SOME ASPECTS OF MAGNETOTELLURIC FIELD PROCEDURES

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Abstract. Progress in magnetotelluric field procedures that has taken place over the past few years is reported upon. These include calibration procedure of equipment, misorientation effects, recording characteristics, in-field processing and trend towards future developments.

1. Introduction

The improvements in the quality of magnetotelluric data has taken place since the pioneering years in the fifties and sixties can be attributed both to better electronic amplifiers and hence better signal to noise ratios of the magnetic and electric sensors as well as to the introduction of digital data aquisition systems, which compared with analogue systems have a much better dynamic range.

Fischer (1982) in his review also emphasizes the improvements obtained by using SQUID magnetometers with their superior noise figures and the remote reference technique to reduce bias from impedance estimates. The papers by Gamble *et al.* (1978), Gamble *et al.* (1979a, 1979b) have now become classical papers on these subjects.

Since the publication of Fischer's review it can perhaps be said, that no major steps forward have been taken in improving measurement techniques and instrumentation. Probably the most important step is that it has now become common use to perform some kind of in-field processing to ensure good data quality before the measurement site is abandoned and a new site is occupied.

I feel that time has come to discuss some effects that will always be problematic irrespective of the sophistication in equipment and processing techniques. A list of questions were sent out to 50 groups around the world dealing with MT-studies. The questions included such topics as calibration, noise characteristics, recording parameters, controlled source/natural source, in-field processing, in-field interpretation and future trends.

10 MT-groups gave their comments and answers to some of the above points, and I shall in the next paragraphs discuss some of these. Unavoidably my presentation is biased from my own experiences gained from using a rather conventional system with induction coil magnetometers and digital acquisition with in-field processing with the possibility of local as well as of remote referencing.

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2. Calibration Procedures

Most groups use fixed bands for recording data. 2 decades seem to be a typical bandwidth. Calibration is done for all channels at a number of frequencies distributed sufficiently close that the transfer functions are adequately sampled. Our group employs a special technique in which the output current of a sine generator coupled in logarithmic sweep mode is monitored via electric sensor input amplifiers. This signal and the corresponding outputs from input amplifiers are regarded as input and output, respectively, to a filter whose transfer function has to be determined. To avoid bias problems we determine transfer functions in narrow frequency bands, typically 20 points per decade, and calibration is usually done over a total bandwidth of 2 decades in one run. Truncation effects of FFT are reduced by using very long time series, typically 32 k points.

The normal procedure for calibrating induction coils is to place them in long cylindrical coils laid out horizontally on the ground. An interesting procedure, reported by the Hungarian group (Varga and Verö (1986)), applies a big horizontal circular loop as magnetic field generator. In the middle of the loop the antenna to be calibrated is placed vertically into the ground. The advantage is that the ambient magnetic field variations in the vertical direction can be made much smaller than the horizontal variations if the calibration site is properly selected. The Hungarian group performs such an absolute calibration once every year, but in addition they also perform a relative calibration in the center of each frequency band at each new site to test the stability of each channel. Secondary fields due to induced currents in the ground as well as capacitive leakage between the loop and the ground puts a limit to the use of this configuration at higher frequencies as pointed out by Vozoff (1961) and Wait (1961).

3. Representation of Transfer Functions of Electric and Magnetic Channels

The point values of transfer functions are either interpolated to any frequency of interest by interpolation or by fitting in each frequency band a polynomial of higher order. If transfer functions vary close to linear as a function of frequency the polynomial fitting procedure will work satisfactorily, but if the transfer functions include effects of bandpass or notch filters it is better to use some interpolation scheme to represent transfer functions between measured frequencies.

4. Noise characteristics

a. INSTRUMENTAL NOISE

The best way to measure instrumental noise is theoretically to place magnetic sensors in a shielded room and directly get a noise figure. However, from the author's own experience from one experiment, the room was not sufficiently well shielded in the 100 secs to 10 msecs period band, so the experiment was not successful.

