On sources of instrument motion in marine MT and how to deal with the resulting disturbances

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Abstract

Many marine magnetotelluric (MT) datasets contain dominant, quasi-harmonic signals at a period of several seconds in the magnetic and (to a lesser degree) in the electric channels. In some cases these signals are strong enough to drive a standard processing into failure. Coherence with tilt records shows that these signals are generated by motion of the instrument. However, the source of this motion is controversial. It is unclear whether the surrounding water performs such oscillations that might be caused by microseisms, or if streaming water incites oscillations of the instrument.
This contribution contains a discussion resulting in a preference of the latter possibility.
Furthermore, the mechanism of electromagnetic noise generation due to that motion is explained, and possible noise-correction and processing strategies for disturbed data are presented. Data examples are from GEOMAR (Kiel) campaigns offshore Costa Rica and Namibia.

1. Introduction or On some differences between onshore and offshore magnetotelluric data

Although this work focuses on just one specific problem of offshore MT data, the way of deployment and the special environment in marine measurements cause phenomena that are unheard of in onshore MT. Here we take the occasion to remind of some of them.

a) The coordinate system
Onshore MT measurements usually take place in the geomagnetic coordinate system. This requires a proper installation of the instruments: The magnetometer must be leveled, and both the magnetometer and the telluric lines have to be aligned to North (or East) by means of a compass. Offshore instruments are usually deployed free falling from the ship: After being dropped from the ship, they sink to the ground and as a consequence orientations cannot be controlled. Hence marine MT data are measured in a rather arbitrary coordinate system and additional steps to rotate them to usable coordinates are necessary before processing. The rotation process requires the information about three angles which are provided by the marine instruments: Two of them, describing the deviation from the true horizontal plane, are provided

by two inclinometers or tiltmeters. The third one controls the deviation from magnetic North and can be provided in different ways: If the magnetometer is a fluxgate instrument, the main magnetic field can be measured (which is superimposed on the magnetic variations that are needed for MT) and the North direction can be derived from it. Another possibility is to take it from a compass. If the MT measurement is combined with a controlled-source electromagnetic (CSEM) one, the North direction can be estimated by means of the transmitter signal (e.g. Mittet et al. 2007). Hence, additional data to the pure magnetic and electric ones have to be taken into account.

b) The coast effect

The coast effect known from onshore MT is based on the fact that data of stations situated close to the shore of a deep sea “perceive” the salty sea water as a good conductor. This emerges most clearly in the induction arrows: the real ones (in Wiese convention, Wiese 1962) point inland, away from the sea. A similar effect occurs in offshore stations situated close to the coast in the conductive sea water (Fig. 1): The land is visible in the data as a high-resistive structure, and real induction arrows point towards it. However, here the station is placed *beneath* a good conductor, and the resistive land is partly in an altitude *above* the station. This causes features in the data that are unusual from an onshore point of view: In the TE mode occur phases below 0 degree and the apparent resistivity rises with more than 45 degree (in an equidistant log-log plot) to a sharp maximum. The induction arrows increase and decrease rapidly over period and reach lengths as they rarely do onshore. For more details and explanation of this phenomenon, see Worzewski et al. (2012).

c) Noise generated by instrument’s motion

Here a problem is outlined which is treated in detail in Neska et al. (2013). Figure 2 shows time series of a station offshore Costa Rica in ca. 3200 m depth that contain a dominant, quasi-harmonic signal with a period of 5.5 – 6 seconds. It is clear that this is not a usual MT source signal, since that period is too close to the dead band, and if such a signal came from above the atmosphere, it would be practically damped away by the conductive salt water layer. However, the strong correlation with the tilt channel (lowermost panel in Fig. 2) indicates that a rocking or swinging motion of the station produces such signals in the electric and magnetic channels. If they are strong, they can interfere with the MT signal even at much longer periods and hamper the data processing. Hence motion of the surrounding medium can cause problems in offshore data that are prevented onshore by burying the sensors in the soil. The noise is particularly large due to two reasons here: a) the instrumentation was of the first generation design, which turned out to be very sensitive to motion. Mechanical weak points responsible for this have been corrected for in the second generation instrumentation, b) a large number of instruments were placed on the steep continental slope causing a relatively weak coupling to the ground. Furthermore the continental slope is subjected to strong tidal currents coming from the open ocean. Although this type of problem has been significantly reduced by giving the GEOMAR stations more stability, we will consider it more closely in the following. Section 2 treats properties of motion-induced noise which has a relatively straight forward explanation, section 3 is an attempt to constrain the discussion on possible sources of the instrument’s motion, and section 4 summarizes conclusions concerning the optimal processing approach for marine MT data affected by motion noise.

