Time lapse in-hole electrical resistivity surveying during a shallow release of CO_2 gas: Harvey, Western Australia

Brett Harris*
Exploration Geophysics
Curtin University
Brett.Harris@curtin.edu.au

Alex Costall
Exploration Geophysics
Curtin University
Alex.Costall@curtin.edu.au

Hoang Nguyen
Exploration Geophysics
Curtin University
Hoang.Nguyen@curtin.edu.au

Karsten Michael
CSIRO Energy
Perth Western Australia
Karsten.Michael@csiro.au

Ludovic Ricard
CSIRO Energy
Perth Western Australia
Ludovic.Ricard@csiro.au

Barry Freifeld
Class VI Solutions
bmfreifeld@classvisolutions.com

Arsham Avijegon
CSIRO Energy
Perth Western Australia
Arsham.Avijegon@csiro.au

Andrew Pethick
Exploration Geophysics
Curtin University
Andrew.Pethick@curtin.edu.au

SUMMARY

An in-hole electrode array was installed and cemented behind a fibreglass casing in a vertical monitoring well as part of an in-situ laboratory test for CO_2 migration in a shallow fault zone in Harvey, Western Australia. The array consisted of 32 electrodes spaced at 3 m intervals, located between 277 m and 370 m below ground level. The intention of the experiments was to assess the value of permanent in-hole electrical resistivity systems, during a shallow-release of CO_2. The distance between the monitoring and injection wells was close to 7 m. Food grade CO_2 gas was injected through a perforated interval located between 336 m and 342 m below ground level. In the order of 100,000 time-lapse dipole-dipole electrode quadrupole measurements were acquired during the experiment. There was a clear change in measurements at the depth of the injection interval during the release of CO_2 gas. Results are being compared with seismic, pressure and temperature data from the monitoring and injections wells from periods before, during and after injection.

Key words: ERI, CCS, CO_2, shallow release

INTRODUCTION

In-hole electrical resistivity imaging is one of several monitoring techniques being investigated at an in-situ carbon capture and storage (CCS) laboratory located in the South-West of Western Australia. During February 2019, a pilot test injection was performed and a small quantity (approximately 38 tonnes) of food-grade CO_2 (i.e. 99.90% CO_2, typically as used in pressure-beverage dispensation) was injected through a perforated interval located between 336 to 342 meters below ground level in the Harvey 2 injection well. The overarching project details are provided in Michael et al., 2019. Injection of CO_2 gas is expected to change electrical properties as it passes through the subsurface (Börner et al., 2013). One objective of controlled release was to evaluate methods for monitoring of unwanted leakage of carbon dioxide from a storage complex. To achieve this, a monitoring well, 7 m to the north-west of the existing Harvey 2 well, was instrumented with in-hole technologies including an electrode array. The electrode array was installed on the outside of casing on 17th December 2018.

The design of the existing Harvey 2 injection well did not permit the installation of a second electrode array, so conventional cross well measurements (Carrigan et al., 2013, Bergmann et al., 2012, Christensen et al., 2006, Schmidt-Hattenberger et al., 2013., Schmidt-Hattenberger et al., 2013, Yang et al., 2014) were not possible. For the In-Situ laboratory experiment, time-lapse detection of changes in electrical properties around the instrumented monitoring well was the objective.

Intensive monitoring was completed immediately before and during the CO_2 injection phase between 5th and 10th February 2019. Less frequent post injection surveys were completed between 10th and 26th of February 2019. Some 145,920 electrode quadrupole measurements were acquired during 135 surveys.

METHOD AND RESULTS

Installation of the In-Hole Electrode Array behind Casing

The electrode array was delivered directly to the Harvey 2 site from the manufacturer 'Pro-Seismic LLC'. Figure 1 shows a schematic of the Harvey 2 site. Figure 2 shows the electrode array and wiring termination prior to installation. Figure 3 is a photograph of the installation of the electrode array along with three other instrument lines. The instrument lines were threaded through the well headworks to be wired to the respective monitoring systems at a later date.

Wiring of the Electrode Array to the SYSCAL PRO Electrical Resistivity Instrument

Curtin University's 'SYSCAL Pro' electrical resistivity measurement equipment was used to acquire data. The SYSCAL Pro deployed to the site accepted 72 channels (e.g. wires from 72 electrodes) via three military-standard style plugs (i.e. each plug accepting 24 channels).

