Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP): Victoria

Data Release Report

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Executive Summary

The Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP): Victoria component magnetotelluric survey was a collaborative project between the Geological Survey of Victoria and Geoscience Australia. Geoscience Australia managed the project and implemented data acquisition, data processing, and data QA/QC. Long period magnetotelluric data were acquired at 100 sites on a half degree grid spacing across the state of Victoria in the south-east of Australia between January and September 2014. Some sites were repeated between December 2017 and January 2018. The newly acquired data were processed in February 2018.

This Geoscience Australia record is published to assist users of the AusLAMP Victoria data in understanding the lineage of the data and subsequent products such as data inversions and data integration. In this record, the field acquisition, data QA/QC, and data processing methodologies are discussed. A separate report will provide information on data analysis, data modelling/inversion, and data interpretation.

Complications arose with the data quality data from a small number of sites using ANSIR/AuScope instruments, however, repeat measurements of these sites has resolved data quality issues.
1 Introduction and Background

1.1 Introduction

The Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP) is a collaborative, multi-year project between the Australian Federal and State Governments, and research organisations. This project will acquire long period magnetotelluric (MT) data at approximately 3000 sites across the Australian continent at a nominal 0.5 x 0.5° (~55 km) station spacing (Figure 1). The national scale MT survey aims to map the electrical resistivity of the continent in three dimensions. The project will provide significant additional information about Australia’s geodynamic framework as well as valuable pre-competitive data for resource exploration. Significant progress has been made under Geoscience Australia’s $100.5 million Exploring for the Future Program.

AusLAMP–Victoria Project is a collaborative project between Geoscience Australia and the Geological Survey of Victoria. The project aims to improve understanding of the lithospheric structure and address some fundamental questions such as how the current geological structure was established, the nature of the geological processes, and how large-scale crustal and lithospheric structures control mineral deposition and hydrocarbon basin formation in the region.

Figure 1: The AusLAMP MT Project status at December 2017. The sites marked by red points – completed sites, black points – planned sites for Exploring for the Future Program, green points – data acquisition in progress, Yellow points - other planned sites.
1.2 Geological background

Victoria is an Australian state, situated at the southern end of the Great Dividing Range, which stretches along the east coast of the continent. The geological history is dominated by east-west compression of predominantly oceanic sedimentary and igneous rocks and their resultant folding, faulting and uplift. The major north-south tectonic movements have also been involved in constructing eastern Australia (VandenBerg, 2000). The state has a rich resource including base metals, oil, and coal. Central and western Victoria hosts world-class gold deposits.

The State's geology can be structurally divided into the Delamerian fold belt, the Lachlan fold belt, and ten structural zones: Glenelg zone, Grampians-Stavely zone, Stawell zone, Bendigo zone, Melbourne zone, Tabberabbera zone, Omeo zone, Deddick zone, Kuark zone, Mallacoota zone (Figure 2). The geology of Victoria is described in detail by Birch (2003) and is summarised here.

The Delamerian fold belt and the Lachlan fold belt show important differences. The Delamerian Fold Belt is mainly composed of Neoproterozoic-Cambrian rocks and was deformed in the Late Cambrian Delamerian Orogeny. It occurred 500 million years ago. The Lachlan Fold Belt is part of the Tasman Fold Belt System in eastern Australia. It contains mainly Cambrian-Devonian rocks with the main deformations occurring in the late Ordovician to early Carboniferous interval. Blocks of older crust consisting of Neoproterozoic-Cambrian rocks, such as the Selwyn Block in central Victoria, were deformed during the late Cambrian Tyennan Orogeny prior to being incorporated into the Lachlan Fold Belt. Granites are age range of 440 to 350 million years in the Lachlan Fold Belt (Birch 2003). Volcanics associated with the granites are also widespread in central and southwestern Victoria, where there are numerous volcanoes and volcanic lakes.

Some of the largest faults separate rocks with different ages and structural histories. The Moyston Fault between Grampians-Stavely zone and Stawell zone is the most important North-South striking fault as it forms the terrane boundary between the Delamerian and Lachlan fold belts.
1.3 Description of the MT method

The MT method is a passive electromagnetic geophysical technique that utilises natural variations of the Earth’s magnetic and electric fields to investigate the electrical resistivity distribution of the subsurface from depths of tens of meters to hundreds of kilometres. The MT source fields are generated by world-wide thunderstorm activity (mainly lightning discharges at frequencies above 1 Hz) and the interactions between the solar wind and the Earth’s magnetic field in the magnetosphere and ionosphere (at frequencies less than 1 Hz). These sources provide a rich spectrum of electromagnetic fields, which are suitable for crust and upper mantle studies. A detailed description of the MT method, including mathematical derivation, can be found in Chave and Jones (2012), Simpson and Bahr (2005), Vozoff (1972; 1991) and other references in the literature.