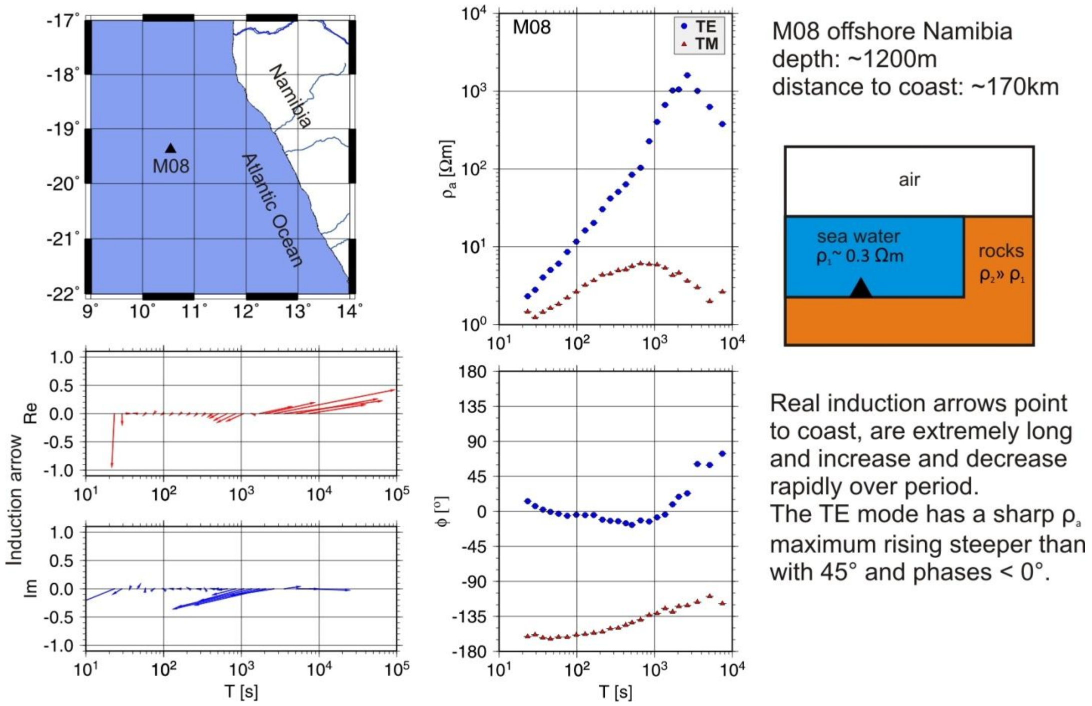

Fig. 1 Principle (sketch on the right-hand side) and exemplary data (sounding curves in the middle column, induction arrows on the left-hand side (bottom), site location on top) of the offshore coast effect

