Deep detection range test for a low frequency subsurface radar system (with reviewable data available online*)

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* https://www.adrokgroup.com/data (data set 2)

1) Introduction

We test the ground penetrating ability of a low frequency pulsed radar system with a centre frequency around 3MHz. We previously (van den Doel et al., 2014) reported experimental results measuring the in-situ attenuation rates through limestone and a reflection mode scan of the surface from 350m below ground. In this study we use this radar system to detect a reflection from the ground surface from 1100m below the ground using reflection mode scans. The main difference with the previous study is an increase of stacking by three orders of magnitude. Previously we stacked 500 traces, with our current setup we stack almost 500,000 traces. Results show a clear reflection in the full stack near 21,500 ns.

The data gathered for this experiment is freely available at (ADROK, 2023).

2) Boulby Laboratory

Boulby laboratory resides underneath 1,100 meters (3,600 feet) of solid rock below the Earth's surface. Boulby Mine is Europe's second deepest mine. Boulby potash occurs at depths between 1,100 and 1,350m in a seam ranging from 0-20m but averaging 7m in thickness. Within a Permian evaporate sequence, sylvinite ore comprises 40% Sylvinite, 40% Halite 15% silts and other impurities. The sedimentary strata above the evaporites include the Triassic Sherwood and Bunter sandstones, which contains substantial volumes of brine under high pressure. Above the sandstones lie Marls (600m to 365m below ground level) and Shales from 365m (bgl) to ground level. See **Figure 1** for a diagram of the laboratory and surrounding geology (https://www.mining-technology.com/projects/boulby).
The low frequency pulse radar system was deployed in the tunnel near the laboratory entrance (**Figure 2).**

