# Conversions of magnetic to magnetotelluric transfer functions

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As both, magnetic and magnetotelluric transfer functions are based on electromagnetic induction phenomena they are not independent of each other. Becken & Pedersen present an algorithm that uses the wavenumber domain formulation of the Hilbert transform to convert induction arrow data to magnetotelluric transfer functions using dense spaces array data. In this paper we extend this algorithm by conversions from horizontal magnetic to magnetotelluric transfer functions. By its application on model data and large, long period datasets from central Australia and Germany we investigate the potential and limitations of the algorithm. Realizing the TE-mode nature of magnetic transfer functions several implications can be extracted from differences between measured and converted results.

# Processing magnetotelluric time series with adaptive filters and neural networks

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Contamination by noise generated by human activity is a common problem in magnetotelluric recordings in populated areas. Cow fences are particularly problematic in that respect, because they continuously generate strong signals with changing characteristics in both electric and magnetic channels. In most cases these signals are present throughout the entire recording and even modern robust remote reference methods fail. Therefore the time series has to be filtered before conventional processing. Adaptive filtering methods can to a certain degree adjust to varying noise characteristics. We present results from linear adaptive methods as well as non-linear neural network based approaches. We will show the impact of these methods on the time-series, the corresponding spectra and the final transfer-function.

# Magnetotelluric Polar Diagrams

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Comparative analysis is performed for magnetotelluric polar diagrams that are helpful for the recognition of geoelectric structures at the stage of qualitative interpretation of magnetotelluric soundings. The following types of polar diagrams are considered: (1) diagrams of the impedance tensor, (2) diagrams of the H and E polarized impedances, and (3) diagrams of the phase tensor. The properties of the diagrams are studied and it is shown that shallow structures of a higher resistivity are identified most reliably with the use of E polarized impedance diagrams, whereas phase diagrams of the impedance tensor and diagrams of the phase tensor provide most reliable constraints on deep (lithospheric) conductive structures. Polar diagrams are free from structural limitations inherent in the standard methods of the separation of local and regional effects. It is important to note that diagrams of the impedance tensor and E and H polarized impedance diagrams are also free from frequency limitations. Evidently, combined application of polar diagrams significantly widens the possibilities for the separate identification of shallow and deep geoelectric structures.

# 2-D inversion of the BC87 data set using series and parallel impedance responses

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The series-parallel (s-p) transformation of the magnetotelluric impedance tensor is used for the 2-D inversion of the public domain BC87 data set. The series and parallel impedance responses are suitable combinations of the four elements of the impedance tensor. The rotation invariance of the s-p responses circumvents the complexity to choice a particular strike direction. In addition, the s-p impedances are complementary in the sense that the series impedance is mostly sensitive to galvanic effects while the parallel one is largely sensitive to inductive effects. Both features are convenient attributes when interpreting complicated data sets. The BC87 data set was inverted using a well-known 2-D algorithm based on Gauss-Newton optimization. This algorithm was adapted to deal with series and parallel responses instead of the conventional TE and TM impedances. We found that the s-p impedance responses yield to 2-D models comparable with those obtained by other authors using different approaches with TE and/or TM impedances. We also explore two data-averaging schemes using the s-p responses. One consists in an iterative application of the series and parallel equivalents in the frequency domain. The second is a spatial moving average of the s-p apparent resistivity and phase curves. Both approaches yield plausible models, smooth and with better data fits than traditional processing.

# Development of a robust procedure to extract a local long-term geomagnetic variation

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We develop a robust statistical procedure to extract a local long-term variation from an observed geomagnetic field. This is an extended version of our procedure which used the Kalman filter algorithm to decompose the geomagnetic field into four different components: a trend, periodic, and externally correlated variations as well as noise. The new version allows non-Gaussian distributions for the noise and the derivatives of the trend so that outliers can be included and step-like variations of the trend are accepted. We report on test results using synthetic data sets to evaluate the procedure and on applications to the geomagnetic total intensities observed at volcanoes to monitor slow demagnetization processes.

