ASEG-PESA 2015
Geophysics and Geology together for Discovery
24th International Geophysical Conference and Exhibition
15 – 18 February 2015 Perth, Western Australia

Natural Field Electromagnetics Using a Partially Known Source: Improvements to Signal to Noise Ratios

Lachlan Hennessy
RMIT University School of Applied Science
GPO Box 2476, Melbourne 3001 Vic Australia
S3138162@student.rmit.edu.au

James Macnae
RMIT University School of Applied Science
GPO Box 2476, Melbourne 3001 Vic Australia
James.macnae@rmit.edu.au

SUMMARY

We aim to provide a novel approach to processing and interpretation of natural fields electromagnetic (EM) data through automated interpretation of sferic source parameters provided by the World Wide Lightning Location Network (WWLLN). Accurate sferic time stamps obtained from WWLLN are hypothesised to improve signal to noise ratios (SNR) through precisely controlled extraction of sferics with amplitudes both above and below observed noise levels in time series audio-magnetotelluric (AMT) measurements. Averaging of extracted data of equal source moment increases signal in proportion to the square root of the number of averages whilst decreasing noise since data between sferic events is inconsequential and can be discarded. Knowledge of source characteristics allows further improvements to data quality to be achieved through discrimination of sferic sources that do not meet the required assumptions of AMT. Since sferic propagation occurs primarily along great circle paths, antipodal sferics propagating around the reverse side of the earth can in principle be extracted for inclusion as additional signal. These increases in SNR afford reduced measurement time and an increase in data quality, leading to more cost effective exploration. Use of source information is unique amongst existing approaches to time domain AMT. The existing approaches are often limited in application to signals with amplitudes well above the noise level.

ARMIT sensors developed at RMIT are sensitive to natural EM fields generated by world wide lightning activity and can measure up to 40 sferics per second. We collected AMT data using one such sensor in order to carry out an initial feasibility study on our hypothesis. Preliminary results are encouraging and demonstrate that WWLLN data are accurate and efficient enough to predict useful sferic arrival times. Future efforts will be applied to characterizing waveform similarity and investigating the relationship between stacking techniques and data reliability. This may improve SNR and hence the prediction of subsurface geological structure.

Key words: Electromagnetic, Magnetotelluric, Signal to Noise, Lightning Detection Network, Natural Field, Lightning.

INTRODUCTION

Conventional AMT processing schemes do not make use of source information, and instead use the horizontal magnetic fields as a reference (amplitude and phase) to the horizontal electric fields (Vozoff, 1990). Such schemes average data over long periods of time, often corrupting results due to the significant presence of non-stationary noise. Additionally, conductivity boundaries situated along the propagation path (local and regional) rotate the azimuths of the source field, leading to static shift (Vozoff, 1990), a distortion that is poorly accounted for without source information. Source parameters recorded by the WWLLN can be used to isolate individual sferic signals in AMT data and accurately predict parameters of sferic propagation. Some of the potential advantages to this approach are, 1) improved SNR, 2) elimination of static shift, and 3) better delineation of highly conductive bodies. We have taken the first steps towards a known source natural fields methodology through extracting individual sferics from limited areas and subjecting them to averaging in the time domain.

Sferic propagation in the earth-ionosphere waveguide

Global lightning activity produces broadband electromagnetic fields that propagate throughout the earth-ionosphere waveguide-cavity (EIWG) at extremely low frequencies (ELF, 3 – 3000 Hz) and very low frequencies (VLF, 3 – 30 kHz). Individual lightning discharges radiate transient electromagnetic signals called radio atmospherics (sferics), which are partially reflected by and transmitted through the boundaries of the waveguide. There are a variety of field representations for propagation of ELF and VLF waves in the EIWG for vertical electric dipole sources, of which Wait`s simplified mode theory of VLF propagation (Wait, 1957) is useful for predicting wave guide phenomena up to 25 kHz. At ELF frequencies (3 – 300 Hz) only the quasi-transverse electromagnetic mode (TEM) mode is radiated to large distances (Porrat et al., 2001).