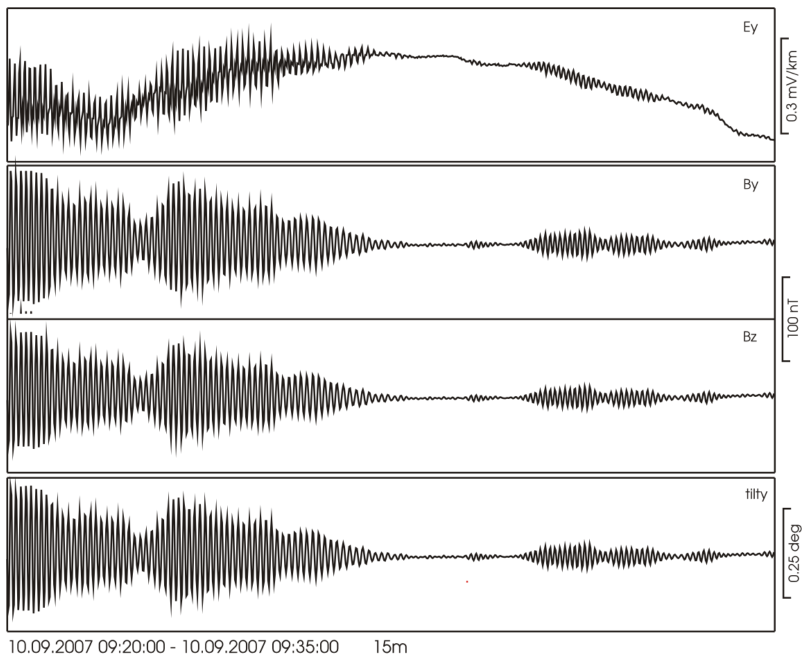

Fig. 2 Time series (instrument's coordinate system) of selected components of station m05 offshore Costa Rica.

2. Consequences of instrument's motion for magnetotelluric records

If an MT measurement is not performed by an instrument fixed to the solid Earth, but by a periodically tilting one, the consequences for both magnetic and electric channels are predictable. First, the static main magnetic field of the Earth will be measured in a periodically changing coordinate system which results in more or less dramatic, disturbing changes between the vertical magnetic component and the horizontal one parallel to the corresponding tiltmeter. This applies even to small tilt movements because the main field is larger than the MT source signals by more than two orders of magnitude. However, these tilt-generated magnetic changes are almost completely determined by the tilt records (the coherence between corresponding tilt and magnetic components is nearly 1 over the whole LMT period range), and this can be used to correct the magnetic records for the tilt-induced disturbances to a certain degree (Neska et al. 2013). Ibid. is pointed out that tilt-induced disturbances on electric channels are generated according to Faraday's law within the instrument, this means that fast tilt changes produce larger electric signals than slow ones. As a consequence, electric channels in the LMT-relevant period range (> 10 seconds) are practically free from motion noise, although it is visible for the dominant period (Fig. 2), and for its first harmonic it is even more pronounced for the electric than for the tilt spectra (Fig. 3). Moreover, the tilt-induced disturbances on electric channels can be predicted from tilt channels via the Lorentz expression

$$\underline{E} = \underline{v} \times \underline{B}$$

where $\underline{E}$ is the tilt-induced electric signal and $\underline{B}$ the static main magnetic field. The velocity $\underline{v}$ at the ends of the telluric tubes due to tilt motion can be calculated from the tilt angle records taking into account the tube length via differentiation with respect to time (Fig. 4).

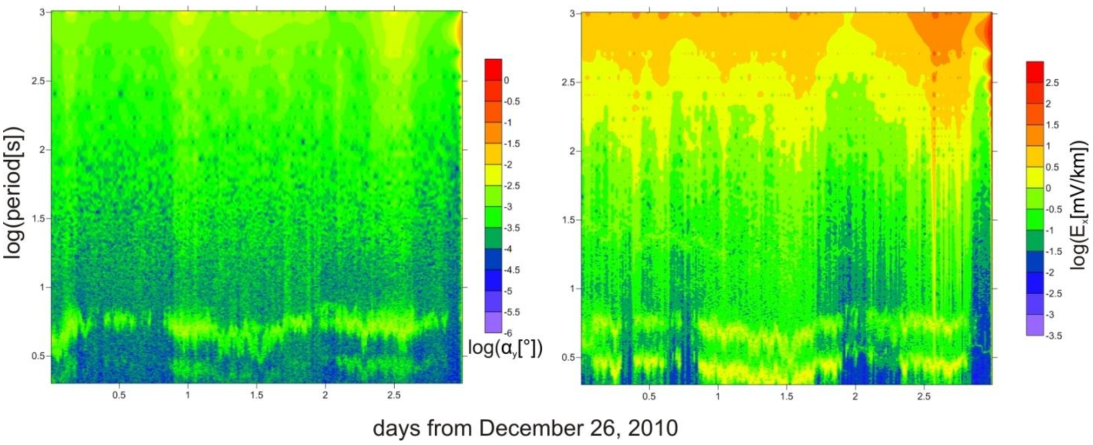

Fig. 3 Dynamic tilt (left-hand side) and electric field (right-hand side) spectra of site M16 offshore Namibia. The dominant period (log(6s) ≈0.8 on y axis) and its first harmonic (≈0.5 on y axis) are visible as horizontal signatures, the latter is more pronounced in the electric channel.