Connection of the 32-channel downhole electrode array to the SYSCAL Pro required design and manufacture of a "patch

box". The patch box splits wiring for electrodes 1 to 24 into the first plug (channels 1-24) and a further 8 wires to channels 25 to 32 onto the second plug. The patch box was designed to facilitate on-site modification to wiring as required.

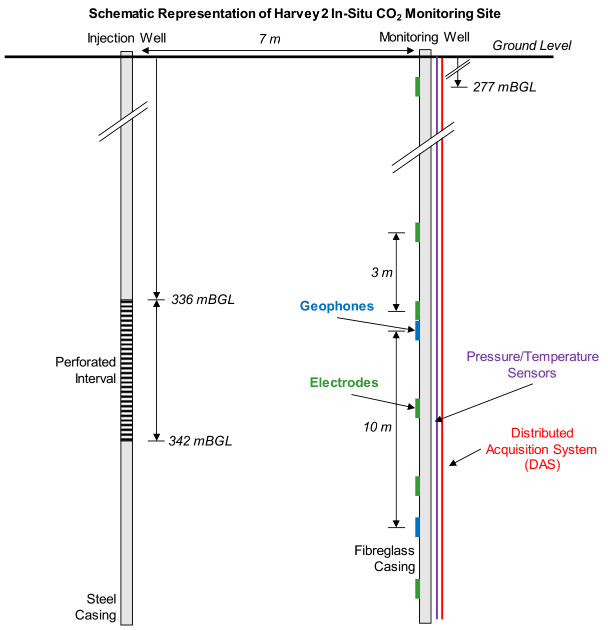

Figure 1: Schematic (NTS) of the Harvey 2 in-situ CO_2 monitoring lab, including the distribution of electrodes and geophones in relation to the perforated interval. The monitoring well is located 7-meters away from the injection well. The sensors (including the DAS/DTS and pressure sensors) are cemented to the outside of the fibreglass casing.

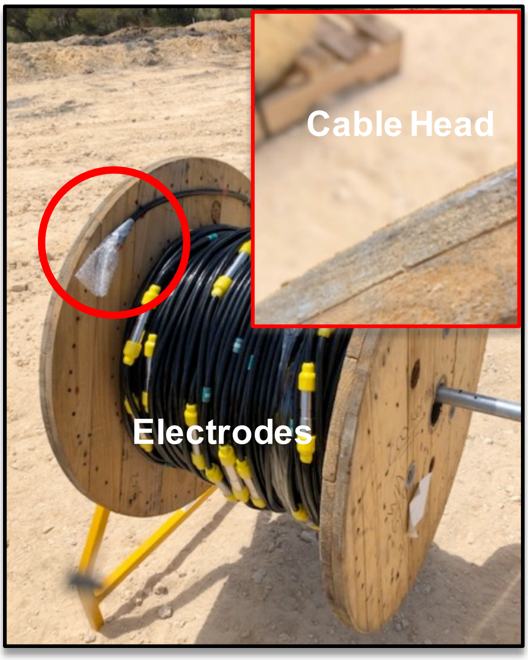

Figure 3. Photograph of the electrode array as delivered to site. The electrode array was manufactured by Pro-Seismic – Services, LLC. There were 32 electrodes spaced at 3 m. The electrode array was delivered to site without a connector to enable the electrode cable be threaded through the headworks.