Three main factors govern the attenuation of electromagnetic waves as they propagate in the EIWG, listed in increasing significance 1) spherical expansion/contraction, 2) inverse distance squared fall-off, and 3) waveguide attenuation approximated by,

$$\sin\left(\frac{a}{d}\right) \quad , \quad \frac{1}{d^2} \quad , \quad e^{-\alpha d} \qquad (1)$$

where d is the propagation distance, a is the radius of earth, and α is an attenuation coefficient which varies with frequency, and the resistivity of the ionosphere and earth.

Lightning Location Networks

Over the past 10 years there have been significant improvements to global lightning detection networks (Rodger et al., 2009). The WWLLN measures the time of group arrival of a sferic relative to GPS time and triangulates a source location using a network of over 50 sensors (Dowden et al., 2002). Hutchins et al. (2012) reported WWLLN timing errors to be within 10 microseconds and location accuracies in the order of the wavelength of the radiation (10-15 km). Abarca et al. (2010) reported WWLLN detection efficiencies of 30 to 50% for cloud-to-ground strokes (CG) and intra-cloud strokes (IC) above 40 kA, and 10 to 15% for all global CG strokes. The WWLLN also provide lightning stroke power estimates integrated over a 1 ms waveform (Hutchins et al., 2012).

Audio-Frequency Magnetotellurics

Natural fields electromagnetic data can be used to predict the electrical resistivity structure of the earth through the estimation of a frequency dependent transfer function (impedance tensor);

$$\begin{aligned} E_x &= z_{xx}H_x + z_{xy}H_y \\ E_y &= z_{yx}H_x + z_{yy}H_y \end{aligned} \quad (2)$$

The impedance tensor (Z) describes the relationship between the measured geo-electric (E) field and the geo-magnetic (H) field for an anisotropic and laterally inhomogeneous subsurface resistivity distribution. Conventional AMT processing schemes require long time series and assume Gaussianity and stationarity in signals to derive reliable auto-power and cross-power spectra (Vozoff, 1990). In reality, AMT data are commonly affected by non-stationary noise with signal levels varying as a function of time and frequency. In other words AMT is significantly affected by low signal to noise ratios, particularly in the dead band of 1to 5 kHz (Garcia and Jones, 2002).

Transient AMT processing schemes have been proposed by a number of workers (Spagnolini, 1994, Nowożyński, 2004), however none of these schemes make use of source information, and are therefore compromised by errors introduced by the path dependent variability of the EIWG parameters, and uncharacterized source azimuths. We have carried out initial brute force investigation into the use of source locations for time domain processing of AMT data. We aim to investigate the relationship between restricting processing to sferics exhibiting similarity (linked to propagation path) and errors in estimated transfer function through comparison to conventional processing schemes. A key research question will be whether our approach benefits more from processing in the time domain than in the frequency domain.

Constrained Least Squares Spectral Analysis

Spectral analysis of sferic data was carried out using a constrained least squares inversion (Puryear et al., 2012). This approach solves for the Fourier series coefficients through inversion of a basis of truncated sinusoids for each of a number of time windowed data segments. The one-sided Hilbert transform is applied to these data as a constraint on the inversion to enforce causality and provide stability in the solutions. This method was adopted in order to reduce spectral smoothing compared to conventional Fourier and Wavelet based spectral methods, particularly at low frequencies.

METHOD AND RESULTS

We carried out an AMT survey near Lancefield, Victoria in order to obtain data for testing of our hypothesis. We used an ARMIT sensor to measure three orthogonal components (MGA north, east, and vertical) of the geo-magnetic field (B and dB/dt). We used four porous pot CuS electrodes configured into two horizontal electric dipoles (50 m) to measure the geo-electric field. We developed Matlab code that used WWLLN sferic timing to predict sferic arrival times at the survey location. We extracted 10 ms windows of data around individual sferics (Figure 1). The predicted arrival time is 2.5 ms after the start of the extracted window. Examination of these data confirmed that sferics originating within the local hemisphere generally have higher amplitudes than those with near antipodal origin. The accuracy and consistency of predicted arrival times (t=d/c) verified that sferic propagation occurs primarily along great circle paths. Accurate extraction of sferics was possible due to the small WWLLN timing errors (up to 10 us), which are typically very short relative to both direct propagation times (10 – 130 ms) and typical sferic wave packet widths (1 ms).

