Improved Responses with Multitaper Spectral Analysis for Magnetotelluric Time Series Data Processing
Examples from Field Data

Comeau, Matthew J.; Rigaud, Rafael; Plett, Johanna; Becken, Michael; Kuvshinov, Alexey

DOI
10.1111/1755-6724.15226

Publication date
2024

Document Version
Final published version

Published in
Acta Geologica Sinica (English Edition)

Acta Geologica Sinica (English Edition), 2024, 98(supp. 1): 14–17

Improved Responses with Multitaper Spectral Analysis for Magnetotelluric Time Series Data Processing: Examples from Field Data

Matthew J. COMEAU[1, *], Rafael RIGAUD[2], Johanna PLETT[3], Michael BECKEN[3] and Alexey KUVSHINOV[2]

[1] *Department of Geoscience & Engineering Delft University of Technology, The Netherlands*
[2] *Institute of Geophysics, ETH, Zürich, Switzerland*
[3] *Institut für Geophysik, Universität Münster, Germany*

Citation: Comeau et al., 2024. Improved Responses with Multitaper Spectral Analysis for Magnetotelluric Time Series Data Processing: Examples from Field Data. Acta Geologica Sinica (English Edition), 98(supp. 1): 14–17.

In order to attain good quality transfer function estimates from magnetotelluric field data (i.e., smooth behavior and small uncertainties across all frequencies), we compare time series data processing with and without a multitaper approach for spectral estimation. There are several common ways to increase the reliability of the Fourier spectral estimation from experimental (noisy) data; for example to subdivide the experimental time series into segments, taper these segments (using single taper), perform the Fourier transform of the individual segments, and average the resulting spectra. To further reduce the bias of spectral estimation, a multitaper approach can be adopted. In this approach, a number of orthogonal taper functions are used to generate independent estimates, from the same time segment, which are subsequently averaged. We apply multitaper spectral analysis to magnetotelluric time series data and we show examples of responses from field data. The results clearly show that this approach improves the transfer function responses, often significantly, particularly at the long periods.

The magnetotelluric method: The magnetotelluric (MT) method is an electromagnetic technique used to image the subsurface electrical resistivity distribution (e.g., Tikhonov, 1950; Cagniard, 1953; Simpson and Bahr, 2005). It uses passive electromagnetic signals that are generated in the atmosphere and ionosphere. At the surface of the Earth, electric and magnetic field variations are measured, comprising the experimental data in the form of corresponding time series. The broad range of periods of the signals gives sensitivity to a range of spatial scales.

Processing of the time series data is required to obtain the (frequency domain) response of the measured signals (specifically, their coherent parts only). The (frequency domain) transfer function between the (horizontal) electric and magnetic fields is the complex-valued impedance tensor, from which the apparent resistivity and impedance phase can be determined. In order to convert the time series into the frequency domain a (discrete) Fourier transform is used. For more details see, for example, Chave and Thomson (2004), and references therein.

Time series processing and the multitaper approach: Theoretically, when obtaining spectral information from a signal by applying the Fourier transform each Fourier coefficient reliably represents the relative phase and amplitude of its corresponding time series. However, this does not hold for experimental (noisy) data of finite length. There are ways to increase the reliability of the Fourier transform for experimental data. These approaches include frequency averaging and window averaging, which can be combined. In these approaches the average over a number of adjacent frequencies is carried out or the average of several smaller segments of the time series is taken. Successive segments can be overlapping, which increases statistical efficiency without significantly effecting the independence of the segments (see Welch, 1967; Welch overlapped section averaging, WOSA). It is common to taper the time series in this way with a single taper. Applying a single taper to window each segment (for example, Hanning, applying the Hann window) reduces bias in the spectral estimation, but at the cost of increased estimate variance (e.g., due to attenuation at the beginning and end of each segment).