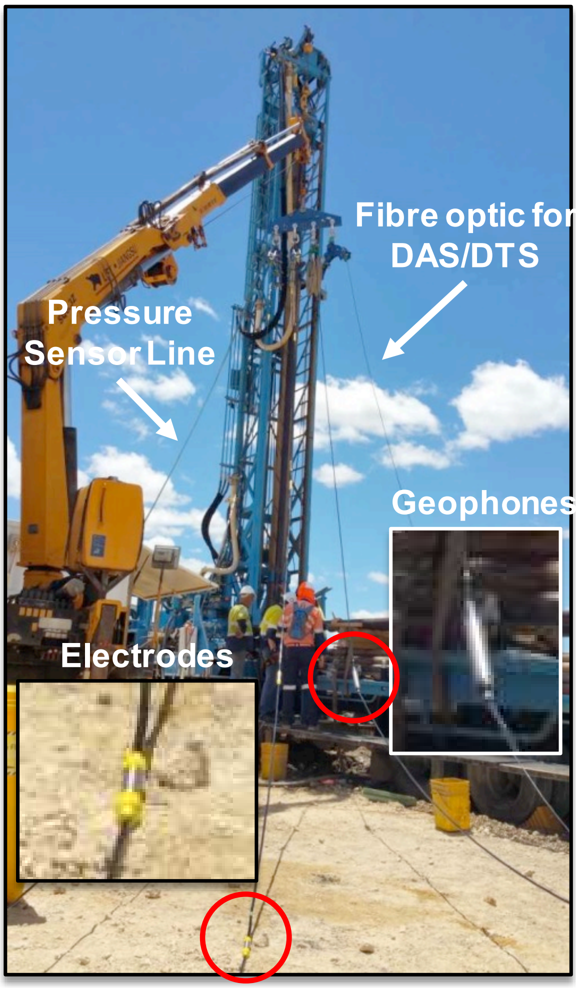

Figure 3. Photograph showing the installation of the downhole monitoring equipment. Electrodes are attached to the outside of the fibreglass casing. The electrode string containing the 32 electrodes at 3 m intervals. The electrodes are located from 277.24 to 370.24 meters below ground level, with electrode 1 located at the top (277.24 m) and electrode 32 located at the bottom (370.24 m). The four instrumentation lines (i.e. fibre-optic sensing DAS/DTS, 3C geophones, ERI electrodes, and pressure sensors) were installed simultaneously.

Parameter Testing

The electrode array and resistivity measurement system (i.e. the array, patch box and resistivity instrument) were tested several weeks prior to the planned injection of food grade CO_2. Regular electrode resistance tests show that the contact resistances were acceptable (< 8 Ohms) and remained consistent over the monitoring period.

Many ERI survey parameters and configurations were tested prior to injection. These included:

1. Fast dipole-dipole configuration with reciprocal measurements (770 quadrupoles), taking approximately 10 minutes to complete.
2. Multiple Gradient configurations (e.g. Dahlin, 2006) (4742 quadrupoles), taking approximately 40 minutes to complete.
3. A comprehensive dipole-dipole configuration with reciprocal measurements (4398 quadrupoles) taking approximately 40 minutes to complete.

Evaluation of different input voltages (e.g. 50, 100, 200 and 400 volts), and current injection times (e.g. 250, 500, 1000 ms) for the 100% duty cycle waveform were compared.

ERI parameter selection requires compromise between practical measurement times, signal-to-noise ratio, and target illumination. There were also project specific restrictions. The most significant restriction was on the available measurement time. That is, it was decided not to collect in-hole electrical resistivity data during acquisition of seismic data, due to the risk of interference with the seismic monitoring system. Data acquisition with the fast dipole-dipole electrode configuration was selected for high intensity measurement periods. This permitted rapid acquisition time and acceptable data quality.

When possible, surveys requiring longer measurement times were acquired to assess alternate configurations. The multiple gradient configuration measures 4742 electrode quadrupoles over approximately 40 minutes recording time. In addition, two comprehensive dipole arrays were acquired. The comprehensive arrays contain a similar number of quadrupoles to the multiple-gradient, with different illumination characteristics.

During the ERI survey period, a total of 145,920 independent voltage and current measurements (i.e. electrode quadrupoles) were acquired from the permanent 32 electrode array installed in the Harvey 2 monitoring well.

Initial Outcomes: 3D Representation of Time Lapse Dipole- Dipole Data

Apparent resistivity for all time-lapse dipole-dipole quadrupoles can be simultaneously represented in 3D space with integer dipole separations on the Y axis, date-time for each measurement on the X axis, and depth below ground level of each quadrupole midpoint as the Z axis. This is shown in Figure 4. A second volume was created to show the percentage change in measurements made before injection from measurements made during and after injection of CO_2 gas.

Three preliminary observations are made from the data:

1. A high-level of repeatability is achieved for measurements above and below the injection interval.
2. A small but clear response is observed specifically at the injection depth.
3. While reciprocity for current and potential electrodes is maintained for the majority of quadrupoles, we note differences in forward and reverse measurements for quadrupoles with small voltage and current electrode spacing, proximal to the injection interval.

