling layers required to achieve the required angle of incidence.

Thus the ramification of the new UltraPole operational concept is that the use of this new operational configuration – incorporating this adaptive loss efficient applicator design - suggests that it is completely feasible to design a deployable, ultrasonic system that could facilitate the effective below-ground scanning of wooden poles for the presence of rot, etc.

Experimentation – Transducers and Display SW

Transducers

As described in the Stage 1 report, a significant amount to work was involved in the 'acquisition of a range of transducers and suitable drive electronics to assess frequency dependency'.

Fig 9 shows the range of transducers, spanning the band of potential operational frequencies, that was acquired for this experimental work, and in the background, the various frequency generators, amplifiers and spectrum analyzers required, and acquired, to create the drive electronics can also be seen.

As already noted earlier in this report, one of the key outcomes of the Stage 1 work was the down-selection from this range of frequencies to the ~40kHz frequency that produced the optimum through-wood absorption performance.

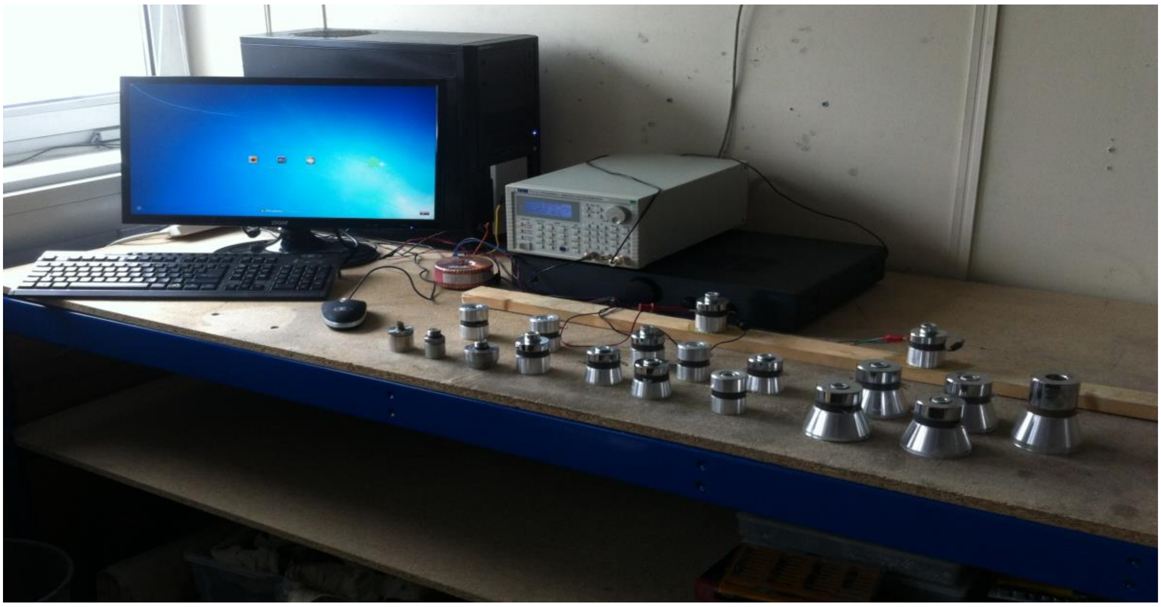

Fig 9 – Range of Transducers

An exemplar of such a 40kHz transducer is shown in Fig 10 and to give this a sense of scale it is worth noting that this transducer has a diameter of ~40mm. It is also perhaps useful in visualizing what the adaptive head of the applicator, noted in the preceding section, would actually look like as, for a transducer with a ~40mm diameter, this head would need to have a larger, say ~60mm, diameter – so something very similar in size to a round teabag!

