RRMC TECHNIQUE FIGHTS HIGHLY COHERENT EM NOISE

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1. Introduction

This paper presents recent advances in the data processing techniques for the magnetotelluric (MT) and magnetovariational (MV) geophysical methods with a special focus on approaches to overcome the distortions from the highly coherent electromagnetic (EM) noise (Junge, 1996) in the observed time series. The effectiveness of these advances is illustrated at the long-period (LMT) data set collected in Polish-German Pomerania within the EMTESZ-Pomerania project (Brasse et al., 2006) and at the broadband data set of simultaneous MT soundings in the industrial area in Central Russia (Yakovlev et al, 2002). In the both cases a strong data contamination takes place with an intensive and widely spread, both spatially and within the period range, industrial EM noise.

The EMTESZ-Pomerania project investigates in the related area the deep conductivity structure of the whole lithosphere across the Trans European Suture Zone (TESZ) using the natural electromagnetic (EM) field of the Earth (EMTESZ-Pomerania WG, Varentsov, 2004). The EM sounding array observed within this project during several field seasons in 2001-2005 years counts more than 100 LMT and 60 audio-MT sites located mainly along the regional seismic profiles P2, LT-7 and LT-2 (Fig. 1). The data acquisition scheme implies the arrangement of the sounding sites into several spatially overlapping simultaneously observed subgroups and the installation of a number of continuously running field stations (G7, P8, P55) to serve as base sites and far remote references together with 3 adjacent observatories (HEL, NGK and BEL). This approach permits to apply effective noise suppressing data processing procedures relied upon simultaneous observations and, finally, to construct a reliably estimated joint set of array-wide inter-station and local transfer functions (TF).

The paper starts from a brief description of the general data processing approach implemented in the PRC-MTMV software system (Varentsov et al., 2003; Varentsov, 2005) primarily applied for the multi-site TF estimation in the EMTESZ-Pomerania EM array sounding. It further presents a new RRMC technique, which is based on the remote reference (RR) scheme and implies the data sorting strategy for partial TF estimates with the account for several criteria exploiting the spatial-frequency homogeneity of the horizontal magnetic field related to the MT signal. This technique was originated in the frames of the EMTESZ-Pomerania project following the goal to construct trustworthy TF data ensemble overcoming the severe correlated cultural noise met at many of array sites, primarily, due to the current leakage from the DC-railway system (Palshin and Smirnov, 2005).

2. Techniques for multi-site TF estimation in simultaneous EM soundings

A number of data processing techniques have been applied in the EMTESZ-Pomerania project to cross-verify the estimates in the presence of strong noise. In this study we will concentrate mainly on the results of the Troitsk team (GEMRC IPE RAS) obtained with a help of PRC_MTMV processing system.