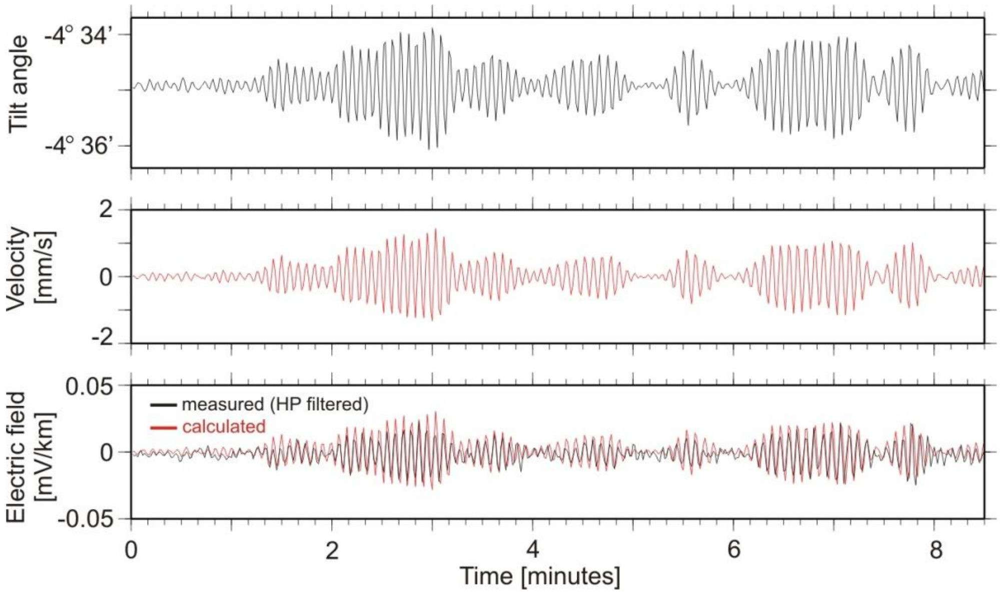

Fig. 4 The predicted electric signal (lower panel, red color) calculated from the tilt record (upper panel) via the velocity (middle panel) and the main magnetic field agrees well with the measured electric signal (after high-pass filtering to remove the large-amplitude natural MT signal, lower panel, black color). Data from site m04 offshore Costa Rica on September 22, 2007, start 08:54.

3. Constraints on the source mechanism of instrument's motion

It is obvious that the marine stations rock because they are forced by water motion. However, details on that water motion are not really known due to the fact that the sites are not accessible to direct observation during their work on the seafloor. On the other hand, from a multitude of marine observations, partly also from other geophysical methods, certain indirect conclusions on the source mechanism of tilt motion have been drawn. In this work we want to contribute to this discussion.

From experience with GEOMAR instruments we can say that the intensity of motion noise varies both between and within data sets and that there is evidence for a dependency on steep bathymetry (Neska et al. 2013), but often that noise is weak and does not pose a problem for further data processing. Nevertheless, it occurs in marine environments all over the world with a dominant period as mentioned above. This has been confirmed directly for data sets from the Pacific Ocean offshore Costa Rica, for the Atlantic Ocean offshore Namibia, for the Baltic Sea, and for the Mediterranean Sea.