Initial inversion of data provides a conductivity distribution consistent with expectations from wireline logging in the monitoring and injection wells. The next stage of research will include inversion of the time-lapse in-hole electrical resistivity surveys.

CONCLUSIONS

Time lapse in-hole electrical resistivity measurements were made from a permanently installed electrode array, during a shallow release of food grade CO_2 at the CCS In-Situ laboratory in Harvey, Western Australia. Measurements were made before during and after injections. In the order of 100,000 dipole-dipole quadrupole measurements were made for the experiment. A subtle but distinct time-lapse change in measured apparent resistivity was recorded at approximately the depth of the injection interval. Inversion of data and integration of from other downhole data set is proceeding.

ACKNOWLEDGEMENTS

The In-Situ Lab project is co-funded by the Australian Government through the Commonwealth Carbon Capture and Storage Research Development and Demonstration Fund CCS49360 and by the CSIRO Energy business unit. Also acknowledged are contributions by the Western Australian Department of Mines Industry Regulation and Safety, including the Geological Survey of Western Australia. Authors are grateful to Dominic Howman for technical support in the field experiments.

REFERENCES

Bergmann, P., Schmidt-Hattenberger, C., Kiessling, D., Rücker, C., Labitzke, T., Henninges, J., Baumann, G., and Schütt, H., 2012, Surface-downhole electrical resistivity tomography applied to monitoring of CO2 storage at Ketzin, Germany, Geophysics, **77**, No. 6; P. B253–B267,

Börner, J. H., Herdegen, V., Repke, J.-U. and Spitzer, K., 2013, The impact of CO2 on the electrical properties of water bearing porous media – laboratory experiments with respect to carbon capture and storage, Geophysical Prospecting, 61: 446–460.

Carrigan, C., Yang, X., LaBrecque, D., Larsen, D., Freeman, D., Ramirez, A., Daily, W., Aines, R., & Newmark, R., Friedmann, J., and Hovorka, S., 2013, Electrical resistance tomographic monitoring of CO2 movement in deep geologic reservoirs. International Journal of Greenhouse Gas Control. **18**. 401.

Christensen, N. B., D. Sherlock, and K. Dodds, 2006 Monitoring CO2 injection with cross-hole electrical resistivity tomography Exploration Geophysics, **37**: 44-49.

Dahlin, T., and Zhou, B., 2006, Multiple-gradient array measurements for multichannel 2D resistivity imaging, Near Surface Geophysics, **4**, 113-123

Michael, K., Avijegon, A., Ricard, L., Myers, M., Tertyshnikov, K., Pevzner, R., Strand, J., Freifeld B., Woitt, M., Peruvkkina, M., Feitz, A., Pejcic, B., Stalker, L., Harris, B., Myers, Jo., Larcher A., Rachakonda Laurent, P., Langhi, Dance, T., Hortle, A., Roberts, J., Woltering, M., and White, C., 2019, In-Situ Laboratory for CO2 Controlled-Release Experiments and Monitoring in a Fault Zone in Western Australia; Australian Explortion Geoscience Conference, 2-5 September 2019, Perth, Western Australia (this volume).

Schmidt-Hattenberger, C., Bergmann, P., Boesing, D., Labitzke, T., Möller, M., Schröder, S., Wagner, F., Schütt, H., 2013, Electrical Resistivity Tomography (ERT) for Monitoring of CO2 Migration - from Tool Development to Reservoir Surveillance at the Ketzin Pilot Site. Energy Procedia. **37** 4268-4275.

Schmidt-Hattenberger, C., Bergmann, P., Labitzke, T., Wagner, F.D., 2016, Permanent crosshole electrical resistivity tomography (ERT) as an established method for the long-term

CO2 monitoring at the Ketzin pilot site, Int. J. Greenhouse Gas Control, **52**, 432-448.

Yang X., Chen X.,, Carrigan C., Ramirez A., Uncertainty quantification of CO2 saturation estimated from electrical resistance tomography data at the Cranfield site, International Journal of Greenhouse Gas Control, **27**, 59-68.