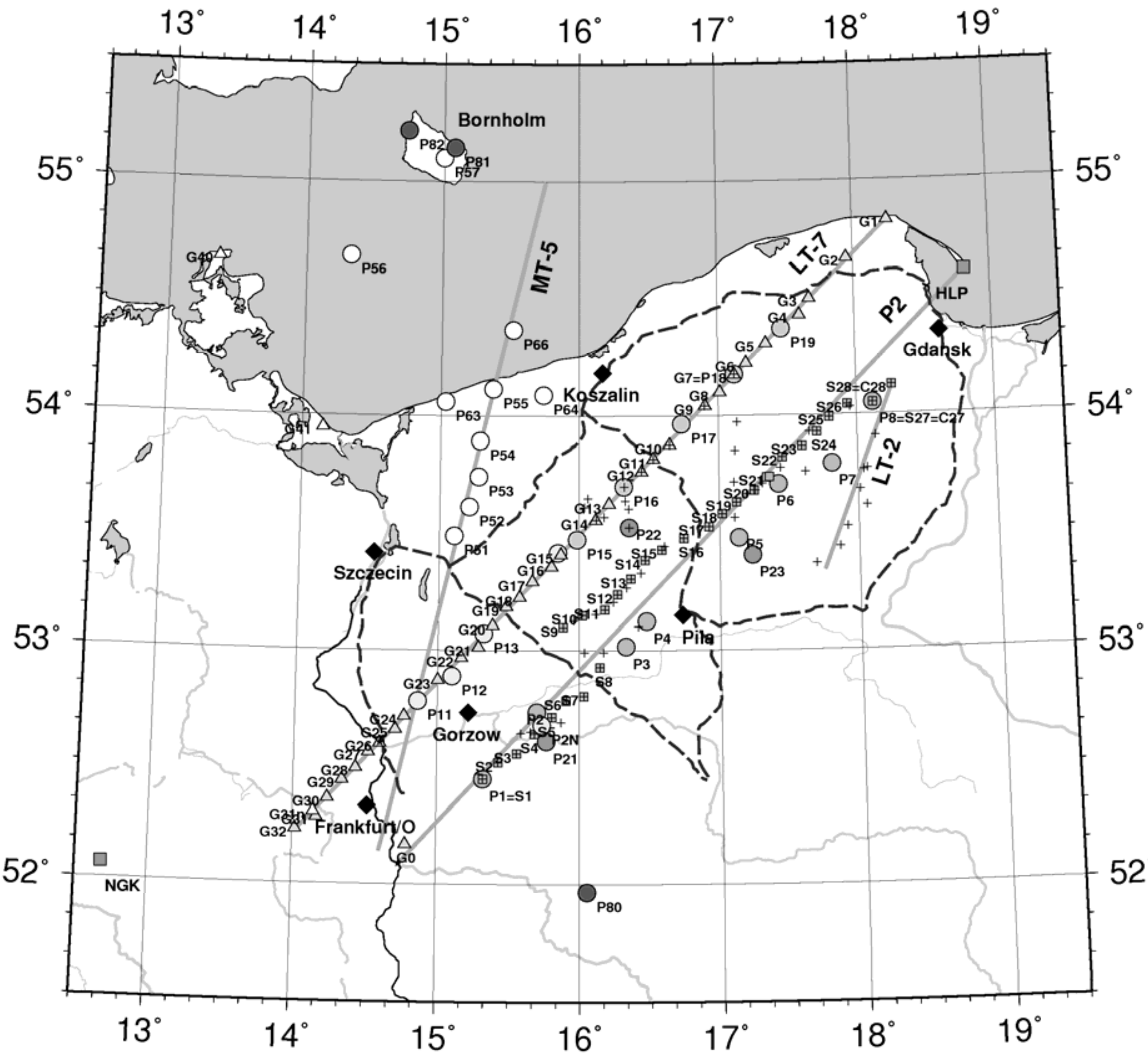

Figure 1. The EMTESZ-Pomerania array of EM soundings (Varentsov et al., 2005): Gxx (triangles) – German, Pyy (circles) – Polish, Szz (squares) - Swedish LMT sites, crosses – Czech, German and Swedish audio-MT sites; NGK and HLP (boxes) – geomagnetic observatories; dashed lines – DC railways.

The following set of transfer operators estimated for simultaneous MT and MV soundings in the frequency domain combines the local operators:

impedance $\mathbf{Z}$, $\mathbf{E}_h(r) = \mathbf{Z}(r)\,\mathbf{H}_h(r)$,

tipper $\mathbf{W}_z$, $H_z(r) = \mathbf{W}_z(r)\,\mathbf{H}_h(r)$,

and inter-station (simultaneous) operators, connecting the geomagnetic components at the sounding (r) and remote (r_{RR}) sites:

horizontal magnetic tensor $\mathbf{M}$, $\mathbf{H}_h(r) = \mathbf{M}(r, r_{RR})\,\mathbf{H}_h(r_{RR})$,

simultaneous (regional) tipper $\mathbf{S}_z$, $H_z(r) = \mathbf{S}_z(r, r_{RR})\,\mathbf{H}_h(r_{RR})$,

here indices $_h$ and $_z$ point to horizontal and vertical EM field components respectively.

The PRC_MTMV system provides the successive application of the following estimation schemes in the construction of the TF ensemble: single site (SS), remote reference (RR) and multi-remote reference (mRR) (Varentsov et al., 2003; Ernst et al., 2002). The pre-processing techniques, used in the software, include multi-record time domain data conversion into first differences with further peak/jump/linear trend elimination. Then follows the high-resolution spectral analysis (within a FFT procedure) for large overlapping windows from 1 to 256 Ksamples and the calculation of partial (single extent) TF estimates. The further sorting of these partial TF estimates implies global (data rejection for the whole record extent) and local (rejection for a period) selection of the acceptable data according to several coherency-based (input and mutual) criteria. Then the multi-level robust stacking of selected partial TF estimates applies in a bi-coordinate scheme with the multi-extent and multi-period smoothing. The next stacking level implies the averaging of partial estimates obtained for the sequence of time record extents for a fixed time-window length. Then the robust multi-window averaging takes place operating with the results obtained for a set of increasing time-windows. This level gives a specific protection from non-stationary noise events with relatively narrow spectra. The final stacking level is the multi-RR (mRR) estimation for a set of different remote sites.

The PRC_MTMV processing system incorporates the following options of the accuracy control: the fit of single-record estimates, the fulfilment of the dispersion relations (DR) for the local TF responses (Ernst et al., 2002) and the comparison of different transitive estimates for inter-station ones (Varentsov et al., 2003).

The experience in the processing of simultaneous MT/MV array data within the BEAR (Baltic Electromagnetic Array Research) deep sounding project (Varentsov et al., 2003; Varentsov, Sokolova, 2003) has proved the effectiveness of conventional coherency weighting and multi-RR technique applied for the suppression of low coherent industrial noise in the short-period band as well as the source effects in middle and long-period range of TF estimation. However, during the EMTESZ-Pomerania experiment, when strong coherent noise was met in the vicinity of DC-railways, this RR estimator appeared to be ineffective. We got a strong need to equip our processing algorithms with specific tools directly fighting highly coherent noise effects.

3. RRMC scheme - remote reference with magnetic control

The dominant local coherent noise sources, like DC-railways, make EM fields at noisy record extents highly coherent, both locally, turning impedance and tipper partial estimates far away from the plane wave responses (Junge, 1996), and regionally, forcing strict variations in the inter-station TF data. The conventional robust stacking cannot properly handle strongly contaminated sets of partial estimates because the conventional coherency sorting fails to reject the noisiest data. A new sorting strategy to discriminate the most unfavourable record extents can be based on the control of the horizontal magnetic field spatial variability in the area between the sounding site and several selected remotes, which can be relatively low for the MT signal and high enough for local noise sources (Ritter et al., 1998). Such an approach requires for the joint estimation of local $\mathbf{Z}/\mathbf{W}_z$ operators with the horizontal magnetic tensor **M** and may be abbreviated as **RRMC** (**RR**-estimator with “**M**agnetic **C**ontrol”).

Three MC sorting criteria are jointly applied to partial **M**-tensor estimates in our current RRMC procedure (Varentsov and Sokolova, 2004; Varentsov, 2005), namely:

the variability criterion: **M**-tensor should be close to *a priori* expectations ($\mathbf{M}^0$, unit, as default), implied by the geoelectric structure, i.e. the misfit $\|\mathbf{M}(\mathbf{r},\mathbf{r}_{\mathrm{RR}})-\mathbf{M}^0(\mathbf{r},\mathbf{r}_{\mathrm{RR}})\|$ should be small;

the reciprocal criterion: the product of direct and "inverse" estimates of the horizontal magnetic tensor between the sounding and remote sites should be close to unit operator, i.e. the misfit $\|\mathbf{M}(\mathbf{r},\mathbf{r}_{\mathrm{RR}})\mathbf{M}(\mathbf{r}_{\mathrm{RR}},\mathbf{r})-\mathbf{I}\|$ should be small;

the coherency criterion: the mutual coherency of partial $\mathbf{M}(\mathbf{r},\mathbf{r}_{\mathrm{RR}})$ estimates should be high.