Another way is to set up electric and magnetic sensors in parallel. Let us assume that channels i and j measure the same component of the electromagnetic field. The sensors should be placed sufficiently far away from each other that they do not interact but sufficiently close that it can be assumed that the signal is the same. Then by averaging over a large number of frequency components we may define the expectation value of the coherence as

$$\hat{\gamma}_{ij}^2 = \frac{\hat{S}_{ij}\hat{S}_{ji}}{\hat{S}_{ii}\hat{S}_{jj}} \approx \frac{S^0_{ij}S^0_{ji}}{\hat{S}_{ii}\hat{S}_{jj}} = \frac{S^0_{ii}S^0_{jj}}{\hat{S}_{ii}\hat{S}_{jj}}$$

where superscript zero denotes noise free crosspowers (i.e. the expectation values of the signal autopowers). The effective signal power and the effective total power may then be defined as

$$S^0_{\mathrm{eff}} \equiv (S^0_{ii}S^0_{\mathrm{eff}})^{1/2} = \hat{\gamma}_{ij}(\hat{S}_{ii}\hat{S}_{jj})^{1/2} = \hat{\gamma}_{ij}S^t_{\mathrm{eff}}$$

giving the following formula for the effective noise power

$$\Delta S_{\mathrm{eff}} = S^t_{\mathrm{eff}} - S^0_{\mathrm{eff}} = (1 - \hat{\gamma}_{ij})\,S^t_{\mathrm{eff}}$$

and a corresponding expression for the signal to noise ratio

$$(S/N)_{\mathrm{eff}} = \frac{S^0_{\mathrm{eff}}}{\Delta S_{\mathrm{eff}}} = \frac{\hat{\gamma}_{ij}}{1 - \hat{\gamma}_{ij}}\,.$$

If for example the coherence $\hat{\gamma}^2_{ij} = 0.9$ the effective signal to noise ratio is 20. An example of such an analysis is shown in Figure 1. The equipment used is similar to the one used by our group, except that analogue recording was used instead of digital recording. The curves ΔS^u refers to the uncorrelated part of the noise, whereas ΔS^c refers to correlated noise produced by the analogue tape recorder used at that time (Nissen, 1981).

It should be noted, that this noise estimation procedure is different from that described by Gamble *et al.* (1979b). Their effective noise includes such noise components as wind noise, non-planar source field, and man-made noise, because their base and remote stations are separated by a large distance. Either method could be used as an extra criterion for data selection.

b. WIND NOISE AND SEISMIC NOISE

The correlation between bad quality data and strong wind is wellknown to the MT society. The remedy against wind noise is to bury antennas and electrical sensors deep in the ground to prevent antennas and electrodes moving. Some groups even bury or fix electrode cables to prevent electromagnetic induction effects being