A multitaper approach, as introduced in the pioneering work of Thomson (1982), overcomes some of the limitations associated with standard Fourier analysis. It does this by generating multiple independent estimates from the same time segment. Each taper is applied to the signal in a given segment to obtain a windowed signal, from which it is possible to estimate the frequency spectrum. Each taper is (pairwise) orthogonal to all the other tapers. This means the windowed signals are uncorrelated with each other. The final spectrum is computed by averaging all the estimated spectra. This approach can also recover part of the potential lost information caused by the partial attenuation of the signal when applying single tapers. The multitaper approach reduces the variance of the estimates beyond what is possible with a single taper, especially when only a small number of segments are available (however, this comes at the expense of a decrease in frequency resolution,

* Corresponding author. E-mail: m.j.comeau@tudelft.nl

http://www.geojournals.cn/dzxbcn/ch/index.aspx
https://onlinelibrary.wiley.com/journal/17556724

although typically the desired resolution can be predefined). Slepian functions (discrete prolate spheroidal sequences, DPSS; Slepian, 1978, and references therein) are typically chosen for the multiple tapers (Thomson, 1982) as they have been proven to be the optimal windowing functions due to their mutual orthogonality and special spectral concentration properties (see Percival and Walden, 1993). For more information about computational procedures for estimating the magnetotelluric response from time series of electromagnetic field variations see, for example, Egbert and Booker (1986), Chave et al. (1987), Chave and Thomson (1989).

Improvements with the multitaper approach: For time series processing we used a code, written in MATLAB, originally developed by Becken et al. (2014) (see also Harpering, 2018; Käufl et al., 2020). In short, the critical processing steps are cascade decimation of the experimental time series, breaking the time series into segments, windowing the segments with a taper, Fourier transform of the windowed segments, and averaging spectra using estimates from different decimation levels. In MATLAB, the multitaper approach can be employed with the function ‘dpss’; packages also exist in other languages, for example in Python (e.g., Prieto, 2022).

Magnetotelluric time series processing was performed in two manners, with the aim of attaining good quality transfer function estimates (i.e., smooth behavior and small uncertainties across all frequencies). First, transfer functions were estimated using coherency masking, in which only time intervals where the bivariate coherency threshold was high (range of 0.80–1.00) were utilized. This improved the quality of the estimates, as compared to no coherency threshold, specifically at shorter periods (e.g., from 0.01 to 1 s). Second, transfer functions were estimated with a multitaper approach, described above, in which we exploited the four leading Slepian sequences (Fig. 1).

The multitaper approach improves responses, often significantly, particularly at the long periods. Figure 2 shows examples of the results from field data. The apparent resistivity and phase for each element of the

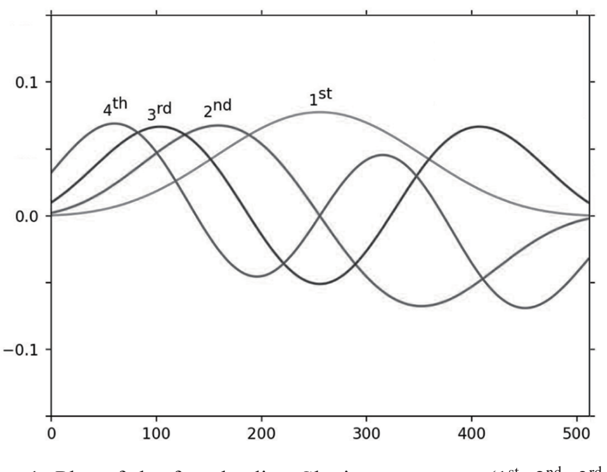

Fig. 1. Plot of the four leading Slepian sequences (1st, 2nd, 3rd, 4th). This was generated with the MATLAB function 'dpss' (for n = 512, window length, and nw = 2.5, half bandwith).

impedance tensor is presented in the top and bottom plots, respectively. The right panel presents responses estimated without the multitaper approach, and the left panel presents responses estimated with the multitaper approach (to make computations faster, we typically do not use all the high-frequency data for this approach, but rather can merge results later).

Most major differences are observed at the long periods, where there is a lack of time sequences, or at periods where the number of samples has been reduced due to the applied coherency threshold. Such differences could have significant effects for magnetotelluric data modeling and interpretation.

Key words: magnetotellurics, electrical resistivity, time series, processing, Fourier analysis, multitaper

Acknowledgments: We thank all those who provided project support and who helped collect field data. We thank our colleagues from the Institute of Astronomy and Geophysics at the Mongolian Academy of Sciences.