# Interpolating magnetotelluric fields using finite elements

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Suppose, that we have magnetotelluric data along a profile across a 2D anomaly. In the ideal 2D case, the E-polarization impedance and the vertical magnetic transfer function provide redundant information. In real cases, data are spatially under-sampled, affected with noise and the electric field may be galvanically distorted. We suggest a consistency check between the E-polarization impedance and the vertical magnetic transfer function, based on Faradayś law to connect the derivative of the horizontal electric field Ex in profile direction y with the vertical magnetic field Hz. For this purpose, we developed an algorithm based on a finite element approach. We fit the data along the profile with continuous, piecewise cubic functions, subject to a smoothness constraint while exactly satisfying Faradayś law. Data variances are used as weighting factors in the inverse solution. As the fields directly are a priori unknown, we incorporate the transfer functions iteratively, using Hy=1 as an initial guess for the magnetic field and successively improved horizontal magnetic fields for subsequent iterations.

# Strong telluric distortion in magnetotelluric soundings

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In 2005 magnetotelluric (MT) measurements were carried out in the Harz Mountains. At short periods ( 128s) the data show evidence of an anisotropic crustal layer. However, for longer periods (¿500s) data are strongly affected by telluric distortion which becomes apparent in electric field directions being almost independent of the magnetic ones. It is shown that in this case tensor decomposition schemes dont́ allow for recovery of any underlying, two-dimensional structure. Therefore an absolute measure is introduced allowing for recognition of such strong telluric distortion.

# Canonical coherences as an indicator for coherent noise

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Magnetotellurics as a passive electromagnetic method is very sensitive to the presence of artificial noise sources, such as power lines, electric fences, anti-corrosion currents in gas pipelines, DC trains and many others. The influence of noise can distort MT data severely, sometimes making measurements impossible. Results can be improved by applying robust processing schemes or with the use of the remote-reference-technique. For the latter it is essential to find a remote site which is not influenced by the same noise source as the local sites. To help identify a suitable remote site and to characterize coherent noise across an array of MT-stations, we apply a modified method from multivariate statistics, the canonical correlation analysis. This technique seeks the linear relationship or correlation between two multidimensional data sets.

Applied to the MT case it allows us to calculate the coherence dimension between the electric and magnetic fields at multiple sites over the entire frequency range. In the ideal case (strong natural signals, absence of coherent noise) only two of the canonical coherences should be significantly large, according to the number of independent directions of the MT-source.

We demonstrate possibilities and limits of this technique with synthetic data. The method is also applied to field data from a magnetotelluric array experiment recorded across the San Andreas Fault in California.

# Dimensionality study of geoelectrical structures in the Alhucemas region (North Morocco)

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The Alhucemas region (North Morocco) is a complex geological area with thrusts and strike-slip faults with different size and direction. In this region a magnetotelluric campaign was performed during February 2006. These data have allowed us to study the dimensionality of geoelectrical structures of this area, where the expected dimensionality cases were 2D or 3D/2D. Three different computer programs (Waldim, Phase Tensor and Strike) have been used in order to compare their results, which show that for shallow structures (frequencies higher than 1 Hz) the dimensionality in this region can be considered 2D or 3D/2D, with a strike of approximately N50°. Main thrusts and strike-slip faults in the area (e.g. the Nekor strike-slip fault) have this direction. For lower frequencies the dimensionality analysis shows 3D structures. The results of the dimensionality analysis obtained by using these three programs are similar, although some differences among them can be found.

# **A** MT array on the edge of an old Australian craton: first results of strike analzsis and modelling

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Fifty MT stations have been deployed across the western edge of the Gawler Craton, South Australia, on a 500 * 400 km grid between November 2005 and July 2006. MT responses between 10 s and 8000 s provide an insight into one of the oldest cratons of the world, which situates a number of world-class mineral deposits, such as Olympic Dam, along its eastern boundaries. Data are carefully analysed using the phase tensor approach and the 7 invariants in order to determine dimensionality and strike. Initial two-dimensional modelling of data helps to give further information for further three-dimensional analysis.