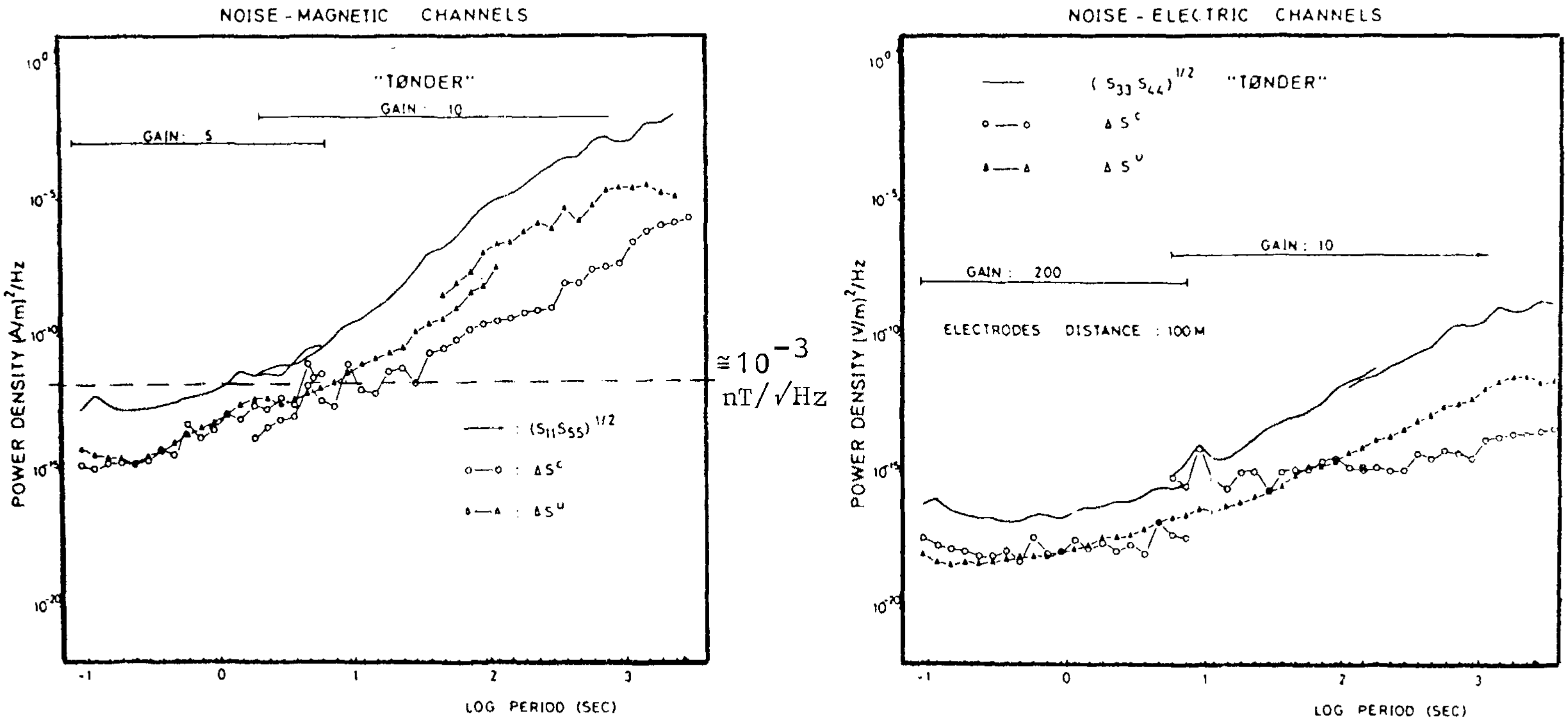

Fig. 1. Equivalent noise figures for magnetic and electric channels of University of Århus equipment obtained by parallel layout.

picked up by the electrode cables. The experiment reported by Goubau *et al.* (1984), where they in addition to a configuration with baseremote stations also employed a local magnetic reference, separated only 2 m from the base station gives a remarkable coincidence between noise figures of the magnetic field when estimated from the local reference and from the remote reference via an estimation of the impedance tensor. This coincidence prevails from about 10 msec to about 1 sec, whereafter the noise estimated from the remote base station set-up starts to increase by a factor of 10 above that from the local set-up in the period interval 2 to 4 secs.

Goubau *et al.* ascribe this phenomenon to a non-planar source field, which according to them should not influence the impedance tensor estimation seriously but have a dramatic effect on the noise estimation. This interpretation was challenged recently by Nichols *et al.* (1985) but before discussing their results we shall briefly describe the effects of seismic noise.

Consider the case where magnetic sensors are laid out along the magnetic meridian and perpendicular to it. We shall assume that the gradient of the main field can be effectively set equal to zero. Then only rotation of the magnetic sensors in the stationary and homogeneous main field will cause spurious signals. We denote the main field by $\mathbf{B} = (B_x, B_y, B_z)$ with the x-axis lying along the magnetic meridian and the z-axis pointing downwards into the Earth. This implies that $B_y = 0$. Consider an arbitrary differential rotation $(+\delta\theta)$ around the unit vector $n = (n_x, n_y, n_z)$. The rotation of a sensor through $(+\delta\theta)$ is equivalent to a rotation of the coordinate system through $(-\delta\theta)$ around n. Thus we may immediately write the relation (to first order in $\delta\theta$) between unrotated $(\mathbf{B})$ and rotated coordinates $(\mathbf{B}')$

$$\begin{pmatrix} B'_x \\ B'_y \\ B'_z \end{pmatrix} = \begin{pmatrix} 1 & -\delta\theta n_z & \delta\theta n_y \\ \delta\theta n_z & 1 & -\delta\theta n_x \\ -\delta\theta n_y & \delta\theta n_x & 1 \end{pmatrix} \begin{pmatrix} B_x \\ 0 \\ B_z \end{pmatrix} .$$

