On the effect of non stationary (synthetic) sources in the magnetotelluric method

We are either progressing or retrograding all the while.
There is no such thing as remaining stationary in life.
— *James Freeman Clarke*

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Abstract

A new, non stationary scheme for the statistical magnetotelluric (MT) transfer function estimation is used to assess the effects of non stationary noise in MT data processing. The scheme uses Empirical Mode Decomposition (EMD) to process spectral data and is referred to as Empirical-mode-decomposition-based Magneto-Telluric processing (EMT) [Neukirch and Garcia, 2012]. We compare EMT with BIRRP by Chave and Thomson [2004], a traditional and efficient processing code based on the Fourier Transform. The benchmark is carried out on synthetic, non stationary data and real data with and without added synthetic, non stationary noise in order to show how easily a quasi-stationary method is compromised by a non stationary source and that the EMT algorithm is able to treat the situation correctly.

Motivation

Natural electromagnetic (EM) field variations are caused by two major working mechanisms, firstly, fast varying sets of strong lightning activities (more than $\mathbf{8\,Hz}$) and, secondly, slow variations of the magnetospheric structure due to solar wind (less than $\mathbf{8\,Hz}$) [Garcia and Jones, 2002]. Both of these sources are clearly non stationary. Nevertheless, practitioners argue that the magnetotelluric (MT) signal is quasi stationary (stationary on reasonably short time windows) and, thus, justify the application of the windowed Fourier transform. In practice this procedure works very well for data with high signal-to-noise ratios but frequently encounters problems in the presence of electromagnetic noise [Szarka, 1987, Junge, 1996]. Even though the MT signal may behave sufficiently stationary, the contained noise clearly does not need to.

In this work we study the effects of non stationary signal and noise on magnetotelluric measurements while focussing on the performance of the two processing algorithms *BIRRP* and *EMT* with respect to synthetic, non stationary signal and noise wave forms. As a synthetic source, we define a chirped electromagnetic wave form with an underlying homogenous electric Earth model. Then, a similar chirped signal is used as an electric noise source which is added to fair real world data to study the effect of non stationary noise sources. Lastly, real world data is presented, that is taken from a site close to train lines and mining activities, in order to support the thesis of non stationary effects on MT.

Ideal, Synthetic and Non-Stationary Data

Two orthogonal magnetic source fields $\mathbf{H = (H_x, H_y)}$ are defined by a frequency $\mathbf{f}$ and an amplitude $\mathbf{a}$:

$$\begin{aligned} \mathbf{H} &= \mathfrak{Re}\left(\mathbf{a \cdot \exp(i \int f dt)}\right) \\ \mathbf{\log(f)} &= \mathbf{A + B \cos(F_f t)} \\ \mathbf{\log(a)} &= \mathbf{C + D \sin(F_a t))}, \end{aligned} \quad (1)$$

with parameters $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$ and $\mathbf{D}$, $\mathbf{F_f}$ and $\mathbf{F_a}$ to define frequency and amplitude range and to control the degree of non stationarity. The time axis $\mathbf{t}$ is sampled at a rate of $\mathbf{4\ s}$ for a total length of $\mathbf{100'000\ s}$.

Fig. 1 displays the magnetic North - South component with its respective amplitude and frequency. Based on Neukirch and Garcia [2013], we obtain the electric fields by $\mathbf{E = ZH}$ with a homogenous impedance model as input: $\mathbf{Z_{xy-yx} = 1000 \cdot \exp\left(i\frac{\pi}{4}\right)}$.

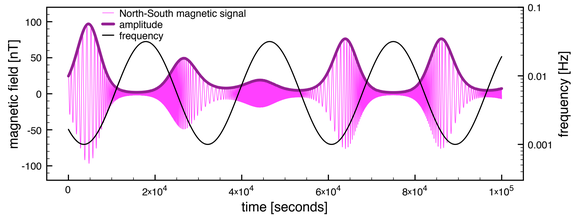

Figure 1: The magnetic source signal is defined by a chirp function with oscillating amplitude and frequency for statistical diversity.

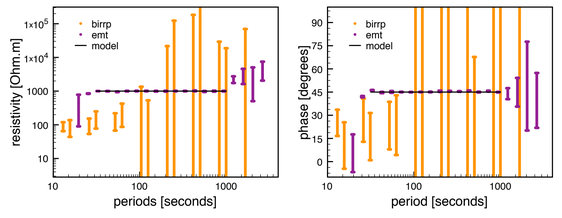

Figure 2: The Fourier Transform based BIRRP cannot analyse correctly the spectra for the non stationarity of the signal, unlike EMT.

