Combined multivariate MT Processing for MTU (Phoenix) and ADU (Metronix) Measurement Systems

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1 Introduction

Phoenix Geophysics and Metronix are two leading companies offering measurement systems for audio magnetotelluric (MT) measurements. So far data aquired with Phoenix and Metronix systems in use had to be processed separately. While Phoenix provides an implemented data-processing software, data logger from Metronix deliver raw data. Calibration curves of magnetic coils are handed out separately. Processing of data collected with Metronix systems therefore can be done independently and transparently whereas data processing with Phoenix software is non-transparent and data calibration mostly depends on their own software. This can pose a problem in areas with strong anthropogenic noise since multi-site processing is limited to the number of devices running simultaneously from each comapny. Thus, a combined processing of Metronix and Phoenix raw data will improve transfer function quality on field surveys using both measurement systems.
On a joint MT measurement survey at Kasane (Botswana) of BUIST (Botswana University of Science and Technology) and Goethe University Frankfurt we applied measurement systems ADU07, ADU07e and MTU-5A from Metronix and Phoenix, respectively. Since the town of Kasane is close to the measurement area, the cultural noise production is assumed to be considerable. In order to reduce the noise a multi-site processing is necessary, meaning Phoenix and Metronix data processing has to be executed together.
This work shows a method how to calculate calibration curves for MTU raw data. Additionally, we present a new graphical user interface (GUI) implemented to the multivariate processing routine EGstart in Frankfurt MT software FFMT (Hering, 2019), which enables a straight-forward calculation of MTU calibration curves. For future studies, the comparison of Metronix and Phoenix magnetotelluric measurement systems facilitates joint measurement campaigns using transparent and independent MT data processing with both measurement systems in the field.

2 Calibration Measurement

So far using both measurement systems at one measurement campaign poses a problem because of missing information about instrument response functions and separated coil calibration curves for Phoenix devices.
To overcome this problem, we did a comparative test measurement setting up all stations at the same spot. The comparison of timeseries of identical channels from Phoenix and calibrated Metronix instruments recording the same signal yields transfer functions between both measurement systems.

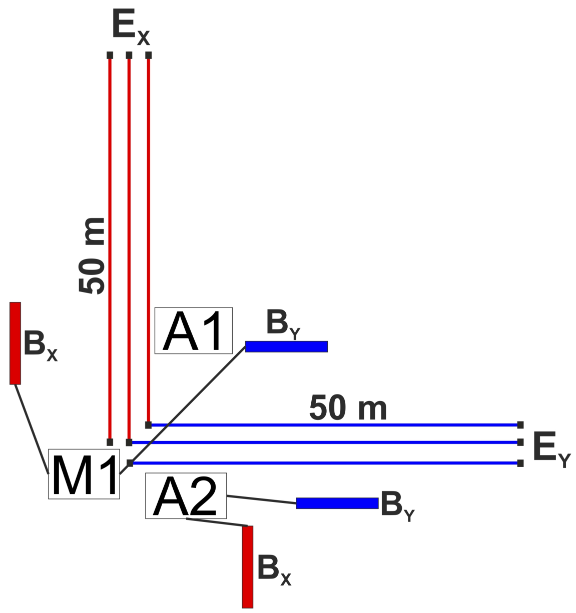


Figure 1: Sketch of the field setup for the calibration measurement with parallel E-lines and coils. ADU07 (A1) was used as a telluric station only, ADU07e (A2) and MTU-5A (M1) measured horizontal $\vec{E}$- and $\vec{B}$-field components.