Or written in components

$$\begin{aligned} \Delta B_x = B'_x - B_x &= \delta\theta n_y B_z \\ \Delta B_y = B'_y - B_y &= \delta\theta (n_z B_x - n_x B_z) \text{ or } \mathbf{\Delta B} = \delta\theta \begin{pmatrix} 0 & 0 & n_y \\ n_z & 0 & -n_x \\ -n_y & 0 & 0 \end{pmatrix} \mathbf{B} . \\ \Delta B_z = B'_z - B_z &= -\delta\theta n_y Bx \end{aligned}$$

A rotation around a vertical axis $(n_z = 1, n_x = n_y = 0)$ is particularly simple

$$\Delta B_x = \Delta B_z = 0 \quad \text{and} \quad \Delta B_y = \delta\theta\, B_x .$$

while a rotation around horizontal axes yields

A. $n_x = 1;\ \mathrm{n}_y = n_z = 0:$

$$\Delta B_x = \Delta B_z = 0; \quad \text{and} \quad \Delta B_y = -\delta\theta\, B_z$$

B. $n_y = 1, \quad n_x = n_z = 0$

$$\Delta B_y = 0; \quad \text{and} \quad \Delta B_x = \delta\theta\, B_z \quad \text{and} \quad \Delta B_z = -\delta\theta\, B_x .$$

Thus the ratio between rotationally induced noise signal will be of the order of the ratio between the main field and the amplitude of the time varying field multiplied by the differential rotation angle. Assume for instance $|B| = 50\,000$ nT and a signal amplitude of 0.05 nT. An apparent signal of the same amplitude will then be produced by approximately 1 μradian, which for a coil of length 2 m corresponds to a relative displacement of one end relative to the other of 2×10^{-3} mm! Note that only the magnetic east-west component is sensitive to rotation in the horizontal plane, while the other components are sensitive only to rotation around an axis pointing east-west.

Nichols *et al.* (1985) observed that there exists a great discrepancy between apparent noise figures and theoretically calculated ones. This discrepancy is particularly noticeable at periods longer than a few seconds as can be seen from Figure 2. Also note that induction coils and SQUIDS show the same apparent noise figures at longer periods, while those of SQUIDS are larger for periods below 1 sec.

To investigate this an experiment with four SQUID magnetometers each having an internal high-sensitivity biaxial tilt meter were deployed at different separations

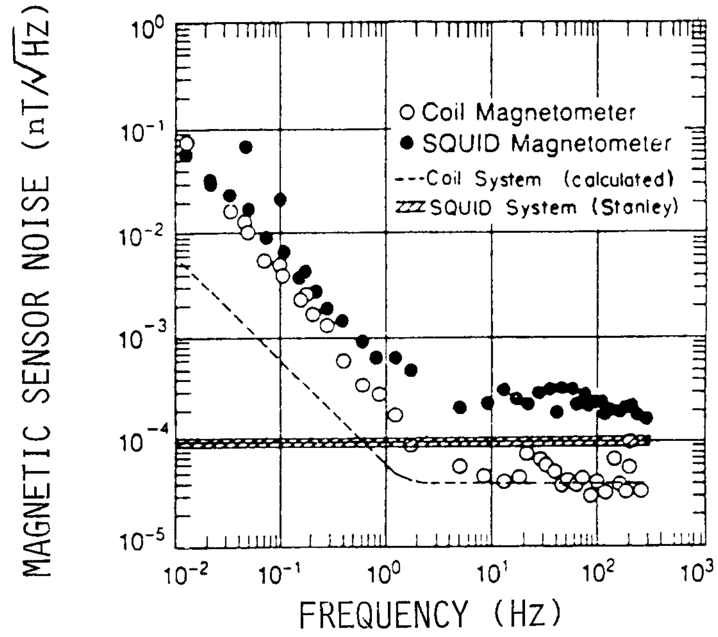

Fig. 2. Comparison of apparent sensor noise for SQUID and coil magnetometers operated in the Earth's magnetic field. Measured results (dots) have similar low frequency response as compared to predicted noise for each magnetometer system. Reference to Stanley and Tinker (1982) for SQUID results.

ranging from 1 m to 3 km. The rotations recorded by the tilt-meter were particularly strong around 6—7 secs. and they were coherent out to the maximum distance of 3 km. A comparison of the difference between the measured magnetic field and the predicted field with and without the removal of the tiltgenerated signal is shown in Figure 3. The predictivity level is increased by 15 dB for this particular pair of tilts separated by 700 m.

