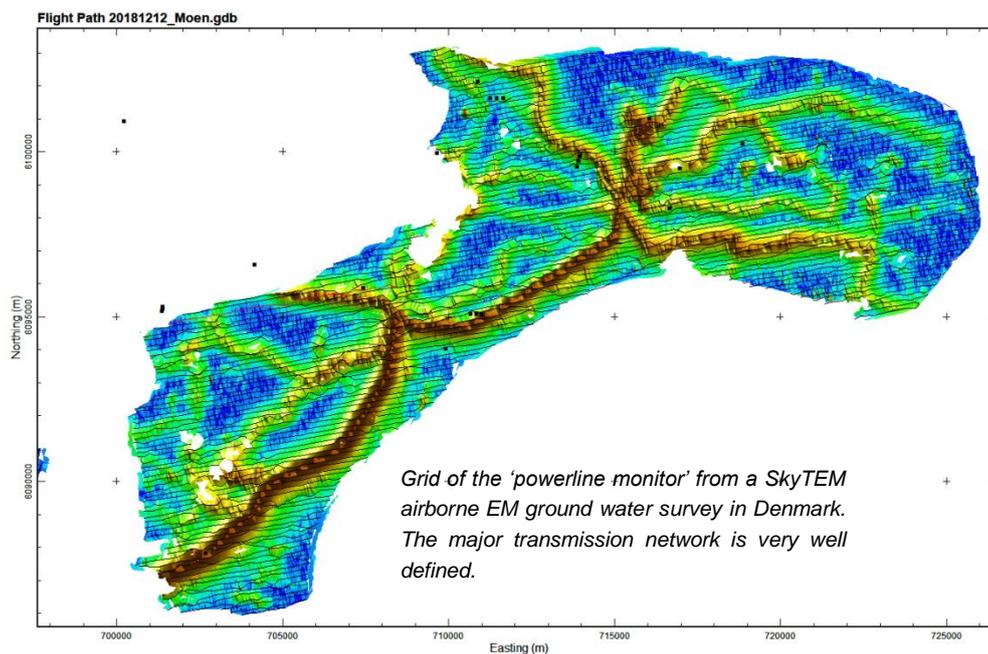


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# EFFECTS OF INFRASTRUCTURE ON GEOPHYSICAL EXPLORATION

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Report prepared for Mineral Resources Tasmania

by Kate Hine and John Bishop

February 2021



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## Summary

This report reviews the impact of large scale man-made metallic infrastructure (powerlines, pipelines, railways and wind farms) on the efficacy of exploration geophysical techniques. Three case studies are presented where infrastructure directly impacted the ore discovery.

Unsurprisingly, airborne geophysical methods of all types, including airborne EM and airborne magnetics/radiometrics, are severely limited by both powerlines and wind farms due to flight height restrictions. Especially for wind farms, although it may be possible to fly selected transects between towers, the resultant survey lines would be too widely spaced to make the survey worthwhile. Furthermore, the associated powerlines and buried cables (such as those connecting wind towers) significantly degrade airborne EM data for at least 150m distance from the cable, sometimes up to 600m. Therefore, where possible, we strongly recommend commissioning such surveys before construction of any infrastructure. The data could then be used as an open-file resource to stimulate follow-up exploration.

Surface electrical geophysical methods, especially EM and IP, are also affected by the increased electrical interference generated by any type of surface infrastructure\*.

DC resistivity, downhole MMR, gravity, small ground/drone magnetic surveys and, probably, some downhole EM surveys (with careful loop placement), should be relatively unaffected. Some other methods not commonly used in mineral exploration, such as seismic tomography, would also be possible.

There is a slight chance it may be possible to get useable ground EM and IP data by using modified equipment and methodology to minimise interactions. One example would be to use the new 'floating dipoles' to create a distributed array of receivers located at least 200m (testing required because it could be significantly further) away from infrastructure. It may also be possible to use a DC power source to 'saturate' the problematic cable/pipeline/powerline, and thus remove its effect from IP surveys. However, this would require extensive R&D to understand the nature of the interference better.

The following table below summarises the impact of different types of infrastructure on the core geophysical methods. Note that, for some types of geophysics/infrastructure, we could not obtain any actual examples, and have extrapolated the likely impact based on our and other's experiences.

\* Note this effect was often present even when the cables/powerlines/pipelines were not energised, i.e., it is the interaction with the geophysical transmitter, not the electricity being carried by the object, that causes the problem. Thus 'turning off' the power often does not solve the geophysical data quality problem.



Table: Effects of Electrical Infrastructure on Geophysical Exploration

Method	Pipeline/railway	Powerlines	Wind farm
<b>Airborne EM</b>	~200-600m wide, strong, EM response along the pipeline corridor, masking the response from basement conductors	Effect depends on the type of powerline. Possible effects up to 500m (even to 1000m) distant.	Survey not feasible due to flight path limitations and interference from buried cables.
<b>Induced Polarisation</b>	Data ok >300m away from pipe/rail	Effect is highly dependent on the type of powerline and ground conductance. Often possible unless SWER*.	Large (up to 400m wide) very strong IP anomalies are coinciding with buried cables, i.e., data quality too poor except where tower spacing is very broad.
<b>Resistivity</b>	Localised response	Localised response	Localised response near cables/towers
<b>Aeromagnetics/radiometrics</b>	If present, response easily filtered from the data	Response easily filtered from data.	Wind towers preclude suitable flight path and generate strongly localised anomalies
<b>Ground/drone magnetics</b>	No known cases, probably a localised anomaly	No known cases, probably a localised anomaly	No known cases. Aeromag shows strong ~200m wide responses associated with towers—similar likely from drone and ground surveys.
<b>Ground EM</b>	No known cases	Generally speaking, no. Some local scale distribution lines are okay (unless SWER*), but regional transmission lines are not.	No known cases, but cable responses observed in airborne EM is likely also to be problematic in-ground EM.
<b>Downhole EM</b>			No known cases

\* Single wire earth return



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# 1 Introduction

Tasmania's mineral wealth is a long-established and significant economic driver. Current mining and exploration operations in Tasmania have identified in-ground resources worth more than AU\$11 billion at current prices (MRT: '*Tasmania Delivers...*' brochure, 2020). With most or all surface deposits found, geophysics, especially electrical methods, is often a critical tool for the discovery of new, buried mineral resources. For example, the Que River and Hellyer mines were direct EM discoveries and significant contributions have been made at Mt Lyell and Mt Lindsay.

Man-made infrastructure is a significant source of noise in geophysical exploration, to the extent that many geophysical techniques are simply not possible in built-up areas. Fortunately, most exploration programs are remote, so this conflict is not common. Recently, these remote areas have attracted large-scale projects such as gas pipelines, new railways, high voltage powerlines and, increasingly, large wind farms. Each of these poses an evident risk to exploration geophysics, and, by extension, the ability of explorers to find new mineral deposits.

Wind farms in particular (with their in-ground transmission cables, foundations, towers, turbines, electrical substations and overhead powerlines) are problematic because of the large land areas required. However, the level of impact never been specifically assessed in any detail, since, until recently, wind farms have not been a significant consideration in major mineral exploration provinces.

Mineral Resources Tasmania commissioned this report to investigate whether, and to what degree, different metallic infrastructure would impact exploration geophysical surveys.

## 1.1 Background Information

For clarity and brevity, this review focuses on 'land-intensive' metallic infrastructure only; namely pipelines, railways, powerlines and large scale commercial wind farms. From the perspective of geophysics, these noise sources can further be grouped into grounded metallic objects (pipelines and railways), and free-standing structures, such as powerlines and wind farms.

The effects from solar farms have not been considered; largely because the authors have no experience with them, nor have they seen any associated geophysical data. However, more and increasingly larger farms are being built and proposed (e.g., a 10GW farm covering 150 sq kms in the NT), and it is probably only a matter of time before there are conflicting land-use claims.

We have focused on the main geophysical techniques used in mineral exploration, namely, magnetics, gravity, induced polarisation-resistivity (IP), airborne EM (AEM, and 'HEM' for helicopter-borne EM), ground EM, and Downhole EM (DHEM). Other methods, such as Magnetotellurics (MT and AMT) and Sub-audio Magnetics (SAM) have not been covered partly because they are much less used and partly because we have no examples.

For wind farms, we assume that it is a commercial-scale wind farm with turbines laid out on a semi-regular grid. A key variable is turbine spacing. Turbine spacing is not straight forward. Manufacturers commonly recommend ~5 rotor diameters in the dominant crosswind direction



and ~7 rotor diameters in the downwind direction (Gaughan, R., 2018), but in practice, turbine layouts range from 3x to 15x rotor diameter spacing depending on topography, access constraints, economics, land availability, etc.

Rather than guess a turbine spacing, we have used the existing Granville Harbour generator as the model of a modern, commercial-scale, wind farm in Tasmanian conditions. At Granville, turbine separation ranges from 450 to 800m, the towers are 150m high (maximum height including blades is 220m), and the rotor diameter is 140m. Thus, for the purposes of this report, we will assume a 600-800m spaced semi-regular grid of wind towers.

The three criteria considered for each geophysical technique are:

- a) How affected the data would be and how confident we are in this assessment
- b) Whether a survey would be physically possible within the wind farm and
- c) How to mitigate the impact if there is one.

## 1.2 Sources of data

We could find no in-depth studies analysing the interaction between infrastructure and ground exploration geophysical techniques, presumably because geophysicists consider the effects 'self-evident' and thus either avoid running EM/IP surveys in this area or ignore the resultant bad data in favour of better data further away (certainly that has been our experience). In the case of airborne geophysics, there is one good study on the effect of powerlines in airborne EM from the Colorado School of Mines (B. Bloss, 2017).

Given the lack of peer-reviewed papers, Mitre researched and obtained data from several recent geophysical surveys (specifically IP/ DC resistivity, aeromagnetism, ground EM, and airborne EM) from public documents as well as our own archives. This, together with Mitre's wide experience with cultural artefacts in electrical geophysical data, conversations with technical experts, and a literature review, provides the foundation upon which the conclusions are made.

## 1.3 Man-made interference in electrical geophysics

Man-made interference is composed of three different types: 1. Physical access limitations preventing the actual data acquisition (e.g., no-go zones around railways or powerlines that limit flight height), 2. Signals emanating from the object itself (e.g., electromagnetic fields associated with the electricity flowing through powerlines, currents associated with active cathodic protection, magnetic fields from water tanks, vibrations from roads, etc.), 3. interference relating to the interaction of the geophysical system with the object (e.g., the coupling between the EM transmitter loop and a powerline earthing system).

The latter type can be divided into two sub-categories: capacitive and inductive coupling. These arise because the magnetic and electric fields generated by EM and IP equipment not only affect the earth, but all conductive media in the vicinity of the transmitter. Figure 1 gives examples of these responses from these two types of coupling in an EM sounding. These are superimposed on the ground response, resulting in degraded data.

Capacitive coupling is generated by large conductive bodies that polarise and only pass current at high frequencies. We can imagine that at lower frequencies these conductive bodies would



polarise and charge just like a capacitor in an electrical circuit, with the current increasing as the frequency increases. Examples of media that cause capacitive coupling include vehicles, buildings, or any large electrically conductive object on or in the earth.

Inductive coupling occurs when time-varying primary magnetic fields induce a current in a conductor, such as a long length of wire or pipe. Here the most common culprits are often strike extensive, intermittently grounded, man-made structures, such as fences, (especially) buried cables, pipelines, and powerlines.

Most common man-made objects give rise to some capacitive and/or inductive coupling, with the amplitude depending on the object's electrical characteristics and how they interact with the particular geophysical system being used.