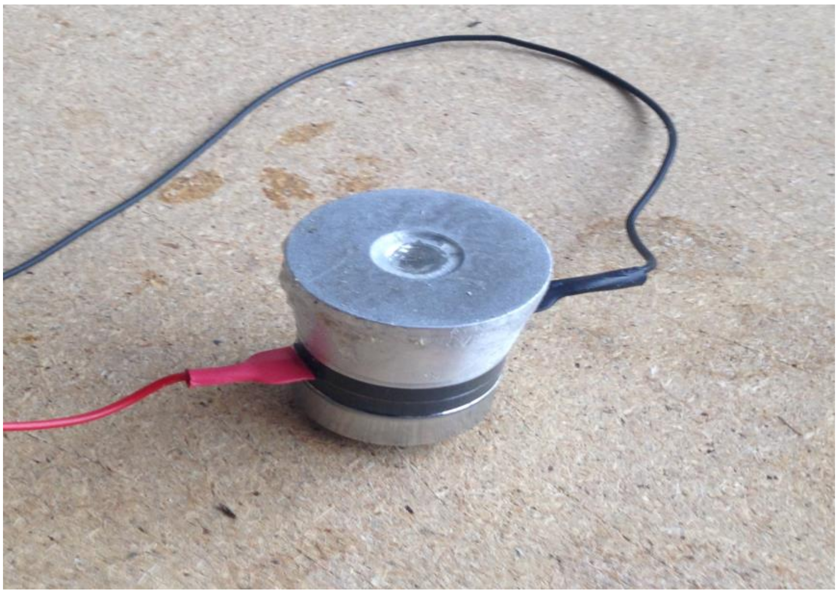

Fig 10 - 40kHz Transducer

Now in the Stage 1 work such transducers were used to fire through sections of wooden pole in order to establish the drop in amplitude caused by the attenuation that the ultrasonic energy suffered whilst transiting through the wood. And, for this experimentation work, as only an amplitude measurement was required, it was sufficient to drive the transducers with a continuous sinusoidal input.

However, the aim of the Stage 2 work has been to actually establish the return strength that can be obtained from 'bouncing' the ultrasonic energy off a rot inclusion in a pole and to do this the transducers needed to be driven with a definite pulse of energy so that once this pulse had been transmitted, the same transducer could then be used to 'listen' for the return pulse.

Unfortunately the only transducers commercially available at this frequency are not designed to be driven in such a pulsed manner, as the only application for which a 40kHz ultrasonic transducer is produced is for ultrasonic cleaning! And for ultrasonic cleaning the requirement is that the transducer design maximizes the water oscillation that is produced from any applied signal. Thus such cleaning transducers are designed to be very 'High Q', i.e. be very resonant at a particular frequency, which means that such transducers are explicitly designed to have minimal internal damping!

This is, of course, completely at the wrong end of the design spectrum if an application, like the UltraPole application, requires the production of a transmitted ultrasonic pulse of energy as, in this case, the transducer should be relatively heavily internally damped so as to stop oscillating shortly after the drive waveform has ceased.

Much time and effort has been spent during the Stage 2 work trying to modify the highly resonant 'ringing' characteristics of these transducers by the application of external 'damping' electronic circuitry but, due to absence of any meaningful internal mechanical damping within the transducers, such external measures have ultimately only been partially successful.

Now it should be clearly understood that this issue with the currently available transducers does not affect the concept of UltraPole as an in-service, field deployable piece of kit, because from Acuity's background Defence experience it is known that it is perfectly possible to design and build transducers that will produce pulsed waveforms at 40kHz – and obviously such an activity would need to be undertaken as part of the Stage 3 work – but within the timescale and budgetary constraints of the the current Stage 2 work this transducer design activity could not be undertaken.

Thus whilst the lack of such an appropriate transducer does not have an impact on a future UltraPole product, is has had a significant impact on the scope of the results that have been obtainable from the current tranche of experimental work.

Reflection Levels and Range Equation

In essence, the severe limitations introduced by the transducers available have made it essentially impossible to obtain direct measurements of the return levels that would be received back from the ultrasonic scanning of a rot inclusion.

