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DC trains and Pc3s: Source effects in mid-latitude geomagnetic transfer functions

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Abstract. Magnetotelluric (MT) data from two sites 150 and 300 km southeast of San Francisco, California (geomagnetic dipole latitude: 43 degrees, L approximately 1.9) show that the usual MT assumption of spatially uniform external magnetic fields is violated to a significant degree in the period range 10-30 s. Inter-station transfer functions exhibit large systematic temporal variations which are consistent with a combination of two distinct sources: electromagnetic noise due to the San Francisco Bay Area Rapid Transit (BART) DC electric railway, and Pc3 geomagnetic pulsations. There is a suggestion in the data that some of the Pc activity may actually be excited by BART.

Since late 1995 researchers from U.C. Berkeley have maintained GPS synchronized magnetotelluric (MT) sites at two rural locations adjacent to the San Andreas Fault (SAF) south of the San Francisco Bay Area. The northern site (SAO) is near Hollister, CA, about 150 km southeast of the center of the Bay Area. The southern site (PKD) is near Parkfield, CA., about 150 km further southeast. Each site is instrumented with an EMI MT-1 system, consisting of three orthogonal induction coil magnetometers, two orthogonal dipoles to measure induced electric field variations, and Quanterra data loggers (digitizing at 1 Hz for this study). The array is being used to explore the possibility that electromagnetic (EM) precursors to earthquakes might be generated by tectonic activity along the SAF. A major rationale for having two stations was to use data from one site to estimate the EM signal of ionospheric/magnetospheric origin at the other site. By doing this one might be able to detect anomalous signals of smaller amplitude, and possibly extend the reported association between anomalous EM signals and earthquakes to more frequent smaller events.

Underlying this plan was the usual MT assumption that external magnetic fields are spatially uniform, at least over distances of a few hundred kilometers. Under this assumption the horizontal magnetic fields at one site (e.g., SAO) can be related to the those at the other site (PKD) via a frequency dependent 2×2 transfer function (TF) $\mathbf{H}_{SAO} = \mathbf{T}(\omega)\mathbf{H}_{PKD}$. If the external sources are uniform (in some average sense) the typically subtle deviations of $\mathbf{T}$ from the identity matrix can be interpreted in terms of conductivity variations within the earth.

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The uniform source assumption has been questioned [e.g., Anderson et al., 1976], and significant variations in the amplitude and polarization of Pc3 pulsations over distances of only a few hundred km have been documented even at low latitudes [Lanzerotti et al, 1981]. However, except at long periods ($T > 1000$ s) and high latitudes, most solid earth induction studies assume that the spatial structure of natural sources can be safely ignored, provided TFs are averaged over a long enough time. Here we show that for periods of 10-30 s inter-station TFs exhibit unphysically rapid variations with frequency which depend systematically on local time. Since the solid earth is comparatively static, such variations in TFs must reflect variations in non-uniform source geometry.

Inter-station Transfer Functions

We analyzed the data using robust multiple station TF methods [Egbert, 1997] to characterize signal and noise in the array, to study possible trends in TFs due to slow changes in earth resistivity, and to search for possible anomalous EM signals. Eisel and Egbert [1999] present results from some of these studies and give a more complete description of the array. Here we estimate TFs using subsets of the data to investigate more rapid systematic variations of TFs.

In Figure 1 we plot the variations with period and local time of amplitude and phase for the principal inter-station TFs estimated using all data from Julian days 140-199 1997, a period when the array was fully functional with few significant noise problems. T_{xx} (T_{yy}) corresponds to the ratio of the geographic north (east) magnetic component at the northernmost site SAO relative to PKD. Features referred to in the following are numbered in Figure 1. Variations are most dramatic in the T_{xx} component, with a pronounced amplitude low centered on a period of about 13 s and at local noon (1). This corresponds to variations in H_x having smaller amplitude at SAO than at PKD. At slightly shorter and longer periods, and still in the middle of the day, the situation is reversed with larger amplitudes at SAO (2). In the early morning and evening hours there is a significant amplification of H_x at SAO across the 10-30 s band (3). From 2-4 am these rapid variations with frequency almost completely disappear (4).