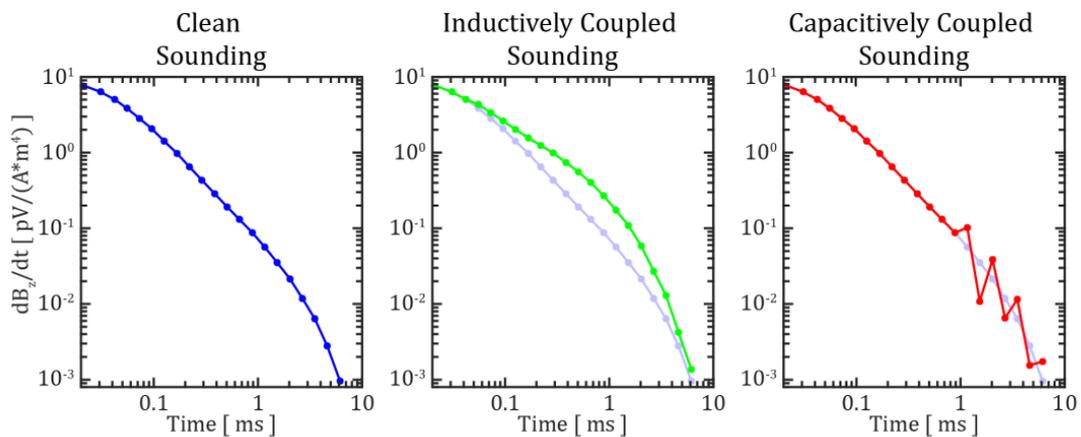


Figure 1: Typical EM soundings showing the impact of inductive and capacitive coupling (Bloss, B.R, 2017).



## 2 Results – pipelines and railways

### 2.1 Aeromagnetics, radiometrics and gravity

Aeromagnetics, radiometrics and gravity are not *significantly* affected by pipelines and railways. Ground magnetics will be affected but only over a limited distance, e.g., within ~50m for a railway, and typically within ~100m for a large metal pipeline.

Figure 2 below shows the 100m line spacing first vertical derivative of reduced-to-pole aeromagnetics over the major road and (only) railway from Broken Hill to Adelaide. The road (to the north of the railway) and the railway both trend WSW, where the magnetic texture varies from NW through to NE. A weak stippling can be seen associated with the railway, but not the road, road base, or local distribution powerlines along the road, show a recognisable response.

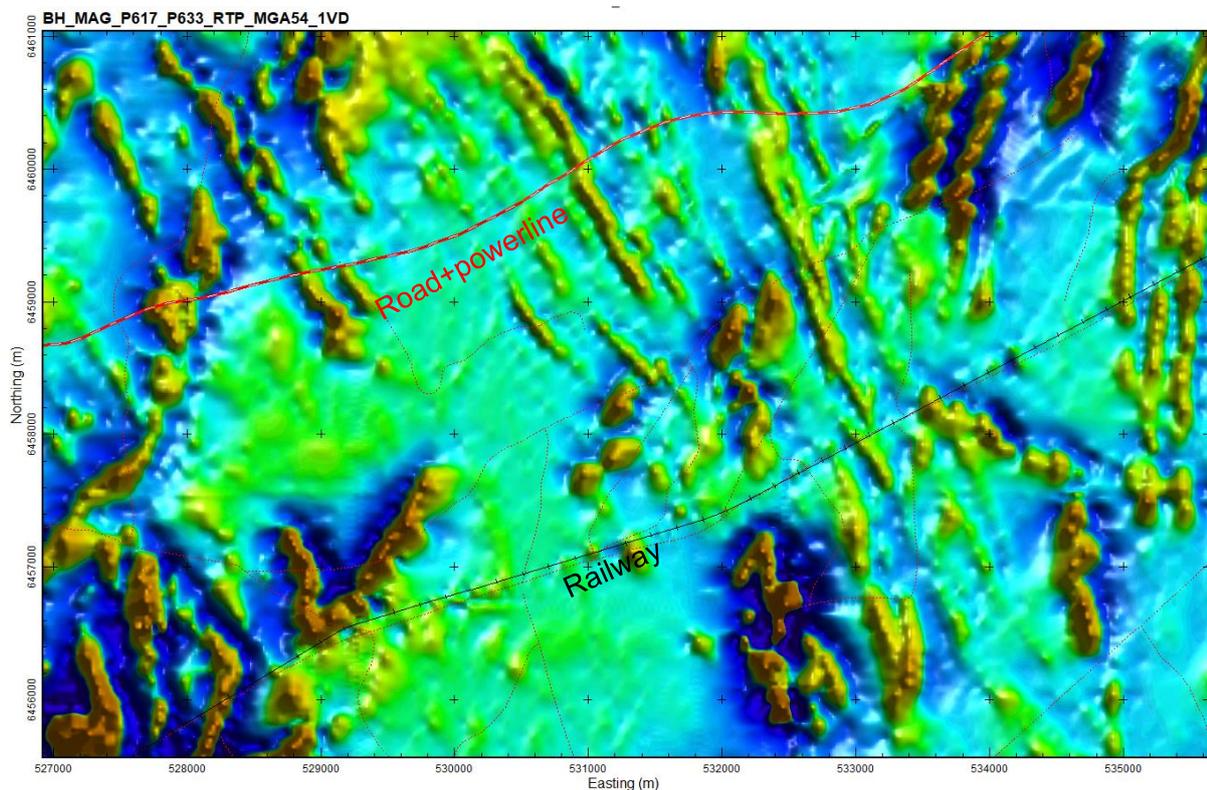


Figure 2: 100m line spacing aeromagnetic data from southwest of Broken Hill, NSW. The road and powerline are not visible, but the railway does produce a small localised magnetic response. These do not affect the usefulness of the data.

### 2.2 Airborne EM over pipelines and railways

Airborne EM is strongly affected by both pipelines and railways. As Figures 3 and 4 show, the response from pipelines (and to a lesser extent, railways) can mimic the response from a steep vertical conductor very closely. The response cannot be filtered out or otherwise removed because it is a true EM response (primarily current channelling).

The example presented is from a 2012 VTEM-max survey at Broken Hill. The flight lines cross several cultural features (a powerline, a pipeline and a railway line) and, notably, the 'Flying Doctor' orebody. Flying Doctor, a near-surface ~1Mt massive sulphide deposit, is apparent as a separate response from the ~700m wide pipeline artefact, but only because it is far enough



away to be discriminated. If it were within, say, 200m of the pipeline, or deeper, it is unlikely this ore deposit would be recognised as a legitimate exploration target in the presence of the much stronger cultural responses.

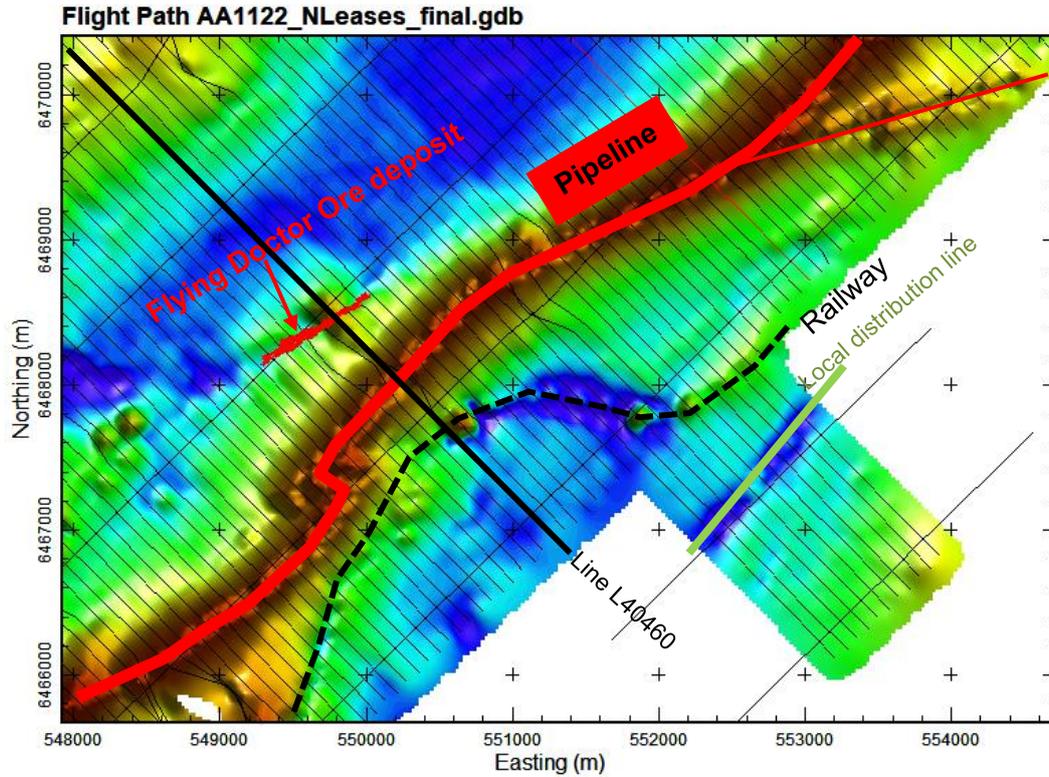


Figure 3: HEM (VTEM) map of channel 30 showing typical overpowering responses from various types of infrastructure (Broken Hill, NSW). The profile from flight line 40460 is shown in the next figure.

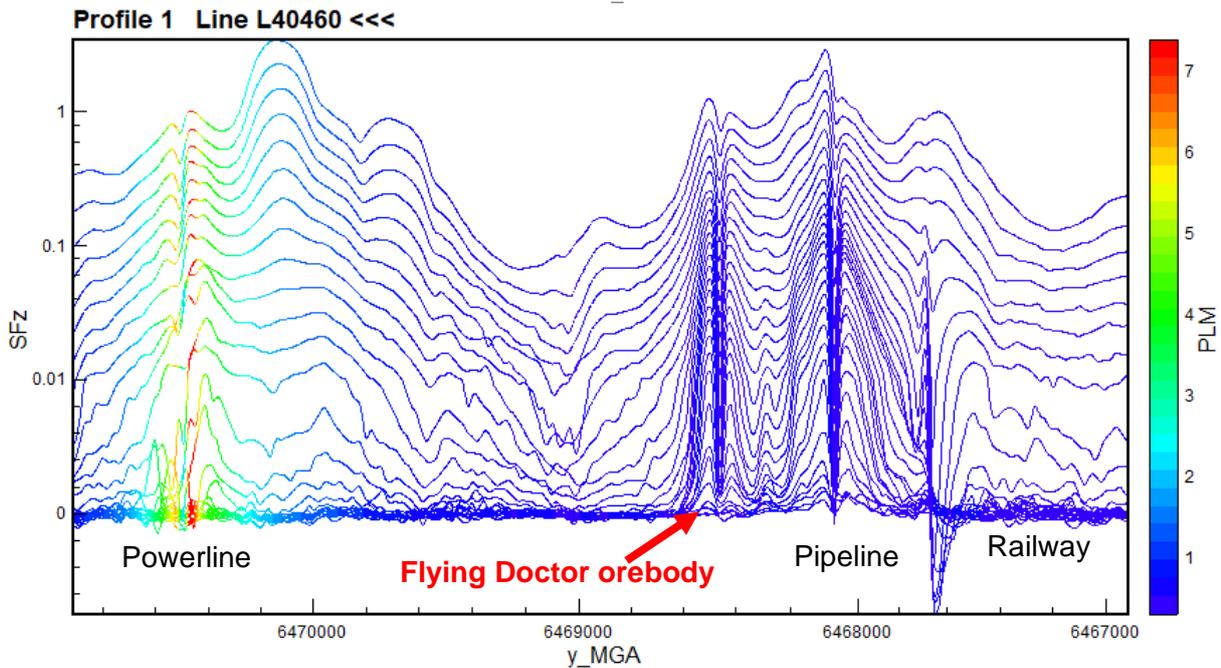


Figure 4: Example data from the 2012 VTEM-max survey over a railway, water pipeline, the Flying Doctor ore deposit, and a powerline. Flying Doctor, if deeper, or closer to any of the other features, would probably not have been resolved.



### 2.3 Ground EM and ground IP over pipelines and railways

It is well established in the literature that pipelines and, to a lesser extent, railways, can cause interference problems. A study (Wynn and Zonge, 1975) on the effect of electrically conductive pipelines on induced polarization shows that the so-called “Pipeline Effect” is a composite of several effects, including current channelling, EM induction, and complex electrode polarization. Various attempts have been made to remove the effect, with limited success.