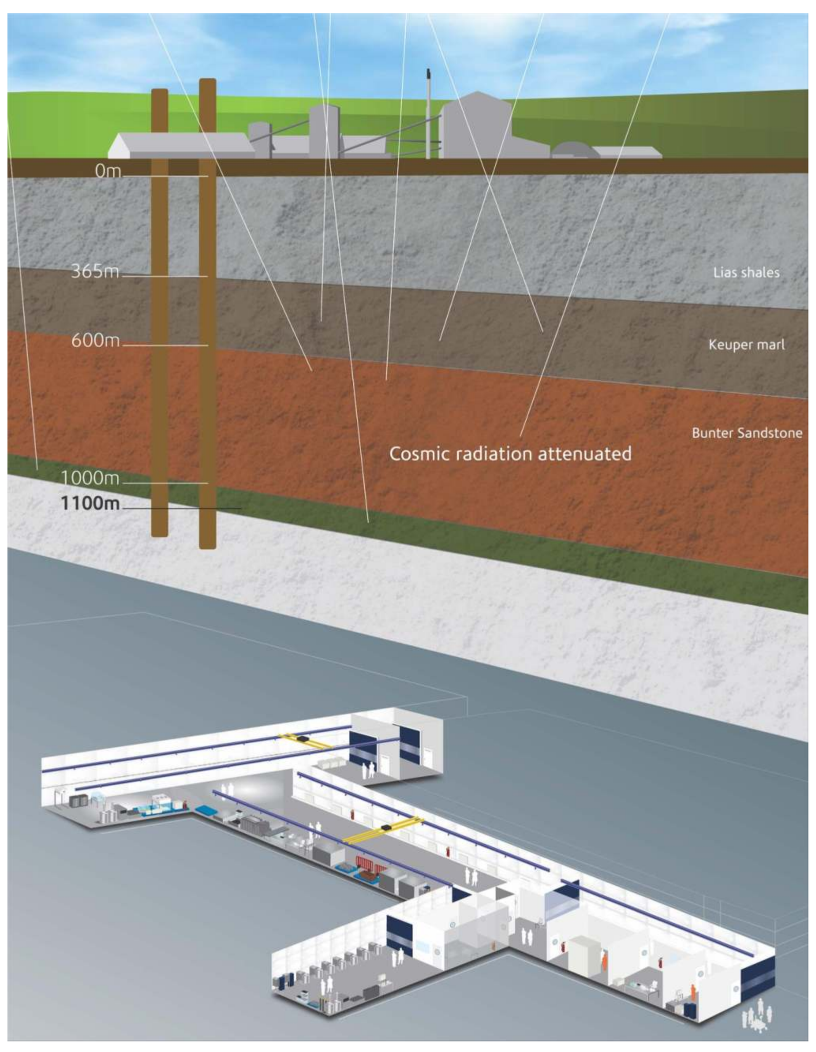

Figure 1 *Boulby Underground Laboratory.*

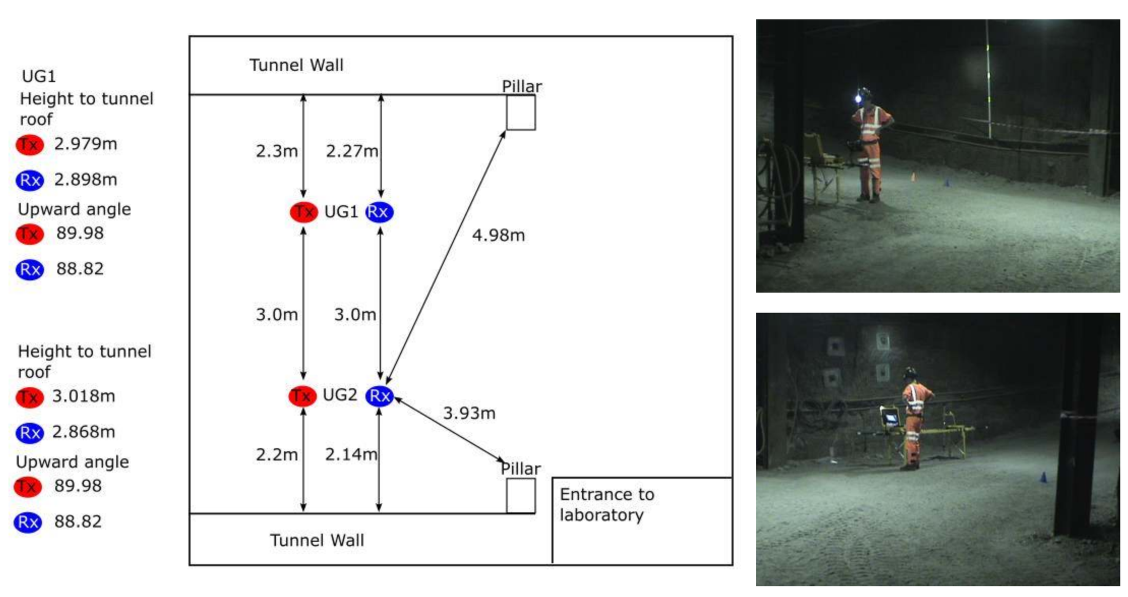

Figure 2 *Data collected at UG1 and UG2 in tunnel*

3) Data Collection

The pulsed electromagnetic system known as the Atomic Dielectric Resonance (ADR) Scanner was deployed (**Figure 3).** Transmitter and receiver were placed in close proximity in the underground excavation and electromagnetic wave packets approximately 200ns long and containing frequency components from 2 to 70MHz with significant peaks at 3, 20, 30, and 65MHz (van den Doel et al., 2014) were emitted in 15 sets of 32,000 at a rate of 10,000 pulses per minute. Such a set will be referred to as a STARE. The return (and clutter) signals were recorded as digital waveforms at a sampling rate of 2.5GHz, resulting in 480,000 traces. Due to space restrictions in the underground facility, it was not possible to obtain a velocity model with a triangulation (WARR/CMP) scan (Stove and van den Doel, 2015), so we use a theoretical velocity model based on dielectric estimates of the materials involved.