For the calibration measurement, we set up the intruments with parallel electrical lines using 1 m spacing and B_x and B_y coils so we could perform MT processing and compare impedance tensors derived from each instrument (see fig. 1). On our survey at Kasane we only measured horizontal magnetic field components. For recording the magnetic field variations, we used MFS07e coils from Metronix and MTC-150L coils from Phoenix. One instrument (ADU07 - Metronix) was used as a telluric station only.
As on our field survey we took sample frequencies of 2048 and 16 384 Hz for Metronix instruments. The Phoenix device measured continuously with 150 Hz and discontinuously with 2.4 kHz saved as *.TS4- and *.TS3-files, respectively. The recording time was four hours for low frequency measurements, high frequency data were sampled for 25 min.
All measurements were done over night for lower noise level. A notch filter at 50 Hz was switched on for the MTU station during the survey because of power line noise. Additionally, the MTU station was set to the AMT mode. When acquiring data with Metronix and Phoenix devices, the following aspects regarding the field work should be considered.

Recommendations:

1. A first test measurement should be done at the beginning of the survey, but for possible changes of the setting, a second test measurement should be planed at the end of the measurement campaign.
2. The calibration measurement setup should be the same as in field so conventional MT processing can be applied to the data.
3. The MTU system needs to record with the same sampling rate for test measurement as for field measurements.
4. When using the GUI implemented to FFMT, the MTU coils must be fixed to the $\vec{B}$-field components they were connected to during the test measurement.
5. Make sure that the MTU notch filter is switched off (this might enable calculation of calibration curves for longer frequency intervalls).
6. Note the highpass filter at the AMT mode of Phoenix devices. Depending on your depth of interest choose broad band mode.

The following sections describes the instrument calibration using 2.4 kHz Phoenix data. The procedure can be applied accordlingly to TS4-files (150 Hz).