There are also substantial variations in TF phase, with a 20 degree phase depression centered around a period of 15 s and local noon (5), and phase increases in early morning and late evening hours (6). Again phase curves vary smoothly from 2-4 am. Note that the T_{yy} variations show a strong asymmetry between dawn and dusk (7). There are a number of other

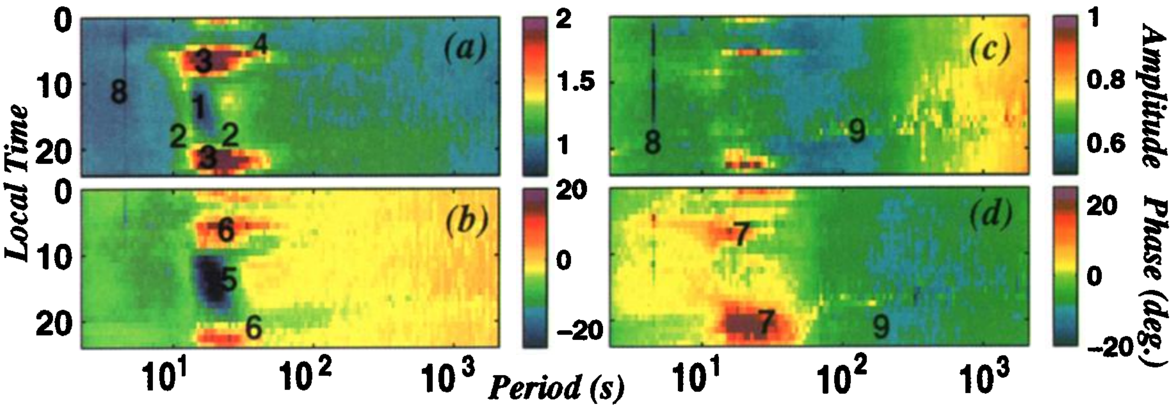

Figure 1. Variation of inter-station TFs as a function of period and local time. (a) Amplitude of T_{xx}; (b) phase of T_{xx}; (c) Amplitude of T_{yy}; (d) phase of T_{yy}. Numbers are referred to in text. Note the difference in scales used for T_{xx} and T_{yy}.

possibly significant features in these plots which are beyond the scope of this paper. For example, observe the line in all plotted components at a period of 4 s (8), and the anomalous behavior of the TFs in late afternoon at longer periods (9).

The multiple-station processing methods used here treat all channels symmetrically, so there should be no downward biases in amplitudes of the predicted (SAO) channels due to noise in the reference (PKD) channels, as would occur with more conventional TF estimation schemes [Egbert, 1997]. However, as a check we repeated calculations using each station in turn as the local reference. Similar patterns were found in all cases, proving that the TF biases of Figure 1 are not due to incoherent noise at either site.

Source Gradients due to BART

Due to the diffusive nature of EM propagation in the conductive earth, induction TFs are expected to vary slowly with frequency. The rapid variation with frequency, and the systematic dependence of the TFs on local time both require systematic variation of the spatial structure of the external source fields. In particular, there must be variable N-S gradients in the magnetic sources. The standard TF approach with two predicting channels is justified by the assumption that sources are spatially uniform enough to be represented by only two independent components. The multivariate array analysis methods described in Egbert [1997] can be used to estimate the actual number of independent coherent sources. Briefly, cross-products of the Fourier coefficients computed from short time segments of all 10 channels are averaged to form the 10×10 spectral density matrix (SDM). Eigenvalues of the 10×10 SDM, scaled by estimates of incoherent noise amplitude for each data channel, correspond to signal-to-noise (SNR) ratios of independent coherent EM sources. The number of eigenvalues significantly above 0 dB thus provides an estimate of the number of independent signal components M resolved by the array. For quasi-uniform (MT) sources M should be 2. For the SAO/PKD array $M = 4$ from 10-300 s (Figure 2). For the two dominant eigenvectors (not shown), the horizontal magnetic components are roughly uniform across the array, consistent with the usual MT assumption. Eigenvectors three and four are dominated by gradients in the EM fields, showing that there are significant time-variable gradients in the magnetic sources from 10-300 s.