However, with a good deal of thought, and some careful experimentation, a good estimate of the level of the returns that would be expected has been obtained via an indirect means of measurement, that utilised the same experimental techniques that were extensively reported on in the Stage 1 Technology Assessment Report and which therefore are not re-reported here.

Simply speaking, when ultrasonic energy comes across an interface between two acoustically different materials, say like good wood and rot, two things happen, firstly, a percentage of the ultrasonic energy is reflected back off this interface and, secondly, the remainder transits on though the interface.

So as the issues with the transducers have meant that it has been impossible to directly measure the energy level reflected monostatically, back off such an interface, i.e. the energy bounced back to the transmitting transducer.

Thus these reflection levels have been estimated by measuring the levels of energy transiting on through the interface, as such measurements can be carried out with a pair of transducers – one transmitting on one side of the interface and one receiving on the other side – thus this experimental procedure circumvents the problems with transmitting and receiving using the same transducer.

The sample pole sections investigated in this manner are shown in Fig 11 – in which the rot section in the one pole sample is clearly visible

Fig 11 – Pole Samples

The actual experimental set-up used is shown in Fig 12.in which the good wood sample is used with two transducers attached to one end of the sample pole section such that the ultrasonic energy is then transmitted down the pole from one transducer and the reflection off the end of the pole received bistatically, i.e. by the other transducer.

This ‘end of pole’ transducer arrangement is shown in Fig 13, which shows the experimentation being repeated on the ‘rot’ pole section to obtain the required transmission level results.

Fig 12 – Good Wood Section Experimentation

Fig 13 – ‘Rot’ Wood Section Experimentation

Carrying out such experimentation, produced typical energy transmission levels of about 90-94%, which imply a typical reflected energy levels of about 6-10%, i.e. a 20-24dB energy loss during reflection.

Now to put these figures into context, in the HV cable scanning work that Acuity majors in, the UltraScreen equipment used on the production line to scan such cables exploits at typical interface reflected energy level of about 4%, i.e. a 28dB energy loss during reflection, to produce highly accurate, micron-level measurements. Which suggest that the 6-10% levels, typifying the rot inclusions, should produce returns that are readily detectable within the envisaged UltraPole system – and this issue is investigated further on the following ‘Display SW’ section.

Further, these transmission and reflection levels tie in well with those that would be theoretically expected if the interface was one between good wood and a ‘wet rot’ inclusion - modelled as being 50% water and 50% wood – and if the inclusion was actually a dry rot decay ‘void’, i.e. air filled, then the reflection level would be considerably higher.

So in summary, based on these observations, it would not seem to be too optimistic to use the worst case 24dB loss figure to characterise such reflection levels.

With this information in place, it is now possible to use the values tabulated below to form the ‘Range Equation’ applicable to the envisaged UltraPole system in order to get a theoretical estimate of the scanning ranges that should be achievable by the system.

Parameter	dB Loss	Comment
Tx/Rx Loss at 15^{o} incident angle	7	See Fig 5
Use of full 3dB beamwidth	3	To scan beamwidth section across pole
Inclusion Reflection Loss	24	Worst case ‘wet rot’ value

What this shows is that the total losses – excluding the absorption losses though the wood – adds up to 34dB. Now, from experience in other application areas, the detection of returns should be achievable providing that the total loss budget associated with them is no greater than ~130dB. This implies that there is a loss budget of ~96dB to accommodate the absorption losses though the wood.

Now it was noted very early in this report that a key finding from the Stage 1 work was that, if two-way propagation is considered at 40kHz, then this implies that the transmission loss through the wood, actually gives rise to a total transmission loss of 80dB per metre of scanned pole length. Thus the 96dB loss budget, evaluated from the range equation considerations above, equates to the losses associated with a two-way propagation through a 1.2m pole length.

Thus if, in operation, the UltraPole equipment is mounted on the pole some 0.2m above ground level, then these considerations imply that the system should be able to scan the pole section lying between its mounting point down to about 1m below ground level - which would seem to tie in very well with its required investigative purposes.