We could find no recent examples of EM or IP over a pipeline or railway in the literature. However, IP data from the 1970s over the same Northern Leases prospect in Broken Hill shows many chargeability anomalies associated with the trend of mineralisation, but others that overlap (suspiciously) with the pipeline. These anomalies have not been tested, presumably because the exploration team also dismissed them as pipeline-related. Figure 5 shows the VTEM channel 25 amplitude (the pipeline is the dominant, sinuous, conductive high) and a compilation of 100ft, 200ft, 300ft and 600ft IP anomalies. Most of the IP lines, where they cross the pipeline, show a distinct IP response.

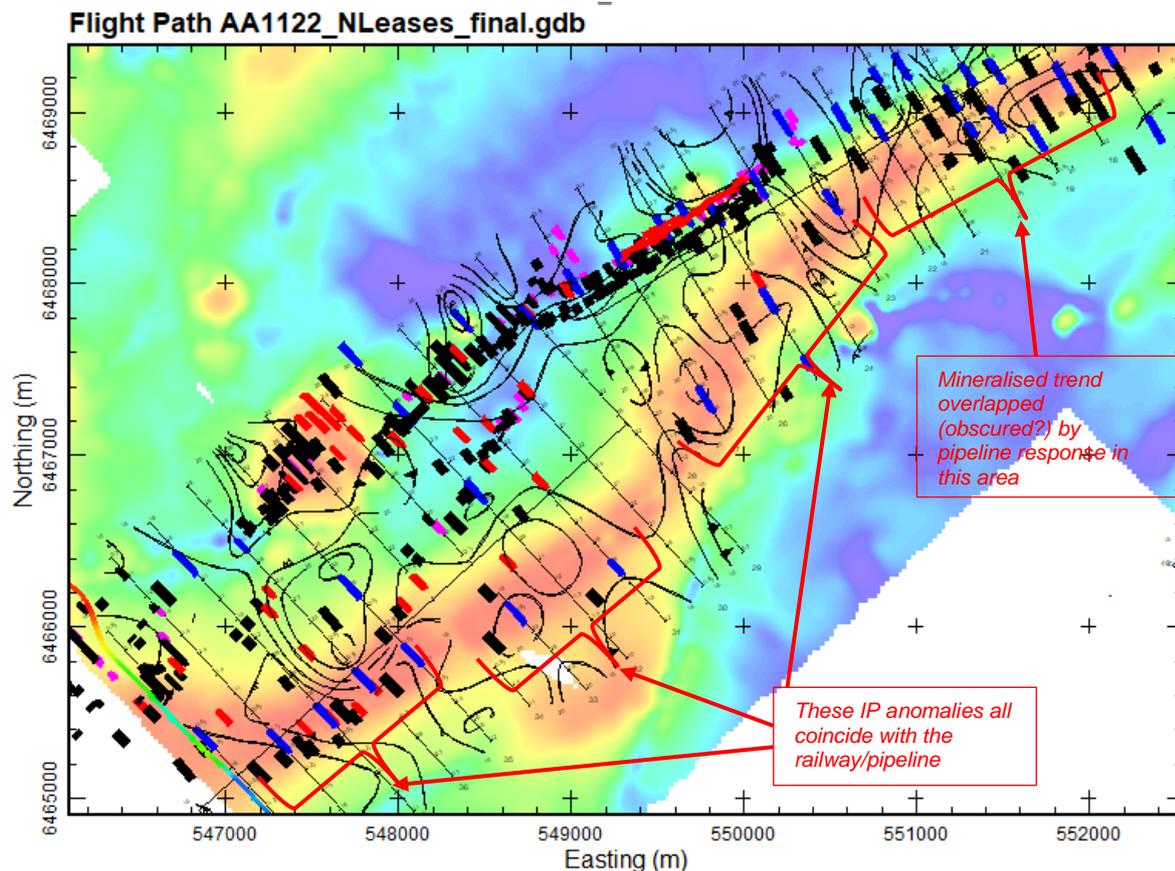


Figure 5: 1970s dipole-dipole (McPhar frequency domain) IP over the Northern Leases, Broken Hill with VTEM channel 25 as the background image. Many of the IP anomalies coincide with a water pipeline, which was also clearly detected by the airborne EM. Contours are the 600ft  $n=3$  IP response.

### 2.4 DHEM beneath pipelines and railway ines

Downhole techniques, such as DHEM (and DHMMR) have much lower noise levels than surface geophysics because the receiver is in a quiet environment, much closer to the target, and usually much further away from infrastructure than surface surveys. DHEM surveys are



routinely effective, even in very noisy mine environments. Our experience is that DHEM is rarely affected by surface infrastructure, even in quite severe cases (such as beneath a methane power plant and operating mine). DHMMR will often show a response from strike-extensive infrastructure, but as long as that is factored into the modelling as another conductor, the effect should not be deleterious to the survey's effectiveness (Figure 6).

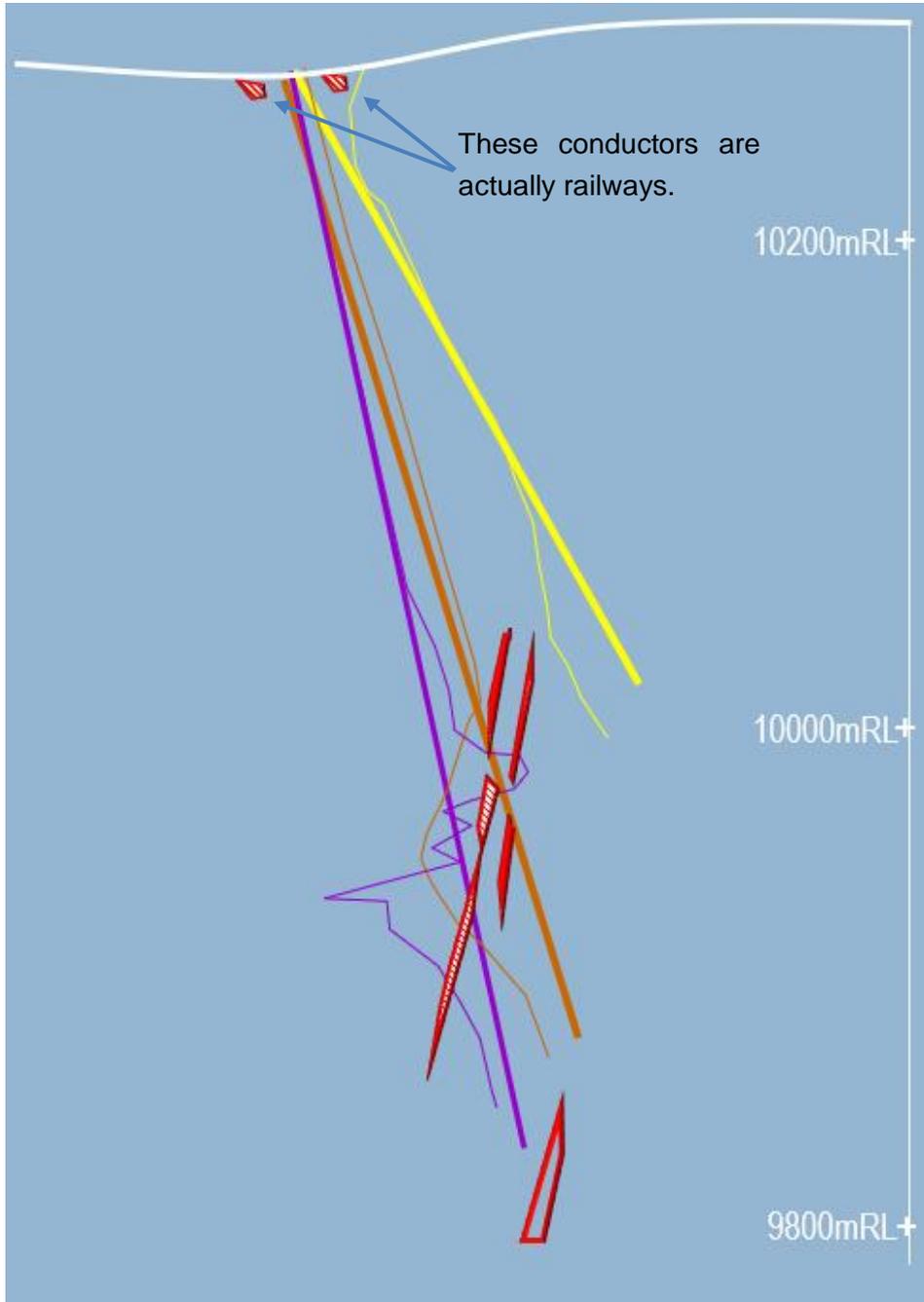


Figure 6: 3 holes of DHMMR data and associated models from the North Mine, Broken Hill. The surface conductors are due to railways at the surface, but mineralisation at depth has been found and defined.



### 3 Results – Powerlines

The interaction between geophysics and powerlines is particularly complex, being highly dependent on the type of powerline, how and where it is grounded, the ground conductivity, and how ‘clean’ the electrical fields being carried are.

#### 3.1 Aeromagnetics, radiometrics and gravity over powerlines

Radiometric and gravity surveys are not affected by powerlines, except that if airborne, the aircraft may need to fly higher to avoid large transmission lines. Aeromagnetics often shows the presence of large regional transmission lines in the data, but the short wavelength of these anomalies means that they are usually readily filtered from the line data before gridding and are thus rarely problematic from an exploration perspective. The response is presumably in large part due to the steel towers, but there also appears to be a component related to the wires themselves, the exact cause of which is uncertain.

Figure 7 shows a semi-regional 200m line-spacing, filtered aeromagnetic image and a later more detailed 100m line-spacing aeromagnetic image over part of the same area. The detailed data has not been filtered and the powerlines can easily be seen.

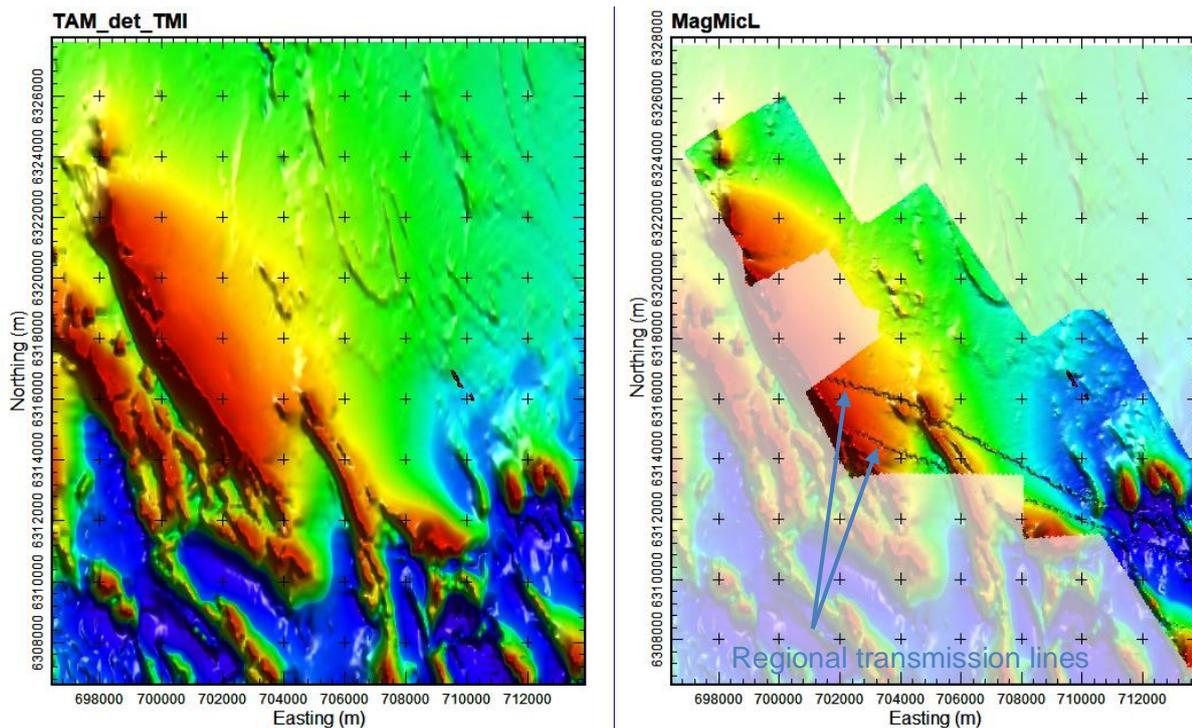


Figure 7: Regional, filtered, 200m line-spacing (left) and detailed, 100m, unfiltered aeromagnetic data (right). Without filtering, the magnetic response from the regional transmission lines are readily apparent. Note that the surveys cross built-up areas with many low-voltage distribution lines, but no magnetic responses from these are apparent in either data set. Note that a pipeline crosses this area as well, but the response is not evident in the magnetics,