Location specific stacking of individual sferics was carried out in an attempt to improve signal to noise ratios to investigate if better observations of distant sferics could be achieved. Before sferic extraction a cluster analysis algorithm was applied to the WWLLN location data to achieve a ranking of highest to lowest density source location clusters. High-density clusters provide the largest number of sferics per unit area, and are therefore optimum locations for a preliminary investigation into improving signal to noise ratios. By specifying a region of interest in which to apply the cluster analysis, we were able to isolate sferic data as a function of source location. Given that source locations have a significant influence on parameters of sferic propagation (attenuation, dispersion, etc), we carried out an initial test on the hypothesis that source locations can be used to improve estimates of earth transfer functions. Future investigations will vary clustering parameters and look at changes in sferic similarity and coherence in the averages.

Figure 2 illustrates the procedure of location-based averaging of sferics originating in Southeast Asia. A total of 1426 individual sferics sourced from the Malacca Straight were extracted from approximately 1 hour of time series AMT data and 150 were averaged to achieve a clear sferic waveform observed well above the noise level. The sferic wave packet began precisely at the target 2.5 ms demonstrating the accuracy off WWLLN, and began to demonstrate dispersion as wavelengths increase and diminish in amplitude towards 3 ms. A CLSSA plot shows a coincident high frequency impulse followed by a trail of lower frequency energy. Significant low frequency energy is observed below the dead band (1-5 kHz). Average sferic profiles were also produced for signals originating in South Africa using the same survey

data. We extracted 119 sferics from these data and averaged 15 to achieve the time series plot shown blue on Figure 3. This average waveform has low amplitudes reflecting greater source-receiver distance and source proximity to the relative equator. The signal level decreased relative to individual sferics, possibly due poor choice of source-cluster thresholds. Again, spectral analysis shows that the majority of useful AMT signal is constrained to frequencies between 5 and 30 kHz. Sferics propagating over near-antipodal distances are significantly attenuated and dispersed by the longer path, day/night and land/ocean boundary losses, and receiver position relative to source with respect to spherical expansion/contraction of the wave front.

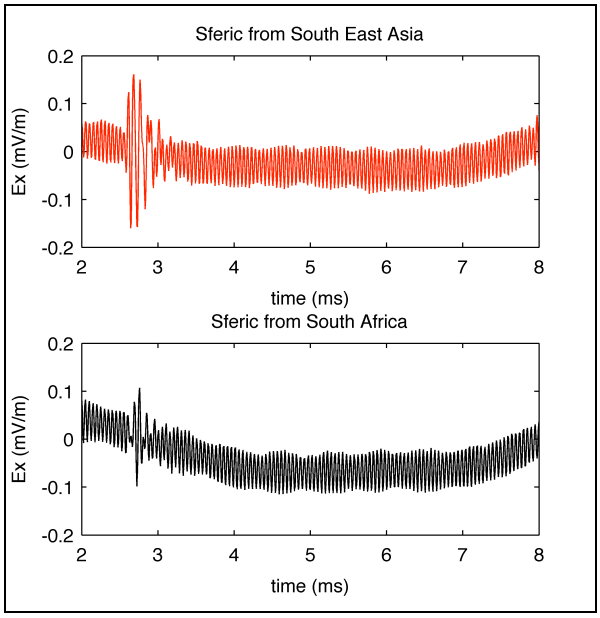

Figure 1: Individual sferics originating from South East Asia (red) and South Africa (black). The North Western Cape source VLF signal is the main contributor to the steady oscillating background.