Under the plane wave source assumption, the horizontal electric field \((E_x, E_y)\) in mV/km and magnetic field \((B_x, B_y)\) in nT have a frequency-dependent linear relationship via a tensors \((M)\) following the notation of Weaver et al (2000):

\[
E_x = M_{xx}B_x + M_{xy}B_y
\]

\[
E_y = M_{yx}B_x + M_{yy}B_y
\]

The M tensors are in units of mV/km.nT. The relation to impedance tensors in ohms is
\[ Z = \mu_0 M = \mu_0 \frac{E}{B} \]  

(3)

where \( \mu_0 \) is the permeability of free space.

The apparent resistivity \( \rho_a(\omega) \) provides a ball-park estimate of the Earth’s electric properties. It has the units of ohm-metres (\( \Omega \text{m} \)), which is related to the amplitude of the impedance tensor

\[
\rho_a(\omega) = \frac{1}{\omega \mu_0} |Z(\omega)|^2 = \frac{1}{\omega \mu_0} \left| \frac{E}{B} \right|^2
\]

(4)

Where \( \omega = 2\pi f \) is the angular frequency of the fields.

This formulation is based on the quasi-static approximation for the impedance and assumes the magnetic permeability of the Earth is approximately the same as the permeability of free space, \( \mu_0 \). It is possible to estimate the electrical resistivity of a medium, if perpendicular components of the electric and magnetic fields are known within a medium. For a half-space model, the Earth’s true resistivity is equal to the apparent resistivity.

Phase is the difference between the electric and magnetic fields, which can be obtained from impedance. Express as phase angle \( \phi \) in degrees

\[
\phi = \tan^{-1} \left( \frac{\text{Im} Z(\omega)}{\text{Re} Z(\omega)} \right)
\]

(5)

The electric field always leads the magnetic field. If electrical property variations are 1D there is a phase difference of 45°. In many situations, phases exceeding 45° correspond to geoelectric structures in which resistivity decreases with depth and phases of less than 45° correspond to resistivity increasing with depth.

The vertical magnetic field transfer functions (VTFs) give the linear relationship between induced vertical magnetic component \( B_z \) and horizontal components \( B_x \) and \( B_y \) of the source field in the frequency domain (Simpson and Bahr, 2005). The induction vectors in Parkinson convention point towards conductive bodies or away from resistive bodies. The length of the arrow is determined both by the magnitude of the anomaly and its distance from the sounding site, with range increasing for longer periods.

\[
B_z = T_x B_x + T_y B_y
\]

(6)

VTFs are often represented as complex induction vectors (or induction arrows)

\[
T_z = T_x \hat{x} + T_y \hat{y}
\]

(7)

Where \( \hat{x} \) and \( \hat{y} \) are the unit vectors in the geographic north and east direction respectively.

The MT method has been well established and widely used for mineral, petroleum, geothermal exploration, and crust and mantle lithospheric studies. One advantage of the method is that it allows great depths of investigation that it is useful for understanding geological structures and tectonic evolution. The penetration of an electromagnetic field into a medium depends on the medium’s electrical conductivity and the frequency of the variations in the electromagnetic field. Lower frequencies penetrate more deeply and greater sub-surface conductivity reduces penetration at a given frequency. Achieving signal penetration to great depths requires recording data for long periods of time. The electrical properties at different depths can be estimated approximately by measured electric and magnetic fields at a given frequency.
2 Data Acquisition

2.1 Survey planning and land access

Initial site location planning was conducted by Geoscience Australia for all AusLAMP sites on 0.5° x
0.5° latitude-longitude grid spacing. Each nominal site location was then examined for site suitability
prior to each field deployment campaign. An area of 100 x 100 m with flat ground is preferred to set up
the electrode array. The location should avoid potential fire risk and water inundation in the area. Sites
also need to be distant from potential sources of electrical noise as far as practicable, such as high
voltage power lines, gas pipelines, main roads, railway track, electric fences, water pumps, human
and animal activity, large trees, and heavily forested areas.

In some instances, sites as planned from a GIS analysis and satellite imagery analysis could not be
accessed due to weather, conflicts with farming activities, or other conditions. Where this was the
case, the field crew made adjustments to the site location on an ad hoc basis.