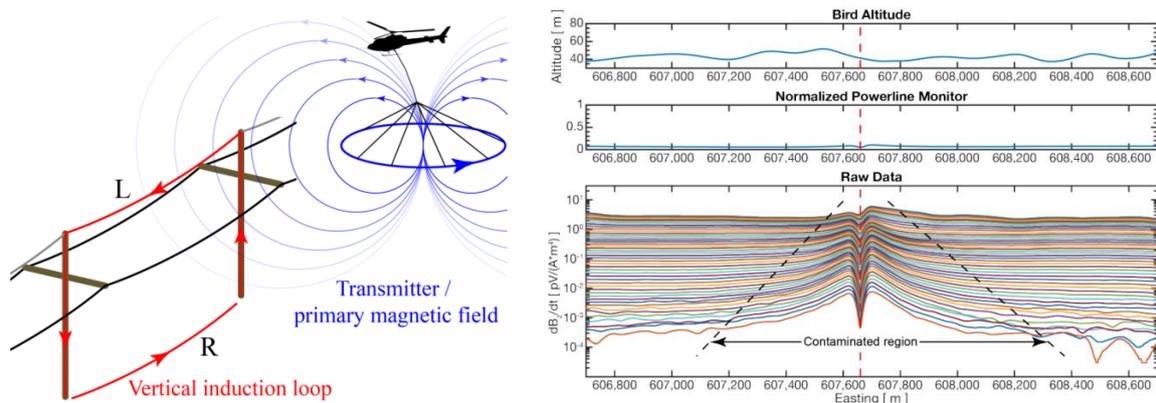


## 3.2 Airborne EM and powerlines

Powerlines are potentially a very serious source of contamination in airborne EM, as shown by the [Lewis Ponds case study \(section 3.2.1\)](#). However, the actual impact is highly variable since it depends on the type of powerline, its earthing system, and the electrical structure of the ground. It is difficult to predict which powerlines will be the most problematic; but, in general, it appears that transmission lines with earthed 'lightning shield sky-wires' are the worst offenders.

Experimental work by Bloss (2017) showed that, contrary to expectation, it is not necessarily just the 50Hz electricity being carried by the powerline that produces the noise, but also the coupling between the EM system and the powerline shield-wire grounding system. Essentially the lightning shield wire and/or neutral (both of which are commonly grounded at each pole) create a vertical induction loop (as shown in Figure 8). The level of response is dependent on the size of this 'vertical induction loop', the soil conductance, and how well the leads were earthed. Thus, for many cases, just 'turning off' the powerline will not remove interference.

Over a large area, regional transmission lines can have a significant effect on the amount of useable data. Figure 9 shows a survey from Idaho, where over 50% of the data needed to be rejected because of powerline interference.



*Figure 8: Schematic (left) showing the vertical powerline-earth induction loop coupling with the HEM's Transmitted fields, and (right) a typical resulting response (from Idaho). It is interesting to note that this effect was observed even with the powerline turned off, i.e., it is inductive coupling with the powerline itself (actually the associated shield or neutral wire to ground loop) which causes the effect, not the fields generated by the 50Hz signal in the powerline. In practice, most powerlines produce a mix of capacitive and inductive coupling.*

Our experience is that while many powerlines will produce characteristic twin peak anomalies (assuming the flight line is roughly perpendicular) (such as in Figure 8), others will produce more capacitive coupling which can be characterised by high amplitude late time oscillations in the data (Figure 17). The region of interference can range from as little as 150m away from the powerline, up to 1000m. On average, we find that around that each powerline produces a roughly 300-600m wide 'gap' in useable data. The effect is generally not proportional to the size of the powerline, as shown in Figure 10.

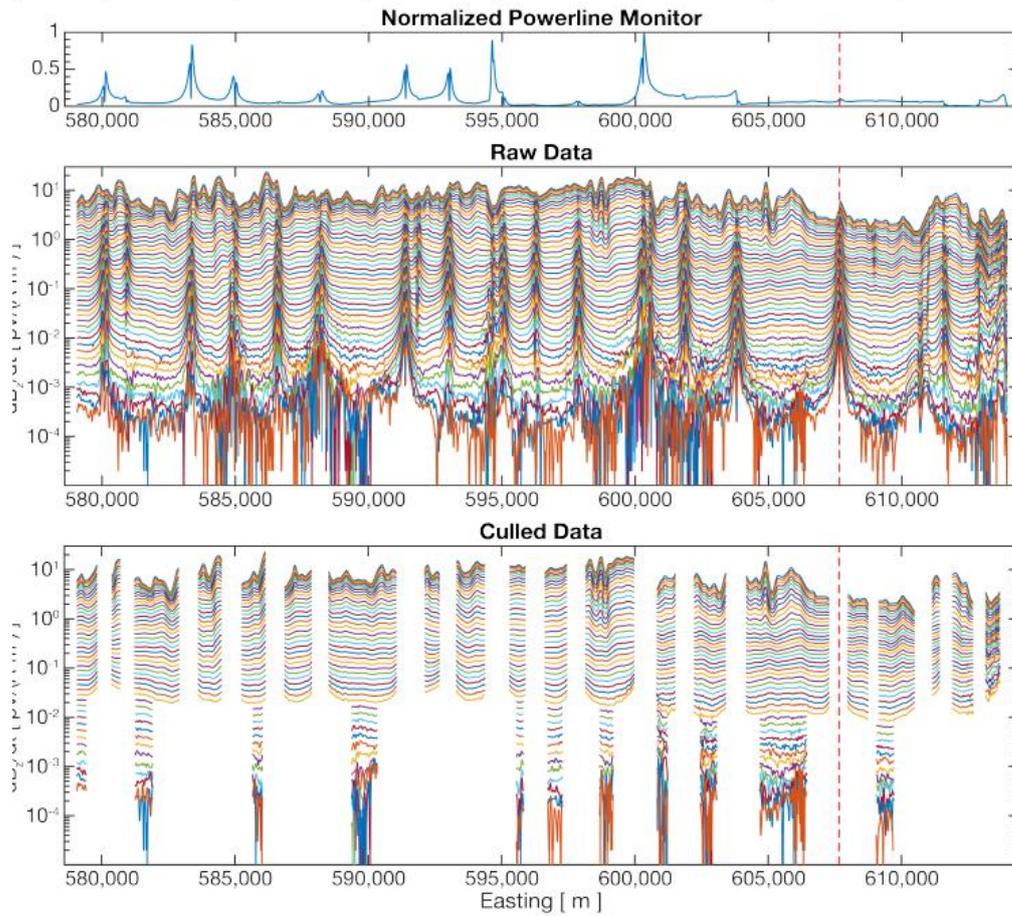


Figure 9: Profile of data from the Idaho survey in Figure 8, pre- and post-editing to remove strong inductive coupling effects associated with the powerlines. Little of the data has been retained, especially at late times.

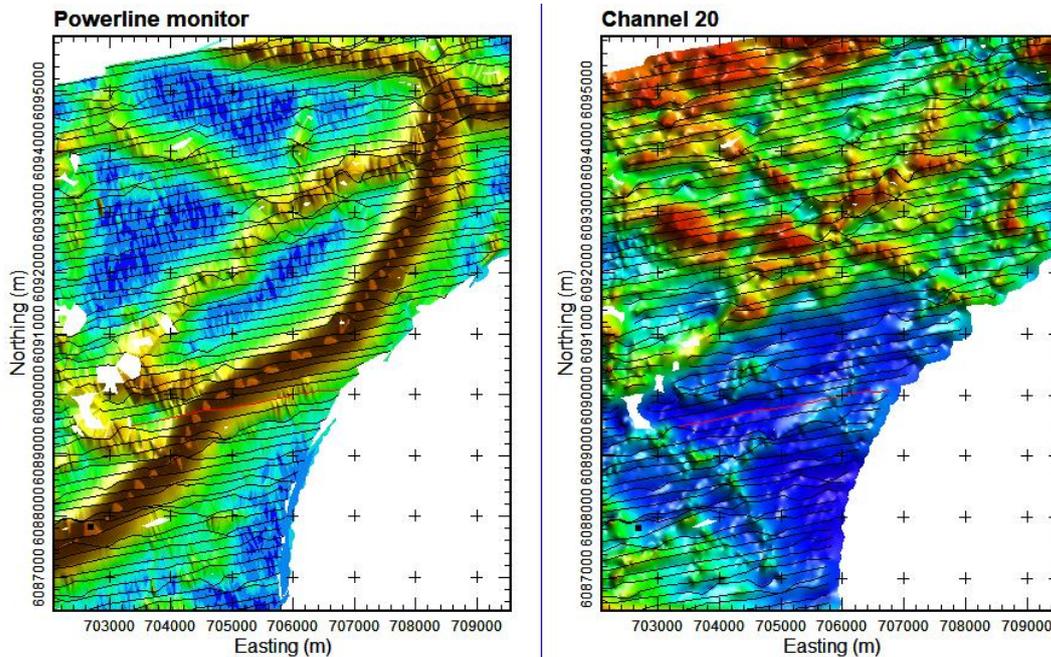


Figure 10: Powerline monitor and channel 20 amplitudes from a SkyTEM survey in Denmark. This shows that the high voltage powerlines do not always produce the largest EM responses. Though 'noise' may be hard to recognise in a single channel grid, such as shown here, a region of noise can be seen associated with most of the powerlines.



### 3.2.1 Case study – Lewis Ponds

Lewis Ponds is a small VHMS deposit in Central NSW. Before Mitre’s involvement, the area was surveyed with VTEM in 2010, which showed many responses, including several extensive zones of pipeline and powerline interference. No mineralisation was intersected in follow up drilling.

Mitre was asked in 2014 to review the existing geophysical data and found that the previous interpreter had missed several EM anomalies in the VTEM, presumably due to noisy data around the transmission lines. These anomalies were typical of large bedrock conductors and, given they are directly along strike from Lewis Ponds, represent excellent exploration targets.