3 Timeseries

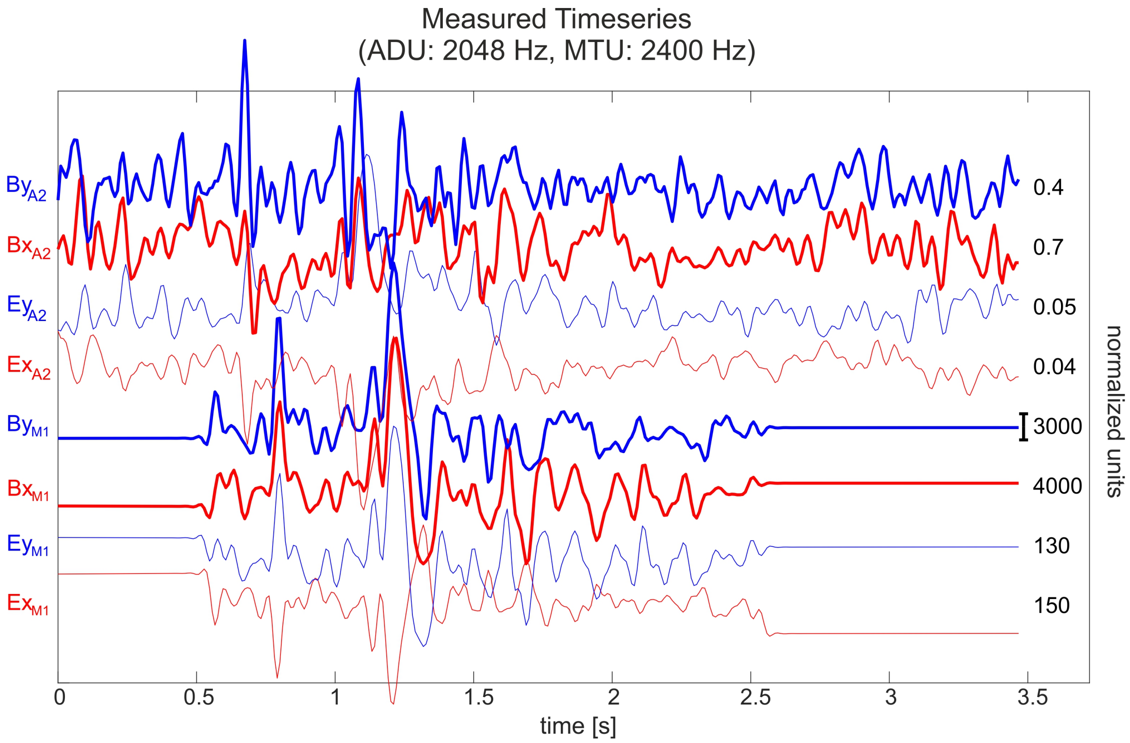


Figure 2: Section of simultaneously measured timeseries with $f_{sample} = 2048$ Hz for ADU and resampled data of MTU measurements with original sample frequency $f_{sample} = 2400$ Hz. The TS3-band of Phoenix devices measures discontinuously from 0.5 s to 2.5 s. Spikes at ∼0.7 s and 1 second on all four channels at Metronix timeseries are recorded with a delay of ∼100 ms on the Phoenix instrument.

At high sample frequencies Phoenix instruments collect data discontinously. For TS3-files ($f_{sample} = 2.4$ kHz) the recording time window is fixed to 2 s with two time windows per minute. In figure 2 we see ADU timeseries and MTU data recorded from 0.5 s to 2 s and resampled to 2048 Hz. Spikes at ∼0.7 s and ∼1 s in ADU data are comparabel to spikes at 0.8 s and 1.1 s in MTU data indicating a delay of about 100 ms.

4 MTU Calibration Curves

The procedure for calculating calibration curves with FFMT software is shown in figure 3. Calculating calibration curves for Phoenix devices using a test measurement requires four steps. First, converting of Metronix data to the recorded field units (mV/km and nT) is necessary and gain factors used on Phoenix channels need to be considered. Subsequently, we can calculate transfer functions between identical channels on both measurement systems in frequency domain. As shown in figure 2 we observe a constant delay on MTU signals. Therefore we correct for the time shift in time domain, do the transformation to frequency domain and recalculate transfer functions. We calculated a polynomial fit to the transfer functions which can be applied to Phoenix field data and used as calibration curves. Finally we use a polynomial fit in order to determine calibration curves for high coherent frequency ranges. This is done for each channel seperately. Applying the calibration curves to Phoenix data can proof the quality of the data fit.

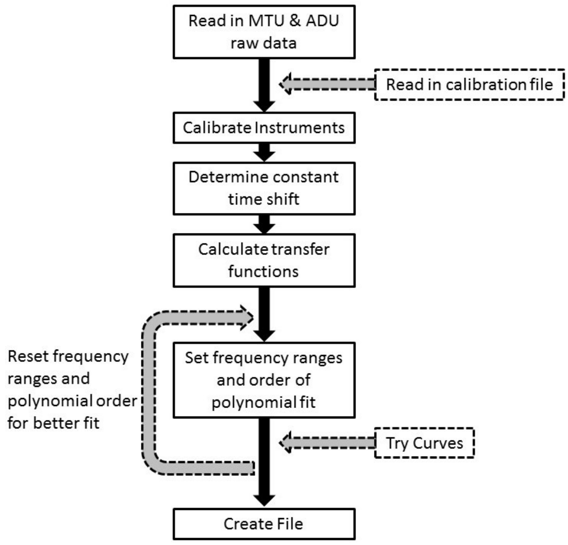


Figure 3: Flowchart of the new GUI implemented to the FFMT software for creating a calibration file for combined processing of Metronix and Phoenix data.