Now of course, as has already been stated, the achievement of a useful scanning performance over such a range is contingent upon the design and realisation of a new transducer capable of producing a pulsed waveform at 40kHz , and that is why this design and development activity is a key aspect of the envisaged Stage 3 work.

Display SW

The final aspect of the work to be undertaken within the remit of the Stage 2 activities was defined in the 'Detailed Proposal for Stage 2 Activities' document as the 'The development of the initial processing and imaging SW …' with a commitment made to implement a 'B Scan' analysis and imaging processing schema, reflecting the analysis requirements of UltraPole.

And it was explained in this document that the choice of a B Scan display for UltraPole was based on many years' experience in Defence sonar processing and imaging as such B Scan processing is particularly suited to the assessment of different levels and structures of returns spread out over an analysis 'range of interest'. And, as such, would seem to be well-suited to the requirements of the imaging processing to highlight areas within the pole from which abnormal returns are received.

In essence, as noted in the preceding subsection, when ultrasonic energy comes across an interface between two acoustically different materials, a percentage of the ultrasonic energy is reflected back off this interface and the remainder transits on though the interface.

So, in effect, the receiving transducer receives back a burst of energy from such an interface reflection with a time delay – after the transmission the transmitted pulse – that is related to the 'range' from the transducer to the interface via the SoS of the wood. So from a display and subsequent processing point of view, two things are important:

- The ability to detect the presence of a received burst of energy.
- The ability to determine the time delay – known as the Time of Flight (ToF) – associated with the detected return.

The B Scan display provides these two capabilities by firstly interpreting the amplitude of any returned energy as a brightness level – thus a burst of energy received back from a rot inclusion would appear as a bright spot of the display, enabling its detection. Secondly such returns are presented in their received time order across the display, so the ToF relating to any detected return can simply be read off the horizontal display axis.

Unfortunately, as discussed in detail in the preceding section, the transducers that are currently commercially available operating at the desired 40kHz frequency are incapable of producing the pulsed waveforms required to underpin such display imagery and inclusion detection work.

So, in order to illustrate the expected display and detection performance to be expected from the envisaged UltraPole system, a scaled-down inclusion exemplar was produced and imaged using a transducer with an inversely scaled-up frequency, in order to produce a 'pulsed' return from an inclusion with the same inclusion size/wavelength ratio as could be expected to be encountered in an UltraPole application.

Specifically, a ~4MHz transducer was used against a 0.5mm inclusion, which scales by a factor of 100 down to a frequency of 40kHz against a 5cm inclusion – which as the wavelength in wood of a 40kHz ultrasonic transmission is ~10cm – is representative of an inclusion with dimensions of about a half-wavelength, which is typically used as the minimum size of object that should expected to be 'seen' by a transmission with a given wavelength.

The 0.5mm inclusion was produced by drilling a hole, with this diameter, radially into a thin cross-section sawn off a pole section. This cross-section was then immersed in a water bath, filling the inclusion hole with water, thereby producing a simulated 'wet rot' inclusion.

This cross-section was then scanned across its surface with the transducer running along a scan line that crossed the inclusion hole at right-angles to its drilled length. Thus the transducer beam was incident on the circular cross-section of the simulated inclusion.

The resulting B Scan image, produced using the new UltraPole display SW, is presented in Fig 14.