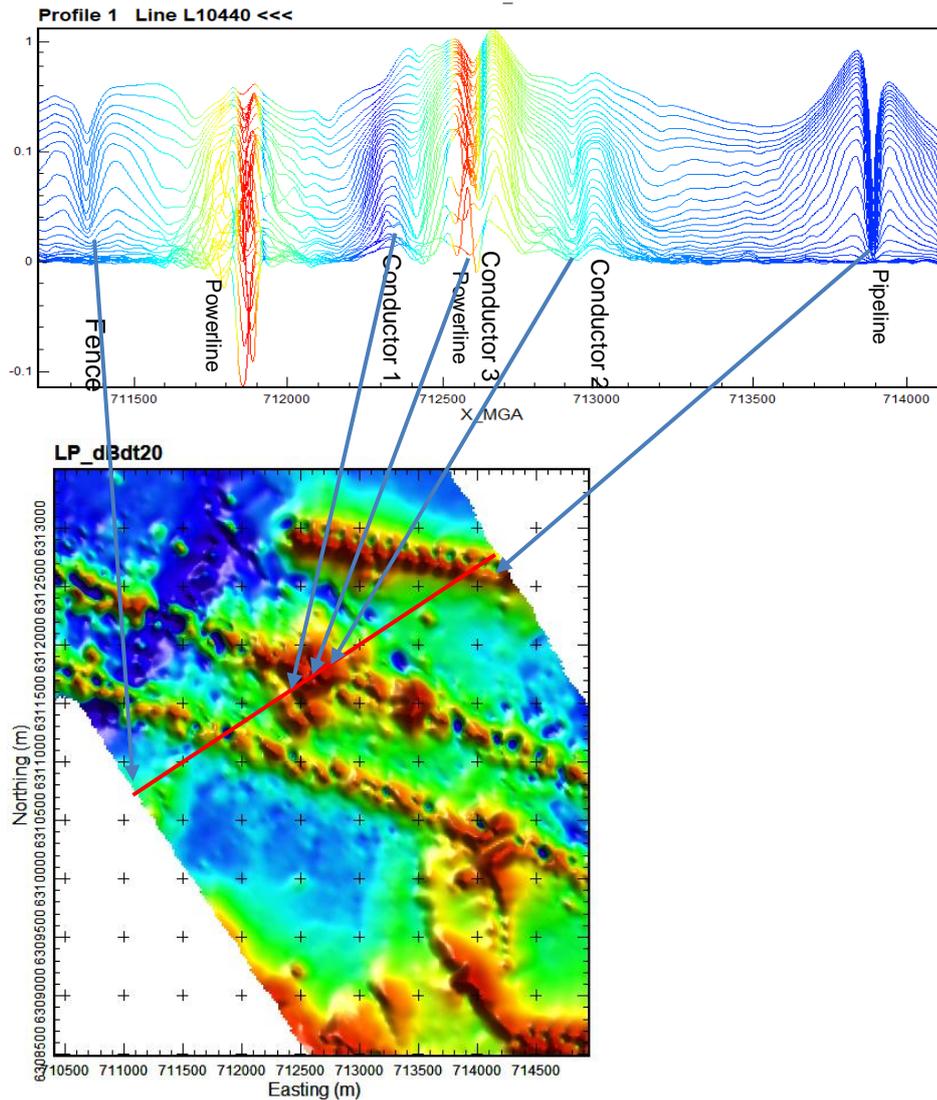


Figure 11: Powerlines can have direct impacts on exploration success. In this example from central NSW, VTEM flight line L10440 crosses two transmission lines but also shows three bedrock conductors: ‘Conductors 1, 2 and 3’. When the survey was first flown, these were not recognised because of the powerline interference. Only when the data were reinterpreted by Mitre 7 years later did it become clear that there were several very interesting conductors requiring follow up.



### 3.3 Ground EM and ground IP and powerlines

Ground IP surveys are routinely conducted beneath powerlines with some success. We, and other authors (e.g. Weiquing and Chen, 2015), have seen robust IP results obtained in even quite challenging conditions, such as beneath an active mine with multiple smelters. However, the effect is difficult to predict: In one survey we conducted in Central America, data from beneath large transmission lines was relatively unaffected whilst data from around the small local single-wire-earth-return power network was effectively useless. In Australia, where SWER are uncommon (except in very remote areas) and the distribution network is (mostly) better managed, IP is more likely to be effective below powerlines.

Ground EM surveys can physically get much closer to a powerline than AEM and, as well as the effects experienced by AEM, ground EM receivers can be saturated by the broadband noise associated with powerlines. The Hellyer deposit in Western Tasmania would not have been discovered if, at the time of the survey, the regional transmission lines above the deposit had been energised (J. Silic, pers. comm., 2019) – see [Section 3.3.1 - Case study Hellyer deposit](#) for more detail.

It is difficult to predict with any accuracy how a particular powerline will affect EM and IP because the exact mechanisms are still poorly understood. As previously mentioned, the observed interference is a combination of current channelling, EM coupling, capacitive coupling, receiver saturation (due to the high amplitude ambient EM fields), natural fields, etc. The exact proportion of these effects and whether they are serious enough to prevent geophysical surveying, seems to vary from region to region and from powerline to powerline. It depends on several factors including the type of geophysical equipment being used, the electrical structure of the ground, whether the powerline has a well-earthed lightning ‘shield’ wire or neutral wire (common in large transmission powerlines), whether it is a single-wire earth-return powerline, the proximity of local step-down transformers at service supply points and the orientation of the geophysical survey lines with respect to the powerline(s).

Figure 12 shows the effect of a powerline on two different generations of EM surveys on a prospect near Woodlawn, NSW. The 1997 survey produced a response which mimicked that of a large basement conductor. Follow up in 2017 with more modern equipment showed it was in fact due to the powerline. Discussions with EM survey contractors suggest that interference from powerlines may be detected up to 200m from transmission lines.

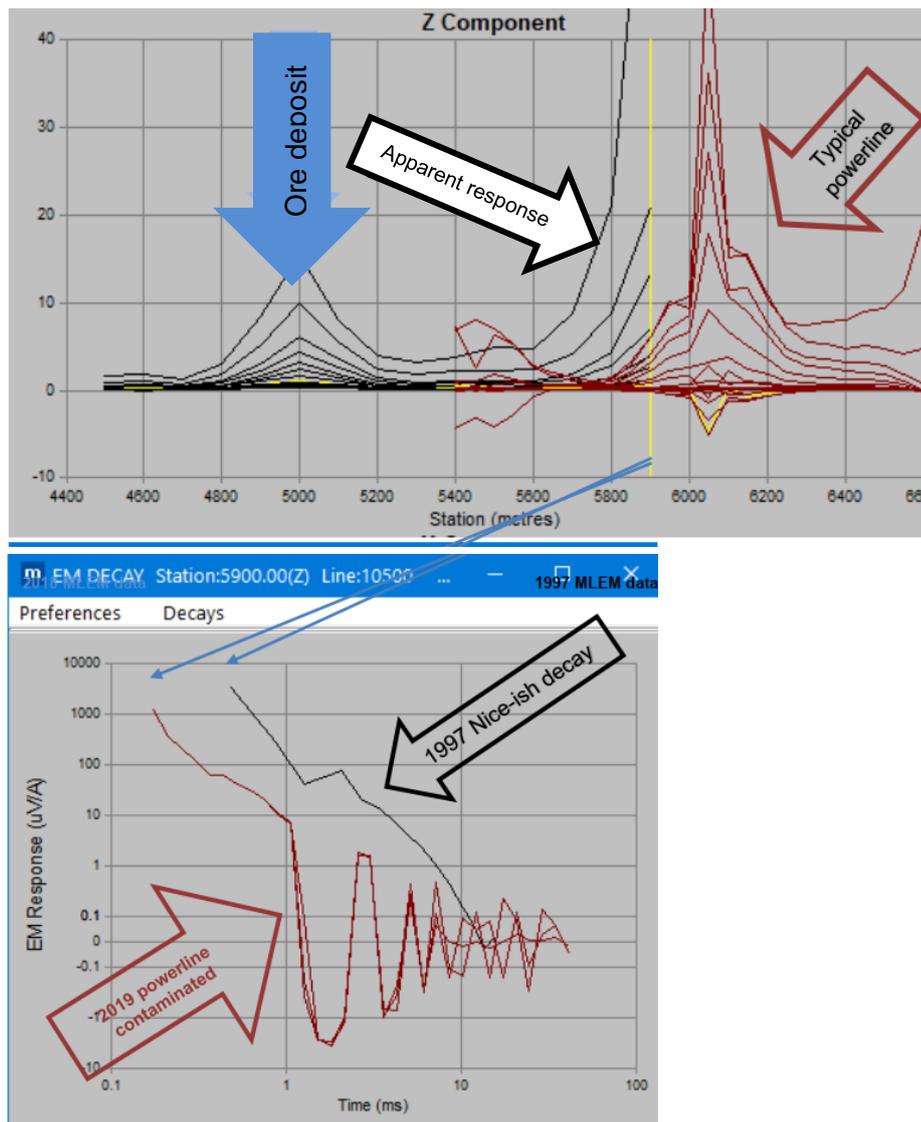


Figure 12: Example of powerlines producing strong responses from a ground EM survey at Woodlawn, NSW. The black ~1997 MLEM showed a possible end-of-line anomaly. Follow up in 2017 with a second MLEM survey showed that this anomaly was probably due to a powerline. Also, if the earlier response was in fact from a small VHMS deposit, the powerline would almost have certainly obscured it.

### 3.3.1 Case study – Hellyer deposit

Following is an abridged case history from Jovan Silic (pers. comm., 2020) regarding the discovery of the Hellyer ore deposit and powerlines.

*“Indeed if the power line was turned on during the survey we would not have detected the Hellyer deposit using the equipment available to us...Prior to the discovery (by an EM survey: Figure 13) a new powerline was installed ... right over the Hellyer deposit...but it **was not energized** until about 3 – 4 months after the identification of Hellyer by the UTEM survey.:*

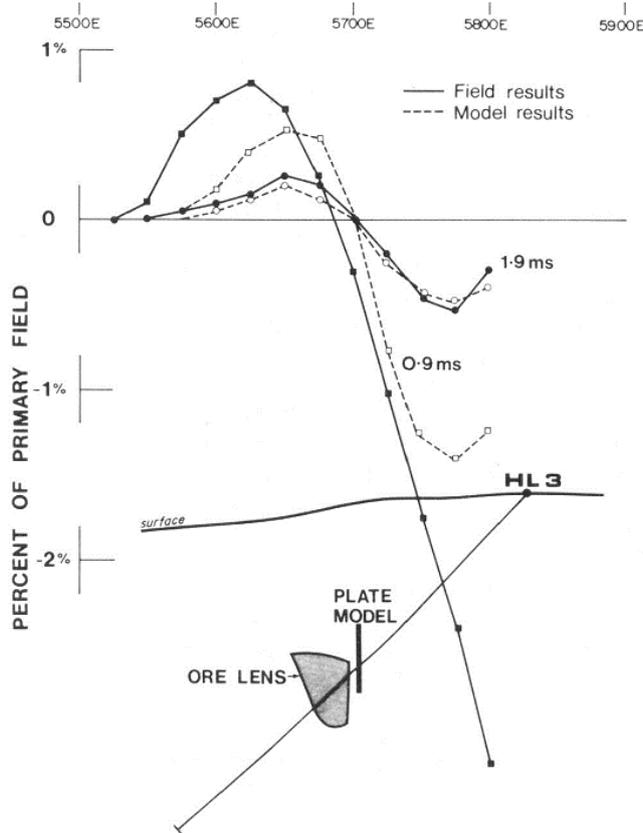


Figure 13: Vertical component, UTEM data on line 10400N, the first line drilled (Eadie et al., 1985)

“I was aware at the time that the location of the (subtle) UTEM anomaly was closely following the new power line but could not explain it as being due to the power line, as it was consistent with a plunging conductive source to the north and not with a shallow source that I would have expected from a powerline. I recall inspecting the powerline to see how it was grounded but could not confirm if the pylons were connected (earthed) through to the ground (author: Subsequent research confirms that it was not grounded which is why it did not produce any EM coupling effects). We concluded that there was no EM response from the powerline.”

.....

“During the UTEM survey, there was another powerline (going towards Waratah?) which was energized. We were unable to collect reliable data within about 200 meters from this powerline due to not being able to filter the large 50 Hz signal accurately. As such, we referred to this as the 200-meter unexplored corridor, and I think that many years later we were considering or indeed did, turn off the power to this older powerline, and resurveyed the area.”

“A number of years later as well, I did a number of experiments with time domain EM and frequency domain EM systems at or close to the powerline over the Hellyer deposit. I was able to confirm that indeed standard TDEM systems at the time just could not collect good enough data close to the power line to identify the deposit. A FDEM system (a Zonge system doing a frequency sweep), although it was quite capable at collecting much better data (due to much better 50 Hz rejection) could not be used, as it was not calibrated well enough at that time for the detection of secondary fields (i.e., estimating and removing the correct primary field), even if we used a very low frequency to estimate the primary field. “



## 4 Results – Wind farms

Wind farms present two specific challenges to geophysical surveying: (1) The potential for poor data quality related to interference from the towers, transmission lines and buried cables, and (2) Safety/access implications. In Section 4.2.1, a case study is presented where the wind farm had a direct and significant impact on mineral exploration. Wind-farms are the most land intensive infrastructure reviewed in this report (Figure 14).

As mentioned previously, this review focuses on a commercial-scale wind farm, with towers spaced at 600-800m (equivalent to Granville Harbour, Tasmania’s newest wind farm at the time of writing). Obviously, a wider tower spacing might have less impact on geophysics for a given area; though, of course, a larger acreage would probably then be involved.