These criteria are applied both locally (at each estimation period) and globally (at a record extent in average for the whole estimation period range). The conventional criteria, limiting the input coherency of local horizontal magnetic fields to exclude strict linear polarization effects (Varentsov et al., 2003), can also be effectively applied in the presence of the coherent noise, while the mutual coherency thresholds for $\mathbf{Z}/\mathbf{W}_z$ are set in this case to quite low values. The partial estimates passing two conventional and three MC sorting criteria enter the multi-level stacking procedure outlined in Sec. 2, which gives the final multi-RRMC response.

The first MC criterion was initially suggested in (Ritter et al., 1998). It can be most effectively implemented with the use of the preliminary estimated "stationary" response $\mathbf{M}^0$. A trivial unit approximation $\mathbf{M}^0=\mathbf{I}$ also works, but needs more efforts in the selection of the related threshold. The reciprocal criterion is better scaled, and it is easier to select the threshold for it. The idea to exploit M-tensor reciprocal properties was also used in (Pek, 2004) for the quality control of the final estimation results, however, in our case it is applied much earlier for the sorting of partial estimates, and thus serves to improve the data quality. The third MC criterion is also important, because the mutual coherence in the RR estimation of the impedance or tipper is dependent on the quality of linear relations between both the local field components and the horizontal magnetic fields in the sounding and remote sites. In the presence of highly coherent noise it is advisable to reject directly partial estimates with a low quality of horizontal magnetic relations, independently of the level of the mutual $\mathbf{Z}/\mathbf{W}_z$ estimation coherency.

Finally, it should be stressed, that the tipper estimates appears to be the most sensitive to the coherent noise influence. Their amplitudes in this case rise up to and even high above the unit level. That is why in the tipper RRMC estimation we suggest also to limit the norm of its partial estimates as a forth MC criterion, just like it was done in (Garcia et al., 1997) for the control of sub polar source distortion effects.

4. Elimination of industrial EM noise effects in the EMTESZ-Pomerania TF data

The "magnetic control" approach in different implementations proved its effectiveness in regions with a high level of industrial noises, in particular, in Italy (Larsen et al., 1996), Scotland (Ritter et al., 1998) and north-eastern Germany (Oettinger et al., 2001). Varentsov and EMTESZ-Pomerania WG (2004) presented the first successful experience in the use of the RRMC scheme in the EMTESZ-Pomerania project. We consider below the project area with highly coherent EM noises in the vicinity of Krzyz–Choszczno segment of the Poznan–Szczecin DC railway, crossed with 2 LMT sounding profiles, LT-7 and P2 (Fig. 2).

The signal/noise separation procedure (Larsen et al., 1996) applied to the EMTESZ-Pomerania data at several sites in the vicinity of the mentioned railway (Palshin and Smirnov, 2005) shows that the coherent noise (CN) in the observed EM field is maximal in the period range of 20-300 s and for the measurements at the LT-7 profile done in 2004 year, when the magnetic activity level was substantially weaker than for sites at the P2 profile in 2003 year. Correspondingly the distance from this railway to the sites, where the coherent noise prevails over the MT signal, changes from 20-30 km (at LT-7) to 10-15 km (at P2). The CN data have quite comparable spectral intensities in different directions, but they are dominant in the northern electric field, because this component of the MT signal is significantly weaker then the eastern one. Naturally, almost the same regularities are observed in the distributions of TF distortions, caused by DC trains.

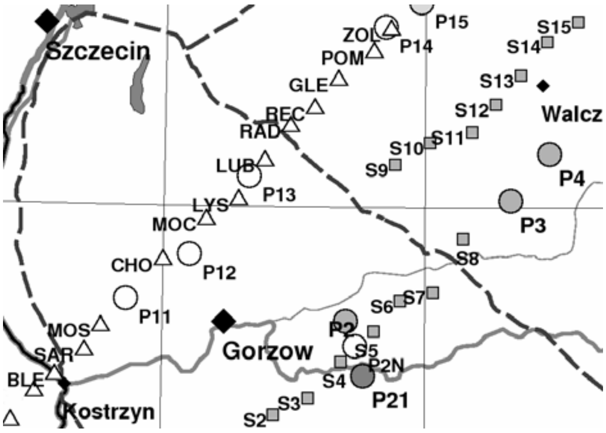

Figure 2. The map of LMT sites crossing the Poznan – Szczecin DC railway (dashed line) at the P2 (2003) and LT-7 (2003-2004) profiles of the EMTESZ-Pomerania experiment.

Fig. 3 presents the results of SS, RR and RRMC estimation of the impedance at the site S07 at the P2 profile, located 8 km apart from the DC railway (Fig. 2). The “northern” impedance Z_{xy} exhibits highest distortions of SS estimates: the phase in the period range of 10-1000 s is strictly shifted to the zero, while the amplitude has a false maximum. The conventional RR estimates for different remotes are shown in different colours at the left panel. They are practically similar to SS responses for 3 closest sites S06, S08, S05 (at distances of 9, 10 and 18 km) and are still disturbed for remote sites S13-S16 (at distances of 60-90 km). Only for remotes P07 and P08 (at distances of 160 and 195 km) noises seem to be suppressed.

The RRMC algorithm effectively eliminates distortions for most of remotes (starting from S05 in 18 km from the railway), rejecting up to 90-95% of partial estimates (Fig. 3, right panels). The following multi-RRMC robust averaging for all the remotes at 18-200 km distances (and even for a part of them at 18-90 km) gives quite acceptable amplitude estimates. But note the obvious difference between the long period RR and RRMC phases even for the most distant remotes P07 and P08. We really need such far remotes and the MC sorting to get reliable phase estimates.