Fair Real World Data with Added Synthetic, Non-Stationary Noise

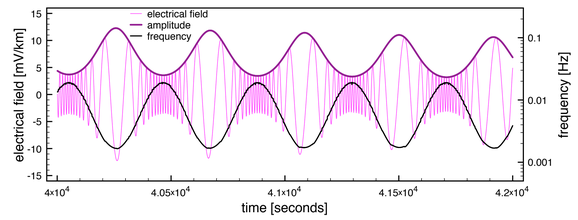

Figure 3: The non stationary source signal (Fig. 1) is now used as noise source (a section is displayed) and added to fair real data.

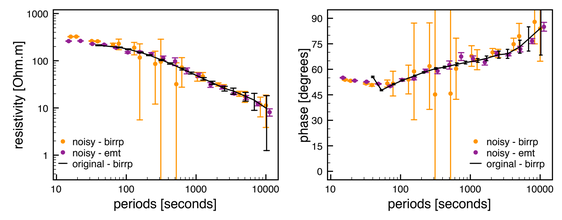

Figure 4: Fair real data is impaired by added non stationary noise. Original data (black) is compared to (non) Fourier based methods.

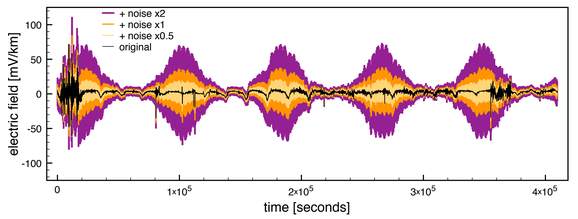

Figure 5: Non stationary noise is added to the electric fields of otherwise fair data to test its effect on different processing strategies.

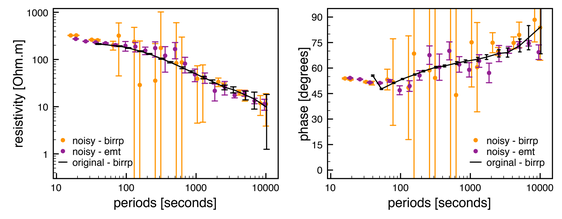

Figure 6: The noise level has been quadrupled compared to Fig. 4. Original data (black) is compared to (non) Fourier based methods.

The real data for this test [#172 with #145, from Evans et al., 2011] has a very fair signal-to-noise ratio (cp. black line in Fig. 4 and 6). We define two synthetic electric sources $\mathbf{e = (H_x, H_y)}$ by Eq. 1 and add them to the electric channels of the data $\mathbf{E_n = E_d + e}$ to emulate a non stationary electric noise source, the magnetic channels remain untouched. A section of the noise is illustrated in Fig. 3 with its amplitude and frequency. The noisy data (e.g. the electric field in Fig. 5) is processed first with a certain noise level, then again with the noise quadrupled. The spectral range of the noise is set between $\mathbf{1.7mHz}$ and $\mathbf{19mHz}$, respective $\mathbf{52\ s}$ and $\mathbf{610\ s}$, hence we expect to see the biggest impact on the processing results in that range.

Noisy Real World Data

This data [#142 with #127, from Evans et al., 2011] has been acquired close to intense mining activity and DC train tracks, suggesting a non stationary character.

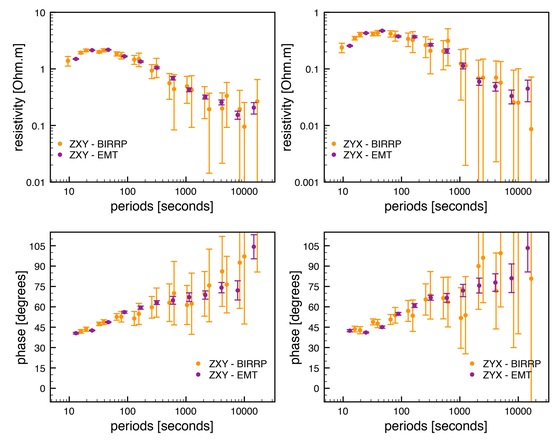

Figure 7: Real non stationary signal or noise can heavily affect data processing when Fourier based methods are applied.

Conclusion

Non stationary sources can impact on traditional MT processing routines that rely on the Fourier Transform. But this effect can be diminished by relying on purely non stationary analyses. Our synthetic, non stationary source is specifically designed to break the assumptions of the Fourier Transform, however the results provide an insight in how bad real non stationary noise can affect MT measurements. To support the thesis, a real world example is provided that is suspected to contain non stationary noise due to train lines and mining facilities.

Acknowledgment

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