Figure 15 shows a typical wind farm configuration. The towers are each connected by a cable in a ‘daisy chain’ fashion which, in turn, connects to substations and the regional high voltage transmission network. This review focuses only on the wind towers and cables since powerlines were addressed above, and substations are a relatively small (spatial) component.



Figure 14: Commercial wind farm, stock image.

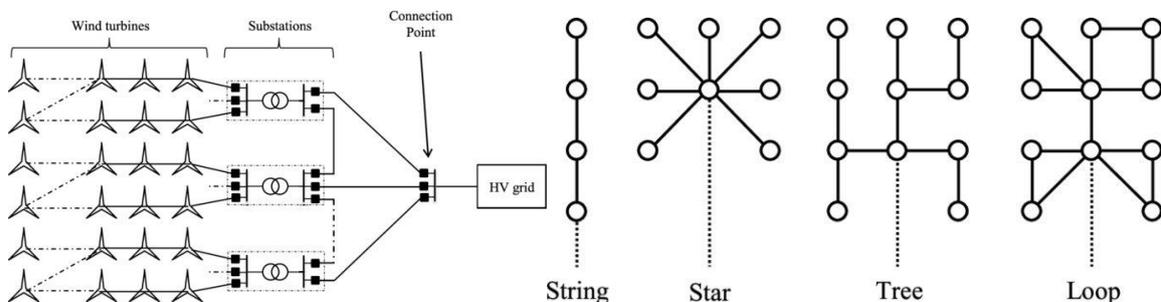


Figure 15: General network configuration and connection topologies of wind towers (Smail et al., 2018)



## 4.1 Airborne electromagnetics and wind farms

**Acquisition:** Wind towers have obvious implications for airborne EM. For an effective survey, the aircraft needs to travel at around the same height above ground as the rotor blades (i.e., 50-100m). Fixed-wing systems (e.g., Tempest, Megatem) simply do not have the manoeuvrability for operations within a wind farm.

Helicopters are more manoeuvrable and, as demonstrated by SkyTEM's in on-going mapping in Denmark and Germany, it is indeed possible to fly between some wind towers (Figures 16 and 17). For a ~450m gap between rotor blade tips (equivalent to a ~600m tower spacing), it should be possible to fly 1 or 2 low level transects using a helicopter-based system on the clear 'avenues' between the wind towers while maintaining a safety margin of ~150-200m from the blades.

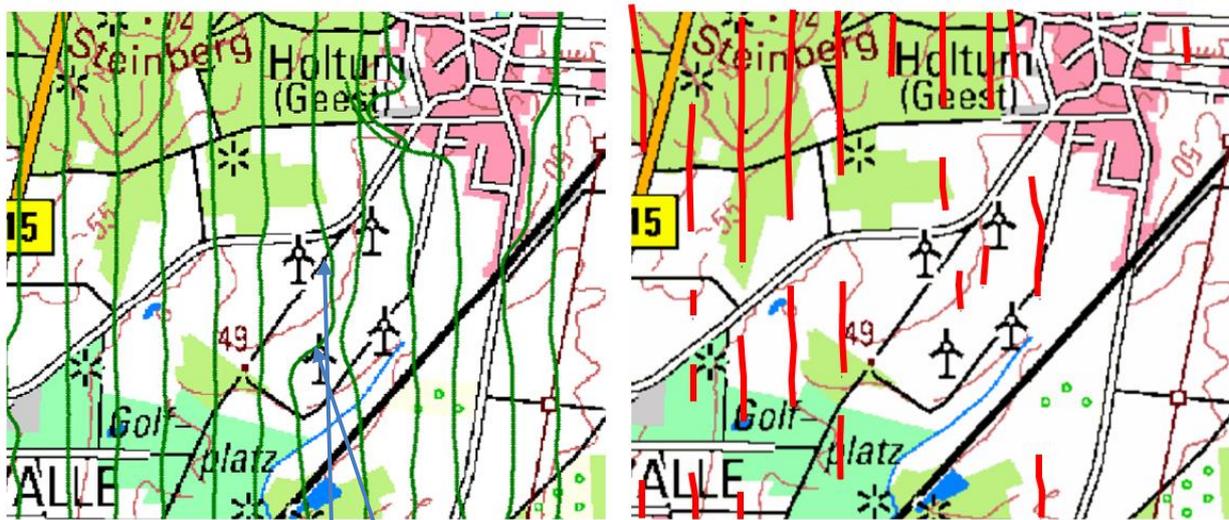


Figure 16: Flight paths (in green left) and retained data (in red right) from a HEM survey in Saxony, Germany. Very little data in the vicinity of the towers was retained.

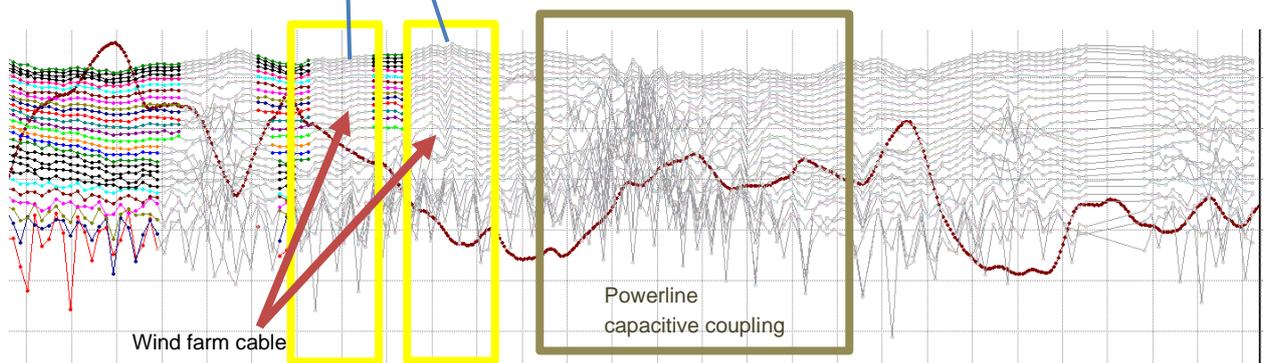


Figure 17: SkyTEM data with the response from two wind farm cables and a powerline labelled. The data in grey is all considered too noisy for modelling, i.e., most of the data is too noisy to be useful. The red line is height above ground.

Safe operation would require several reconnaissance flights and a slower survey speed to maintain manoeuvrability and ensure margins are maintained from turbine blades (70-80km/hr vs. 110-120km/hr for standard helicopter-borne EM), thus significantly increasing the survey cost. Furthermore, helicopter EM surveys are more usually flown at a 100-200m line spacing,



perpendicular to strike (pers. comm, Sam Borg, Chief Pilot United Aero). Post-construction, the wind farm would dictate both the survey line spacing and direction and these would most likely not suit exploration requirements. In most cases a significant number (or majority) of the required survey lines would need to be cut short, deviated, or deleted altogether to maintain appropriate safety margins.

Data quality: The other major impact is data quality. While we could find no examples of an airborne EM survey within the bounds of a large wind farm, surveys around small-scale wind farms (3-6 windmills) with older (smaller) generators are quite common in Germany and Denmark. This allows us to assess the electrical noise related to towers and cables. The example presented above is from the Lower Saxony in Germany (Figure 17), and the data presented below is from Denmark (Figure 18). These show that buried cables between windmills can affect the data at distances of up to 400m from the cable.

In the case from Denmark, the interference appears to be mostly from inductive coupling/currently channelling with the cable connecting the towers\*. Additionally, the interference high voltage powerlines (such as those connecting the wind farm to the electricity grid) can be seen to cause capacitive coupling in other sections of the data.

For the German example (Figure 17), a group of four small wind towers shows responses typical of buried cables, i.e., mostly inductive coupling up to 200m away from the peak, and, further away, responses typical of capacitive coupling from a powerline leading away from the wind farm. The Danish example (Figure 18) shows inductive coupling up to 150m from the cables and towers.

\*Thus turning off the cables/powerlines will not help because the coupling is due to the interaction between the EM transmitter and the powerline/buried cable, not the power flowing in the cables.

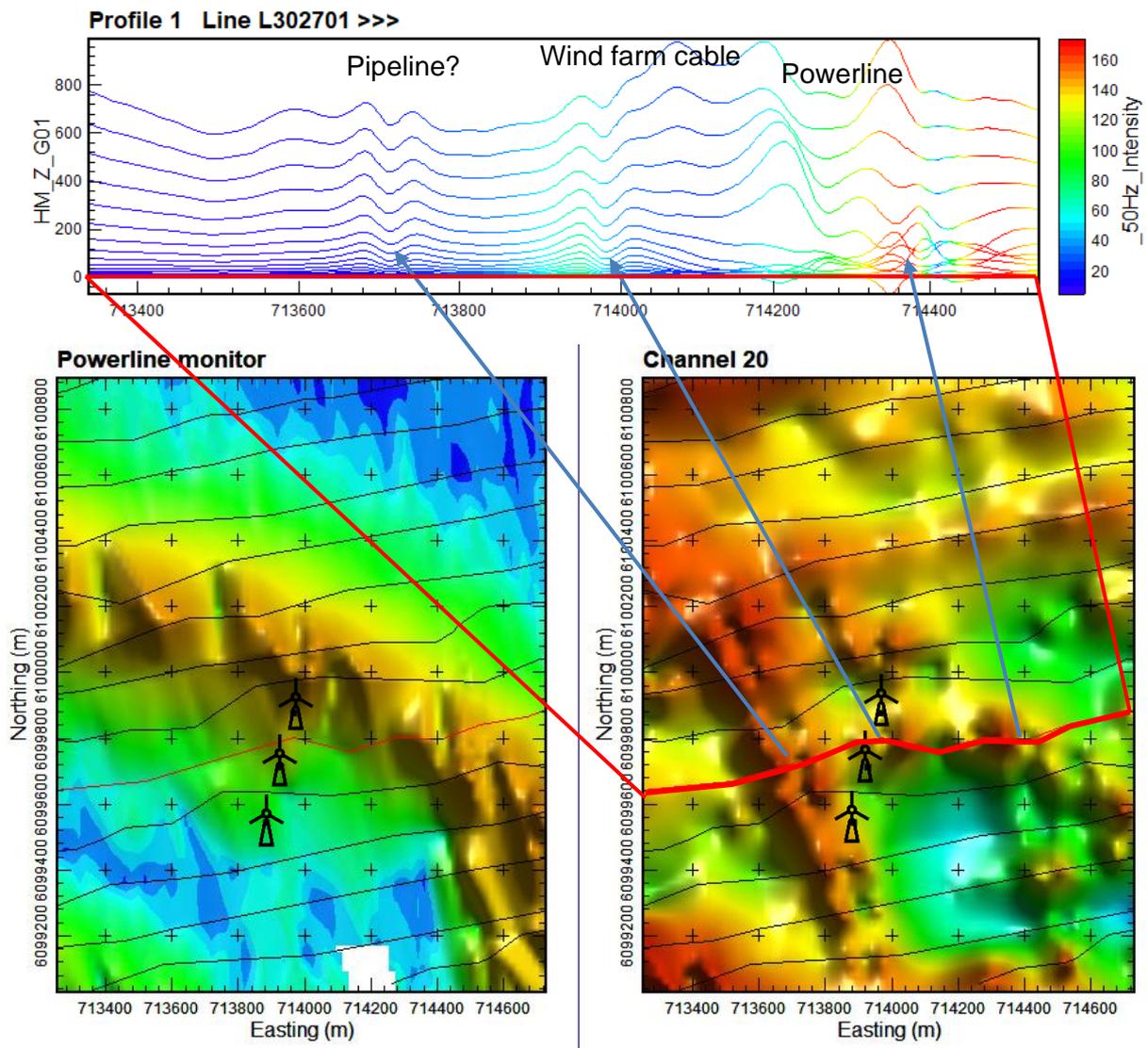


Figure 18: 2013 SkyTEM data from a survey, including a single chain of (small) windmills in Denmark. The effect from the cable connecting the tower can be seen up to 150m distance from the cable. Note: this is a small wind farm with associated small cables. We would expect large cables to have a much larger zone of influence.



