How remote can the far remote reference site for magnetotelluric measurements be?

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[1] Remote reference (RR) magnetotelluric (MT) measurements are made to reduce the bias caused by noise in electric field **E** and magnetic field **H** at a local site. RR only works when noise at a local and remote sites are uncorrelated. A study has been undertaken to find the farthest distance of a far remote site for crustal study which maintains the effectiveness of the RR technique. From theoretical studies the conditions for valid RR estimates have been obtained. The study shows that the remote site can be kept at a considerably large distance from the local site. In a field experiment a fixed local site and several remote sites have been selected at distances of 80, 115, and 215 km away in the frequency range of 30 Hz (~0.03 s) to 0.00055 Hz (~1800 s) at midlatitudes where the wavelengths of the source magnetic fields are long compared to the site separation. The remote sites are distributed over diverse geological settings. All the data of the fixed local site have been remote reference processed with the corresponding remote sites. The study reveals that using a remote site located at as large a distance as 215 km results in unbiased observations and remains effective in improving the MT data quality for all frequency ranges. If the data were acquired at long periods and or in the high latitudes, then to extract the stable uniform field estimates of the impedance one has to carry out robust processing technique. *INDEX TERMS:* 0619 Electromagnetics: Electromagnetic theory; 0910 Exploration Geophysics: Data processing; 1645 Global Change: Solid Earth; 2435 Ionosphere: Ionospheric disturbances; *KEYWORDS:* Solid Earth, EM theory, data processing, ionospheric disturbances, remote reference

1. Introduction

[2] Since the early work of *Cagniard* [1953] and *Tikhonov* [1950], there has been considerable progress using magnetotellurics (MT) in the interpretation of multidimensional geoelectrical problems [*Vozoff*, 1991]. The source signal of MT field consists of naturally occurring fluctuations in the Earth's magnetic field covering a wide range of frequencies. In the frequencies below 1 Hz most of the MT signal is due to micropulsations caused by the interaction of the solar wind with the ionosphere.

[3] In the MT method, horizontal, orthogonal components of time-varying electric field and all the three orthogonal components of the magnetic field are recorded as time series. These time series are typically filtered and fast Fourier transformed (FFT) to estimate the impedance, which relates the observed electric field **E** to the magnetic field **H** and is given by

$$\mathbf{E} = Z\mathbf{H}. \quad (1)$$

The information about the Earth resistivity structure is encoded in the impedance tensor (Z) as a function of frequency. Typically, Z is estimated by postmultiplying both sides of equation (1) by the conjugate of electric or magnetic fields. The products $\langle E_x \mathbf{E}_x^* \rangle$ and $\langle H_x \mathbf{E}_x^* \rangle$ are called autopowers and cross powers, respectively. The presence of noise in the magnetic field (H_x), for example, can bias the autopower $\langle H_x \mathbf{H}_x^* \rangle$ resulting in upward or downward biased estimates of Z [*Sims et al.*, 1971; *Kao and Rankin*, 1977; *Stodt*, 1983; *Egbert and Booker*, 1986; *Chave et al.*, 1987; *Chave and Thompson*, 1989; *Jones et al.*, 1989; *Larsen*, 1989; *Sutarno and Vozoff*, 1991; *Egbert and Livelybrooks*, 1996; *Larsen et al.*, 1996]. *Gamble et al.* [1979a, 1979b] showed that employing cross powers incorporating a remote referenced (RR) magnetic field reduces the bias effect present in the impedance estimate. In such cases, it is necessary to assume that noise at the RR site is uncorrelated with that of the local site and that the signals are correlated. So the impedance estimates in such cases are effectively unbiased.

[4] Until now, relatively little information has been available about the maximum distance up to which the far RR has been found to be effective. The initial work of *Gamble et al.* [1979a] was for a separation of 4.8 km only. *Goubau et al.* [1984, p. 432] states that "sources of noise are not well understood, but general experience has indicated that a separation of several kilometres between the base and reference stations is sufficient to ensure that the data are unbiased." *Jones et al.* [1989] suggested that to minimize the bias errors, RR should be undertaken. They have reported RR measurements with 135 km separation between stations for MT measurements over 5-day intervals. *Chave and Smith* [1994] suggest that greater attention be given to galvanic distortion of magnetic fields during MT surveys. In Japan, Tarakura et al. [1994, p. 24] find that "the separation between a measurement site and a reference site is usually at most 20 km." However, they carried out a field experiment in Higosi-Kubiki area, Niligata prefecture, where the noise could be removed sufficiently only when the reference site was 147 km away from the measurement site. *Larsen et al.* [1996] used a relatively clean MT site in central California ~100 km from the local site to test their code. *Egbert* [1997] used a remote site at a distance of 100 km from the local site while using his robust processing approach based on multivariate statistical methods.