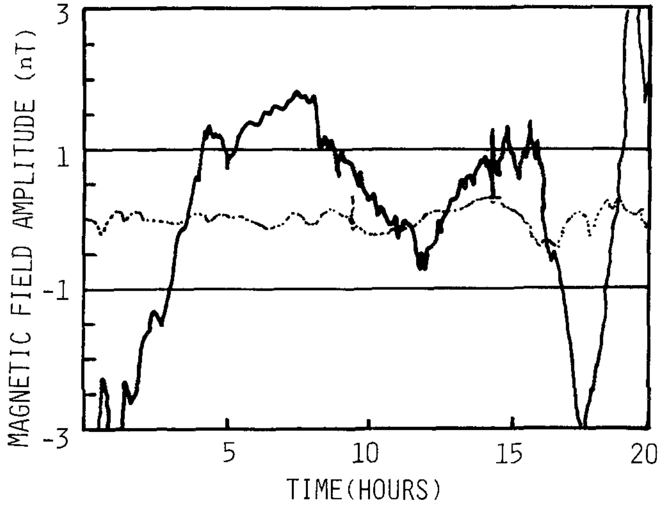

Fig. 3. Full drawn curve: residual magnetic field after cancellation to correct for static calibration and orientation error. Dotted curve: residual magnetic field with additional reduction obtained by including tilt motion. Redrawn after Nichols et al. (1985).

C. DISTORTIONS OF IMPEDANCE TENSOR DUE TO NOISE AND MISORIENTATION

In a recent paper, Pedersen and Svennekjaer (1984) demonstrated how the effects of noise on magnetic channels could disturb the impedance tensor. In addition to the well-known downward bias that results from autopower noises, the effect of highly polarized magnetic fields, where shown to lead to coupling between rows of the impedance tensor.

Here we shall consider another bias effect that originates from misorientation of electromagnetic sensors.

We take the x- and y-axes to represent the true magnetic North and East directions, respectively, and denote the misorientations of the magnetic and electric sensors by (δ_x^H, δ_y^H) and (δ_x^E, δ_y^E), respectively, as illustrated in Figure 4. Then any field component along the measurement direction, δ_x^H or δ_x^E, say δ_x can be expressed as

$$F_x^* = F_x \cos \delta_x + F_y \sin \delta_x$$

and analogously for F_y^*

$$F_y^* = -F_x \sin \delta_y + F_y \cos \delta_y .$$

Then, we find approximately for small δ_x and δ_y

$$\begin{pmatrix} F_x \\ F_y \end{pmatrix} = \begin{pmatrix} \cos\delta_y & -\sin\delta_x \\ \sin\delta_y & \cos\delta_x \end{pmatrix} \begin{pmatrix} F_x^\star \\ F_y^\star \end{pmatrix} .$$

We define the true impedance tensor through the distortion free fields **E** and **H**, by

$$\mathbf{E} = \mathbf{Z}\mathbf{H}$$

and by inserting the expressions for the distorted fields we find the distorted impedance matrix

$$\mathbf{Z}^\star \approx \begin{Bmatrix} \cos\delta_x^E & \sin\delta_x^E \\ -\sin\delta_y^E & \cos\delta_y^E \end{Bmatrix} \begin{Bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{Bmatrix} \begin{Bmatrix} \cos\delta_y^H & -\sin\delta_x^H \\ \sin\delta_y^H & \cos\delta_x \end{Bmatrix}$$

which may be further approximated to (using $\cos \approx 1$ and $\sin\delta \approx \delta$)

$$\mathbf{Z}^\star \approx \mathbf{Z} - \delta_x^H \begin{Bmatrix} 0 & Z_{xx} \\ 0 & Z_{yx} \end{Bmatrix} + \delta_y^H \begin{Bmatrix} Z_{xy} & 0 \\ Z_{yy} & 0 \end{Bmatrix} +$$

$$+\ \delta_x^E \begin{Bmatrix} Z_{yx} & Z_{yy} \\ 0 & 0 \end{Bmatrix} - \delta_y^E \begin{Bmatrix} 0 & 0 \\ Z_{xx} & Z_{xy} \end{Bmatrix} .$$