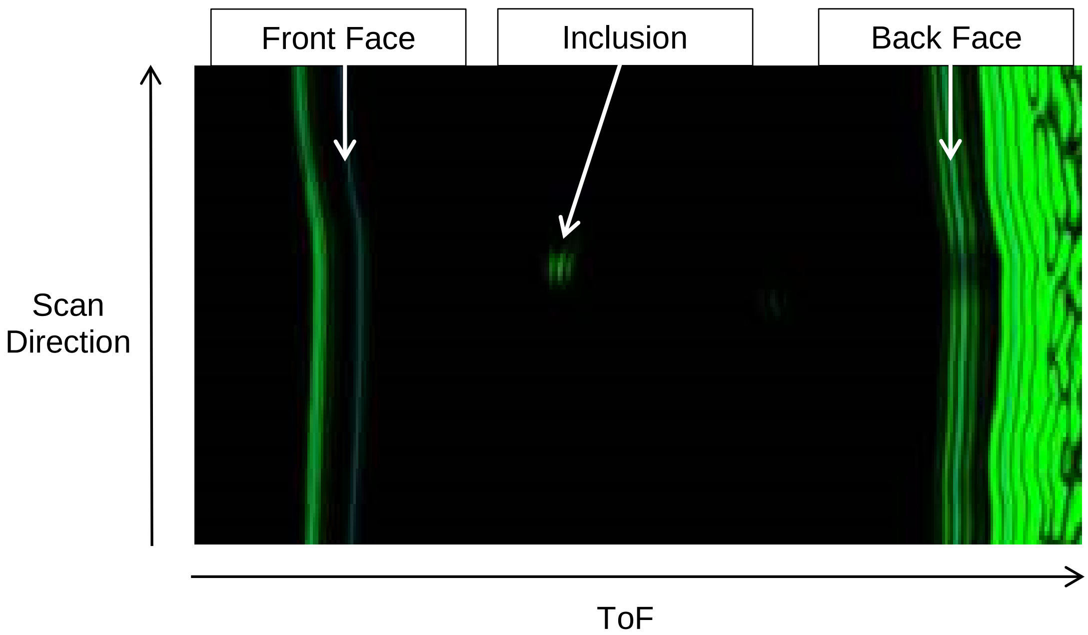

Fig 14 – B Scan Display Exemplar

The ToF is displayed on the horizontal axis running from left to right, thus returns on the left-hand side of the display come from 'features' nearer to the transducer than those on the right hand side of the display. And in the vertical direction, the display is constructed from a set of lines from successive firings of the transducer as it scans over the surface of the pole cross-section.

Ignoring the left-most and right-most features shown on the display – as these are produced by the weight keeping the wooden cross-section down in the water bath, and the base of the water bath, respectively – the two lines inside these features show the position of the front and back faces of the pole cross-section. Now these surfaces don't look very flat but what needs to be borne in mind is that, at these high frequencies, the ToF sampling period is ~20ns, giving a range resolution of ~40micron, which accentuates the surface roughness.

Of most interest, of course, is the return from the simulated 'wet rot' inclusion, positioned towards the centre of the display. Incidentally, the reduction in the energy transmitted onwards through the inclusion can be seen by the clear presence of a 'dimming' of the back face return at the vertical position of the inclusion.

The important fact to understand here is that the reflection and transmission levels associated with the inclusion are not frequency dependent, and so the presence of a 5cm rot inclusion 'illuminated' by a 40kHz transducer would appear with the same brightness, and contrast relative to its surroundings, as does the 0.5mm inclusion shown in Fig 14.

Thus it can be seen that it is to be expected that such a rot inclusion will not only be easily visually detected, but also will have a return with a high enough signal-to-noise ratio to facilitate automatic detection without producing any problematic false alarm rates. Further, the ToF to the inclusion, and hence its range from the transducer can be readily found.

Thus, whilst not created in an optimum manner, the B Scan presented in Fig 11 not only illustrates the suitability of such a B Scan display for the UltraPole application, but also shows how the display SW generated for this project facilitates both the detection and the localisation of the presence of a rot inclusion within the scanned pole section.

Of course, in the envisaged UltraPole system, four such displays would be generated – one for each of the four applicator heads – however, in theory, if an inclusion is detected on more than one display then the ranges calculated for it, in conjunction with the known applicator head geometry, could be used to triangulate a position for this inclusion within a 3D cylindrical model of the scanned pole section, thus providing an estimate of where the inclusion lies relative to the ground surface, for instance.