CONCLUSIONS

We carried out a brute force investigation into novel usage of lightning location data to extract and process sferic anomalies from AMT data. We demonstrated that detailed knowledge of source parameters can be derived from the WWLLN and used to discriminate, extract and process individual sferics. Initial results suggest the value of further efforts towards development of a known source perspective on natural fields electromagnetics. Location based discrimination of data could in principle be used to ensure against corruption of estimated impedance tensors by sferics having rotated azimuths, non-planar wave fronts, or poor SNR. The choice of lightning clusters also allows control of the dominant TE or TM mode coupling with local geology and independent interpretations could in principle be drawn from each mode.

Averaging of individual sferics originating from a single storm cluster in Indonesia best demonstrated the promise of our proposed approach. Results from distant source locations are also encouraging, but further work will be required to improve the signal to noise.

FUTURE DEVELOPMENTS

Our immediate steps will be to investigate similarities between distant sferics, since meaningful estimates of the earth impedance tensor are expected to require coherent signals and high SNR. We also aim to determine deviations between measured and WWLLN derived amplitudes and azimuths and use these to predict subsurface conductivity structures along the propagation path and local to the receiver station. We anticipate that deviations in E and H component azimuths will provide useful information on preventing distortions such as static shift. These are just some of the ways in which we aim to improve AMT processing for better estimation of earth impedance tensors. We will also investigate methods to extract low amplitude Schumann resonances (7-100 Hz).

ACKNOWLEDGMENTS

The authors wish to thank the World Wide Lightning Location Network (http://wwlln.net), a collaboration of over 50 universities and institutions, for providing the lightning location data used in this paper.

REFERENCES

Abarca, S. F., Corbosiero, K. L. & Galarneau, T. J. 2010. An Evaluation Of The Worldwide Lightning Location Network (WWLLN) Using The National Lightning Detection Network (NLDN) As Ground Truth. *Journal Of Geophysical Research: Atmospheres (1984–2012),* 115.

Dowden, R. L., Brundell, J. B. & Rodger, C. J. 2002. Vlf Lightning Location By Time Of Group Arrival (TOGA) At Multiple Sites. *Journal Of Atmospheric And Solar-Terrestrial Physics,* 64**,** 817-830.

Garcia, X. & Jones, A. G. 2002. Atmospheric Sources For Audio-Magnetotelluric (Amt) Sounding. *Geophysics,* 67**,** 448-458.

Hutchins, M. L., Holzworth, R. H., Rodger, C. J. & Brundell, J. B. 2012. Far-Field Power Of Lightning Strokes As Measured By The World Wide Lightning Location Network. *Journal Of Atmospheric And Oceanic Technology,* 29**,** 1102-1110.

Nowożyński, K. 2004. Estimation Of Magnetotelluric Transfer Functions In The Time Domain Over A Wide Frequency Band. *Geophysical Journal International,* 158**,** 32-41.

Porrat, D., Bannister, P. R. & Fraser-Smith, A. C. 2001. Modal Phenomena In The Natural Electromagnetic Spectrum Below 5 Khz. *Radio Science,* 36**,** 499-506.

Puryear, C. I., Portniaguine, O. N., Cobos, C. M. & Castagna, J. P. 2012. Constrained Least-Squares Spectral Analysis: Application To Seismic Data. *Geophysics,* 77**,** V143-V167.

Rodger, C. J., Brundell, J. B., Holzworth, R. H., Lay, E. H., Crosby, N. B., Huang, T. Y. & Rycroft, M. J. Growing Detection Efficiency Of The World Wide Lightning Location Network. Aip Conf. Proc, 2009. 15-20.

Spagnolini, U. 1994. Time-Domain Estimation Of MT Impedance Tensor. *Geophysics,* 59**,** 712-721.

Vozoff, K. 1990. Magnetotellurics: Principles And Practice. *Proceedings Of The Indian Academy Of Sciences-Earth And Planetary Sciences,* 99**,** 441-471.