The temporal variability of power in the gradient fields (expressed in SNR units as described in Egbert [1997]) is plotted at 10 day intervals as a function of local time (two hour resolution) for 1996-97 in Figure 3. Plotted on the side is the average electric power consumption of the BART system as a function of local time for Nov. 1998. Several features in this plot demonstrate that BART is the source of most of the magnetic field gradients. First, for periods of 25 s and longer the gradient noise peaks twice per day, exactly when BART power consumption peaks during the morning and evening rush hours. Second, there is a pronounced low in gradient power from approximately 0:00-4:00. These bins include the time when the BART system shuts down each evening (1:00-4:00). BART activity should thus be minimal in the second two hour bin (2:00-4:00). However, we used UT for bining the data (and PST for labeling the figure), so from April-October when daylight savings time is in effect the minimum BART activity actually occurs during the first bin (1:00-3:00 PDT). These times correspond exactly to the minimum in gradient power, with even the change from PST to PDT clearly discernible. Finally, there is one ten day period for which gradient power is anomalously low. This interval includes a labor strike by BART workers (days 251-258, 1997), when the transit system was shut down. We conclude that BART is the cause of the bulk of the gradient variation seen in the array. Note that evidence for large scale BART EM fields has been reported previously at similar periods [Fraser-Smith and Coates, 1978; Egbert, 1997], at stations closer to the SF Bay Area. That there are significant effects even 300 km away is perhaps more surprising.

Pc3s

The daily variation of gradient power seen in Figure 3 is significantly different for the 15 s band, where there is only a single broad peak in the middle of the day. This peak, which is also somewhat evident in the adjacent 9 and 25 s bands, does not go away during the BART strike. Thus there are significant local gradients in magnetic variations near a period of 15 s in the middle of the day that do not appear to result from BART. These are exactly the periods and local times where the magnetic fields are actually anomalously large at PKD, the southernmost site (Figure 1). This sort of amplitude variation cannot be reasonably explained by passive propagation of EM fields from a source in the Bay Area.

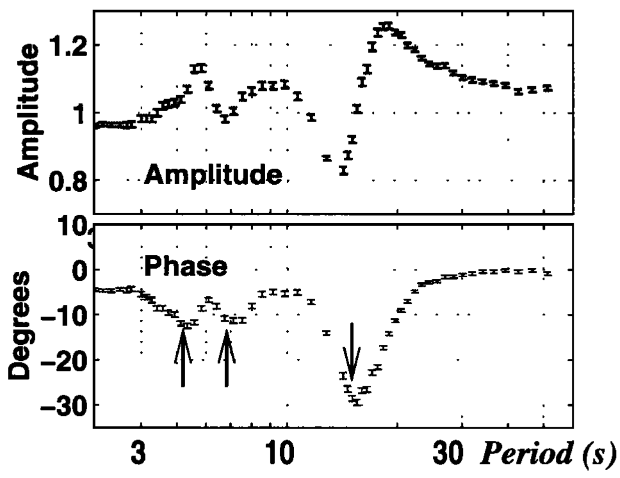

Figure 2. Eigenvalues of the scaled SDM for the PKD/SAO array provide clear evidence for coherent noise for periods from 10-300 s.

We suggest that the narrow-band enhancement of the magnetic field amplitudes at PKD results from natural sources, namely Pc3 geomagnetic pulsations due to resonance of hydromagnetic (HM) Alfven waves propagating along field lines [e.g., Chen and Hasegawa, 1974]. Rapid variation of the resonant period with latitude can result in spatially localized magnetic variation amplitude maxima [e.g., Baransky et al., 1985]. In Figure 4 we plot amplitude and phase of T_{xx} computed using data from daylight hours during the BART strike. The oscillation in amplitude and dip in phase seen in this figure between 10-20 s is essentially identical to the schematic diagram used by Waters et al. [1991] to justify use of cross-power phase for estimation of Pc3 resonance frequencies. Using the well-defined dip in the phase curve for the BART strike (Figure 4), and following Baransky et al. [1985] and Waters et al. [1991], we estimate the resonant frequency for the latitude midway between the two sites (42.99° geomagnetic dipole; L = 1.89) to be about 15.5 s. There are additional local minima in phase at approximately 7.3 and 5.3 s. These are quite plausible periods for the second and third harmonics of the fundamental mode.

Discussion

The 15 s field line resonance is most strongly excited during daylight hours, with peak amplitudes occurring around local noon. Effects on TF bias and gradient power do not correlate with BART power consumption, and persist through the BART strike. These Pc3s thus must obviously be excited by natural sources. The peak at local noon, and minimum during the night, is consistent with other observations of local time variations of low latitude Pc3 intensity [e.g., Lanzerotti et al., 1981], and with the proposal that radial pressure waves in the magnetosphere due to variations in the solar wind excite field line resonances at low latitudes [e.g., Yumomoto, 1986].