## 4.2 IP and DC-Resistivity and wind farms

### 4.2.1 *Case study – Bodangora Wind Farm*

IP surveys within wind farms are exceedingly rare. By good fortune, we were able to view the data from an extensive 3D pole-dipole IP/resistivity survey acquired in 2019 through the Bodangora wind farm (NSW), and compared this with data from a similar survey over the same area, pre- wind farm construction. This example is particularly relevant because it is this *pre-wind farm* IP survey that led to Alkane Ltd.'s discovery of the significant new Boda porphyry gold-copper deposit in 2019. The discovery of Boda has led to a vast increase in exploration activity (and exploration success) across on the Lachlan Fold Belt in New South Wales.

On the Boda project, the wind farm had two important impacts. Firstly, it actively prevented ground access for Alkane's drill rig to drill the IP anomaly (as identified in the pre-wind farm IP survey), delaying the exploration programme by some 2 years, then, post-construction, it limits the ability of new IP surveys to delineate similar deposits nearby (pers. comm. 2020, David Meates, exploration manager, Alkane Resources Ltd).

The publicly available portion of the data is presented in Figure 19. The effects of the wind farm are much more apparent in the vertical sections through the data which are currently commercially sensitive and unfortunately cannot be displayed here.

Data quality: *For the IP component of the data*, the underground transmission cables/turbines appear to cause very strong ~400m+ wide chargeability responses which would certainly overwhelm any bedrock anomalies of potential interest in this 'envelope'. It should be noted that we cannot be sure these are not legitimate bedrock responses until they are drilled, but the fact that these anomalies are missing on those sections of the earlier IP confidently suggests it is the cables. These responses were observed even near cables that were not yet connected to turbines, i.e., again, the responses are not related to electricity in the cables, but rather to the cables themselves.

*For the resistivity component of the data only*, responses from the turbines and underground transmission cables are present but not as severe as for the IP. On some lines, there is a clear, moderate strength, narrow, and depth extensive conductive zone coinciding with the cable location (this anomaly was not present in the pre-construction survey, so can be confidently ascribed to the cable), but on other lines, the cable produces only a small, localised anomaly. Professor James Macnae (pers. comm.) reported a similar result, with only minimal effects on a resistivity survey through a wind farm. If the main source of the noise in IP surveys is indeed inductive and capacitive coupling, then this would explain why the DC-resistivity is not severely affected. It is worthwhile noting that large AC 'noise' from the electricity in the cables would also not be seen in a DC resistivity survey.

Acquisition: IP and Resistivity surveys, being ground-based, should not be hampered by the wind farm infrastructure and indeed the extra roads should facilitate access. However, in this particular example, the Bodangora wind farm prevented ground access for Alkane's drill rigs for about 2 years and may conceivably limit access for ground geophysics crews.

The balance of evidence is that the wind farm cables and foundations would create localised responses in resistivity data (but that it should be possible to discriminate these from basement features), and very strong, deleterious responses in the IP data. For IP, with a single wind farm



cable, such strong responses might be separated in favour of those not spatially associated with the cable, but for a large scale, a grid-style wind farm with numerous regularly spaced towers and cables at ~600-800m intervals, the chargeability data would almost certainly be effectively useless.

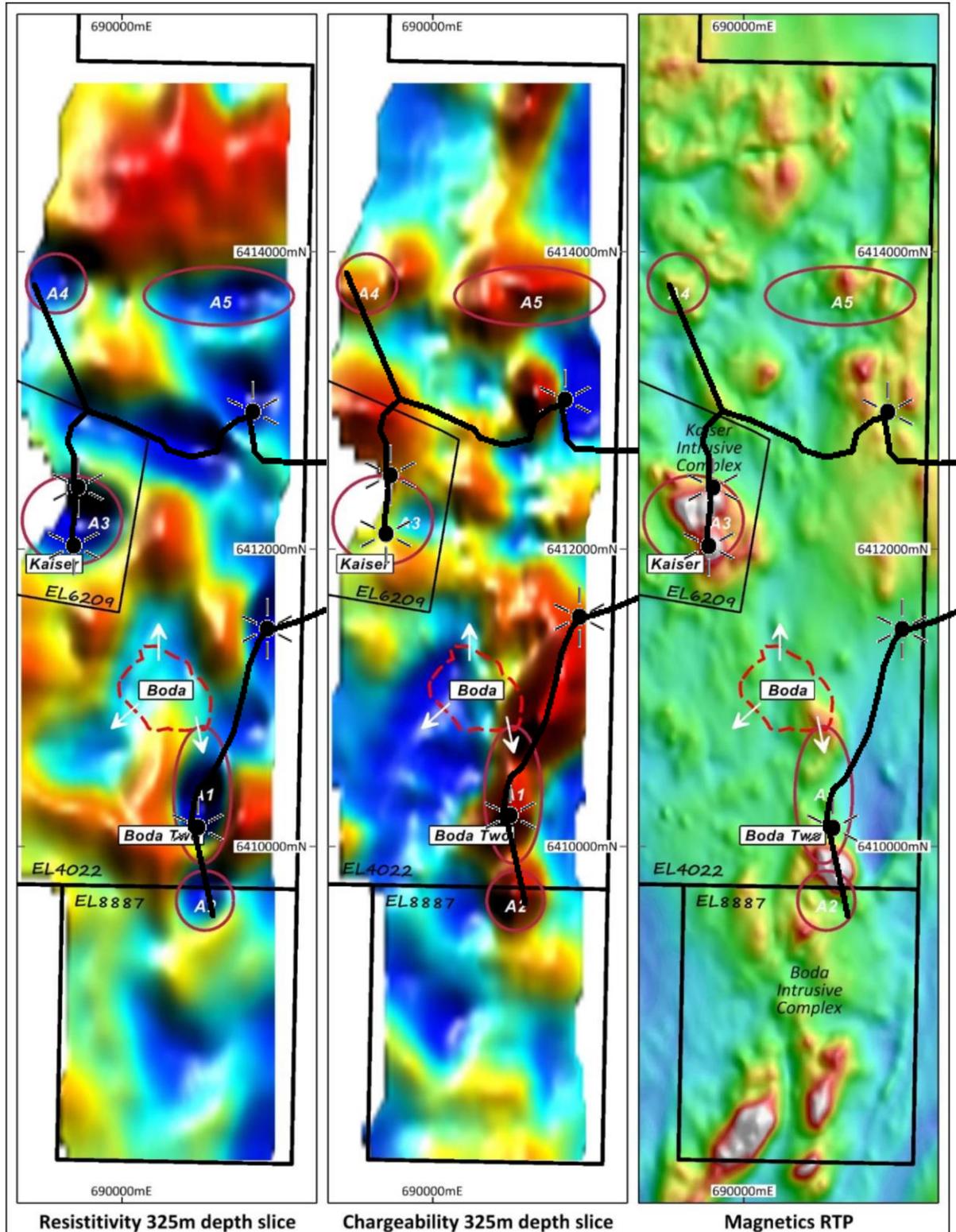


Figure 19: Resistivity and chargeability (at 325m) depth slices from the post-wind farm Bodangora IP survey, with buried cables and wind towers superimposed. Plus pre-wind farm aeromagnetics. There is a strong spatial association of cables with chargeability responses and, to a lesser extent, resistivity anomalies (Earner, N., 2020)



**Mitigation:** The cause of the interference is probably inductive and capacitive coupling; therefore, it cannot be avoided by just 'turning off the network'. None of the alternatives listed below are considered 'good' options:

- Ensuring ground access for exploration is maintained post-construction.
- A distributed array of IP receivers away from cables (using isolated dipoles not connected to each other) may be effective for large-scale, deep, reconnaissance surveys and should avoid the capacitive coupling issues
- A pre-construction sterilisation IP survey would be effective, but expensive if covering all a planned large-scale wind farm.

### 4.3 Ground electromagnetics and wind farms

**Data quality:** Ground EM also suffers from inductive and capacitive coupling but to a lesser extent than airborne EM because the signal to noise ratio is higher and the transmitter loop geometry can often be modified to minimise coupling from problematic cables.

The lack of actual ground EM data through a wind farm makes a definitive conclusion impossible. We have seen data over buried cables with minimal interference and, conversely, data so severely affected the results are meaningless. On balance, we consider that the cables most probably would produce significant interference since they also produce significant interference in airborne EM and ground IP.

Figure 20 is an example of severe interference from a buried cable in-ground fixed loop EM data from Currawang, near Woodlawn, NSW. The source of the interference was eventually attributed to a buried copper-core Telstra cable on the western margin of the transmitter loop. The normal smooth exponential EM decays were overwhelmed by a high amplitude oscillation which, initially, could not be identified. Tests showed the noise was not due to ambient external signals (such as 50Hz noise from a powerline); rather, the signal was only present when the transmitter loop was operating. In addition, the level of interference depended on the proximity of the transmitter loop to a buried copper Telstra cable. This led to the conclusion that capacitive coupling between the transmitter loop and buried cable was the source of the noise. This type of problem is quite intractable.

**Acquisition:** The practical aspects of carrying out a ground EM survey would not be significantly affected by the wind farm infrastructure and the improved road access would probably assist survey procedure (in the unlikely event that one was commissioned).

**Mitigation:** The obvious first step would be to fly a regional airborne EM survey before construction of a proposed wind farm. While AEM is not a direct replacement for ground EM, it does have a large overlap in the 0-300m depth interval for moderate to good conductors, and it can be effective for highlighting areas that need the ground to follow up.

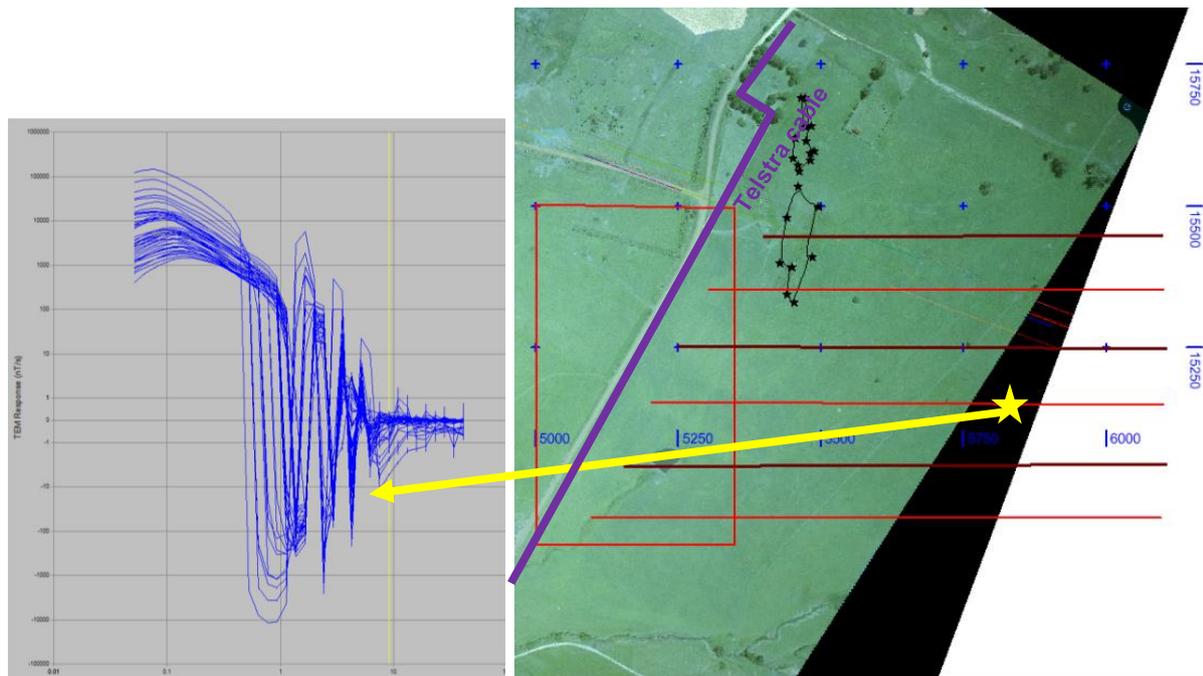


Figure 20: EM sounding from a fixed loop EM survey over a buried (copper core) Telstra cable showing very strong interference. No noise was evident when the EM transmitter was turned off and the observed 'ringing' is attributed to capacitive and/or inductive effects between the EM transmitter and receiver and buried Telstra cable and possibly other cables and powerlines.

