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NOISE CORRELATION LENGTHS IN REMOTE REFERENCE MAGNETOTELLURICS

W. M. Goubau,^{*†} P. M. Maxton,^{*‡} R. H. Koch^{*†} and J. Clarke^{*}

In remote reference magnetotellurics one uses a reference magnetometer, located typically several kilometers from the magnetotelluric site, to obtain estimates of the impedance tensor that are unbiased by random noise. Measurements have been made of the correlation length of this noise by using a third SQUID magnetometer as a local reference. The impedance tensor was determined as a function of the separation between this magnetometer and the magnetotelluric site, and compared with the tensor obtained simultaneously using the remote reference. This study yielded the surprising result that a separation of as little as 200m was sufficient to obtain an unbiased estimate of the impedance tensor. The magnitude of the magnetic noise was determined with two different techniques, one involving the impedance tensor, and the other involving a magnetic transfer tensor. The second method produced a substantially lower estimate of the magnetic noise at periods above about 1 second. It is concluded that a component of the noise arises from the non-plane wave nature of the magnetic and electric fields.

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INTRODUCTION

In remote reference magnetotellurics (Gamble et al, 1979a) one obtains unbiased estimates of the plane-wave impedance of the earth and of the tipper provided that the noise at the reference station is uncorrelated with the magnetotelluric signals and the noise at the base station. The sources of noise are not well understood, but general experience has indicated that a separation of several kilometers between the base and reference stations is sufficient to ensure that the data are unbiased. In magnetotelluric (MT) surveys in which data from a number of relatively closely spaced stations are recorded simultaneously it is often much more convenient and also more economical to use the magnetic fields from one base station as the reference for the fields at the other station rather than to establish a distant independent reference site. Thus, one would like to know how severe the bias errors from correlated noises are likely to be when the separation of the MT site and the remote reference is less than (say) 1 km. This paper describes an investigation of this problem.

We carried out MT soundings in the San Antonio Valley about 30 km south of Livermore, California using three SQUID magnetometers to determine typical correlation lengths for magnetic noise in an environment that is relatively free from cultural noise. In these soundings we measured the apparent resistivity as a function of frequency at a fixed base station with the usual remote reference method. In addition we used a third magnetometer as a local reference whose distance from the base magnetometer was varied from a few meters to several hundred meters.

The fields from the local reference were recorded simultaneously with those of the remote reference, and used to obtain an independent estimate of the apparent resistivity. This estimate was expected to be biased with respect to the remote reference estimate by the fraction of the noise power that was correlated between base and local reference magnetometers.

EFFECTS OF CORRELATED NOISE ON ESTIMATES OF $\underline{Z}(\omega)$

The natural low-frequency magnetic and electric fields measured in the magnetotelluric method are linearly related through the 2×2 impedance tensor $\underline{Z}(\omega)$:

$$\vec{E}(\omega) = \underline{Z}(\omega) \vec{H}(\omega), \quad (1)$$

where $\vec{E}(\omega)$ and $\vec{H}(\omega)$ are the Fourier transforms of the horizontal (x,y) components of the time-varying electric and magnetic fields. If there is noise (any non-plane wave disturbance) in the fields, one estimates $\underline{Z}(\omega)$ by correlating the fields in Eq. (1) with a reference field $\vec{R}(\omega)$ to obtain (following the notion of Gamble et al., 1979b)

$$[\vec{E}\vec{R}] = \underline{Z}[\vec{H}\vec{R}], \quad (2)$$

where

$$[AB] \equiv \begin{bmatrix} \overline{A_x B_x^*} & \overline{A_x B_y^*} \\ \overline{A_y B_x^*} & \overline{A_y B_y^*} \end{bmatrix}, \quad (3)$$

and the bars denote an average over data records and/or a narrow band of frequencies. For example, for Z_{xy} one obtains

$$Z_{xy} = \frac{\overline{E_x R_y^*} \overline{H_x R_x^*} - \overline{E_x R_x^*} \overline{H_x R_y^*}}{\overline{H_y R_y^*} \overline{H_x R_x^*} - \overline{H_x R_y^*} \overline{H_y R_x^*}}. \quad (4)$$

To illustrate the effect of noise that may be correlated between R and H, consider the case in which the magnetic fields have random polarizations so that $\overline{H_x R_y^*} = \overline{H_y R_x^*} = 0$, and Z_{xy} reduces to $\overline{E_x R_y^*} / \overline{H_y R_y^*}$. Writing $E_x = E_{xo} + E_n$, $H_y = H_{yo} + H_n$, and $R_y = R_{yo} + R_n$, where E_n , H_n , and R_n are noise fields that are uncorrelated with the MT signals E_{xo} , H_{yo} , and R_{yo} , one finds

$$Z_{xy} = \frac{\overline{E_{xo} R_{yo}^*} + \overline{E_n R_n^*}}{\overline{H_{yo} R_{yo}^*} + \overline{H_n R_n^*}}. \quad (5)$$