[5] In this paper we present the results of RR estimates for a fixed local site with respect to three remote sites (80, 115, and 215) located 80, 115, and 215 km away from the fixed site (Figure 1) in the frequency range of 30 Hz (~0.03 s) to 0.00055 Hz (~1800 s) at midlatitudes where the magnetic field is uniform. Uniform magnetic field means that the wavelength of the source magnetic field

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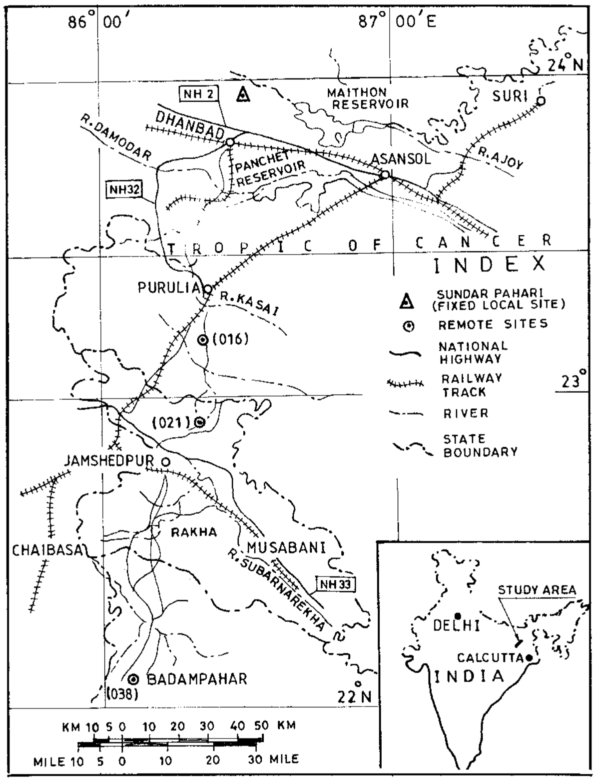


Figure 1. Location map. Three remote sites (80, 115, 215) located 80, 115, and 215 km away from the fixed site.

is long compared to the site separation. The wavelength depends on at least two factors: first, the frequency range of the MT signals and second, at high latitudes where the source field is not always a plane wave. The spatial variations of the source field become significant at periods exceeding first thousands of seconds. For these cases the estimated MT transfer functions would not give geologically valid conducting structures. If the data were acquired in long period and/or in the high latitudes, then to extract the stable uniform field estimates of the impedance, one has to carry out robust processing technique [*Garcia et al.*, 1997].

2. Magnetotelluric Impedance Estimates

[6] The equation of estimating RR MT impedance in terms of power spectral densities for magnetic field reference is given by [*Vozoff*, 1991]

$$Z_{xy} = \frac{\langle E_x \mathbf{R}_y \rangle \langle H_x \mathbf{R}_x \rangle - \langle E_x \mathbf{R}_x \rangle \langle H_x \mathbf{R}_y \rangle}{\langle H_x \mathbf{R}_x \rangle \langle H_y \mathbf{R}_y \rangle - \langle H_x \mathbf{R}_y \rangle \langle H_y \mathbf{R}_x \rangle}, \tag{2}$$

where $\mathbf{R}_x$ and $\mathbf{R}_y$ are the remote magnetic field components. The field components in bold indicate complex conjugate. For local reference method, $\mathbf{R}_x$ and $\mathbf{R}_y$ are from the same site. Thus the equation for impedance estimation by local reference for magnetic field reference is

$$Z_{xy} = \frac{\langle E_x \mathbf{H}_y \rangle \langle H_x \mathbf{H}_x \rangle - \langle E_x \mathbf{H}_x \rangle \langle H_x \mathbf{H}_y \rangle}{\langle H_x \mathbf{H}_x \rangle \langle H_y \mathbf{H}_y \rangle - \langle H_x \mathbf{H}_y \rangle \langle H_y \mathbf{H}_x \rangle}. \tag{3}$$

If it is assumed that the signals are coherent but that signals and noise are incoherent, the auto-power estimates are biased upward, whereas the cross-power estimates are unbiased. Thus every equation such as (3) will be biased upward, while equations like equations (2) will be unbiased. Thus the need for RR MT is seen. Estimating the impedance in terms of auto and cross power terms helps in understanding the bias effect.