References

Becken, M., Schmalzl, J., Bömer, B., and Ueding, S., 2014. Development of a E-field data logger and of time series processing tools in Matlab. In: Abstracts for the 22nd Electromagnetic Induction Workshop (EMIW), Weimar, Germany, 24–30 August 2014.

Cagniard, L., 1953. Basic theory of the magneto-telluric method of geophysical prospecting, Geophysics, 18(3): 605–635.

Chave, A.D., Thomson, D.J., and Ander, M.E. 1987. On the robust estimation of power spectra, coherences, and transfer functions. Journal of Geophysical Research, 92(B1): 633–648.

Chave, A.D., and Thomson, D.J., 1989. Some comments on magnetotelluric response function estimation. Journal of Geophysical Research, 94(B10): 14215–14225.

Chave, A.D., and Thomson, D.J., 2004. Bounded influence magnetotelluric response function estimation. Geophysical Journal International, 157(3): 988–1006.

Egbert, G.D., and Booker, J.R., 1986. Robust estimation of geomagnetic transfer functions. Geophysical Journal of the Royal Astronomical Society, 87(1): 173–194.

Harpering, D., 2018. Robust processing scheme for magnetotelluric data, MSc dissertation; University of Münster.

Käufl, J.S., Grayver, A.V., Comeau, M.J., Kuvshinov, A.V., Becken, M., Kamm, J., Batmagnai, E., and Demberel, S., 2020. Magnetotelluric multiscale 3-D inversion reveals crustal and upper mantle structure beneath the Hangai and Gobi-Altai region in Mongolia. Geophysical Journal International, 221 (2): 1002–1028.

Percival, D.B., and Walden, A.T., 1993. Spectral Analysis for Physical Applications, Cambridge U. Press.

Prieto, G.A., 2022. The Multitaper Spectrum Analysis Package in Python. Seismological Research Letters, 93(3): 1922–1929.

Rigaud, R., Comeau, M.J., Becken, M., Kuvshinov, A.V., Tserendug, S., Batmagnai, E., and Demberel, S., 2023a. Magnetotelluric data across Mongolia: Implications for intracontinental deformation and intraplate volcanism — Report on new measurements. In: Abstracts for the European Geosciences Union (EGU) General Assembly 2023, Vienna, Austria, 24-28 April 2023, EGU23-9485. https://doi.org/10.5194/egusphere-egu23-9485.

Rigaud, R., Comeau, M.J., Kuvshinov, A.V., Grayver, A., Batmagnai, E., Tserendug, S., Kruglyakov, M., Becken, M., and Demberel, S., 2023b. Extending Magnetotelluric Study from Central to Eastern Mongolia: Preliminary 2-D and 3-D Inversion Results. In: Abstracts for the International Union of Geodesy and Geophysics IUGG General Assembly 2023, Berlin, Germany, 11–20 July 2023, IUGG23–4312.

Simpson, F., and Bahr, K., 2005. Practical magnetotellurics.