Although noise can always be considered as a non-plane wave component of the fields, there are at least three distinct sources of noise that one might consider:

- (i) *Equipment noise*. If the noise arises solely from the instruments used to measure the fields, E_n , H_n and R_n are uncorrelated, $\overline{E_n R_n^*} = \overline{H_n R_n^*} = 0$, and Z_{xy} is unbiased:

$$Z_{xy} = \overline{E_{xo} R_{yo}^*} / \overline{H_{yo} R_{yo}^*}. \quad (6)$$

- (ii) *Mechanical (non-inductive) magnetic noise*. We suppose that there is noise in H_y and R_y due to the motion of the magnetometers in the earth's magnetic field. This motion could be induced, for example, by wind or seismic vibrations. We assume that this motion does not affect the electric field, so that $E_n = 0$. We set $R_n = \alpha H_n$, where α is a complex quantity, so that equation (5) becomes

$$Z_{xy} = \frac{E_{xo} R_{yo}^*}{H_{yo} R_{yo}^* + \alpha^* |H_n|^2} . \quad (7)$$

In this case, Z_{xy} is biased downwards provided $\alpha^* > 0$, as one might reasonably expect. Clearly, the properties of α depend on the nature of the mechanical disturbance, rather than on the properties of electromagnetic waves. It is important to realize that the bias error vanishes not only when $|\alpha| = 0$, but also when $\bar{\alpha} = 0$, that is, when the phase of α is random although the amplitude may be non-zero. The practical situation is obviously extremely complicated. For example, a seismic disturbance propagating in a direction roughly perpendicular to the line joining the two stations may produce correlated noise even when the separation between the stations is very large. On the other hand, if the disturbance is propagating at velocity v exactly along the line joining the stations, the noise produced by a component with period τ will tend to be random at the two stations when the difference in its phase exceeds (say) 2π , that is, when the separation exceeds $v\tau$. For $v \sim 1 \text{ kms}^{-1}$ and $\tau \sim 1 \text{ second}$, the corresponding separation would be 1 km. In the case of a local source such as wind-induced motion, the situation is different again in that one might expect the amplitude of the ground motion to be damped out over distances of a few tens or hundreds of meters, so that $|\alpha| = 0$ for separations exceeding this decay length.

(iii) *Electromagnetic (inductive) noise* We suppose now that the noise arises from a non-plane wave component of the electromagnetic field; the source of this noise may be intrinsic to the naturally occurring fields, or may be man-made, for example, noise from a passing vehicle or from

power transmission lines. We set $R_n = \alpha H_n$ and $E_n = \beta H_n$ in equation (5) to obtain

$$Z_{xy} = \frac{\overline{E_{xo} R_{yo}^*} + \alpha^* \beta |H_n|^2}{\overline{H_{yo} R_{yo}^*} + \alpha^* |H_n|^2}. \quad (8)$$

One sees that Z_{xy} may be biased either upwards or downwards, depending on the nature of α and β . For example, electromagnetic noise from a single man-made source that propagates through the ground has a characteristic decay length equal to the skin-depth, $\delta(\omega)$. Thus, if the source is near the MT station, β would be large but $|\alpha|$ would tend to zero as the separation between the base and reference stations is increased beyond $\delta(\omega)$, thereby eliminating the bias error. On the other hand, if the non-plane wave component is intrinsic to the incident field, not only β but also $|\alpha|$ and $\bar{\alpha}$ may be non-zero even for very large separations between the base and reference stations, and the estimate of Z_{xy} will then be biased.

EXPERIMENTAL TECHNIQUES

The experimental arrangement for the determination of the correlation length of the magnetic noise is shown in Fig. 1. The horizontal components of the electric field were measured with three CuSO_4 electrodes arranged in an "L" shaped array having a 200 m baseline. The common electrode of the array was approximately 2 m from the recording vehicle. The magnetic fields were measured with three 3-axis dc SQUID magnetometers of our own design, as described in Clarke et al (1983). Because the relatively high level of spherics caused the unshielded magnetometers

to lose lock from time to time, we surrounded each cryostat with a copper shield that served as a low-pass filter with a roll-off frequency of about 55 Hz. We estimate that the Nyquist noise in these shields produced a magnetic field noise of about $10^{-4} \text{ nT Hz}^{-\frac{1}{2}}$. The remote reference was only 800 m from the base magnetometer because of constraints imposed by local topography and property boundaries. However, from the results of preliminary experiments at another site, in the Livermore Valley, we expected that this separation would be adequate. Signals from the remote reference were transmitted to the base station via FM telemetry. The local reference magnetometer was initially set about 2 m from the base magnetometer and was subsequently moved to sites 100 m and 200 m away. Signals from both the base and local reference magnetometers were transmitted via coaxial cables to the recording vehicle. We eliminated any ground loops that could give rise to common-mode signals by electrically insulating each magnetometer from the earth and powering the magnetometers with independent sets of batteries.