[7] Equation (2) can also be written in terms of coherency as

$$Z_{xy} = \frac{|E_x|}{|H_y|} \left(\frac{\operatorname{coh} E_x \mathbf{R}_y \operatorname{coh} H_x \mathbf{R}_x - \operatorname{coh} E_x \mathbf{R}_y \operatorname{coh} H_x \mathbf{R}_x}{\operatorname{coh} H_x \mathbf{R}_x \operatorname{coh} H_y \mathbf{R}_y - \operatorname{coh} H_x \mathbf{R}_y \operatorname{coh} H_y \mathbf{R}_x} \right). \tag{4}$$

The coherency is a quantitative measure of the similarity between the two data series. Thus the coherency measures the consistency of the phase difference between the two data series. It is defined as the ratio of the cross power to the root mean auto powers. For data series A and B it is defined as the ratio of the cross power to the root mean auto powers

$$\operatorname{coh}(A\mathbf{B}) = \frac{\langle A\mathbf{B} \rangle}{\langle A\mathbf{A} \rangle^{1/2} \langle B\mathbf{B} \rangle^{1/2}}. \tag{5}$$

Here $\langle A\mathbf{B} \rangle$ is cross power and $\langle A\mathbf{A} \rangle$ and $\langle B\mathbf{B} \rangle$ are auto powers. If remote magnetic field is local, then coh $(H_x\mathbf{R}_x)$ = coh $(H_y\mathbf{R}_y)$ = 1 and coh $(H_x\mathbf{R}_y)$ = coh $(H_y\mathbf{R}_x)$. Thus equation (4) reduces to equation for local reference method [*Madden and Nelson*, 1986; *Swift*, 1986]:

$$Z_{xy} = \frac{|E_x|}{|H_y|} \left(\frac{\operatorname{coh} E_x \mathbf{H}_y - \operatorname{coh} E_x \mathbf{H}_x \operatorname{coh} H_x \mathbf{H}_y}{1 - |\operatorname{coh} H_x \mathbf{H}_y|^2} \right). \tag{6}$$

From equation (6) it is clear that for small coh $(H_x\mathbf{H}_y)$ the impedance is proportional to the coh $(E_x\mathbf{H}_y)$. Obviously coherent noise in both E_x and $\mathbf{H}_y$ will degrade the impedance estimation process. Therefore the need for RR method is seen.

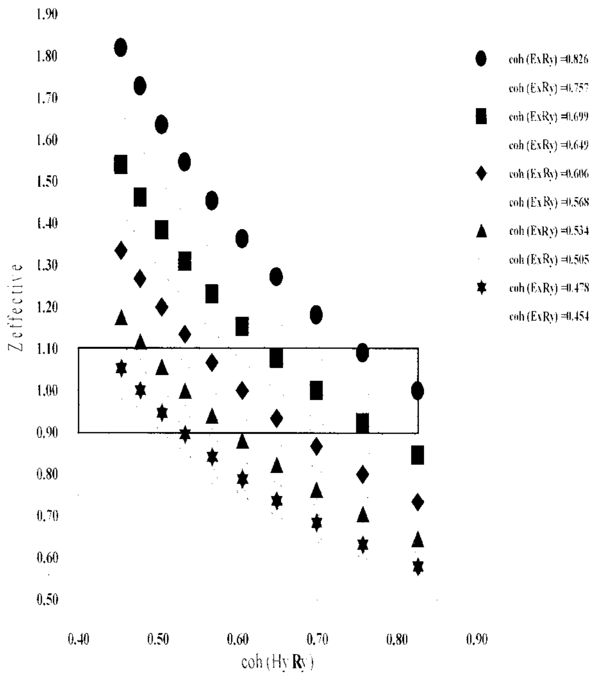


Figure 2. Effective impedance ($Z_{\text{effective}}$) with varying normalized coh($H_y\mathbf{R}_y$). Window shows $Z_{\text{effective}}$ within ±10% error.