The suspicion that the phenomenon of microseisms (Longuet-Higgins 1950) could influence marine electromagnetic measurements as well has been pointed out a long time ago (Cox et al. 1978). Microseisms is generated by meteorologic conditions like storms at the open ocean or by interaction of surface waves with coasts (Chevrot et al. 2007), and it is encountered in seismic data at similar frequencies as our motion noise (Kedar et al. 2008), hence it seems to be a possible explanation for the tilt motion. Microseisms between stations in the same region is strongly correlated (Bromirski 2001). Hence we check the coherence between tilt records of neighboring stations to test this hypothesis.

The coherence between tilt channels α_1 and α_2 of two stations is given by the formula

$$coh^2 = \frac{|\langle \alpha_1 \alpha_2^* \rangle|^2}{\langle \alpha_1 \alpha_1^* \rangle \langle \alpha_2 \alpha_2^* \rangle}$$

which is a function of frequency and where the asterisk * denotes the conjugate complex and brackets a stacking over a number of coefficients having the same frequency.

Acoustic waves in water have a propagation velocity of ca. 1500 m/s. Taking into account that the distance between neighboring stations considered here is about 20 km, the difference between arrival times at both stations can amount to somewhat more than a dozen seconds. This is much more than one would expect in an analog consideration of electromagnetic coherence and needs time windows of sufficient length during the calculation. The calculation has been done in a sort of cascade decimation with a start length of 4096 samples (= 4096 s). The results are displayed as dynamic spectral plots, where time dependence is shown along the x axis, period dependence along the y axis, and coherence (or amplitude, resp.) as color. The time resolution is (according to the basic time window length) one hour with a small overlap. Coherence values at periods > 100 s originating from this calculation are stacked only over a small number of coefficients (~10) which leads, unfortunately, to a "numerical" bias that is always directed upwards.

This operation has been applied to a pair of neighboring stations of the Costa Rica data set (Fig. 5) and of the Namibia data set (Fig. 6). From both perpendicular tilt channels of each station the ones have been selected which by incident are oriented roughly parallel (but the remaining three pairings have also been analyzed – with the same final result). The tilt motion is stronger for the Costa Rica example (note that the amplitude color scale is the same in both pictures) although streaming conditions and bathymetry at the Namibian Walvis Ridge are difficult, this reflects the enhanced stability of the new-generation GEOMAR instruments. The dominating frequency is visible in every amplitude plot as a horizontal structure sticking out from the background, and the latter is rising gently with period and varying over time. These time variations may appear roughly similar in both pairs of neighboring stations. However, the coherence plots for both pairs show one pervasive result and this is zero or values very close to zero. Tilt motion is not coherent between neighboring stations. Hence it cannot be connected to microseisms.