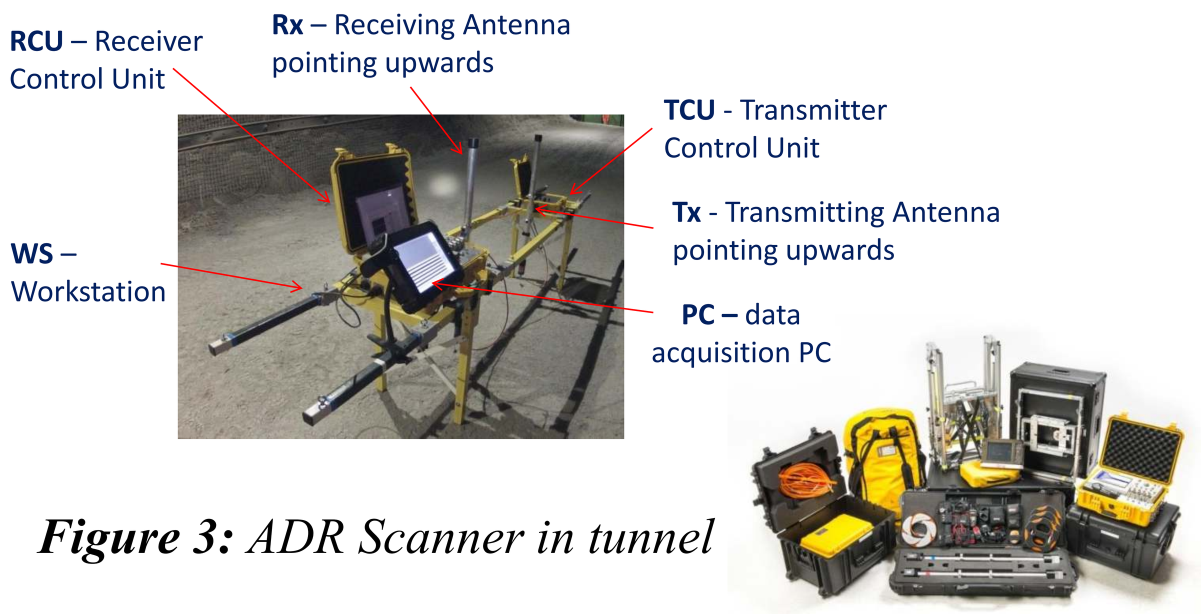

Figure 3: *ADR Scanner in tunnel*

The specification of the ADR Scanner is as follows:

ADR Fieldwork Setting	Typical Value
Tx emitting frequency maximum	300GHz*
Tx emitting frequency minimum	10kHz
Time Range	2ns to 250,000ns
Number of pixels per trace	100,000
Pulse Repetition Frequency (PRF)	10-200kHz
Pulse Width	0.1ns to 10ns
Power supply	4 off 24Vdc Li-Ion batteries
Power consumption	150W for ADR equipment *plus* 100W for tablet PC
Power transmission	< 5 miliwatts (mW)

* Carrier waves (or "Standing Waves") are the high frequencies within the transmitting antenna, modulated by resonances between the mirrors to result in a pulse with spectral content of 1MHz to 100MHz. The generation of these Standing Waves is outlined in **Figure 4**.