Thus, misorientation of a magnetic field component which is the most difficult to orient correctly perturbs the column corresponding to the other component, whereas misorientation of an electric field component perturbs the row corresponding to the other component. As an example take $\delta_x^H = \delta_y^H$ and $\delta_x^E = \delta_y^E = 0$ and let $Z_{xx} = Z_{yy} = 0$ and $Z_{xy} + Z_{yx} = 0$. Then, the perturbed tensor has the form

$$\mathbf{Z} = \begin{Bmatrix} \delta_y^H Z_{xy} & Z_{xy} \\ Z_{yx} & -\delta_x^H Z_{yx} \end{Bmatrix} .$$

The off-diagonal elements are unaffected but the diagonal elements are perturbed to give an apparent skew, $S^\star$

$$S^\star = \delta_x^H \frac{Z_{xy}}{Z_{yx}} = \delta_x^H$$

Assuming a maximum misorientation of 5^0 this would correspond to an apparent skew of 0.1.

Consider instead the case that $\delta_y^H = -\delta_x^H$ and otherwise the same conditions as before. Then the apparent skew would be zero but the apparent strike $\theta_s^\star$ of the apparent 2-D structure defined by

$$\tan 2\,\theta_s^\star = -\frac{Z_{xx}^\star - Z_{yy}^\star}{Z_{xy}^\star + Z_{yx}^\star}$$

would give the solution $\theta_s^\star = 45^0$, whereas if $Z_{yx} = -2\,Z_{xy}$ we could find

$$\tan 2\,\theta_s^{\star} = -\frac{-\delta_x^H Z_{xy} - 2\delta_x^H Z_{xy}}{Z_{xy} - 2Z_{xy}} = -3\delta_x^H.$$

For $\delta_x^H = 5^0$ we find $\theta_s^H \approx -7.5^0$ and $S^\star = 0.03$.

With the increased accuracy of MT data the misorientation effect should not be neglected. It is also interesting to note that misorientation of electric field components influences the impedance tensor in much the same way as does near surface inhomogeneities as studied recently by Zhang *et al.* (1987).

5. Recording Characteristics

MT-measurements are usually recorded in wide bands. The Phoenix system (Jones and Foster (1986)) operates in two modes: 1—384 Hz and 1—2000 s. These bands are somewhat wider than the two decades used by most groups. The reason is probably that the Phoenix system employs a 16 bit A/D converter whereby the effective dynamic range of the analogue system can be fully exploited. Other groups use 12 or 14 bit A/D converters. The Utah Group (Olsen *et al.*, 1986) considers 14 bits adequate for dynamic range coverage. The Geological Survey of Canada (private communication, A. G. Jones (1986)) is developing a ring core fluxgate magnetometer to be used for MT and GDS studies. In addition to 14 bits A/D conversion a 12 bits D/A offset ranging scheme is employed to replace the usual post-amplifier stage with it's variable gain possibilities.

6. In-Field Processing

Present light-weight and cheap CMOS microcomputers are likely to have great impact on those groups that cannot afford to buy commercial equipment. A number of steps that used to be done at home in the laboratory can now be performed directly in the field. This not only speeds up the whole field operation and processing work, but it also helps to control data quality and even to monitor directly if malfunctions occur.

Data quality for single station setups is usually controlled by some coherence measure. For example coherences between predicted and actual electric field components. Thresholds can be predetermined to guarantee that only segments with predicted coherences exceeding the threshold be accepted for stacking of cross- and autopowers. The threshold should be chosen as close as possible to one to take away such parts of the data that could give rise to an appreaciable bias of impedance elements or simply cause too large scatter. Under good conditions it is common to set the threshold of γ^2 to 0.9. Under less favourable conditions values above 0.7 should be aimed at, even though it could mean that considerable time