Another important view on the EM noise effects at the sites S05-S10, closest to the railway, is presented for the tipper estimates in Fig. 4. In the left panel real induction arrows, calculated for strongly distorted SS tipper estimates and given in Wiese convention, clearly point to the railway at sites S06-S08 till the period of 512 s. The effectiveness of the mRRMC “cleaning” for these data is shown in the right panel, where the railway becomes almost “invisible”.

The next figure compares pseudo sections of the “cleaned” mRRMC and the distorted SS estimates for real induction vector lengths (Fig. 5a) and Z_{xy} impedance phases (Fig. 5b) along the whole P2 profile. The mRRMC estimator was constructed for a number of remote sites ranging from 3 to 6 at distances greater than 50 km, including the observatories (BEL, HLP and NGK). The mRRMC data are almost free from strict distortions, clearly seen in the SS pseudo sections as the strongest tipper anomalies at periods around 50-100 s and impedance phases approaching the zero.

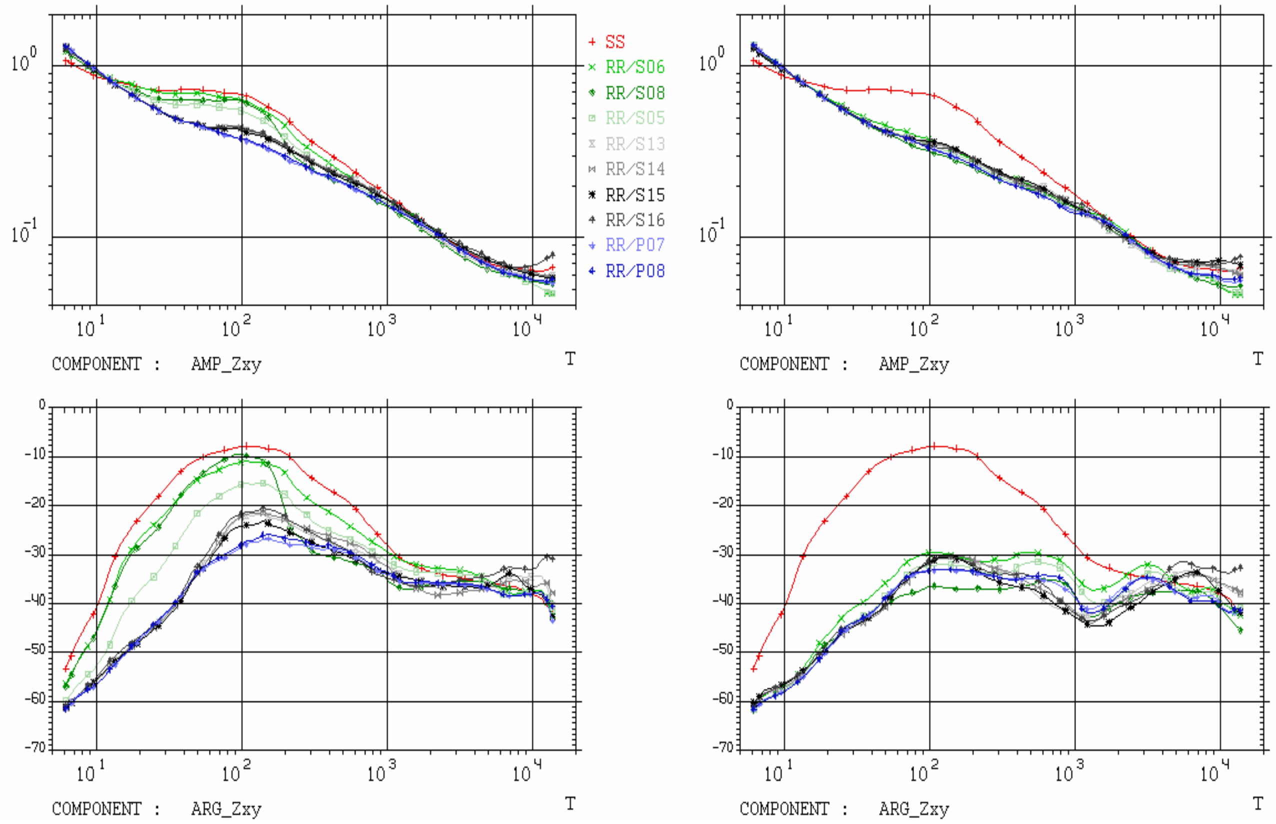

Figure 3. The results of SS, RR (left) and RRMC (right) estimation of Z_{xy} impedance at the site S07 (amplitudes in practical units at top panels, phases in degrees at the bottom ones).

The next figure compares pseudo sections of the “cleaned” mRRMC and the distorted SS estimates for real induction vector lengths (Fig. 5a) and Z_{xy} impedance phases (Fig. 5b) along the whole P2 profile. The mRRMC estimator was constructed for a number of remote sites ranging from 3 to 6 at distances greater than 50 km, including the observatories (BEL, HLP and NGK). The mRRMC data are almost free from strict distortions, clearly seen in the SS pseudo sections as the strongest tipper anomalies at periods around 50-100 s and impedance phases approaching the zero.

The impedance and tipper mRRMC estimation can be further improved with the switch in the “variability” MC criterion from the currently used simplest assumption $\mathbf{M}^0 = \mathbf{I}$ to the final robust **M**-tensor estimate. Even the conventional two-site **M**-tensor estimation scheme (without the use of RR approach, which requires simultaneous records at 3 sites) results in sufficiently “clean” responses. In fact, Fig. 6 presents invariants, namely, principle amplitudes and directions (Varentsov, 2005; Varentsov et al., 2004, 2005) of such **M**-tensor estimates at the same sites and periods as for induction arrows in Fig. 4, hardly displaying any influence of the railway.