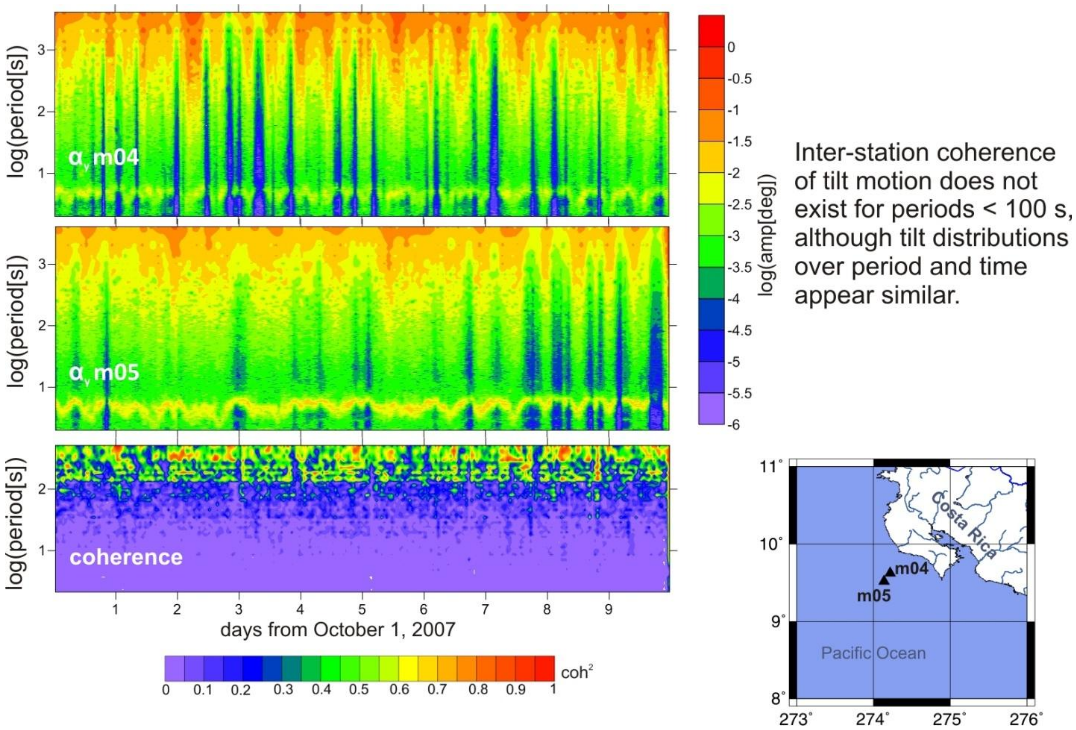

Fig. 5 Dynamic spectral power of tilt channels of stations m04 and m05 offshore Costa Rica (both upper panels) and coherence between them (lower panel). See text for interpretation.

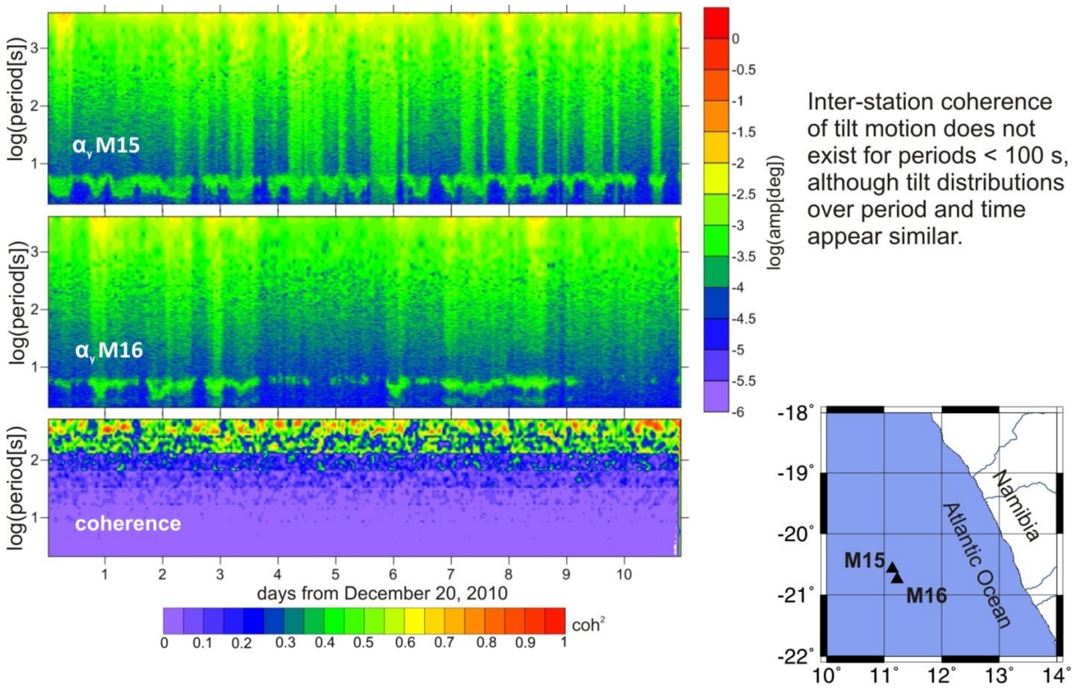

Fig. 6 Dynamic spectral power of tilt channels of stations M15 and M16 offshore Namibia (both upper panels) and coherence between them (lower panel). See text for interpretation.