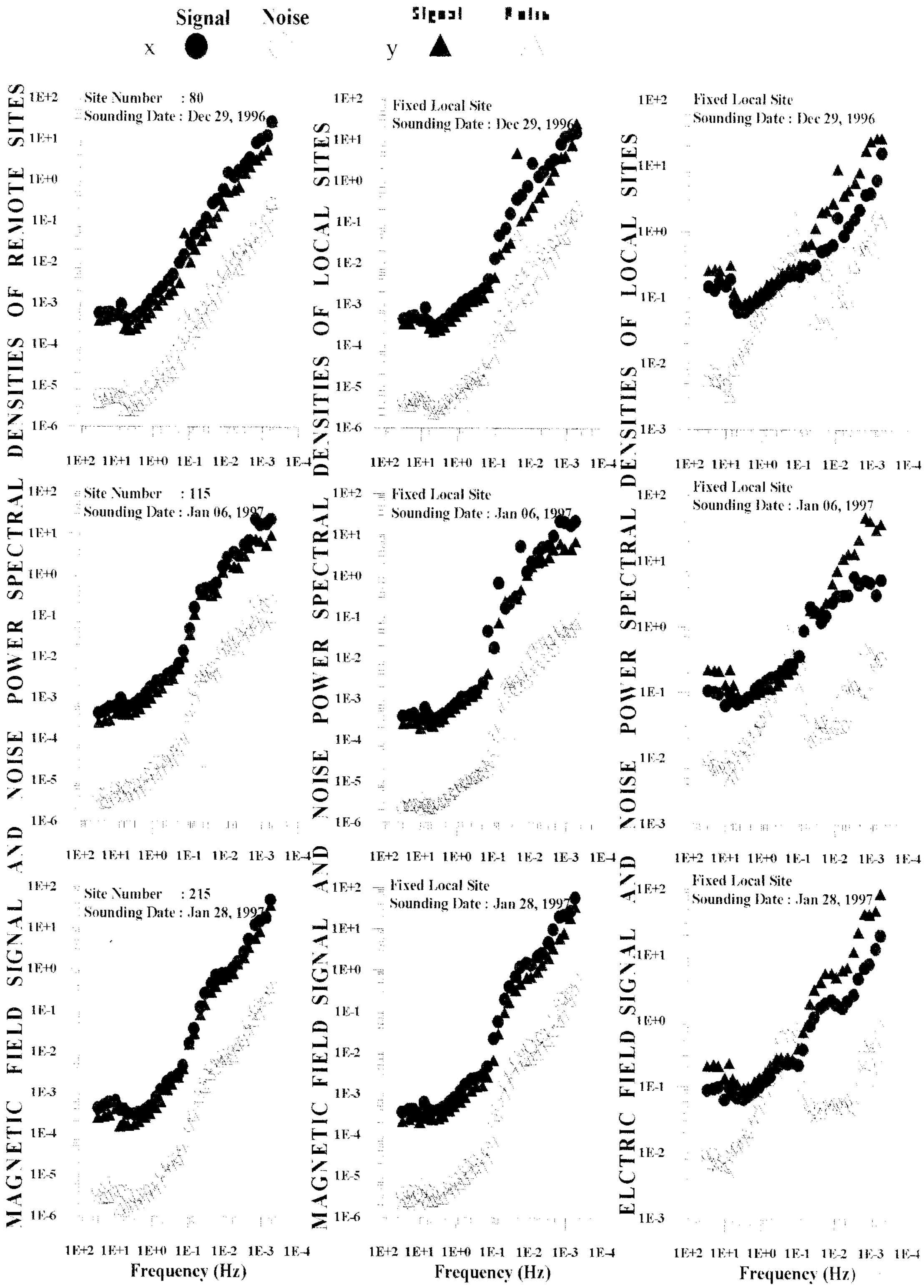


Figure 3. Remote magnetic reference signal and noise power spectral densities and signal and noise power spectral densities of the corresponding fixed local site (magnetic and electrical fields): (a) remote reference sites for magnetic field; (b) fixed local sites for magnetic field; and (c) fixed local sites for electrical field.

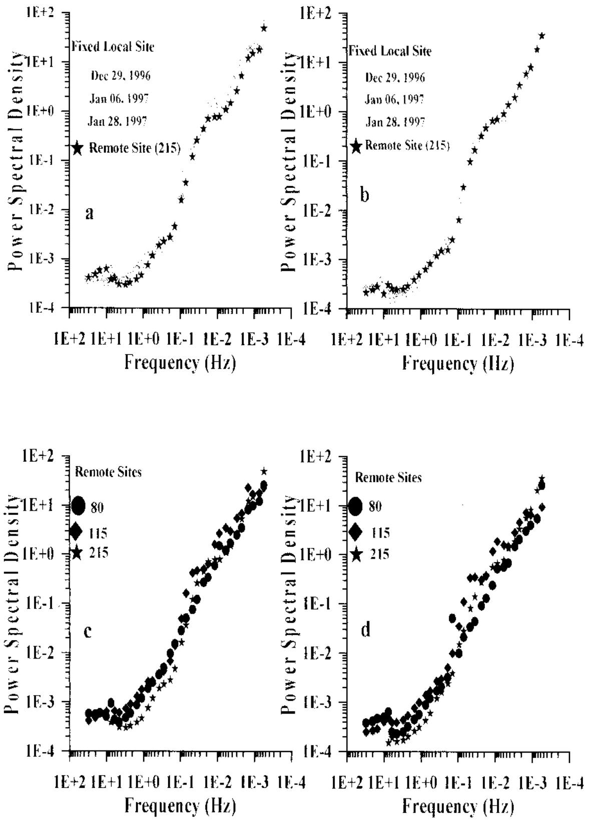


Figure 4. Magnetic field signal power spectral densities versus frequency for fixed local site of all the 3 days of measurements with three remote sites and compared with the farthest remote site (215): (a) H_x of fixed local site and remote site (215); (b) H_y of fixed local site and remote site (215); (c) H_x of all the three remote sites, and (d) H_y of all the three remote sites.