When opening the graphical user interface *Calculate MTU/ADU Cal-Curves*, calibration measurement data of one ADU- and one MTU-device have to be loaded. There is an additional option to load a calibration file. This can be used if measurements were done using more than one MTU sampling band or several Phoenix devices were used on the same survey.
The output file contains a structural variable with the size 1×1 if no calibration file was read in before. If a calibration file was loaded instead, a new row containing all information about recent instrument calibration will be added to the structural variable.
After loading calibration data, instrument settings need to be inserted. Phoenix' *.TS-files contain effects of gain factors (Phoenix Geophysical Limited, 2015) and E-line length that have to be taken into account. For Metronix data we calibrate magnetic field data, correct for the instrument response according to the recording board (Metronix Meßgeräte und Elektronik GmbH, 2010) and include E-line length.
Comparing downsampled MTU TS3 data with 2048 Hz ADU data gives a significant time shift of about 100 ms. Since this could be seen in the whole timeseries, we suspect a constant time shift between Metronix and Phoenix systems that might be caused by a filter in Phoenix devices.
As described by Häuserer (2007) and Löwer (2014), a constant time shift is linearly frequency-dependent and can be calculated by fitting the angle $\Delta\phi$ of the transfer function in frequency domain. The univariate transfer functions between identical channels of both measurement systems (for example $E_{y,ADU}$ to $E_{y,MTU}$) is given by equation 1.

$$TF_{M\to A}(f) = \frac{\sum_{n=1}^{N} F_{n,ADU}(f)F^*_{n,MTU}(f)}{\sum_{n=1}^{N} F_{n,MTU}(f)F^*_{n,MTU}(f)} \quad (1)$$

F represents the frequency-dependent Fourier coefficient and the star marks its conjugate complex value. Transfer functions are averaged over N time segments. For TS3-data we get time segments of simultaneously measured data with a length of 2 s and continously measured low frequency data are cut to time windows with a length of 5 min. The transfer function is complex and thus can be described by its amplitude A and phase ϕ (see eq. 2).

$$TF_{M\to A}(f) = A(f)e^{i\phi(f)+i\phi_{\Delta t}(f)} \quad (2)$$

For a constant time shift as assumed in the comparison, the angle $\phi_{\Delta t}$ depends linearly on the frequency f, since $\phi_{\Delta t}$ can be written as product of frequency f and a constant factor including the static time shift Δt (3).

$$\phi_{\Delta t} = f2\pi\Delta t \quad (3)$$

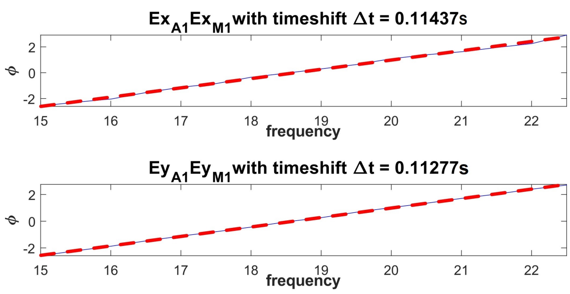
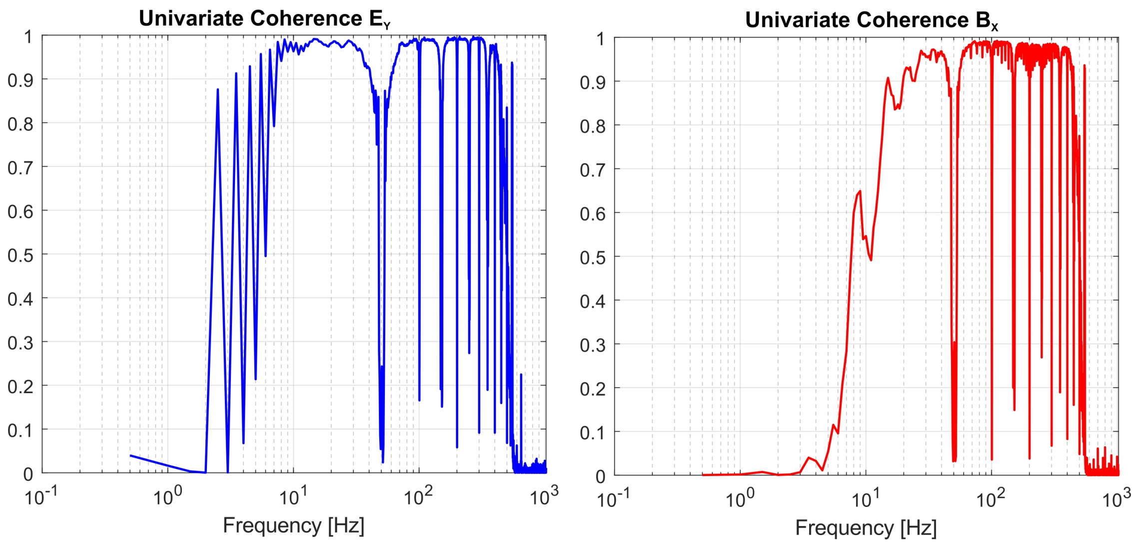