All the data were processed by the battery-powered acquisition system that we have described elsewhere (Clarke et al, 1983). The eight analog signals (E_x , E_y , H_x , H_y , R_{rx} , R_{ry} , R_{lx} , and R_{ly} , where R_r and R_l are the remote and local magnetic references) were filtered with a matched set of Ithaco filters and then digitized and Fourier transformed. The length of the 8-channel-FORTRAN program restricted us to 512 point transforms rather than the 1024 points that we generally use for MT. The program computed all of the 36 possible average cross- and autopowers and stored them on a floppy disc for subsequent processing. The floppy disc was an innovation in our system that replaced the troublesome digital

cassette recorder that we had used previously. It was powered by a dc-ac converter that was turned on only for the few minutes required to load computer programs and to dump data. From these spectra we computed the apparent resistivities $\rho_{xy} = 0.2\tau |Z_{xy}|^2$ and $\rho_{yx} = 0.2\tau |Z_{yx}|^2$ (τ is the period in seconds and the Z 's are in $\text{mVkm}^{-1}\text{nT}^{-1}$) using the remote and local references and also using a least squares analysis (Sims et al, 1971) to determine the elements of $\underline{Z}$. The latter method, which we refer to as "auto-reference," is equivalent to using a magnetic reference whose noise is perfectly correlated ($\alpha = 1$) with the noise at the base station magnetometer. We emphasize that all three analyses were carried out on the same set of data for each position of the local reference. Typically, the data in each band represented averages over about 3 hours.

APPARENT RESISTIVITIES

Figure 2 shows the unrotated apparent resistivities ρ_{xy} and ρ_{yx} with 50% confidence limits vs. period for the auto-reference and remote reference, and for the local reference at separations from the base magnetometer of 2 m, 100 m, and 200 m. We note that the random errors are much smaller for ρ_{yx} than for ρ_{xy} , indicating that the magnetic signals were strongly polarized in the x (north) direction. As expected, the auto-referenced results are biased significantly below those obtained with the remote reference, particularly at periods less than 1 second. However, almost all of the bias errors present with the auto-reference analysis vanish when the local reference is used, even when its separation from the base-magnetometer is as low as 2 m. Significant bias errors when the local reference is used are apparent only in ρ_{yx} at periods

above 1 second for separations of 2 m and 100 m, and in ρ_{xy} for a separation of 100 m at periods between about 0.2 and 1 second. In both cases, the bias vanishes (to within the random error) for a separation of 200 m.

At the longer periods, these results imply that there is a significant non-plane wave contribution to the fields that produces correlated noise at the base and reference stations for distances less than about 200 m. At larger separations, the bias errors in the apparent resistivities from this source are small compared with the random errors. In the following section we describe a more sensitive method for testing the validity of the plane wave approximation that involves the determination of the magnetic noise power by two independent methods.

SIGNAL AND NOISE COMPONENTS OF MAGNETIC FIELD

We first compute the signal and noise in the magnetic fields at the base station using the impedance tensor, $\underline{Z}^R$, obtained using the remote reference. The predicted value of the spectral density matrix of the magnetic field signals at the base station is given by (Gamble et al, 1979b)

$$[\vec{H}_s \vec{H}_s]^P = \frac{1}{2} \{ [\vec{H}^P \vec{H}] + [\vec{H} \vec{H}^P] \}, \quad (9)$$

where
$$[\vec{H}^P \vec{H}] = (\underline{Z}^R)^{-1} [\vec{E} \vec{H}] = [\vec{H} \vec{R}] [\vec{E} \vec{R}]^{-1} [\vec{E} \vec{H}]. \quad (10)$$

The superscript "P" implies "predicted." The corresponding spectral density of the magnetic field noise is given by

$$[\vec{H}_n \vec{H}_n] = [\vec{H} \vec{H}] - [\vec{H}_s \vec{H}_s]^P. \quad (11)$$

The estimate of $[H_s H_s]^P$ involves a knowledge of $\tilde{z}^R$. In the presence of non-plane wave disturbances that are correlated between the base and reference stations, the value of $\tilde{z}^R$ will fluctuate with time as these disturbances vary. The fractional fluctuation in the value of $\tilde{z}^R$ may be very small, yet still have a large effect on $[H_n H_n]$ when $[HH]$ and $[H_s H_s]^P$ are almost the same, so that $[H_n H_n]$ represents the difference between two nearly equal large quantities.