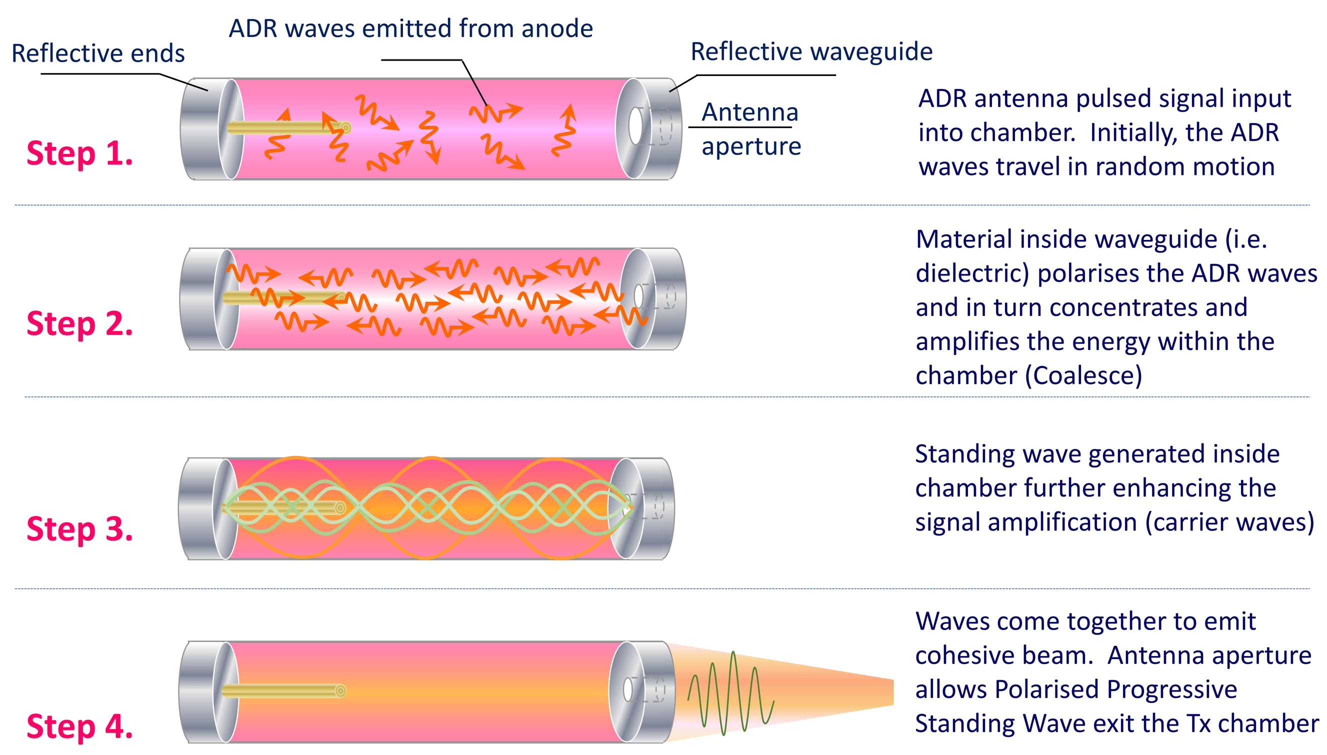

Figure 4: *Transmission of ADR Standing Waves*

The depth of penetration of the transmitted ADR wave packets can be tuned to different transmission frequencies and energies (and two-way travel times) to suit different distance scales of propagation through solid objects. Depth is measured from time and velocity by ray tracing and Normal Move Out (NMO) computations (Doel, van den, K., 2023, Propagation and attenuation of Electromagnetic waves in complex media, https://www.adrokgroup.com/technology/how-it-works).

4) Velocity model

Reflection from surface interface will be extracted from ADR data stacks which will give us the two way travel time to the surface. Time domain ADR data is migrated to spatial domain (data vs depth instead of time) using a velocity model based on geology and Adrok database of dielectric values based on previous projects. Mean bulk dielectric from transmitter to ground surface level is 8.6, as shown below:

Depth	Rock Layer	ε_r
0 to 365m	Lias Shales	9
365 to 600m	Keuper Marl	8
600 to 1000m	Bunter Sandstone	5
1000 to 1100m	Polyhalites (Potash)	2.5

Velocity varies with dielectric as $v=c/\sqrt{\varepsilon}$ with c speed of light in vacuum and the ε relative permittivity (dielectric). The bulk dielectric through sections i=1,…,N with values ε_i and layer thicknesses di is given by

$$\varepsilon = (\Sigma_i(\sqrt{\varepsilon_i}\, d_i)/ \Sigma_j d_j)^2 = 8.6.$$

Corresponding two way travel time to surface and back is t=10750ns.

5) Results

We show the results of applying the stacked correlation method (van den Doel, U.S. Patent 10,444,390 B2) to detect the reflector using the velocity model (of section 4 above) to migrate the data to the spatial domain. This method is clearest, but simpler signal processing methods will also show the reflection, provided the full stack is used. Stacked correlation plotted versus depth. The dominant peak at 1100-1130m is a clear indication of the rock/air ground level surface interface (**Figure 5**). Individual stacks at UG1 and UG2 are shown in **Figure 6.**