Figure 4: Using Phoenix recording band TS3 and ADU data sampled with 2048 Hz, the linear fit to univariate transfer functions of the electrical field components yields a mean constant timeshift of ∼0.113 s.

Therefore, by plotting the phase of the transfer function with respect to the frequency, the slope of a linear fit corresponds to the constant time shift $\Delta\, t$ multiplied by the factor 2π.
Figure 4 shows the phase of the univariate transfer functions and a linear fit for frequency intervall of 15 Hz to 20 Hz at a common sample frequency of 2048 Hz. Averaging (arithmetic mean) the slopes of the horizontal electrical and magnetic field components gives a constant time shift of 113.9 ms for 2.4 kHz MTU sample frequency.
Using the GUI, the user can deselect channels because of bad data quality or empty channels. The frequency intervall can be set by choosing maximum and minimum frequency. The linear fit and the arithmetic mean of the the time shift of all channels will be calculated automatically. Finally, if the linear fit yields reliable time shift values, by clicking on *Save Time Shift* MTU timeseries will be shifted, the univariate coherency will be determined (see eq. 4) and new transfer functions will be calculated.

$$coh_{uni}(f) = \frac{|\sum_{n=1}^{N} F_{n,ADU}(f)F^*_{n,MTU}(f)|^2}{\sum_{n=1}^{N} F_{n,MTU}(f)F^*_{n,MTU}(f) \cdot \sum_{n=1}^{N} F_{n,ADU}(f)F^*_{n,ADU}(f)} \tag{4}$$

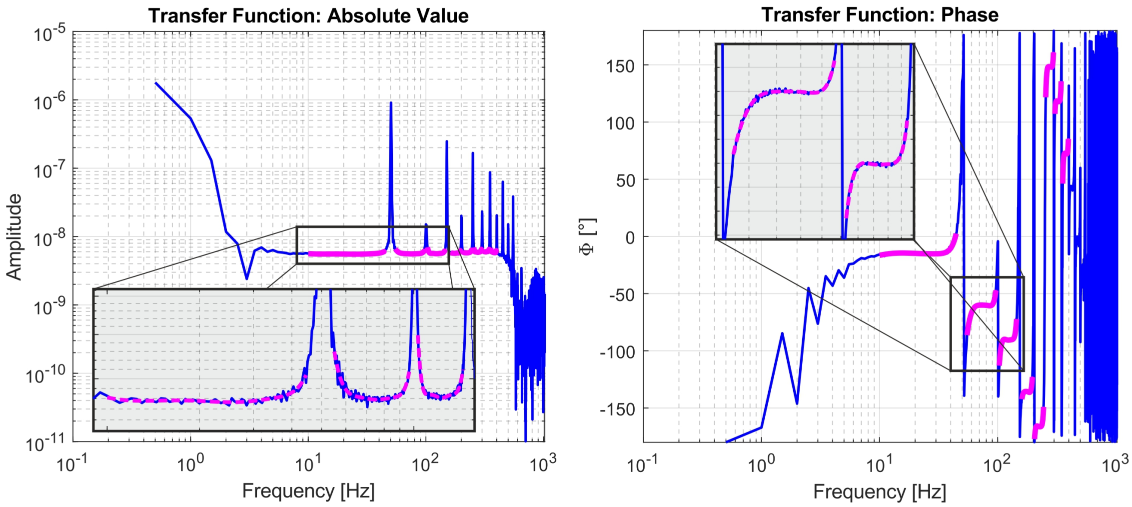
High coherency indicates similiar signals on both instruments. Thus only frequency intervalls with coherency close to $coh_{uni} = 1$ were selected for calibration curve fitting (see fig. 5).