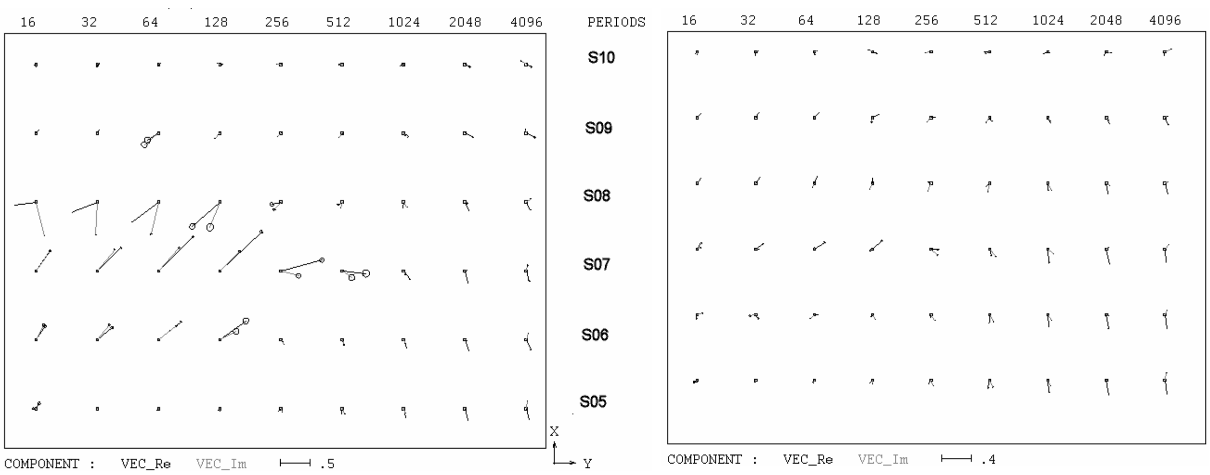

Figure 4. The spatial-period image of induction arrows (Re and Im, Wiese convention) for the SS (left) and mRRMC (right) tipper estimates at 6 sites (S05-S10) along the P2 profile segment; arrows are presented in geographical coordinates with scales indicated below panels; the railway passes between S07 and S08 sites in the NNE direction.

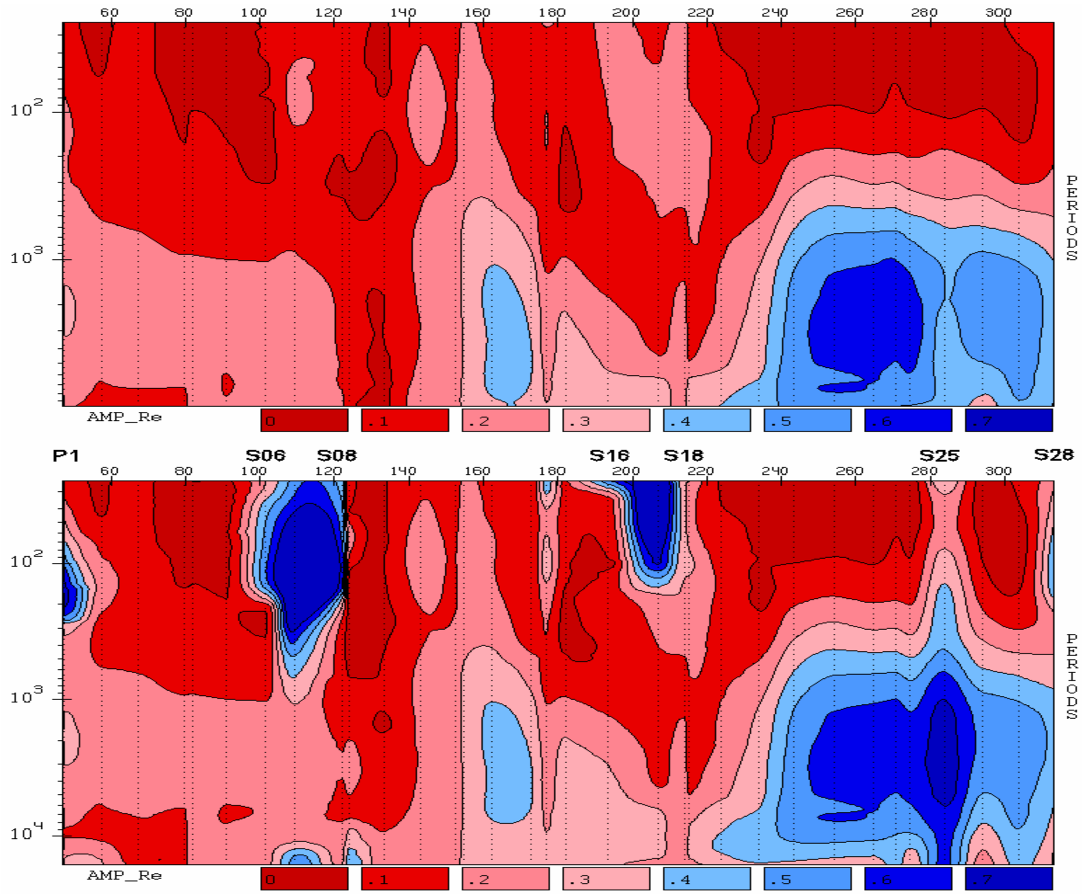

Figure 5a. The pseudo sections of mRRMC (top) and SS (bottom) estimates of real induction arrow lengths along the whole P2 profile; DC-railways cross the profile between sites S06 and S08, S16 and S18; the airport is located at the left end of the profile close to site P1.