Even though the MT survey is considered to be a low impact activity with minimum ground
disturbance, there were still significant effort involved to gain land access permission. Sites that were
within Victoria National Parks were acquired under a scientific research permit, and sites located in
State Forests were acquired under a permit from Department of Environment and Primary Industries.
Sites located in Crown Lands were conducted through permission of the Crown Leaseholders. Finally,
sites located in private land were done under permission of each of the private landholders.

All of the landholders, both private and government, are thanked for their support in acquiring these
data.

Prior to survey commencement, Hazard Identification and Risk Assessments were conducted.
Standard Operating Procedures or the Health Safety Environment field manual were reviewed as
outcomes of these assessments.

2.2 Instrumentation

Two different MT instruments were used for acquiring AusLAMP-Victoria data. In the initial data
acquisition campaign, 20 sets of ANSIR/AuScope MT equipment were used for data acquisition. The
instrumentation included a high dynamic-range Earth Data Logger PR-6, a three component
Bartington fluxgate magnetometer, three non-polarising Pb/PbCl₂ electrodes with cables, a deep cycle
12V battery, and a 60W solar panel (Figure 3 and Figure 4). Inbuilt GPS provided the accurate timing
required for synchronisation between simultaneously acquired sites, as well as for the determination of
the site location, and precise time-stamping of the observed magnetic and electric field
measurements. Precise timing is critical for use of the remote referencing technique to reduce the
effect of local coherent noise in the measured fields by estimation of the cross-powers spectra
between the electric and magnetic fields at the sounding site and a remote reference site (Gamble et
al., 1979).
Figure 3: A typical ANSIR/AuScope MT data acquisition system. The weatherproof plastic case contains a data logger, a deep cycle 12V battery, an electric line junction unit, and a solar charge system.

Figure 4: Fluxgate magnetometer of ANSIR/AuScope instrument setup in the ground.

A total of 18 sets of LEMI-424 instrument from Geoscience Australia were used to acquire data at repeated sites for AusLAMP-Victoria. The LEMI-424 data acquisition unit consists of a data logger, the electrode line junction unit, four electrodes (Cu-CuSO4 solution) with cables, earth lightning protection unit, and a LEMI-039 three component fluxgate magnetometer (Figure 5). The instrument is housed in
a weatherproof plastic case and is powered using a deep cycle 12 V battery charged by a 60W solar panel.

The 24 bit resolution data logger can record 5 channels, with in-built GPS module, simultaneously. The three component fluxgate magnetometer was fully sealed by silicon compound for waterproofing and protection against dust and moisture. The magnetometer gives a measurement range in total magnetic field of ±70000 nT. For each component, the magnetometer can measure the frequency band DC-0.5 Hz with low noise and small temperature drift. It also includes automated offset compensation band along each magnetic component. A thermometer has been built inside the housing of magnetometer to monitor the temperature. This information provides the possibility to correct magnetometer thermal drift.

The LEMI-701 non-polarised electrode is environmentally friendly, low noise and has small temperature drift. It is made of porous ceramic contact with Cu-CuSO4 solution. Matched pairs of electrodes have achieved experimentally low drift of 50-60 microvolts over four months.

2.3 Data acquisition

Long-period MT data were acquired for AusLAMP-Victoria at two different periods (Figure 6). Initially, data from 98 sites were acquired using ANSIR/AuScope instruments across Victoria in the period from January 2014 to September 2014.
In total, 24 out of 98 MT initial sites had poor quality data due to instrumentation. These sites could not be repeated at that time because instruments had been redeployed elsewhere.

Geoscience Australia purchased LEMI-424 MT long-period instruments in 2016. These instruments enabled Geoscience Australia to make significant progress on AusLAMP programs such as, Exploring for the Future Program and AusLAMP-NSW. These instruments also provided the opportunity to repeat some sites for AusLAMP-Victoria. Data from 18 repeated sites were acquired using LEMI-424 MT long-period instruments between December 2017 and January 2018.

In the initial data acquisition campaign, 20 sets of ANSIR/AuScope MT equipment were used for data acquisition. At each long-period MT site, magnetic data were acquired using a fluxgate magnetometer in three orthogonal directions (north-south, east-west and one vertical). The electrical field data were acquired with the electrical field oriented the magnetically north-south and east-west directions. Two orthogonal electric field components were measured through 50 m dipoles with non-polarising Pb/PbCl₂ electrodes, which were set up as an ‘L’ shape layout. Data were recorded as time series for approximately four weeks at a sampling rate of 10 Hz. The long recording time ensured that the instruments captured longer period data to image the base of the lithosphere. Multiple sites were deployed at a time to enable remote-referencing.