# Examples of using singular spectrum analysis in magnetotelluric data processing

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Quality of magnetotelluric data often suffers from high noise level. The most common sources of this noise (such as railways, electrical devices, thunderstorms etc.) are very hard to avoid especially in urbanized areas. Singular Spectrum Analysis (SSA) is a numerical method based on eigenvector and eigenvalues analysis of lagged covariance matrix (Toeplitz matrix). This method can extract information from noisy, short and even gaped time series without any knowledge of physics of observed dynamic phenomena. After decomposition and sorting in order of eigenvalues reconstructed components can be easily recognized and filtered. This is possible because amount of information about raw time series included in each component is proportional to corresponding eigenvalue.

# Use of anomalous horizontal magnetic field in geoelectromagnetic studies

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Anomalous fields in horizontal magnetic components are related with horizontal normal field by tensor [b] of second rank. We analyze invariants of [b] and the conditions of 2D dimensionality. The indication of 2D behavior of [b] is det [b] = 0. We give evidence that tensor [b] satisfies 2D conditions in much more sites than tipper does, because [b] carry more local information than tipper which "collects" anomalous fields from larger territory. We review set of regional conductivity anomalies (CA) over which the anomalous field (norm of [b]) is larger 1, that proves their conductive (not inductive) nature. The most interesting and complicated data we present for Timan CA. We discuss optimal methods of tensor [b] representation. Conclusion: Tensor [b] carry most local, reliable and least distorted information on electrical CA-ies and we recommend to use it in geoelectromagnetic studies.

# Mode separation of magnetotelluric responses in three-dimensional environments

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Magnetotelluric (MT) responses in complex, three-dimensional (3D) terrains are in general characterised by (i) elliptical polarisation states of horizontal electric and magnetic fields; (ii) the non-orthogonality of electric and magnetic fields and (iii) a coupling of the tangential electric (TE) and tangential-magnetic (TM) modes, giving rise to a mode-mixed surface electric field. These 3D effects are propagated into the MT impedance tensor, which is derived from horizontal electric and magnetic fields, recorded at the earth's surface. The 2 * 2 impedance tensor is in general fully occupied, and each of its elements is a mode-mixed quantity. Hence, it is impossible to interpret such data using a two-dimensional (2D) modelling approach, which can only explain the two single-mode, off-diagonal elements. To study 3D effects of MT (impedance) data, the TE and TM mode contributions must be separated which is generally not possible with single site impedance data. With the inclusion of the single-mode vertical magnetic transfer function (the ratio of vertical to horizontal magnetic fields), however, the individual modes can be resolved without prior knowledge of the underlying 3D conductivity structure. For this purpose, we consider (i) the spatial relations between electromagnetic field components recorded in an array of sites (Faraday's law) and (ii) that the magnetic TE mode and electric TM mode fields are potential fields within the insulating air half-space above the earth's surface. Based on these two dependencies, it is possible to reconstruct the entire electromagnetic field from (measured) mixed-mode impedances and vertical magnetic transfer functions and to separate it into TE and TM modes, and into normal and anomalous parts. Hereby, we can not only study the contribution of the two modes on the observed impedance tensor but also quantify the influence of 3D effects at each location and frequency of a particular data set. Results of a modelling study suggest, that (i) none of the elements of a 3D impedances tensor can be regarded as favourable for a 2D interpretation (only 3D models can explain 3D data) (ii) a heterogeneous crust generally obscures identification of responses originating from the lower crust or upper mantle even at very long periods (iii) the TE mode magnetic transfer functions are effectively blind to shallow heterogeneities and are therefore sensitive to deep anomalies.