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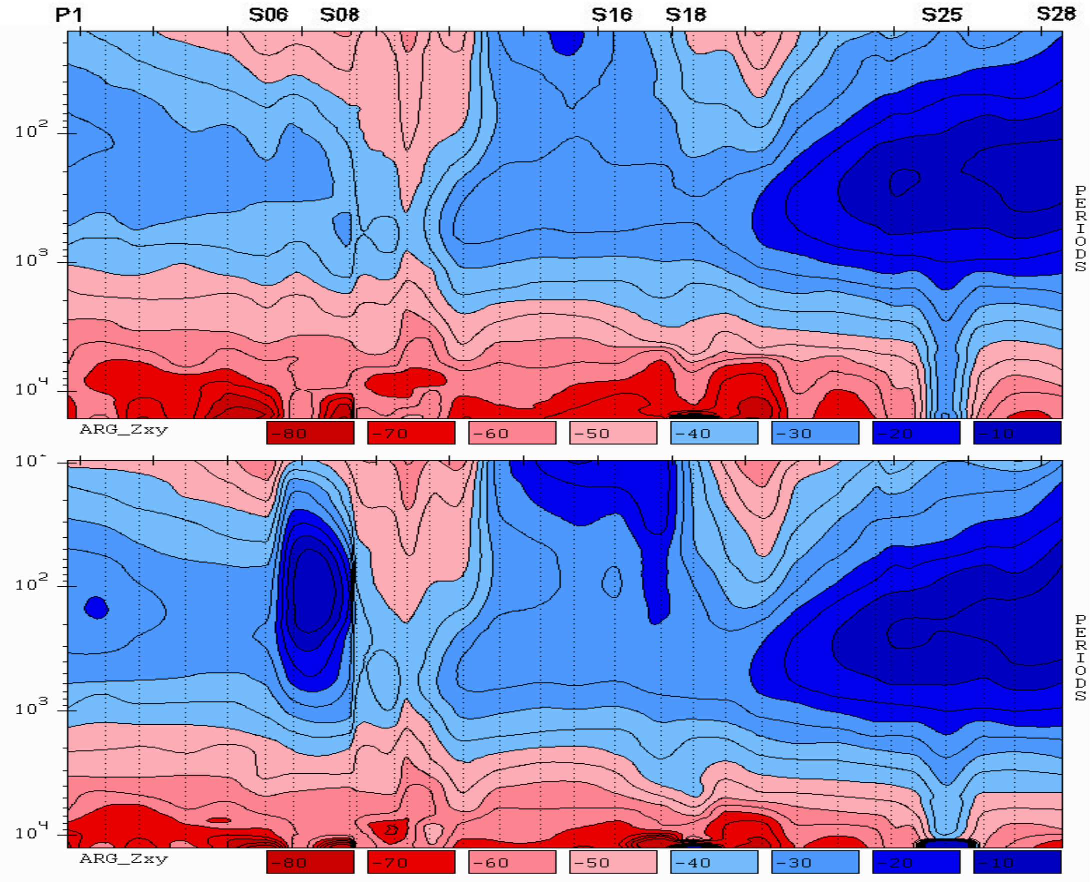

Figure 5b. Pseudo sections of mRRMC (top) and SS (bottom) estimates of Z_{xy} impedance phases along the whole P2 profile, see legend to Fig. 5a.

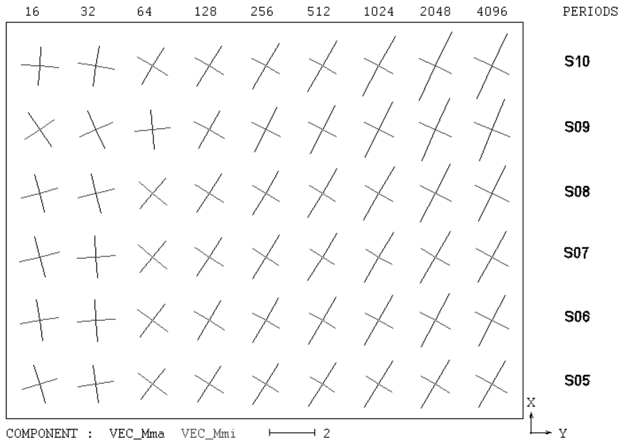

Figure 6. The spatial-period image of minimal and maximal amplitudes and azimuths of the **M**-tensor (given as crosses) at 6 sites (S05-S10) from the same P2 profile extent as in Fig. 4.

The MC sorting criteria are now implemented in the mentioned two-site **M**-tensor estimation procedure and with this enhancement we recently reprocessed data at a number of “critical” Pomeranian sites located close to railways to improve the final horizontal magnetic tensor estimates.

5. Temporal monitoring of partial impedance estimates at “noisy” and “clean” sites

The deeper insight on the specific features of the TF distortions caused by EM noise effects typical in Pomerania may be obtained in the course of the temporal monitoring of partial impedance estimates, using the approach developed by Sokolova (2002), Varentsov and Sokolova (2003). Two 5.5 days long simultaneous data records at very noisy site S07 and almost clean P8 (Fig. 1) were analysed at a sequence of non-overlapping 4.5 hour long extents. Fig. 7 presents Z_{xy} pseudo sections, revealing the temporal variability of partial SS estimates in a broad period range in the comparison with the final mRRMC estimates, placed in 3 left and right side columns on each plot. The moderate temporal variability observed at the site P08, far distant from the DC railway, seems to be controlled by the local signal/noise ratio primarily dependent on the MT source intensity. On the contrary, the pseudo section for the site S07 at the periods up to 500 s represent dominantly the responses of the coherent DC-events, and only in the morning hours, when the MT source intensity (in particular, for magnetospheric pulsations) is maximal (Palshin and Smirnov, 2005), rare extents favourable for the unbiased estimation can be found.