[8] Equation (4) for small coh ($H_x\mathbf{R}_y$) reduces to

$$Z_{xy} = \frac{|E_x|}{|H_y|}\left(\frac{\mathrm{coh}\ E_x\mathbf{R}_y}{\mathrm{coh}\ H_y\mathbf{R}_y}\right). \tag{7}$$

Therefore the impedance estimate is proportional to coherency of E_x with $\mathbf{R}_y$ and inversely proportional to the coherency between H_y and $\mathbf{R}_y$. Therefore, if the noise in H_y is uncorrelated with noise in R_y and if H_y and R_y are fairly coherent, the RR estimation of impedance is an improvement over local reference method.

[9] A question naturally arises that how far away can a RR site for magnetotelluric measurements be? There are basically three things that affect RR estimates: (1) noise at both local and remote sites, (2) coherency of the MT signals between local and remote sites, and (3) coherency of the noise between local and remote sites.

[10] Therefore, in order to answer the question posed by the title of this article, we first analyze theoretically the impedance relationships and the effect of varying amounts of local and remote noise, varying field and varying signal-to-noise levels. Finally, a study has been made to find the distance over which the magnetic field at local and remote sites are coherent.

2.1. Effect of Varying Uncorrelated Noise in Local and Remote Uniform Magnetic Fields on Impedance Estimation

[11] If $x(t) = u(t) + n(t)$, and $y(t) = v(t) + m(t)$, where $u(t)$ and $v(t)$ are true signals and $n(t)$ and $m(t)$ are uncorrelated noise components respectively, then the effect of uncorrelated noise on the measured coherency (γ^2_{xy}) is given by [*Bendat and Piersol*, 1971],

$$\gamma^2_{xy}(f) = \frac{\gamma^2_{uv}(f)}{\{1 + [G_n(f)/G_u(f)]\}\{1 + [G_m(f)/G_v(f)]\}}, \tag{8}$$

where $G_u(f)$ and $G_v(f)$ are the spectral density functions of the true signals $u(t)$ and $v(t)$, and $G_n(f)$ and $G_m(f)$ are the spectral density functions of the uncorrelated noise components $n(t)$ and $m(t)$. The parameter γ^2_{uv} is the coherency between true signals $u(t)$ and $v(t)$. Equation (8) illustrates the behavior that would be expected when uncorrelated extraneous noise is present in both the input and output measurements. The measured coherency will theoretically always be less than the desired coherence function whenever the noise terms $G_n(f)$ and or $G_m(f)$ are greater than zero. The contribution of uncorrelated inputs other than the measured input $x(t)$ will appear as uncorrelated extraneous noise at the output. In RR MT measurements, $x(t)$ and $y(t)$ are local H_y and R_y, respectively.

[12] Figure 2 shows the change in impedance ($Z_{\mathrm{effective}}$) from the initial impedance of unity with the variation of normalized coh ($H_y\mathbf{R}_y$) with unit coherency ($\gamma^2_{uv} = 1$) for different coh ($E_x\mathbf{R}_y$) using equation (7). These coherences have been obtained by varying the amount of uncorrelated noise from 10% to 100% in steps of 10% in local H_y and E_x for a fixed 10% of uncorrelated noise in R_y. The maximum and minimum coh ($E_x\mathbf{R}_y$) are 0.826 and 0.454, respectively, for 10% and 100% uncorrelated noise in E_x, respectively. The rectangular window in Figure 2 gives different combination of

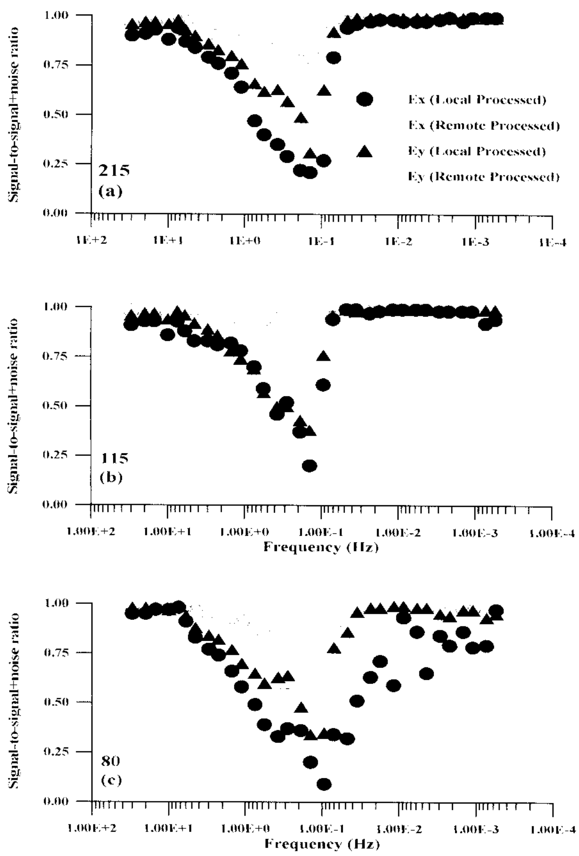


Figure 5. Signal-to-signal+noise ratio of the electric field (E_x and E_y) for the fixed local site for both the local and remotely processed data with sites (a) 215, (b) 115, and (c) 80. Solid symbols, local processed; open symbols, remote processed.