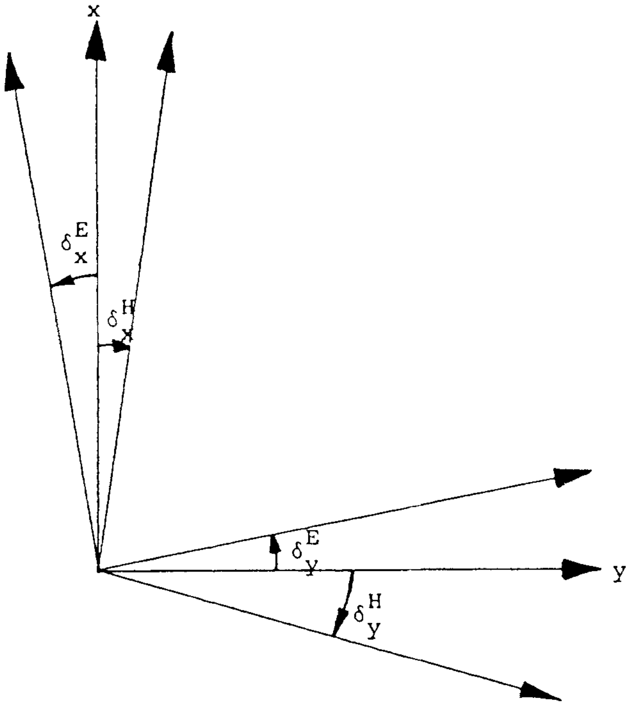

Fig. 4. Coordinate system for definition of misorientation angles for magnetic and electric components.

has to be spent at the site before reasonably smooth curves can be obtained. According to the model of Pedersen and Svennekjaer (1984) a predicted coherence of 0.7 only guaranties — under strictly depolarized magnetic field conditions — that bias of principal impedance elements is less than 30%. A closer investigation of the smoothness of impedance phases and magnitudes (or real and imaginary parts) will normally tell the operator if data quality is acceptable.

For systems with a local or remote reference it is not clear as to which criteria are employed generally for data selection. A combination of predicted coherences has been in use by our group. We estimate the transfer function between reference field and base station field. If the predicted base field does not agree within some threshold no stacking is performed. If it does agree stacking is performed if the electric field can be predicted from the reference field within some limit. The idea is that data selection for stacking should preferably be done in such a way that all the 6 horizontal electromagnetic components involved have relatively small noise contributions. Normally these thresholds can be set to lower values than for the single station case, because the effect of bias errors is reduced and the random error can be reduced by taking in more data.

The estimation of geomagnetic transfer functions or tipper seems generally to be less reliable than impedance estimates. Both the Utah group (private communication) and ours have experienced such a trend. An interesting development of tipper estimation for a single station setup was described by Labson *et al.* (1985) who used the horizontal electric components as a local reference in tipper estimation for frequencies 10 Hz—20 kHz, where the intrinsic electric component noise is much smaller than the intrinsic magnetic component noise. This enabled them to determine tipper and related functions over a wide band hitherto not covered by any MT or AFMAG system. Only tipper functions were presented, though it is not clear why no impedances were shown.

Jones and Foster (1986) went a step further than that of estimating good transfer functions. While collecting data they perform a 1-D inversion on the most recently estimated principal impedance elements. A sensitivity analysis of the derived layered model revealed if it were worthwhile to collect more data in specific period bands or if data collection should be continued to improve the impedance estimation to constrain the parameters of the layered 1-D model further. This cost-benefit approach may also be of value for dynamic planning of field campaigns. For instance the inversion may indicate if it is necessary to measure more densely than was planned from the outset.

Closely connected with in-field processing is the site occupation time. Different groups spend quite different times on a measuring site. The reasons may be manifold. Tradition, maximum period wanted, data quality wanted, area of study (noise level), season of the year (signal level), and last but not least, the signal to noise ratio of the equipment used.

7. Future Developments

The future developments are probably going to be controlled more by the refinements of in-field processing techniques and of the density of measurements than of developments of new and better instrumentation. Instruments of to-day are generally believed to be sufficiently accurate from the point of view of signal to noise ratio. Many university systems may be clumsy and lack the streamlineness of those systems that will be built in the near future. Some of the existing commercial systems have perhaps already been developed into a state of perfectness.

In my view the community will have to attack problems related to artificial man made noise as well as to those related to static distortions. The potential that would lie in measuring very densely using a seismic data acquisition system has to my knowledge not been exploited. Such dense measurements (100 m between points for example) would allow for an identification of low noise sites, that could be measured with conventional systems at a later stage for a longer occupation time. Combinations of potential differences along the measuring line could also help to average out the effects of small scale near surface heterogeneities.