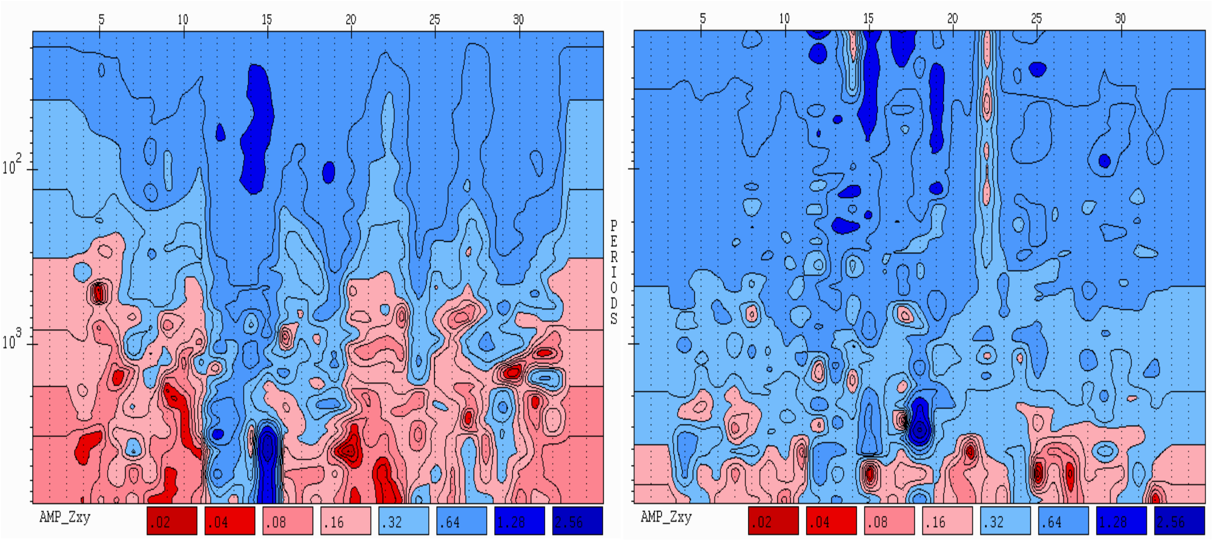

Figure 7. Temporal variability pseudo sections of Z_{xy} amplitude of SS partial estimates at 4.5 hour long non-overlapping record extents at sites S07 (left) and P8 (right); the horizontal axis gives record extent numbers, the vertical axis gives periods (s); three leftmost and rightmost columns at both panels present corresponding final mRRMC responses.

A different view on the temporal monitoring results is given in Fig. 8 in the form of Z_{xy} amplitude histogram at the site S07 and the period of 32 s for the same SS partial estimates as in Fig. 7. Two dominant modes are obviously traced in the histogram with amplitudes about 0.8 and 0.5, respectively. The first, most numerous cluster corresponds to intensive DC noise events (Fig. 3, SS amplitude curves), the second, considerably less numerous, represents extents with sufficient intensity of the MT signal. Amplitudes in this second cluster correspond to the level of the final mRRMC estimate (Fig. 7, side columns in the left panel). In the conditions of a middle range geomagnetic activity in 2003 the number of extents favourable for MT transfer function estimation counts at least in few percents even at sites 10 km close to DC railways. The RRMC technique effectively focuses the estimation at these extents.

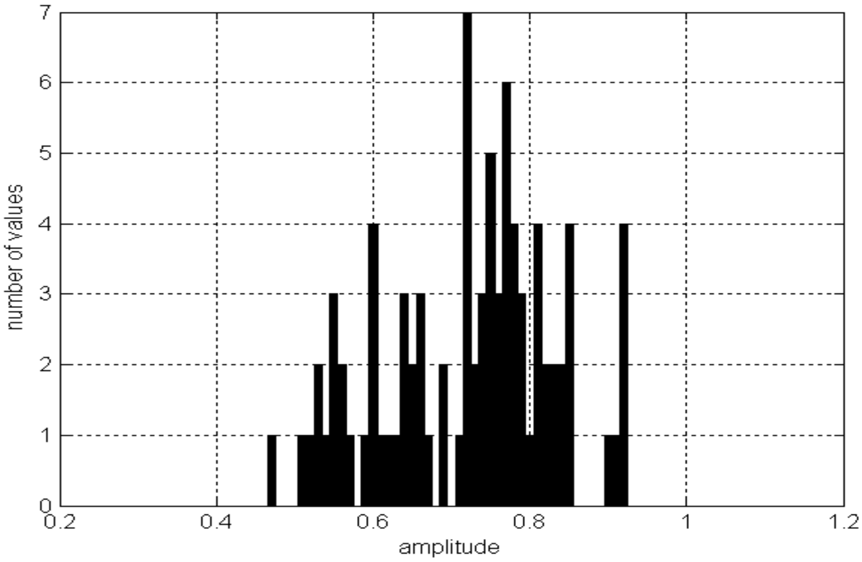

Figure 8. The histogram of Z_{xy} amplitudes at the site S07 and period of 32 s for single site partial estimates already shown in Fig. 7.

However, at few sites from the LT-7 profile, located closer than 20 km to DC railways and observed in 2004 at a lower geomagnetic activity level, the improvement in the mRRMC estimates looks considerable, but not sufficient. Only the final **M**-tensor estimates at these sites obtained in the two-site scheme with the MC sorting seems to be completely acceptable.

6. Application of the RRMC technique in the industrial Nyzhniy Novgorod area

Finally we demonstrate the effectiveness of the developed RRMC approach in the data processing of the simultaneous broadband MT survey carried out in the urban area of the Nizhniy Novgorod region (Yakovlev et al., 2002). This area is also characterized with a strong and highly coherent EM noise, produced by a number of sources of different nature, including power plants and lines, a dense railway system and a network of pipelines. The considered simultaneous sounding was performed with 3 Phoenix MTU-5 systems during two 20-hour intervals. The most distant remote site was located in the countryside about 100 km from the observation site.

Fig. 9 presents a set of different impedance estimates obtained both with our PRC_MTMV and the standard Phoenix software. We see dramatic distortions in both single-site estimates (amplitude and phase) in the period range of 1-30 s. The conventional RR estimators even for the carefully selected distant remote site cannot overcome these distortions. Only in the frames of the RRMC approach the amplitude estimates preserve the monotonous decrease with a period and both main impedances display the comparable shape in the noisy period range.