The two components of $\vec{H}_s$ and $\vec{H}_n$ obtained using the remote reference are plotted in Fig. 3. As we have observed in almost all our data (see, for example, Figs. 3 and 4 of Gamble et al, 1979b) there is a pronounced tendency for the noise to scale with the signal at periods longer than about 1 second.

An independent way of determining $\vec{H}_s$ and $\vec{H}_n$ is available to us through the use of the local magnetometer. The magnetic field at the base magnetometer, $\vec{H}$, is related to that at the local reference magnetometer, $\vec{R}_\ell$, via a transfer tensor $\tilde{G}$, where

$$\vec{H} = \tilde{G}^{-1} \vec{R}_\ell. \quad (12)$$

If the two magnetometers are side-by-side the tensor $\tilde{G}$ will depend only on the relative orientations of the magnetometers, and not on properties of the earth or on the plane wave nature of the magnetic fluctuation. For example, if we replace $E_x = E_{x0} + E_n$ with $R_{\ell y} = R_{\ell y0} + R_{\ell n}$ in equation (5), we find

$$G_{yy} = \frac{\overline{R_{y\ell 0} R_{y0}^*} + \overline{R_{\ell n} R_n^*}}{\overline{H_{y0} R_{y0}^*} + \overline{H_n R_n^*}}. \quad (13)$$

If we set $R_{ylo} = H_{yo}$ and $R_{ln} = H_n$, we see immediately that $G_{yy} = 1$, whether or not the waves are plane.

To find $[H_n H_n]$, we replace $\vec{E}$ by $\vec{R}_\ell$ in equation (10), obtaining

$$[\vec{H}^P \vec{H}] = \underline{\underline{G}}^{-1} [\vec{R}_\ell \vec{H}] = [\vec{H} \vec{R}] [\vec{R}_\ell \vec{R}]^{-1} [\vec{R}_\ell \vec{H}], \quad (14)$$

so that $[\vec{H}_s \vec{H}_s]^P$ and $[\vec{H}_n \vec{H}_n]$ can now be obtained from equations (9), (11), and (14). If the MT fields were entirely plane wave, the values of $[\vec{H}_n \vec{H}_n]$ predicted from both methods should agree. However, if there is a non-plane wave component in the MT fields, the value of $[\vec{H}_n \vec{H}_n]$ predicted from $\underline{\underline{G}}$ should be smaller than that predicted from $\underline{\underline{Z}}^R$ because even a non-plane wave source serves as a valid signal for the determination of $\underline{\underline{G}}$ provided that magnetic gradients are negligible over the separation between the magnetometers. Since $[\vec{H} \vec{H}] = [\vec{H}_s \vec{H}_s] + [\vec{H}_n \vec{H}_n]$ is identical for both methods of analysis, a minor relative increase in $[\vec{H}_s \vec{H}_s]$ must be accompanied by a substantial relative reduction in $[\vec{H}_n \vec{H}_n]$ when $[H H]$ and $[H_s H_s]$ are nearly equal.

As an example, Fig. 4 shows $|H_{nx}|^2$ obtained from $\underline{\underline{Z}}^R$ and $\underline{\underline{G}}$; in the latter case the base and local magnetometers were separated by 2 m. For periods below about 0.7 s the data are remarkably similar, but for longer periods the values determined from $\underline{\underline{G}}$ lie substantially below those determined from $\underline{\underline{Z}}^R$. Several other sets of data analyzed in the same way showed similar tendencies, although the differences at long periods were generally somewhat smaller.

DISCUSSION

We see in Fig. 2 that for periods below about 1 second the apparent

resistivities obtained using the local reference 2 m away from the base magnetometer are indistinguishable from those obtained using the remote reference. This result suggests strongly that the noise arises in the magnetometers in this range of frequencies. From Fig. 4, we note that the magnetic noise at periods below about 1 second is the same for both measurement techniques and is remarkably white, except for a small peak at 60 Hz, with a spectral density of about $2 \times 10^{-18} (\text{nT})^2 \text{Hz}^{-1}$. This value is compatible with our estimate of the noise generated by the copper shields.* Thus, it is probable that the large bias error in this frequency range obtained with the auto-reference originates in the copper shields. Since the noises in the two magnetometers are independent, a reference placed a small distance away from the base magnetometer serves as well as a distant reference to eliminate the bias errors. This is a clear example of equipment noise discussed in case (i).