#### 4.4 Downhole EM and wind farms

**Data quality:** The data quality in DHEM is usually several orders of magnitude better than surface and airborne EM because a) the receiver is in a nice quiet environment, b) sample density is often much higher and, c) the receiver is much closer to the target conductor while simultaneously being further away from surface interference. We suggest that, if the transmitter loops can be located away from the transmission cables, DHEM would be possible. Certainly, a DHEM survey near the same problematic cable at Currawang showed that moving the transmitter loop away from the cable improved data quality such that useable data was obtained.

**Acquisition:** The practical aspects of a DHEM survey would not be significantly affected by the wind farm infrastructure.

#### 4.5 Magnetics/radiometrics and wind farms

Magnetic surveys map the presence of magnetic material in the ground. Line spacing for fixed-wing and helicopter surveys is generally between 50m and 200m for mineral exploration, with ground clearances of 30-50m. Ground and drone surveys cover smaller areas and use line spacings of 5-25m with ground clearances of 1-10m. Currently, the majority of Tasmania is covered with either 200m or 400m line spaced data. Radiometric data is typically also collected on aeromagnetic surveys but not ground or drone surveys.

**Acquisition:** Helicopter surveys and fixed-wing surveys would not be practical over a grid pattern of wind towers because aircraft are required to be at least 250m clear of the turbines. For fixed wings, ~ 2km laterally is required to gain the required 250m clearance, and for



helicopters ~ 500m. The extra height would act as a low pass filter, reducing the responses from shallower magnetic material.

Ground and small drone surveys would be practical: the operator or drone would simply divert to avoid the wind tower by at least 50m (A. Rada, pers. comm. 2020). However, it may be necessary to ‘turn off’ cables since currents flowing could cause a very strong magnetic response.

**Data quality:** As demonstrated by a 2015 high resolution (50m line spacing, Figure 21) aeromagnetic survey in NSW, typical wind turbines are responsible for a circa 200m diameter disturbance in the magnetic field. This means that, if a high-resolution ground/drone survey is conducted, we could expect >200m wide zones of poor/no data associated with the wind towers. Note that for this survey, the aircraft increased its elevation to approximately 500m above ground level for a ~4km wide zone to ensure it passed safely above the wind towers.

**Mitigation:** A detailed aeromagnetic survey on 50m line spacing before wind farm development. Data from modern aeromagnetic surveys do not go ‘out of date’ because the main limitation on data quality now is the flight height, not technology. A 50m line spacing is the best possible sampling resolution for an airborne survey (because ~50m is the flight height) and any interesting areas could be filled in with high-resolution ground magnetics. This would be sufficient for exploration needs and allow areas which need lower altitude/higher resolution to be subsequently covered with ground magnetics.

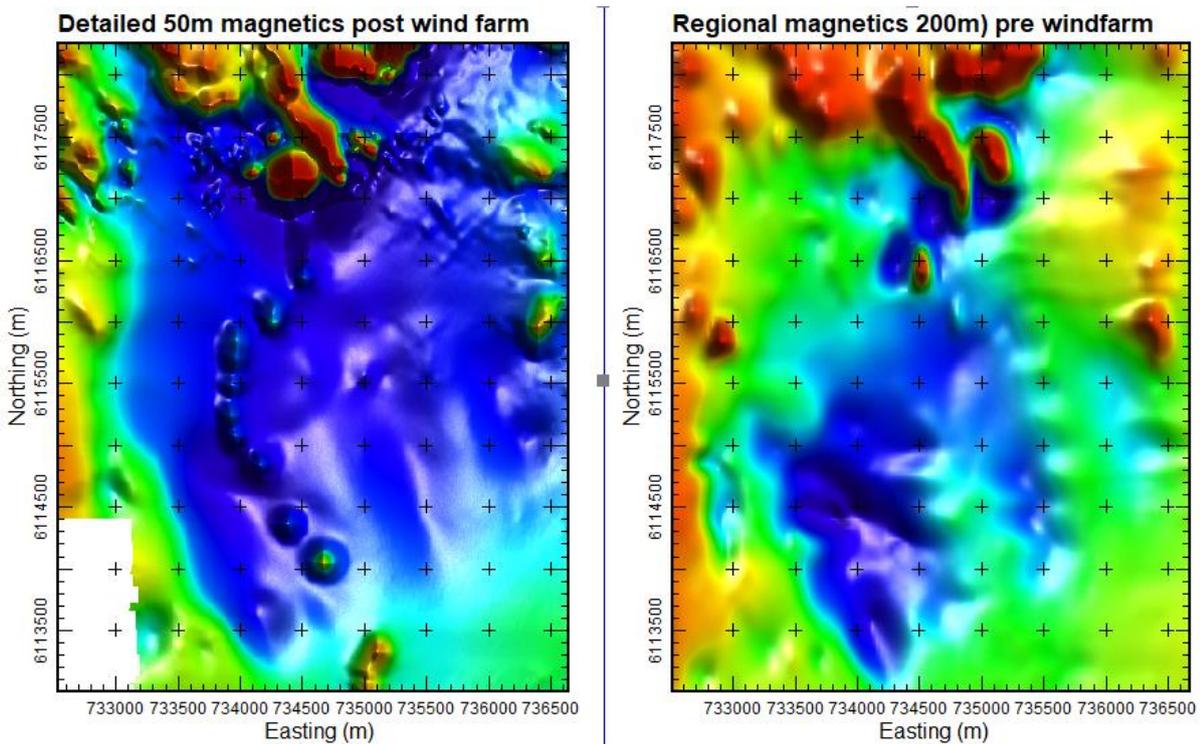


Figure 21: Post and pre- wind farm aeromagnetic data. The typical wind tower in a central NSW project produces a ~200m diameter, 50nT response. Ground magnetic surveys would be possible post-construction in areas at least 100m away from the towers.

## 4.6 Gravity and wind farms

**Data quality:** We have no direct evidence about the effect of wind farms on gravity surveys. Leon Mathews, Director of Atlas Geophysics with 20 years’ experience in gravity acquisition



and processing, indicated that he considered it exceedingly unlikely that the wind turbine would have any significant effect. He cited two examples. 1. A large ground survey around the edges of an active wind farm showed no observable effect on the gravity reading standard deviation and 2. Modern heli-supported ground surveys routinely record gravity readings only 15m away from the helicopter, blades still spinning, and still show excellent ( $<0.01\text{mGAL}$ ) repeatability. Modern gravity meters, unlike older spring-based systems, are much less susceptible to low-frequency noise sources.

**Acquisition:** The practical aspects of a ground gravity survey would not be affected by a wind farm and may, in fact, be significantly improved by better access along new roads.

**Mitigation:** To confirm L. Mathews' hypothesis, we suggest a trial near an operating wind farm to confirm ground gravity surveys would be possible post-construction.

Airborne gravity gradiometry (AGG) would not be possible over a wind farm due to the limitations on height clearance. However, ground gravity is preferable to AGG, except for exceptionally large surveys where an airborne system can be more cost-effective.



## 5 Discussion

Land intensive infrastructure projects have direct implications for geophysical surveys, but, with the exception of Bloss' (2017) work on the effects of powerlines on HEM, very little research has been conducted on the exact nature of the interference. Broadly speaking, the impact of any infrastructure depends on its electrical characteristics, the electrical structure of the ground it covers, and the type of geophysical method employed.

By far the least concerning are pipelines and railway lines since they use comparatively little land, are relatively uncommon and do not impact aerial operations. Nevertheless, a pipeline over a highly prospective piece of land presents a direct threat to future discoveries. The best example of this is from the Northern Leases, near the mining town of Broken Hill, where the main town water supply pipeline/railway sits on top of the same highly prospective trend that also hosts the giant Pb-Zn-Ag Broken Hill mine. The pipeline thus simultaneously solves the town's short-term need for water whilst also potentially limiting its long term economic viability. This pipeline and the adjacent railway have rendered airborne EM and ground IP unreliable within ~300m of both structures.

The Boda example is another case where a mineral discovery has been directly impacted by infrastructure. Boda (a very significant, new porphyry Au-Cu discovery in NSW), has caused a paradigm shift in exploration attitudes in the Lachlan Fold Belt with a new understanding that large, highly valuable, ore deposits are still to be found in this region. It was discovered because of IP surveys (pre wind farm) over geochemical anomalies. Importantly, the wind farm blocked ground access for the drill rig to test the IP anomaly (and thus make the discovery) for 2 years. Then, after Alkane made the discovery, they naturally wanted to repeat and extend the IP to test deeper and wider. The second survey, conducted as the wind farm was being built, shows broad, very high amplitude anomalies spatially associated with the newly buried cables. While we cannot be certain that the cables are causing the anomalies until they have been drill tested, the fact is that many of the responses are not apparent in the pre-wind farm survey.

Unfortunately, we were not able to obtain any examples of ground EM over pipelines, railways, or through wind farms. However, airborne EM is badly affected by buried cables, pipelines and railways (most due to inductive coupling), and we expect a similar type of problem with ground EM.

Sterilisation surveys, similar to that required by mines before plant and other construction, is one option to address the impact of a wind farm on exploration. This would mean a large scale, ground IP survey (since, as yet, there is no airborne version of IP). In the case of EM, the argument could be made that the ability of a first-rate, high power, airborne EM overlaps to a significant extent with ground EM at least in Tasmania, where the ground is resistive with minimal conductive overburden (although ground EM has a better depth of investigation especially for very good conductors and very weak conductors).

Looking into the future, it is clear some types of geophysical equipment will get superseded as new and better technologies arrive. However, for the focus of this report, the rate of technological improvement has slowed since the Western Tasmanian Regional Minerals Program (WTRMP) Hummingbird FEM' surveys were carried out in 2001. Indeed, a VTEM-



Max survey flown in 2019 is only of slightly better quality than a survey flown in 2012. This is partly because of the laws of physics (e.g., the strength of an EM signal still decreases as  $1/(\text{distance}^3)$ ), and partly because the equipment meets physical limitations, such as helicopter lifting power, tree height, towing weight, etc.

We estimate that an airborne EM survey flown with the latest technology now would not be worthwhile re-flying for at least 15 years, maybe significantly longer. Even if superseded, the newer technology would most likely just extend the depth of investigation and not necessarily resolution nearer to the surface. For magnetics, a 50m line-spaced aeromagnetic/radiometric survey would not go 'out of date' and would provide the best possible data for future greenfields exploration.

## 6 Conclusions and recommendations

Pipelines and railway lines invariably produce strong unwanted responses in electrical geophysical surveys (airborne EM, ground EM, and IP) which are, essentially, unavoidable. Potential fields methods (magnetics and gravity) are much less affected.

Wind turbines and the associated transmission cables within and around the wind farm produce very strong artefacts in ground IP and airborne EM and prevent the low-level flying required for high-resolution results. For a commercial-scale wind farm, with towers spaced at 600-800m, ground IP, airborne EM, possibly some types of ground EM, and aeromagnetics would all be severely limited post-construction.

Note that in each of these examples, it is the presence of the wind farm infrastructure itself, not the just electricity being carried, which causes the problem. Thus 'turning off' the wind farm would not be a solution.

The impact of powerlines is harder to predict. Some powerlines affect EM data at distance up to 1000m away, while for others, it may be a tenth this distance. Magnetics/radiometrics and gravity are usually not affected by powerlines, except with respect to flight height. Ground EM surveys are frequently not possible within ~200m, and the impact on ground IP is too variable to predict, but can be significant.

Some forms of geophysics, such as DC resistivity, DHMMR, gravity, and (with careful loop placement) DHEM, may still be possible. Ground-based magnetics may also still be possible if a suitable buffer between the wind tower foundations/buried cables/electrical substations is maintained.

We could identify no ready way to lessen the effect of these types of man-made infrastructure on the main exploration methods. Therefore, we suggest that either pre-construction sterilisation surveys, or careful planning to place the project away from prospective areas, be considered.



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