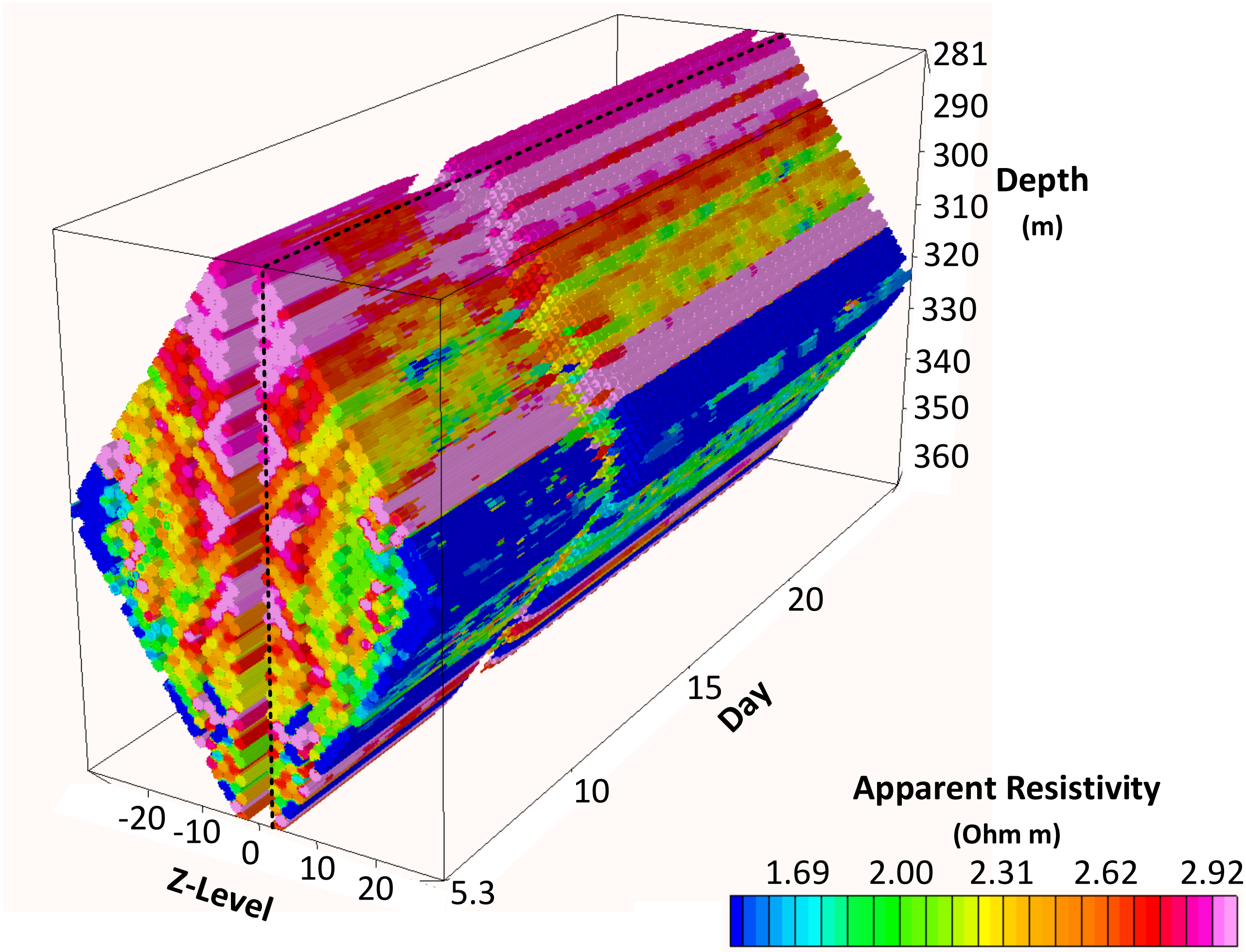

Figure 4. Image representing the 3D apparent resistivity pseudo-plots of all in-hole time-lapse dipole-dipole quadrupoles measured before, during, and after a shallow release of food-grade CO_2 into a fault system from an in-hole electrode array. The X-axis is date/time in February 2019, the Y-axis is expanding dipole-dipole quadrupole separations (positivity is current electrodes above potential electrodes and negative is the opposite), and Z-axis is depth below ground level of the quadrupole midpoint. By slicing into the volume, it is possible to identify changes in apparent resistivity close to the injection depth interval (336 – 342 mBGL). The apparent resistivity for the smaller integer multiple of electrode spacing (i.e. 3 by 3m electrode spacing is the minimum) is highly reasonable compared to wireline logs (see figure 4). We observe excellent survey repeatability. Significant changes in dipole-dipole apparent resistivity are observed at the injection interval from the 9th of February (see Figure 4). The next stage of work involves inversion of the time-lapse electrical resistivity data.