In December 2017, 18 sets of LEMI-424 instruments had been released from the AusLAMP Exploring for the Future Program. MT field crew took the opportunity to conduct a field campaign in Victoria just...
prior to Christmas 2017. Eighteen (18) repeated sites for AusLAMP-Victoria were acquired using the LEMI-424 long period data acquisition units. These sites were chosen based on data quality from the initial acquisition, proximity to regions of geophysical interest, and ability to organise land access permission within the given timeframe. Data were recorded as five channels of time series for approximately one month at a sampling rate of 1 Hz.

At each long-period MT site, magnetic field data were acquired using a three-component (two horizontal and one vertical) LEMI fluxgate magnetometer (Figure 7). The magnetometer was buried at a depth of ~60 cm in holes for thermal and vibration stabilisation. Burying also reduced the noise from environment.

Two orthogonal horizontal electric field components were also measured through two 100 m dipoles with non-polarising copper/copper sulphate electrodes (Figure 8). Cross-electrode layout was used for electrical field measurement. Electrical channel E1 of the acquisition unit was oriented magnetically north-south, with positive connected to the northern electrode and negative connected to the southern electrode. Channel E2 of the acquisition unit was oriented magnetically east-west. E2 positive was connected to the eastern electrode and E2 negative connected to the western electrode. Electrodes were ~50 m from the centre of the array. The total dipole length of ~100 m was used for each electric channel.
The installation of electrodes is very important for long term measurement. Selecting similar ground condition is critical to achieve good quality data; for example, choosing locations with similar soil composition and moisture conditions. LEMI-701 electrodes were buried in holes that were generally greater than 50 cm deep, and were oriented at an angle into moist mud at the base of the holes to avoid gathering oxygen inside the electrodes which may increase contact resistance and prevent good electrical contact (Figure 9). This installation method also prevents thermal variations and secures the electrode against unintended excavation. Electrode contact resistances were checked using a digital multimeter. The contact resistance measurement was used to isolate electrode problems and to ensure good electrical contact. DC and AC voltage across the dipoles were also checked during site set up to ensure low level noise of environmental. These measurements were also checked upon site retrieval to examine how ground contact had changed during the deployment and to provide indications of any equipment issues that may have occurred during the deployment.

Achieving good measurements of electric field can be difficult due to wildlife and cultural noise. Time series data were checked for data QA/QC purpose during instrument installation. This step was to ensure that there has been adequate variation in the geomagnetic and electric fields. Data sometimes needed to be re-acquired due to wildlife disturbance, defective electrodes, or other unforeseen disturbances.
For some sites, different deployment methods were used. For example, one site was located in a densely forested area; it was deployed using two batteries in parallel as a solar panel may not receive enough sunlight to adequately charge a battery. Some temporary fences around the data acquisition units were built with star pickets and fencing wire to avoid instrument damage from cattle (Figure 10).

*Figure 10: Craig Wintle from Geoscience Australia sets up a temporary fence around the data acquisition unit.*
3 Data Processing

3.1 Data processing

Time series data were plotted out for visualisation and inspection (Figure 11). Pre-processing of the time-series data is a manual selection process to remove contaminated data, such as spikes, outliers or obvious disturbances. Bad segments of data were removed prior data processing. The battery voltage, power consumption and temperature records were also analysed during data processing.

In general, despite some spikes of artificial origin there were good quality data for most sites. There is a high correlation between the corresponded telluric and magnetic field variations, although the amplitudes of the telluric fields vary significantly between different sites.

Figure 11: Simultaneous time series of the magnetic and electric field components at a site for 34 days. It also shows temperature of the system and battery voltage for the recording period.
The Ap-index across each acquisition period was also plotted and inspected (Figure 12). This is a measure of the daily average level of geomagnetic activity. Higher values should correlate with higher signal-noise ratios across the acquired sites. Tracking the index can assist in windowing sections of time series with strong signal.

![Ap-index: Nov 2017 - Jan 2018](image)

*Figure 12: Plot of Ap-Index for the data acquisition in November 2017 - January 2018.*

MT data processing fundamentally involves a Fourier transformation of the electric and magnetic field time-series data into the frequency domain for deriving the complex impedance tensor of the subsurface. The impedance tensor links the horizontal components of electric and magnetic fields in the frequency domain and contains the Earth’s resistivity information beneath the measurement point. The apparent resistivity and phase as a function of frequency are derived from the impedance tensor.