7. **Conclusions**

The new RRMC technique was developed in the course of the EMTESZ-Pomerania data processing work, which provides an effective suppression of the bias effects from the DC-railways and other dominant industrial noise sources. The essence of this technique is the application of an additional TF sorting strategy, based on the variability of the horizontal magnetic field spatial structure between the sounding and remote sites. The MC-sorting serves as an important resource in the estimation of local and inter-station responses. The multi-RR technique is now better equipped to meet the danger of highly coherent local and regionally distributed noise.

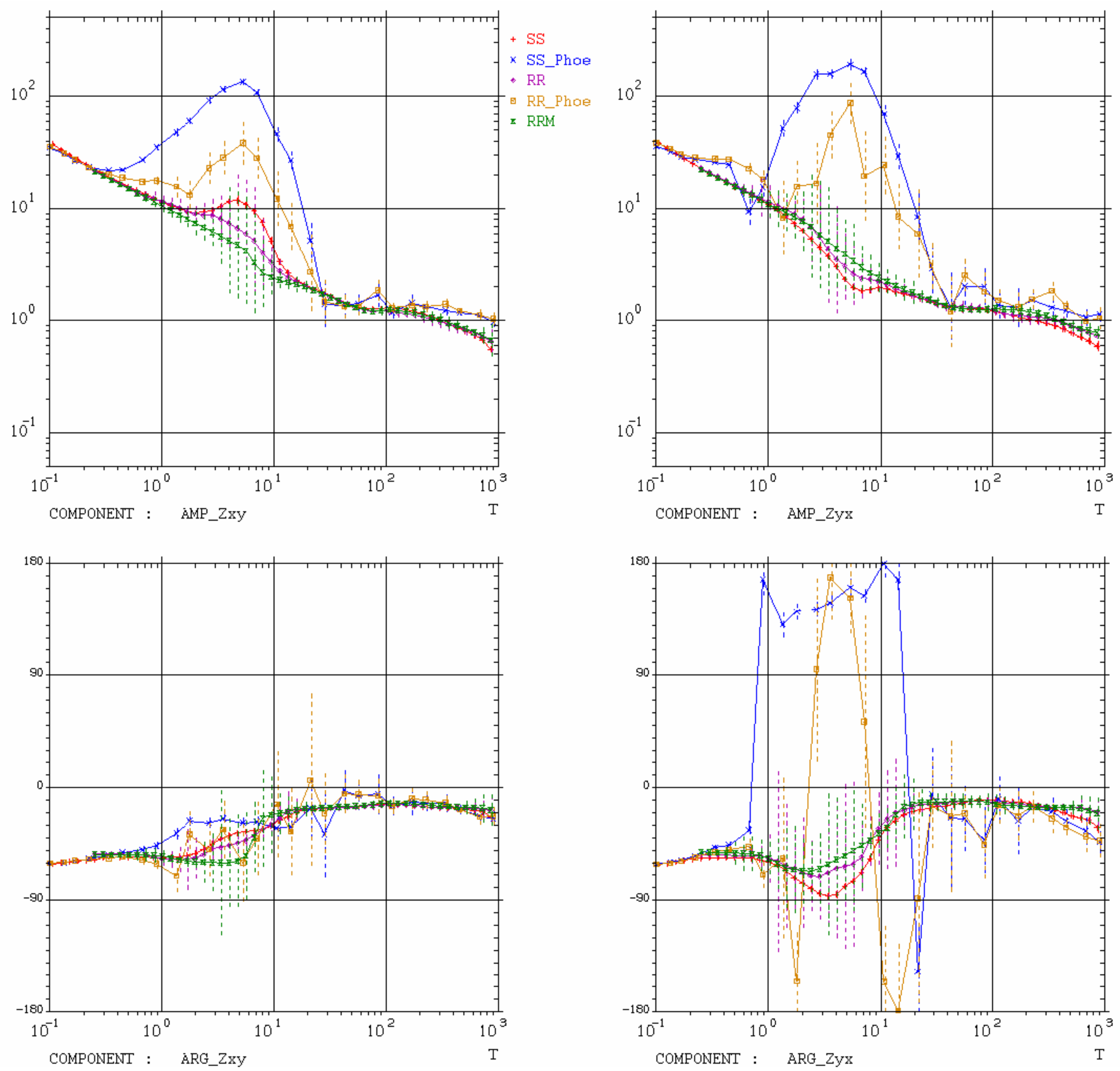

Figure 9. The period dependence of two main impedance estimates (amplitudes at top panels and phases at bottom ones) for the site in the industrial area in Nizhniy Novgorod region: single-site responses estimated in the PRC_MTMV system (SS) and obtained with the Phoenix data processing software (SS_Phoe); corresponding remote reference estimates (RR and RR_Phoe) and, finally, our RRMC estimate (RRM).

The developed approach in the Pomeranian conditions makes possible to concentrate the robust estimators at small, but favourable portion (till the very first percents) of the available data. It improves estimates for distant remotes (at hundreds of km), cleans results for medium remote separations (30-100 km) and thus simplifies the selection of remote sites for the multi-

RRMC procedure. An encouraging experience is obtained in the use of adjacent geomagnetic observatories as distant and long-term operating remotes.

All these efforts brought for the whole EMTESZ-Pomerania array (with very few exception sites) the reliable estimation of the impedance in the period range of 10-10000 s, of the tipper in the range of 30-10000 s, and of the horizontal magnetic tensor in the range of 60-20000 s. And at many sites with long enough observations, especially at the LT-7 profile, the longest estimation periods for the impedance and the **M**-tensor were further extended. The comparably good quality was achieved for different TF data components, main and additional, amplitudes and phases.

We advanced in the understanding, how the arrays of simultaneous EM soundings serve for the quality increase in the estimation of local TF operators based on the simultaneous analysis of multi-site data records. The unique experience in the construction of the array-wide system of inter-station geomagnetic responses from a series of observation campaigns is obtained. Several steps are made towards the construction of a new generation of multi-site data processing procedures, jointly estimating a number of EM field transfer operators with a deep exploiting of there specific features and inter-relations.

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