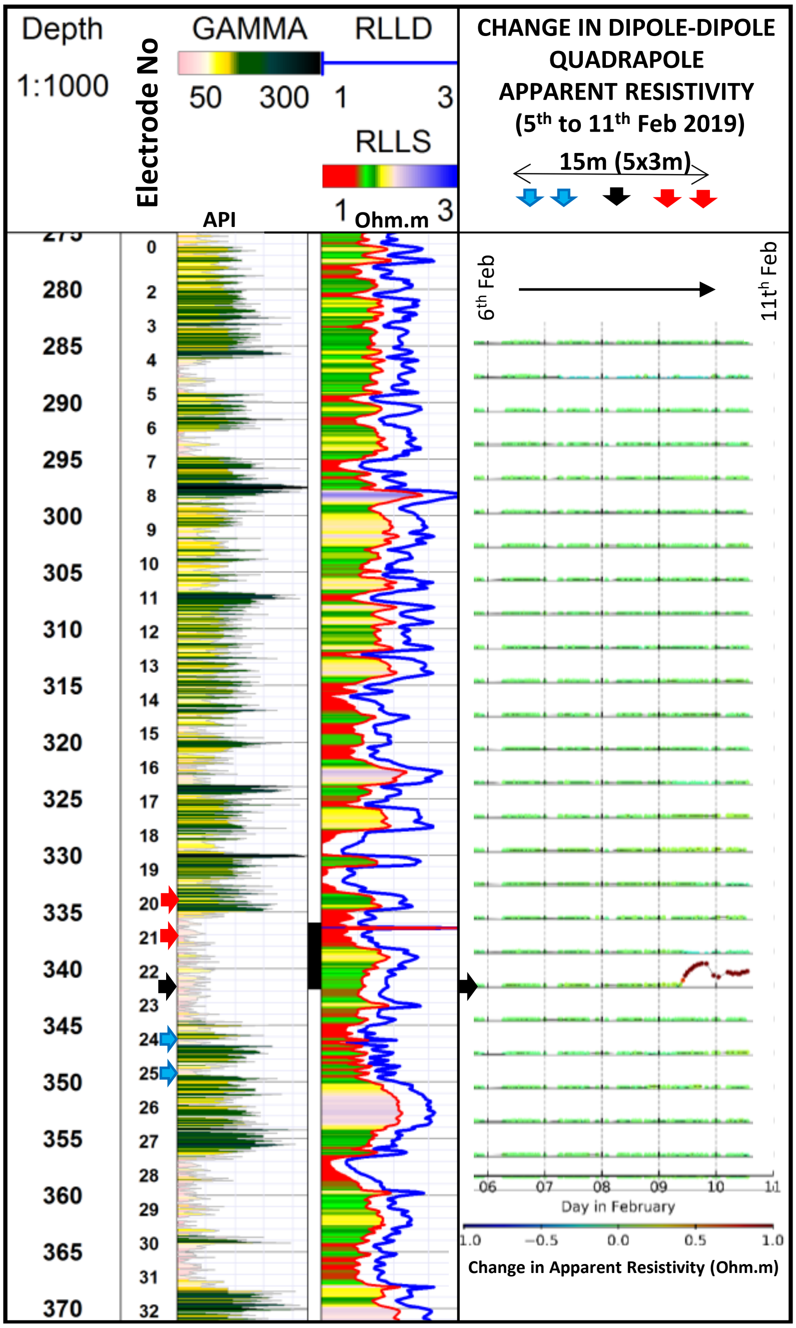

Figure 5. Comparison of gamma and resistivity wire-line logs with change in time lapse dipole-dipole apparent resistivity for 15 m quadrupoles (i.e. 5 x 3m electrode spacing's) between 6th and 11th of February 2019. A large positive change in apparent resistivity commences in the quadrupole with midpoint closest to 340 m depth (i.e. the injection interval) on the morning of the 9th of February 2019. Responses are also clear in the 9 m, and 12 m quadrupoles. At larger integer spacing for electrodes (greater than 15m), the response is small and tends to commence earlier.