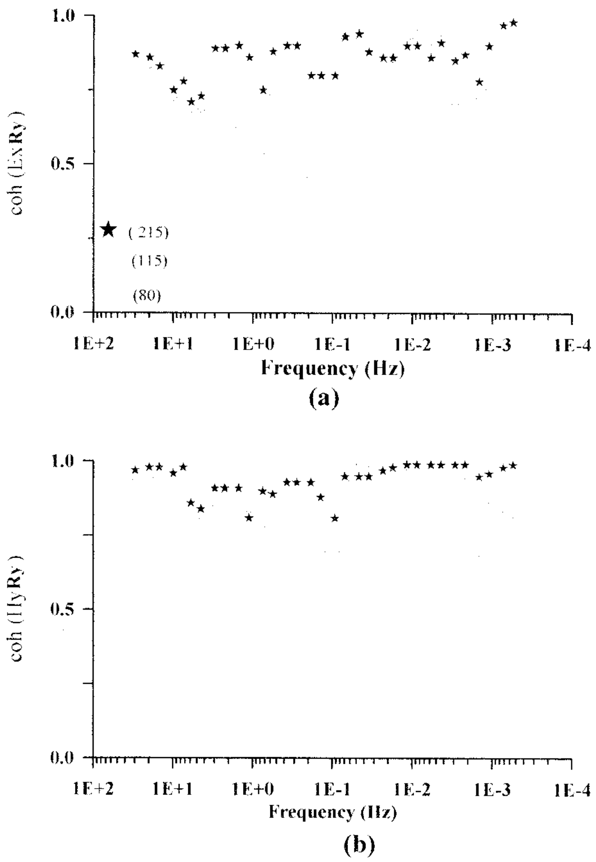


Figure 6. Estimation of coherences for fixed local site with remotes sites 80, 115, and 215: (a) coh ($E_x\mathbf{R}_y$) and (b) coh ($H_y\mathbf{R}_y$).

uncorrelated noise on local H_y and $\mathbf{R}_y$ for which the impedance is ±10% of the actual.

2.2. Effect of Varying Uncorrelated Noise in Local and Remote Varying Magnetic Fields on Impedance Estimation

[13] The effect of varying field ($H_y \neq R_y$) on estimation of impedance has been studied for varying amounts of uncorrelated noise in local H_y and E_x. The change in impedance ($Z_{\text{effective}}$) with varying field for different uncorrelated noise levels in local H_y selected from the window of Figure 2 shows that the estimates in most of the cases remain valid within the accuracy of ±10% provided R_y must be at least 0.3 times the local H_y (figure not shown). However, if $Z_{\text{effective}}$ is 0.6 times the initial impedance, then R_y can be as low as 0.1 times the local H_y.

3. Field Measurements

3.1. Remote Reference Magnetotelluric Measurements

[14] RR MT measurements were carried out over a traverse length of ~300 km between Badampahar and Dhanbad in India (Figure 1). The traverse covers widely different lithogolical units: Iron-Ore group (Late Middle Archaean, >3.1Ga), Singhbhum granite (Late Middle Archaean, 3.1Ga), Dalma Volcanics (Early Middle Proterozoic, 1.5 Ga), Chhotanagpur Gneissic Complex (CGC) (Late Middle Proterozoic, 1000 Ma), Gondwana sediments (Upper Carboniferous, 320–286 Ma) [*Saha*, 1994]. The sounding data at the sites comprise two orthogonal telluric (electric) fields and three orthogonal magnetic fields collected using the Phoenix V5-16 system, PbCl electrodes, and Phoenix induction coils. The fixed local site for this work was kept fixed at a location (Sundar Pahari, Dhanbad; 23°57′46″N; 86°32′09″E) which is 80, 115, and 215 km, respectively, from the remote sites 80, 115, and 215. The fixed local site is located over CGC. The remote site 80 is also over CGC, whereas the remote site 115 over Dalma volcanics and remote site 215 at Badampahar is over the Iron-ore group bordering Singhbhum granite. At the remote sites synchronous data were collected using another Phoenix V5-16 system. MT data acquisition in the V5 is divided into two frequency ranges: (1) high range, 12 frequencies ranging from 320 to 7.5 Hz and (2) low range, 28 frequencies ranging from 6.0 to 0.00055 Hz.

[15] The measurements at both the fixed local site and RR sites were 18 hours long using GPS clock synchronization. Out of these 18 hours of measurement, 3 hours were for the high range (320–7.5 Hz) and 15 hours for the low range (6–0.00055 Hz). Time series for all five components for the entire frequency range were converted to tensor impedances using standard techniques [*Vozoff*, 1991]. Impedances were converted to apparent resistivities and phases.