8. Summary and Conclusions

The development of new equipment for the measurement of electric and magnetic fields in the MT-band 10 000 s—10^{-2} s has been relatively quiet over the past few years. The breakthrough that occurred with the introduction of the reference station technique using SQUID magnetometers (Fischer, 1982) has not lead to an extensive use of SQUIDS among the MT community. The reason is due, partly, to the cost of acquiring and running these instruments, and partly due to their performance, which is degraded in practice because of movements of the ground in the Earth's main magnetic field. Thereby their noise figures are increased to levels above those of good induction coils. Adding tiltmeters to the system to measure the ground movement seems to be an unnecessary and costly complication.

The problem of wind noise and seismic noise is particularly pronounced in the 'dead' band at periods 1—3 secs. The application of a local magnetic reference will generally be sufficient to remove the bias effects that would prevail due to instrument noise in that band.

With the increased accuracy of present day MT data it is important to realise the effects of misorientation of the electric and magnetic sensors. The estimated impedance tensor becomes distorted in much the same way as that due to near surface inhomogeneities and that due to strongly polarized fields.

In-field processing has developed rapidly over the past few years. It is now common to do preprocessing to estimate impedances and to make one-dimensional inversions prior to leaving the actual measuring site for the next one. The steadily increasing performance of portable micro-computers is likely to accelerate this trend in the next few years.

References

Clarke, J., Gamble, T. D., Goubau, W. M., Kock, R. H., and Miracky, R. F.: 1983, 'Remote-Reference Magnetotellurics: Equipment and Procedures', *Geophys. Prosp.* **31**, 149—170.

Fisher, G.: 1982, 'Magnetotelluric Observational Techniques on Land', *Geophys. Surveys* **4**, 373—393.

Gamble, T. D., Goubau, W. M., and Clarke, J.: 1979a, 'Magnetotellurics with a Remote Magnetic Reference', *Geophysics* **44**, 53—68.

Gamble, T. C., Goubau, W. M., and Clarke, J.: 1979b, 'Error Analysis for Remote Reference Magnetotellurics', *Geophysics* **44**, 959—968.

Goubau, W. M., Gamble, T. D., and Clarke, J.: 1978, 'Magnetotelluric Data Analysis: Removal of Bias', *Geophysics* **43**, 1157—1166.

Goubau, W. M., Maxton, P. M., Koch, R. H., and Clarke, J.: 1984, 'Noise Correlation Lengths in Remote Reference Magnetotellurics', *Geophysics* **49**, 433—438.

Jones, A. G. and Foster, J. H.: 'An objective real-time data-adaptive Technique for efficient Model Resolution Improvement in Magnetotelluric Studies', *Geophysics* **51**, 90—97.

Labson, V. F., Becker, A., Morrison, H. F., and Conti, U.: 1985, 'Geophysical Exploration with audio-frequency natural Magnetic Fields', *Geophysics* **50**, 656—664.

Nichols, E. A., Morrison, H. F., and Clarke, J.: 1985, 'Signals and noise in magnetotellurics', Paper presented at the 1985 annual SEG meeting in Washington, D.C.

Nissen, J.: 1982, 'Magnetotelluriske Sonderinger i Jylland', M.Sc. Thesis, Laboratory of Geophysics, University of Aarhus, Denmark. In Danish.

Olsen, S. L., Stodt, J. A., Wannamaker, E., and Hohmann, G. W.: 1986, 'University of Utah Research Institute Magnetotelluric Data Acquisition System', Internal Report.

Pedersen, L. B., and Svennekjaer, M.: 1984, 'Extremal Bias Coupling in Magnetotellurics', *Geophysics* **49**, 1968–1978.

Stanley, W. D., and Tinkler, R. D.: 1982, 'A Practical, Low Noise Coil System for Magnetotellurics', U.S. Geological Survey, open file report.

Wait, J. R.: 1961, 'Comment of K. Vozoff's paper: Calibration of pulsation detector coils', *J. Geophys. Res.* **66**, 3603.

Varga, G., and Verö, L.: 1986, 'Private Communication', Lorand Eötvös Geophysical Institute of Hungary.

Vozoff, K.: 1961, 'Calibration of pulsation detector coils', *J. Geophys. Res.* **66**, 1983.

Zhang, P., Roberts, R. G., and Pedersen, L B.: 1987, 'Magnetotelluric Strike rules', *Geophysics* **52**, 267–278.