(a) (b)

Figure 5: a) Univariate coherency between $E_{y,ADU}$ and $E_{y,MTU}$ for data resampled to 2048 Hz. b) Coherency between magnetic field channels B_x for f_{sample} =2048 Hz. The coherency is low for 50 Hz and multiples.

Due to a high pass filter in the Phoenix system and strong effects of the 50 Hz notch filter, the frequency range is limited to eight intervalls between 1 Hz and 400 Hz for *.TS3-files. When saving the timeshift, five additional window tabs are created showing coherency, autospectra and transfer functions of every field component. In the GUI, the number of frequency intervalls for calibration can be defined. Subsequently, frequency range and polynomial order for amplitude and phase can be set for each intervall. The order of the polynomial is equal for all channels. When reviewing the data fit, every channel has to be considered.



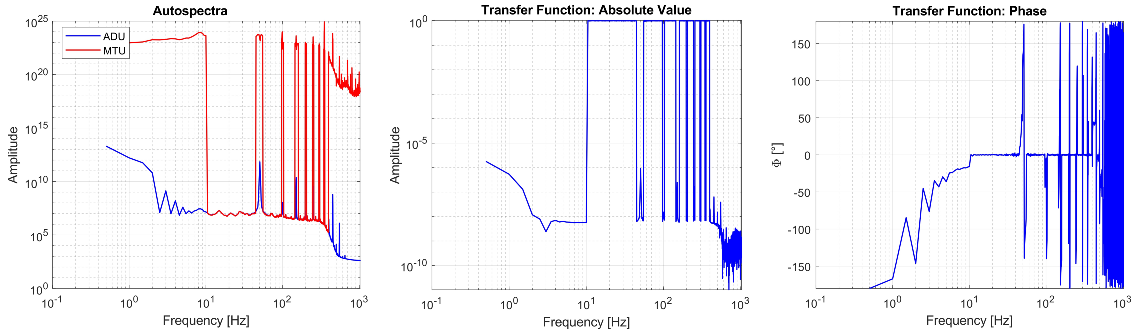
(a) (b)

Figure 6: Polynomial fits (magenta) of eight frequency intervalls to the transfer function of E_y (blue). a) Fit to the absolute value using a polynomial order of $p = 7$. The phase (b) was fitted with polynomial order $p = 5$. Zooming in shows a very good fit with only minor deviations of $\sim 2°$ for phase values.

In figure 6 polynomial fits of the transfer function of E_y are shown for eight frequency intervalls. The order of the polynomial was set to $p = 7$ and $p = 5$ for amplitude and phase, respectively. Zooming in reveals a good phase and amplitude fit with only minor deviations using the polynomial fitting tool.

5 Results

For evaluating the quality of the fit we applied the polynomial fit to MTU data. By calibrating the Phoenix data, recalculated transfer functions are expected to yield an amplitude of $A = 1$ and a constant phase $\Phi = 0$ within the selected frequency intervalls. The autospectra of MTU and ADU data should overlap at the given frequencies as shown in figure 7.
For verifying the new FFMT ADU/MTU environment, we set two jobs using the calibration measurement data acquired with Phoenix measurement bands TS3 as well as TS4 and ADU sample frequency $f_{sample} = 2048$ Hz. For the Kasane data set, we could calculate MTU calibration curves between 5 and 400 Hz so processing is possible for target frequencies within this frequency range (8 Hz to 265 Hz).