3.2. Application to MT Field Data

[16] Magnetic field signal and noise power spectral densities of three RR sites (80, 115, and 215), and the corresponding magnetic and electrical field signal and noise power spectral densities of fixed local site are shown in Figures 3a, 3b, and 3c, respectively. The power spectral density function of random data describes the general frequency composition of the data in terms of the spectral density of its mean value. The signal power spectral density of the remote magnetic field component is obtained by averaging the cross product of R_xR_x\{predicted\} and R_x\{predicted\}R_x, where R_x\{predicted\} is estimated from admittance calculation between H_x and R_x. Similarly, the spectral density matrices for the other fields can be estimated. The noise spectra are calculated by

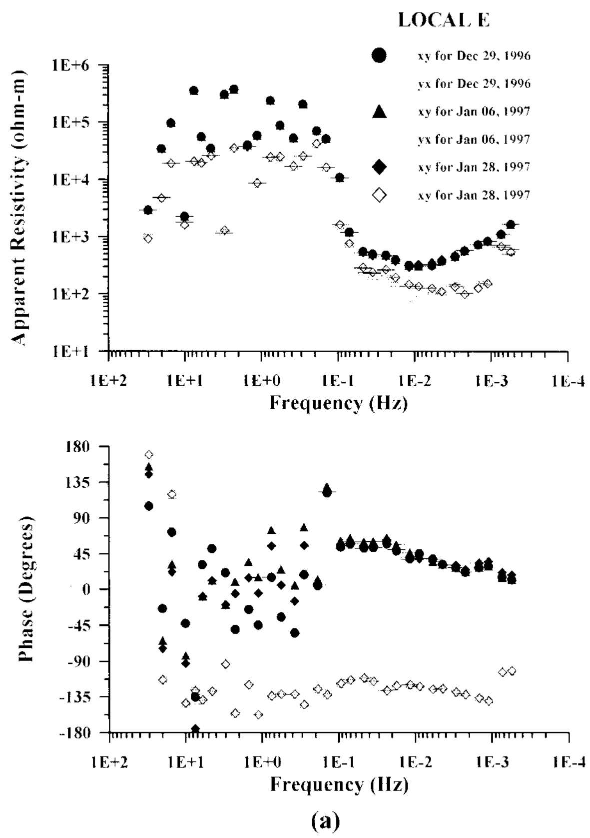
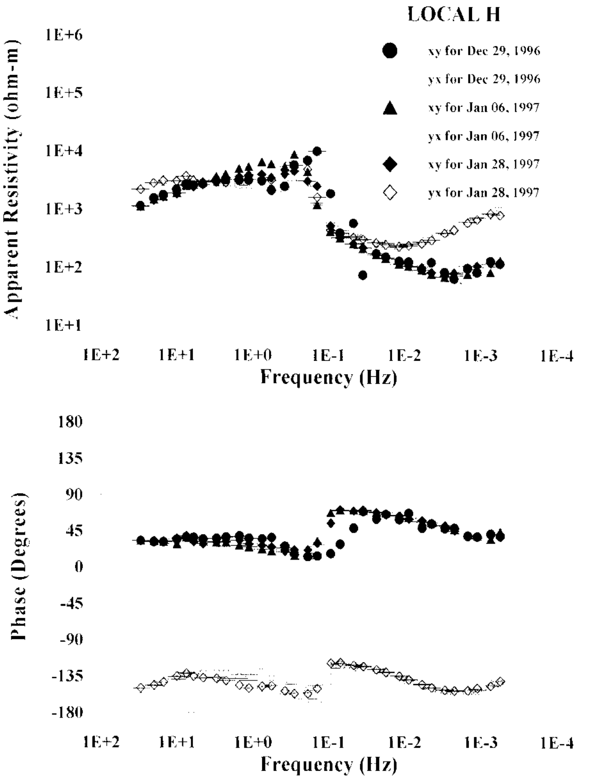


Figure 7. Estimation of (top) apparent resistivity and (bottom) phase for fixed local site with (a) local E, (b) local H, and (c) remote H processing.



(b)

Figure 7. (continued)