# Self-consistent inter- and extrapolation of magnetic transfer functions

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We have developed a new method to predict the spatial variation of the surface magnetic fields for the two independent source polarizations, given that magnetic transfer functions between the horizontal components at a reference (normal) site and the three components at all other sites have been measured in an array. In theory, the vertical magnetic transfer function contains all the information which can be extracted from GDS array measurements, provided that the measurements are placed sufficiently dense and cover a sufficiently large area such that all induction anomalies decay at the borders of the measurement area. In this case, the horizontal magnetic transfer functions carry redundant information, because the vertical and horizontal magnetic field components are connected via a spatial Hilbert transform. In practice, stations are not distributed sufficiently dense over the whole area, the anomalous magnetic field rarely vanishes at the borders of the measurement area, because the effects of neighboring conductors start to dominate, neighboring conductors may even significantly distort induction anomalies in the middle of the array because of slow decay of anomalous magnetic fields at long periods, real transfer functions will invariably be inconsistent due to noise effects, and the reference site is not a 'normal' site. Especially the vertical transfer functions will be strongly affected by neighboring conductors because they become small directly over conductors, whereas the horizontal transfer functions become large over conductors. Taking this together, it means that the transfer functions provide complementary information, especially in cases where the underlying conductors have 3D geometry. That can be used to improve the interpolation between less densely spaced measuring sites. To accomplish a self-consistent prediction of the magnetic field, which satisfies the constraints provided by the measured transfer functions, we incorporate a (static) equivalent source model for real and imaginary parts separately. Our equivalent model neglects induction effects; it only aims at reproducing the spatial variation of induction anomalies at a certain period. Under these circumstances, the model is linear, and all periods are treated separately. For inter- and extrapolating, we do not require the estimation of the equivalent source model explicitly; it only plays a role in estimating the effective number of degrees of freedom required to fit the data in a self-consistent way. A stable solution to the linear relation is most conveniently obtained by truncated singular value decomposition (TSVD). The truncation level determines in this context the effective number of degrees of freedom in the data, and is estimated by trading off between model variance and model bias (mean square error approach). We finally iterate the solution of the linear equation in order

to remove the effect of anomalous fields at the reference site. In a first approximation, we only use vertical transfer functions and assume that the reference site is indeed ‘normal’. Then, the vertical transfer functions are treated as the vertical magnetic fields for the two independent source polarizations. This gives us a first approximation of the anomalous fields at the reference site, which – in conjunction with the transfer functions – allows us to estimate a first set of magnetic fields. Subsequent iterations then include both vertical and horizontal transfer functions. Upon convergence, we obtain a continuous description of the magnetic field including data variances and resolution at measurement and interpolation points. We show synthetic cases for array geometries used in the recent EMTESZ and DEEPROOT (Parkfield) projects to illustrate the power of the new method.

# GEOELECTRIC STRIKE DETERMINATION USING MAGNETOTELLURIC PHASE TENSOR

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In MT method, natural em field is used to investigate the electrical conductivity structure of the earth. The near surface heterogeneity distorts the amplitude of the electric field but the phase relationship between electric and magnetic field vectors are unaffected. The phase relationship contained in MT impedance tensor are second-rank tensor. The phase tensor analysis doenot require any assumption about the dimensionality of the underlying conductivity distribution. The phase tensor can be depicted graphically as an ellipse, the major and minor axes representing the principal axes of the tensor. The map of phase tensor ellipses at different frequencies provide a simple way of depicting the direction and of visualizing lateral change in regional conductivity structure at different depths.

A MT sounding data has been analysed using phase tensor. The obtained strike of the regional feature varies from 50o to 60o for frequency 10-3 Hz to 103 Hz. The ellipse plot shows that the feature is 2-D in nature for higher frequencies but becomes complex (3-D) for lower frequencies.

# Influence of rotation on the processing of MT time series

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The rotation of the impedance tensor is an important step during the analysis of magnetotelluric data. In theory there should be no difference whether the time series is rotated prior to data processing or the obtained impedance tensor is rotated directly. We expect therefore that time series rotated by a specific angle prior to processing and later rotated back into its original coordinate system give the same impedance tensor results like an unrotated time series. In practice, however, at sites with either strong noise contamination or strong 3D influence the above described rotation processes do not result in the same impedance tensor. We assume that this is caused by the robust weighting of the impedance tensor elements. It is desirable to find the b̈estc̈oordinate system prior to data processing. Different approaches of rotating electric and magnetic fields on the basis of maximising and minimising electric field amplitudes or maximum and minimum coherencies are tested on data sets with noise and strong 3D effects. In addition we report on an experimental set-up using more electrode lines than the usual two in NS and EW direction (e.g. every 30deg). With the redundant information of the electrical channels we are able to describe Ex and Ey by using any other combination of recorded electric fields. Additionally, we can compare the impedance results obtained from an over-determined equation system with the directly measured electromagnetic fields.