Wait, J. R. 1957. The Mode Theory Of VLF Ionospheric Propagation For Finite Ground Conductivity. *Proceedings Of The Ire,* 45**,** 760-767.

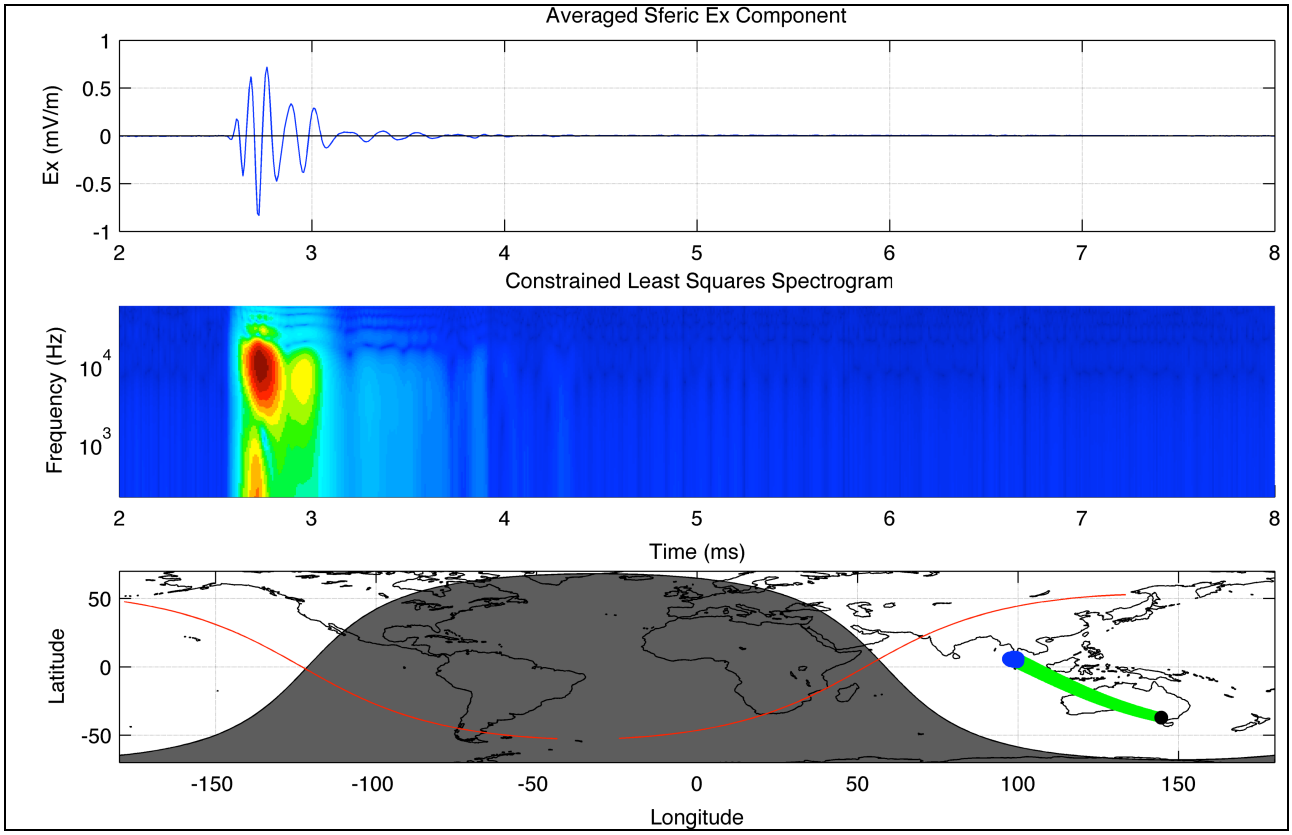

Figure 2. Average of sferics originating in the Malacca Straight. Top panel, Ex component of averaged data (blue). Middle panel, CLSSA spectra. Bottom panel, source and receiver locations (blue and black, respectively), day/night terminator (shaded), and relative equator to the receiver location (red).