The noise at longer periods, above about 1 second, shows a different behavior. We note first that at long periods, τ , the intrinsic noise of the SQUID in a superconducting shield has a spectral density of typically $(10^{-11} \tau) (\text{nT})^2 \text{Hz}^{-1}$. This value is 3 to 4 orders of magnitude below the long period noise in Fig. 3. Although it is possible that in the absence of the superconducting shield there are other sources of low frequency noise in the magnetometer, we have not been able to identify any mechanism capable of generating the observed large levels of noise. Furthermore, a study of Fig. 2, particularly the data for ρ_{yx} , reveals that at

* V. F. Labson (private communication) has recently measured the magnetic noise in the presence and absence of the copper shields. His results in the presence of the shields are compatible with ours. In the absence of the shields, the noise was substantially lower, indicating that the noise was in the shields rather than in the magnetometers.

periods above 1 second the apparent resistivity obtained with the local reference 2 m away is biased below that obtained with the remote reference. The difference is reduced with the local reference 100 m away, and has become smaller than the random noise when the local reference is 200 m away. This trend implies that at least a major fraction of the noise at long periods arises not from the magnetometers, but from another mechanism. The fact that the noise power in Fig. 3 tends to scale with the signal power, suggests that this mechanism may well be the non-planar nature of the incident fields rather than mechanical or man-made electrical noise; however, we cannot reach a definite conclusion on this issue with the existing information.

The reduction in the measured values of the magnetic noise at periods above about 1 second when one uses that magnetic transfer tensor rather than the impedance tensor is striking. This observation suggests that at least part of the observed noise in the magnetic fields arises from non-plane waves that are correlated between the base station and the remote reference 800 m away. The bias error that this effect induces in the apparent resistivity is less than the random errors in this case, but the presence of non-plane waves will impose a limit on the ultimate accuracy with which the impedance tensor can be determined for a given location of the remote reference. Obviously, the magnitude and nature of the departure from the plane-wave approximation depends on many factors, for example, the location, the time of day and year, and the presence of man-made disturbances.

From a practical point of view, the main conclusion from Fig. 2 is that one does not need to use a large separation between the base and re-

ference stations; even a separation of 200 m produces data that are indistinguishable from those obtained with a separation of 800 m. Thus, in carrying out a magnetotelluric survey one can generally use the magnetometer at each of two neighboring MT sites as the remote reference for the data obtained at the other site, thereby obtaining data at the two sites simultaneously without the need for a distant magnetometer. This conclusion is, of course, based on limited experience, and may not be correct under all circumstances. For example, in an area of high seismic activity where the motion of the magnetometers in the earth's field is the major source of noise, or in an area with high levels of cultural noise, one might reasonably expect the noise to be correlated between two sites only a few hundred meters apart, so that a larger separation would be necessary.

It would be of considerable interest to extend these preliminary measurements to make a more quantitative study of these effects. To investigate possible noise due to the motion of the magnetometers one could attach sensitive tiltmeters to them, and correlate the magnetic noise with the outputs of the tiltmeters. It would be of particular interest to use magnetometers without copper shields so that the instrumental noise at periods below 1 second would be greatly reduced. It would then be possible to study departures from plane waves at higher frequencies, where the effects might be larger. SQUID magnetometers now available have slewing rates sufficiently high that copper shields should not be necessary. As a further extension of these techniques, with three magnetometers it should also be possible to determine the magnetic gradient noise, by subtracting the outputs of two carefully aligned magnetometers and using the third as

a remote reference. The magnetic gradient fluctuation could then be compared with the magnitude of the tipper. Data from these measurements may well provide valuable additional information on the nature of the magnetic field fluctuations.

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FIGURE CAPTIONS

- Fig. 1 Magnetometer and electrode sites at San Antonio Valley, California.
- Fig. 2 Apparent resistivities ρ_{xy} and ρ_{yx} vs. period for three separations of base station and local reference. Error bars represent 50% confidence limits.
- Fig. 3 Power spectral densities of magnetic field signal and noise versus period, using impedance tensor method.
- Fig. 4 Power spectral density, $\overline{|H_{nx}|^2}$, calculated using impedance tensor and magnetic transfer tensor with local reference 2 m away from base magnetometer. The impedance tensor data are the same as those in Fig. 3, with band overlap data suppressed for clarity.

XBL 8211-6900

Fig. 1

XBL 8211-6899A

Fig. 2

XBL8212-6979

Fig. 3

Fig. 4

XBL 832-5337

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