However, there is evidence that the frequency of the instrument's motion depends on the device type: For the marine MT instruments of the Woods Hole Oceanographic Institution (WHOI), a dominant noise period of 4.5 s is reported (Lezaeta et al. 2005), which is significantly different from the GEOMAR one. Together with the first harmonic of our tilt frequency mentioned in section 2, this supports another idea of how the instrument's motion is generated. The dominant frequency of tilt motion and its harmonic(s) could be eigenfrequencies of the instruments that are excited by water motion, and it is not necessary to assume that the water motion is periodic or wave-like, but a simple streaming would be sufficient to explain the observed effects.

4. How to deal with the resulting disturbances

If the "signal packages" of tilt motion occur frequently and have large amplitudes as in Fig. 2, the motion noise on magnetic channels becomes so strong over the whole period range that a usual data processing can fail. This does not happen in many data sets nor in all stations of them, but occasionally (as for a part of the Costa Rica 2007 survey) strict manual selection of quiet time series fragments was necessary to obtain usable processing results (Worzewski 2011). In such cases it is advisable to correct the magnetic time series for the part induced by tilt motion before the processing. This is possible in two ways:

First, one can re-rotate every sample of the magnetic field vector into a fixed coordinate system by means of the corresponding tilt values (e.g., Nowożyński 2005). This works on the condition that the whole field vector including the static main field is known. Hence this method is limited to marine MT stations utilizing fluxgate magnetometers. Moreover, a careful calibration of the instrument's offsets (that are closely connected to the static field, but not relevant for field variations and therefore sometimes neglected in MT) is required for an effective performance of this method.

Second, a tilt-response correction can be carried out, which does not require the whole field vector. Here a transfer function is estimated between the tilt channels and the magnetic ones, that is used to reconstruct the tilt-induced part of the magnetic records, which, in turn, is subtracted from the original magnetic data. Both methods significantly improve the processing results of data affected by heavy motion noise (details in Neska et al. 2013).
If motion noise is present in a dataset, but not strong enough to justify an explicit correction for it, or if tilt records are unavailable, it is advantageous to apply a processing approach that takes the special distribution of motion noise into account. Many processing codes treat the horizontal magnetic channels by default as input channels during transfer function estimation, because they are usually less noisy than the electric ones in onshore MT. This would be an inopportune approach here, where electric channels (except for the shortest periods) are practically free of motion noise even where magnetic ones are strongly affected (cf. section 2). Here magnetic channels should not be used as input channels, neither in a single-site processing nor as reference channels in case of an application of the remote-reference technique (Gamble et al. 1979, note that a remote reference processing with offshore stations is allowed because motion and motion noise is not coherent between different sites as shown in section 3). Instead, one should either use electric channels as input and reference ones or apply a processing approach that is independent of such input/output schemes. Egbert's multiple-station processing (Egbert 1997) based on a Principal Component Analysis (PCA) can be recommended in this context, particularly because it has another advantage from a marine point of view: Its facility (or even need) to process data of many synchronous stations in one run fits to the fact that stations of marine arrays are both dropped and collected within a short time, hence their data are synchronous to a great extent. However, one should be cautious when estimating geomagnetic transfer functions with this method, because motion noise is highly coherent between the vertical and the horizontal magnetic components of a station (Fig. 2), and the PCA is sensitive to such complications.
Figure 7 shows which meaning the choice of an appropriate processing approach can have for the quality of a sounding curve.

5. Conclusions

Based on the datasets analyzed here, the hypothesis that microseisms are the source of instruments' motion in marine MT has to be regarded as improbable. Important arguments are first, that tilt motion is not coherent between neighboring stations as it is the case for wave fields connected to microseisms, and second, that the dominant frequency of tilt motion seems to depend on the device type. The latter favors rather an interpretation of the tilt motion patterns as an eigenfrequency of the instrument excited by an arbitrary water motion (e.g., streaming). However, these conclusions are drawn in a rather indirect way and further data may confirm or refute them.
The motion noise on the magnetic channels can either be reduced explicitly by means of a re-rotation or the tilt-response correction utilizing the tilt records, or its influence on transfer functions can be suppressed by applying processing approaches that do not use magnetic records as input channels.

Acknowledgements

The authors thank Sebastian Hölz and Lars Planert for sharing valuable information on microseisms.