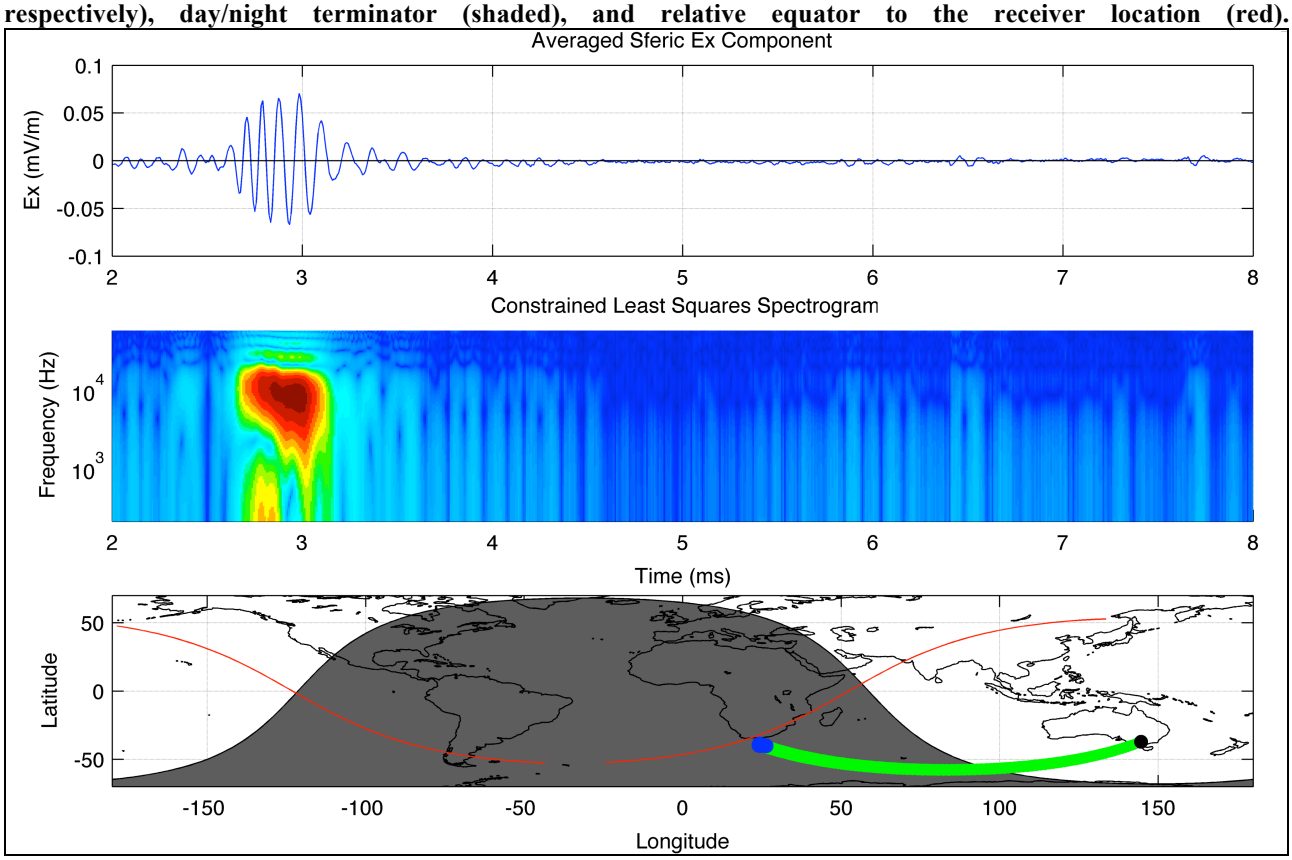

Figure 3: Average of sferics originating in South Africa. Top panel, Ex component of averaged data (blue). Middle panel, CLSSA spectra. Bottom panel, source and receiver locations (blue and black, respectively), day/night terminator (shaded), and relative equator to the receiver location (red).