For this reason, the development of such SW functionality is include as a potential Stage 3 activity, however first the usefulness of, and thus the operational requirement for, such functionality needs to be assessed.

Conclusions of Stage 2 Activities

The overarching conclusion of the Stage 2 work detailed in this report is that the use of the new UltraPole operational configuration – including the new adaptive applicator design - suggests that it is completely feasible to design a deployable, ultrasonic system that could facilitate the effective below-ground scanning of wooden poles for the presence of rot, etc.

One way to appreciate this potential is to consider the actual envisaged in-service, operation of the equipment.

Envisaged System Operation

In its operational configuration, four applicator heads would be attached onto a strap that would be secured around the pole under investigation. The position of the heads on the strap would be flexible, so as to allow the heads to be installed in a NSEW configuration around poles of different diameters.

Prior to attaching the equipment, the operator would select a position on the pole ~20cm above ground level and measure both the height above ground of the installation position and the circumference of the pole at that point – with these measurements being entered into the equipment.

After the equipment had been attached, the transducers would initially be sitting in their base, horizontal position and, once the equipment had been activated, the first activity would be to fire each of the four transducers across the pole in order to determine the ToF of the ultrasonic energy across the pole diameters and back. These ToF measurements would be used, in conjunction with the circumference – and hence diameter – measurement input by the operator to evaluate the SoS characterising the wood at the installation position.

The values of the SoS, the installation height (H) and the pole diameter (PD) would be used within the equipment to derive the required incident angle - utilizing Eq 1 defined earlier in this report – to achieve a pre-defined value depth below ground focal point (D).

The four applicator heads would then be automatically inclined to this required incident angle and the equipment would then be configured for the 'below ground scanning' phase of its operation.

In this phase, the four heads would be fired sequentially around the pole to build up a picture of the status of the below ground section of the pole – which would be displayed in the form of a set of B scan displays and stored as an electric record along with any reference information input by the operator.

Now depending upon the level of functionality ultimately desired from such equipment the potential exists for the B Scans to be automatically interrogated, and for any detected abnormal returns to be flagged up, along with the ToF and hence range of the return from the relevant applicator head. Further, as any abnormal returns are likely to be detected on more the one of the heads, the ranges from the heads can be 'triangulated' so as to infer the actual position of the rot within the cylindrical 3D section of the pole.

In terms of the pole section that the equipment should be able to scan, whilst this aspect of system performance would need to be revisited and optimised during Stage 3, the expectation is that UltraPole would be able to scan the section of pole lying between a height above ground roughly equal to the installation position of the equipment down to a depth below ground of about 1 metre.

However, it needs to be clearly understood that the depth scanned will not be a fixed performance as it will be dependent upon the actual absorption characteristics of the particular wood in the pole under investigation.

It may be a possibility to infer some knowledge of these absorption characteristics during the initial across-pole firing phase of the UltraPole operation, and thus give a better estimate of the scanned depth on a pole-by-pole basis – but this functionality has yet to be proven.

Issues to be Addressed in Stage 3

In order to achieve the envisaged operation of the UltraPole equipment a number of more detailed design issues need to be addressed in the Stage 3 activities, which will be aimed at producing an actual prototype deployable UltraPole system. Note that, in this section, these issues are only listed as they are defined in more detail in the separate 'Detailed Proposal for Stage 3 Activities' Report contractual deliverable.

- New transducer design and development.
- Mouldable adaptive applicator final specification and fabrication.
- 'Constant head position' transducer incident angle changer design and fabrication.
- Angle control functionality development.
- Overlaid display SW and rot feature detection alerting functionality.
- Localisation of rot feature based on overlaid / triangulated detection range / detection presence logic and calculations.
- Determination of local wood absorption characteristics and scan depth estimation functionality.

Note that, it may be deemed that some of the functionality noted in the latter part of the list is not required by the potential user and thus, at this stage, the nature of the functionality is only described at a top-level overview, even in the separate 'Detailed Proposal for Stage 3 Activities' Report.