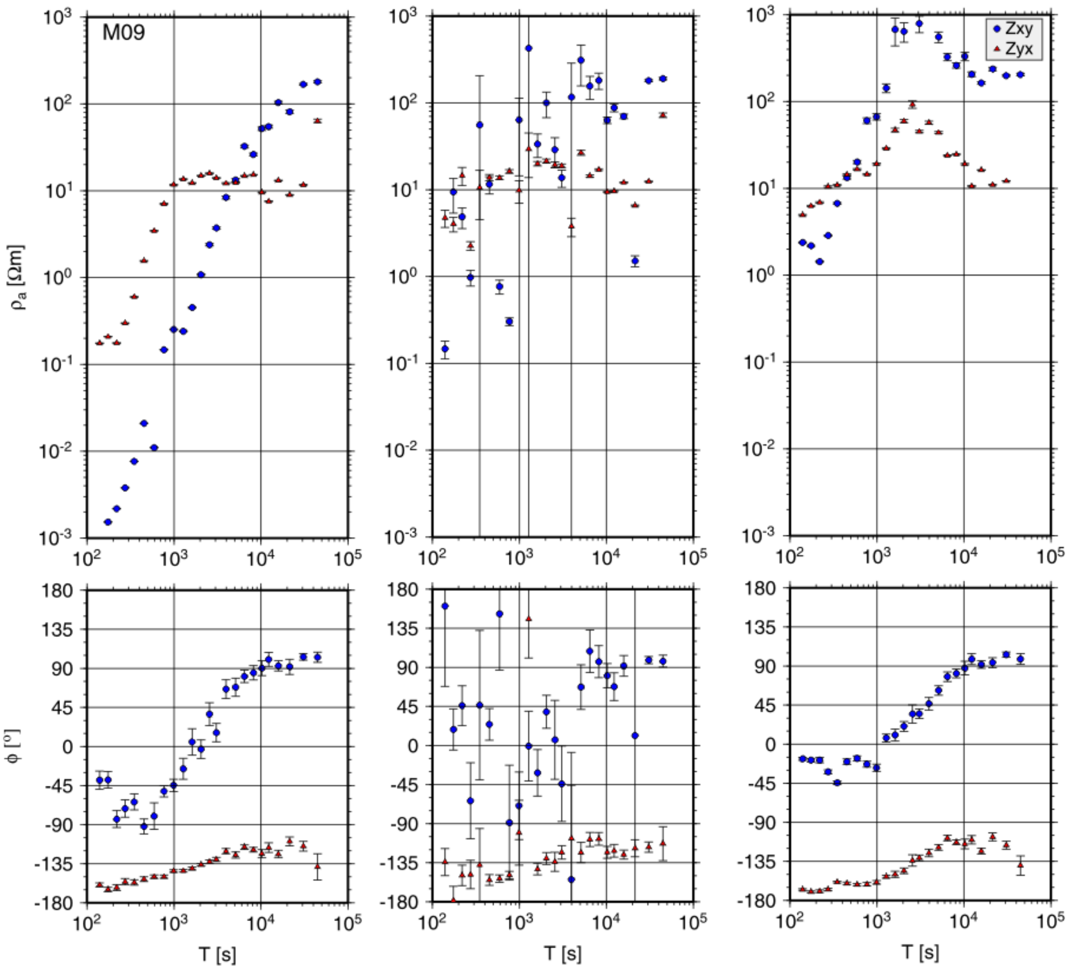

Fig. 7 Sounding curves of site M09 offshore Namibia rotated to geomagnetic coordinates. Left-hand side processed single-site after Egbert & Booker (1986) which leads to a heavy down-bias of ρ_a because of motion noise in the magnetic channels. Middle processed with the remote reference M15 and the same code which corrects the bias but leads to wild scattering due to magnetic motion noise in the reference. Right-hand side after multiple-station processing (Egbert 1997) of both sites which yields a reasonable, somewhat scattered result, cf. Fig. 1. Both stations are affected by moderate motion noise (cf. Fig. 6 for M15). Of course, including more stations significantly improves the multiple-station result, but here we want to draw attention on the fact that not only the amount of stations or data used matters, but also the method they are processed with.

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