The time series data from the initial acquisition were processed by using the BIRRP robust processing algorithm of Chave et al (1987, 1989, and 2004) with remote referenced data (Gamble et al., 1979). Another method (Egbert et al., 1986 and 1997) was also tested to obtain the best possible estimates of the transfer functions. The BIRRP method uses robust statistics to remove non-Gaussian data outliers and errors. Coherence analysis of the electric field and the magnetic field were carried out for assessing data quality during the processing stage.

The time series data from repeated sites were processed using the Lemigraph software (Korepanov, 2014). To ensure the most stable spectral estimates, large artificial spikes were removed from the raw time series before processing. The robust algorithm with remote reference was applied to all sites. A tolerance for coherence pre-sorting was applied for the data processing. Pre-whitening was also applied to increase spectral stability.

The reference sites were chosen out of the other sites acquiring during a given acquisition block. Appropriate reference sites were picked based on the following criteria:

- Low noise (particularly on magnetic channels);
• Acquisition period encompasses or is close in length to the primary site to ensure maximum intersecting time series is used;

• Greater than 100 km from the primary site to reduce the chances of coherent noise being present in both time series.

Instrument layout errors were corrected during data processing where possible. Apparent resistivity and phase were determined for each site. These data were then rotated to true north using the declination for the site location from the Australian Geomagnetic Reference Field. The final apparent resistivity and phase values were stored in EDI format, which is the industry standard format for processed MT data as defined by the Society of Exploration Geophysicists.

3.2 Data quality control

In general, data quality from the survey is good for most sites. The processed data provide good quality impedances and vertical magnetic transfer functions at period range of 10 s – 10,000 s for most sites. However, some data are of poor quality due to instrument issues and anthropogenic noise. Especially high cultural noise is present in central Victoria. Some of the MT stations suffered from strong coherent noise in the electrical channels. This noise could not be simply removed by the standard remote referencing data processing scheme.

Data quality varies for the acquired 100 sites (including repeated sites), which can be summarised as below:

- 74 sites with periods between 10 s to 10000 s
- 22 sites with periods between 10 s to 3000 s
- 4 sites are not released due to poor data quality

Several techniques were used to recognise errors and to ensure good data quality. These approaches help to decide whether the data are of high quality or need to be reacquired.

Apparent resistivity and phase (Figure 13) were plotted as a function of period to visually inspect data quality, data error, layout error of instrument, and instrument issues. Rho+ estimates was also used to estimate data quality for instrument layout error and inconsistencies between apparent resistivity and phase.

Other parameters such as the tipper magnitude, tipper phase, and standard deviation were also extracted from the data for quality control.
Power spectra densities (PSD) and coherency between channels were displayed for analysing data quality and characteristics during data processing. Coherency plots from the processed results are shown in Figure 14 and Figure 15. Coherency plots and PSD can also be generated prior to full processing to assist in QC of time series (Figure 16 and Figure 17). PSD plots allow for inspection of signal consistency across channels and can highlight frequencies contaminated by external noise. A minimum coherence value 0.7 was used as threshold for data processing and assessing data quality. Values below 0.7 are generally indicative of poor quality data. Low coherencies are typically observed around 10 s where the signal is poor due to the natural dead-band.
Figure 14: Example coherence plot from processed result of site VIC098

Figure 15: Example coherence plot from processed result of site VIC099
Figure 16: Example coherency and PSD plot for channels from site VIC016R (selected time series window)

Figure 17: Example coherency and PSD plot for channels from site VIC051R (selected time series window)
4 Conclusions

Long-period MT data were acquired at 100 sites for AusLAMP-Victoria by Geoscience Australia in 2014 and 2017. Two different MT instruments were used for acquiring the data. In the initial data acquisition campaign, 20 sets of ANSIR/AuScope MT equipment were used for data acquisition. 18 sets of LEMI-424 long-period instruments from Geoscience Australia were used for acquiring data at repeated sites. Three component magnetic field and two component electric field time series data were recorded for approximately one month at each station.

Reliable transfer function and impedance tensor data were derived from the time series data by applying difference processing algorithms. Several techniques of data quality control were used to recognise errors and to ensure good data quality.

Data quality for this survey is good for most sites, with 74 sites providing data in the period range of 10 s to 10,000 s and 22 sites providing data in the range of 10 s to 3000 s. However, data quality at 4 sites is poor due to instrument issues and anthropogenic noise.
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