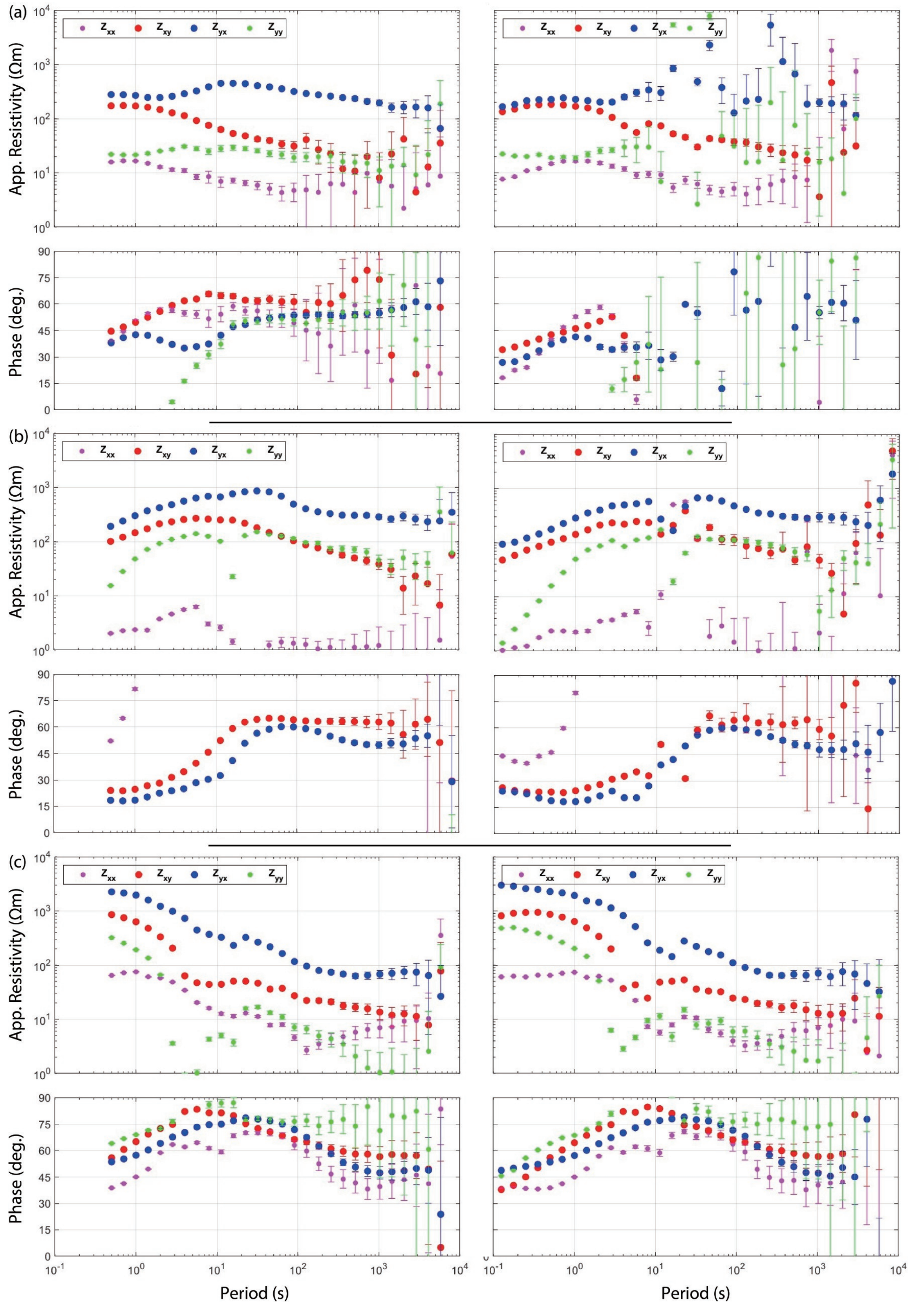

Fig. 2. Apparent resistivity and phase for each element of the impedance tensor against period.

Left panel uses a multitaper approach; right panel does not. Magnetotelluric sites are (a) 2023-n5-650; (b) 2023-9-350, and (c) 2023-11-050, acquired in Mongolia (Rigaud et al., 2023a; Rigaud et al., 2023b).

Cambridge University Press.
Slepian, D., 1978. Prolate spheroidal wave functions, Fourier analysis, and uncertainty-V: the discrete case. The Bell System Technical Journal, 57(5): 1371–1430.
Thomson, D., 1982. Spectrum estimation and harmonic analysis. Proceedings of the IEEE, 70(9): 1055–1096.
Tikhonov, A.N., 1950. On determining electrical characteristics of the deep layers of the Earth's crust. Doklady Akademii Nauk SSSR, 73(2): 295–297.
Welch, P.D., 1967. The use of the fast Fourier transform for the estimation of power spectra: a method based on time averaging over short, modified periodograms. IEEE Transactions on Audio and Electroacoustics, 15(2): 70–73.

About the first and corresponding author

Matthew J. COMEAU, Assistant Professor at the Department of Geoscience and Engineering, Delft University of Technology, Delft, The Netherlands. Expertise in applied electromagnetic geophysics and the quantitative interpretation of data. Primarily engaged in acquiring and analysing electromagnetic geophysical data to understand volcanic and geothermal regions, mineral systems, and tectonics at various scales, with the integration of other geoscientific data. Other interests include thermo-mechanical modeling to investigate lithospheric dynamics.