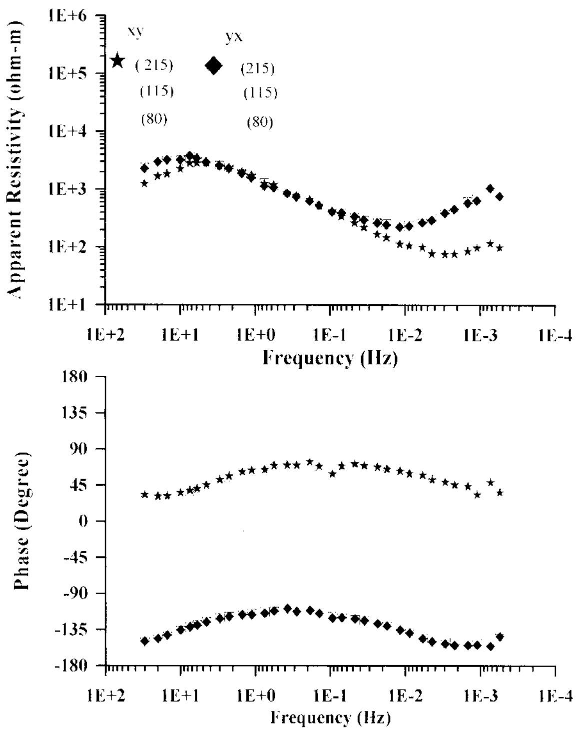
subtracting the estimated signal density matrices from the measured signal density matrices. The magnetic field signal power spectral densities at the fixed local site (Figure 3b) and also at all the RR sites (Figure 3a) show that it is stronger by ~2 orders as compared to the noise power spectral densities for all the frequency ranges. The electrical field signal and noise power spectral densities of the fixed local site (Figure 3c) show that the electrical signals are stronger than the noise for all frequencies excepting for the "dead band." The source for higher frequencies is broadband radiation from lightning strikes that propagates between the Earth and the ionosphere to the measuring site, and the dead band is the range of frequencies (5.0–0.1 Hz) that lies between the frequency ranges of two types of sources. In this range the noise is either equal or stronger than the signal. Figure 4 shows the magnetic field power spectral densities for the fixed local site for three days (29 December 1996; 6 January 1997, and 28 January 1997) on which these were measured along with corresponding remote sites. It is seen that the magnetic fields vary at the fixed local site, during the period of measurements, within a certain range (Figures 4a and 4b) and the magnetic fields of the farthest remote site (215) fall well within the range of variation of the magnetic fields at the fixed local site. Figures 4c and 4d show the magnetic power spectral densities for three remote sites (80, 115, and 215). It is seen that the range of variation of magnetic fields at all the three remote sites vary in the same range as that of the local site. Figure 4 shows that even when the remote site is as far as 215 km away, the signal strength is comparable. Figure 5 shows the signal-to-signal+noise ratio of the electric field (E_x and E_y) for the fixed local site for both the local processing and remotely processed data with sites 215 (Figure 5a), 115 (Figure 5b), and 80 (Figure 5c). Signal-to-signal+noise ratio at the fixed local site improves after RR processing for almost all the frequencies including the processing with the farthest site (215). There are cases where the signal-to-signal+noise ratios have degenerated, but they are infrequent. Figures 6a and 6b show the coh ($E_x\mathbf{R}_y$) and coh ($H_y\mathbf{R}_y$) of the local site processed with the remote sites 80, 115, and 215. It is seen that values of coh ($E_x\mathbf{R}_y$) remain above 0.5 for all the frequencies excluding the dead band when processed with the sites 80 and 115.

[17] Figures 7a and 7b show the apparent resistivity (top) and phase (bottom) of fixed local site on the three days with reference as local E and local H respectively. The estimates are not stable. Figure 7c shows the RR estimation of apparent resistivity (top) and phase (bottom) for the fixed local site for 3 days when RR processed with the corresponding remote sites. The error bars are smaller than the plotting symbols. RR estimates of apparent resistivity and phase of a fixed local site with three different remote estimates for RR sites at 80, 115, and 215 km are one and the same. However, there is a major deviation in phase in dead band for estimates with RR sites 80 and 115 and it is consistent with the results obtained for coh ($E_x\mathbf{R}_y$) (Figure 6a). It is seen that only the RR at 215 km is sufficiently far enough that the RR processing results in smooth MT transfer functions over the entire frequency range including the dead band. Note that there is difference between the apparent resistivities and phases for different RR processing at the longest periods (>300 s). This could be due to the active period of magnetic activity.

4. Conclusions

[18] RR estimation for uniform magnetic field remains valid for different combination of noise in local E_x and H_y. The range of permissible noise in local H_y is dependent on the percentage of uncorrelated noise in local E_x. RR estimations for varying magnetic field remains valid within the accuracy of ±10% for most of the cases of uncorrelated noise in local E_x provided R_y must be at least 0.3 times the local H_y.

[19] MT field studies show that the signal-to-signal+noise ratio for RR processed data for a local site even with a RR site located



(c)

Figure 7. (continued)

215 km away improves for the entire range of frequencies. RR estimates of apparent resistivity and phase of a fixed local site with three different remote estimates for RR sites at 80, 115, and 215 km are one and the same. However, there is a major deviation in phase in dead band for estimates with RR sites 80 and 115. It is seen that only the RR at 215 km is sufficiently far enough that the RR processing results in smooth MT transfer functions over the entire frequency range including the dead band. Thus the study reveals that a minimum distance of 215 km is needed between the remote and local site to obtain an unbiased observations and smooth MT transfer functions over the entire frequency range including the dead band.

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