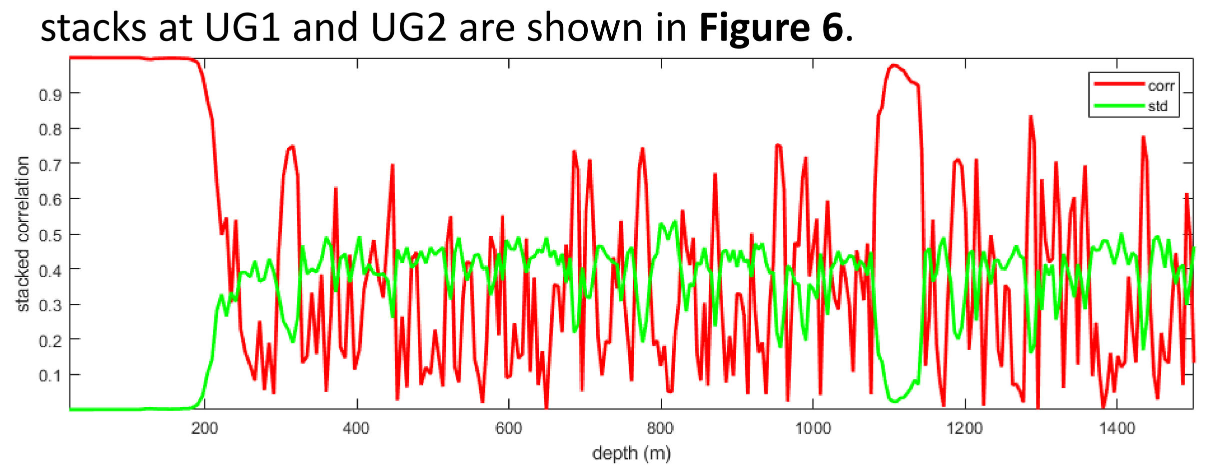

Figure 5: *STARE stacked correlations plot. Peaks of stacked correlation (blue) above the stacked standard deviation (green) indicate coherent reflected signal. The ground reflection is very prominent around 1100m.*

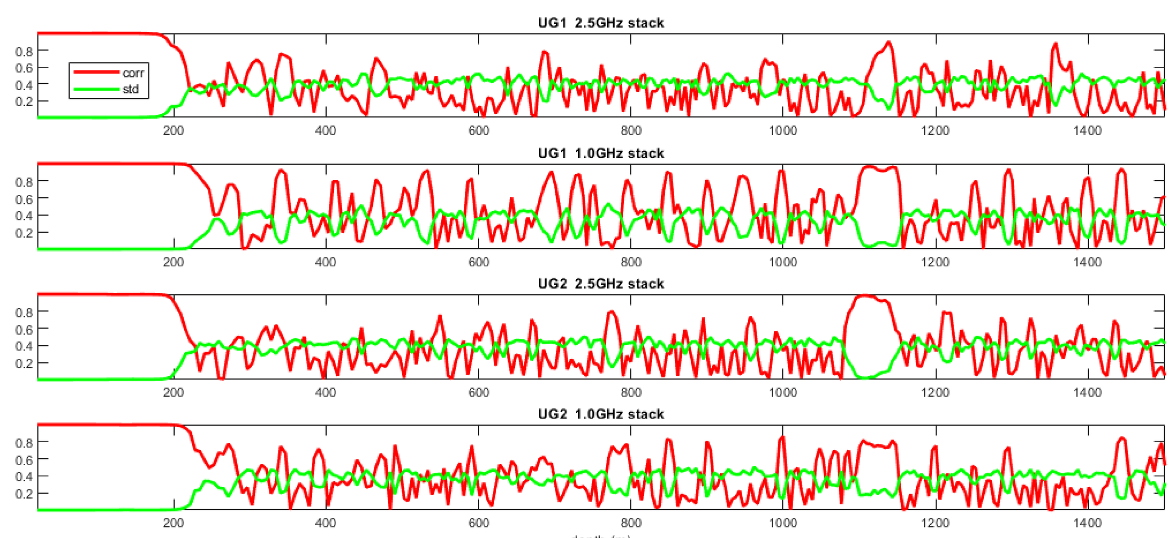

Figure 6: *Individual STARE stacked correlations all show the ground surface at sites UG1 and UG2*

6) Conclusion

The purpose of experiment was to identify rock/air interface from 1100m below ground level from underground tunnel at Boulby Laboratory We demonstrate the detection of the ground-air interface from a low frequency radar scan 1100m below the surface. The detection is possible by using a very low centre frequency for the pulsed radar wave packet, and extensive stacking to reduce noise and clutter.