(a) (b) (c)

Figure 7: a) Amplitude of the transfer function between calibrated MTU using the fitted curves shown in figure 6 and calibrated ADU signal. As expected, the amplitude becomes 1 in the predefined section (b). At the same frequency ranges the phase is set to $\Phi = 0$ (c).

In figure 8 ρ_a-curves for the off-diagonal elements of the impedance tensor as well as their phases are shown with respect to the period. Data at all stations give similar curves indicating correct combined ADU/MTU multisite processing. Low phases are caused by coherent cultural noise between both stations.

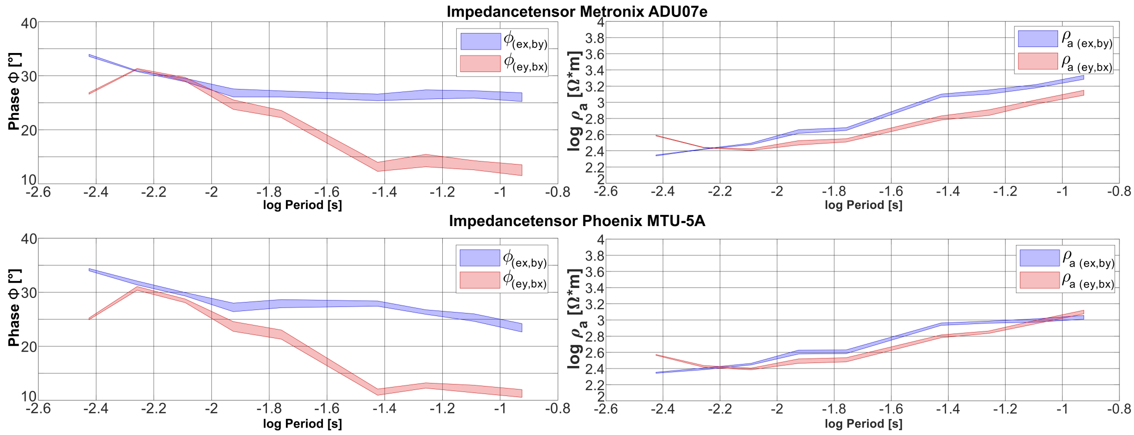


Figure 8: The rows show results for the impedancetensor of Metronix (top) and Phoenix (bottom) device of calibration measurement data using FFMT software jointly for Metronix and Phoenix data. Processing was performed with TS3 and TS4 Phoenix recording bands and 2048 Hz sample frequency for the Metronix device.

6 Conclusion

The comparison of MTU and ADU devices measuring the same signal enables the calculation of calibration curves for Phoenix devices. Using a new version of the Frankfurt processing software EGstart, transparent and independent multi-site MT processing of field data acquired using both measurement systems can be performed. Additionally, the graphical user interface *Calculate ADU/MTU Calibration Curves* implemented to the FFMT software provides a tool for calibration curve calculation.
The calibration curves enable processing of field data from Kasane at target frequencies ranging from 8 Hz to 265 Hz. The comparison of MTU and ADU test measurement data

yields a high coherency for electric and magnetic field channels. For $f_{sample,MTU} = 150$ Hz (TS4-files) the calibration is limited to a range from 5 Hz to 45 Hz. The low coherency at frequencies below 5 Hz is due to the high pass filter at 1 Hz for coils in the AMT mode of Phoenix instruments. At higher sample frequency (Phoenix $f_{sample} = 2.4$ kHz) the notch filter causes strong effects. Therefore the calibration curve has to be splitted to several intervalls between the notches.
A combined processing of test measurement data gives similar ρ_a-curves and phases for all stations. For future surveys using both measurement systems, a calibration measurement between each Phoenix instrument and at least one Metronix instrument has to be performed. Requirements concerning field settings were presented.

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