Superposed on the resonance effect is an upward bias in TF amplitude with a corresponding peak in phase, extending over a broader range of periods (10-30 s). The upward bias can be quite extreme (on average a factor of 3 from 5-6 am), but disappears when BART stops running. This peak thus clearly results from magnetic fields which originate with BART, and have larger amplitudes (and phase leads) at the site closest to the source (SAO). The bias in TF amplitudes and phases due to the BART fields is largest and most obvious during evening and early morning hours when other EM signals (in particular the natural source Pc3s) are weak. However, Figure 1 shows that mid-day TFs are also biased upwards in the broader 10-30 s band when BART is running. From 2-4 am when no trains run and excitation of Pc3s is weak the external inducing fields are most nearly uniform, and inter-station TFs best behaved (Figure 1).

There are significant issues which deserve further study. In particular, why is the bias so strongly peaked in frequency? The induction coils used maintain good signal-to-noise ratios (30-50 dB) to at least 3000 s period (Figure 2; see also Egbert [1997]), so this cannot be due to instrument sensitivity. It is possible that the biases are reduced at periods longer than 20-30 s because of the steep increase in

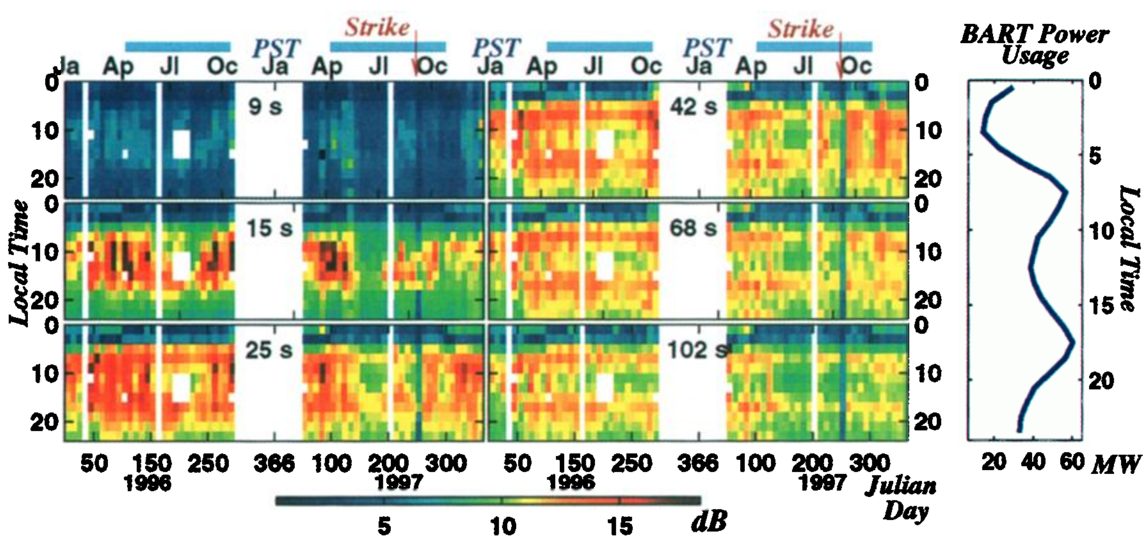

Figure 3. Power in magnetic field gradients in SNR units vs. local time and Julian day for 1996-1997 for six periods. Times of poor data quality are white. The BART strike is indicated by the red arrows, and daylight savings time is indicated by the light blue bars at the top. Average power consumption of BART (in MW) is plotted vs. local time on the right.

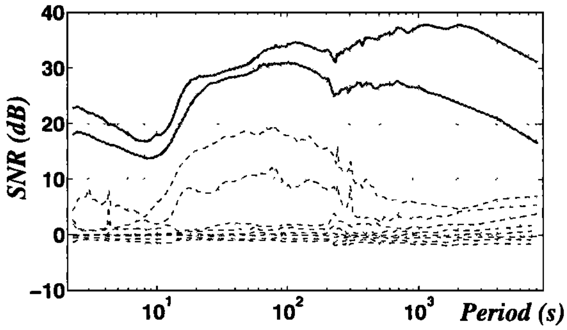

Figure 4. Amplitude and phase of T_{xx}, with statistical error bars, computed using data from days 252-257, during the BART strike. The three distinct phase lows (arrows) are interpreted to be the fundamental and first two harmonics of the Pc3 field line resonance

power of natural sources with increasing period. These (presumably longer wavelength) sources may simply overwhelm the BART signals. The most intriguing possibility is that the peak in the BART component of the TF bias results from the same sort of field line resonance effects responsible for localized amplification of HM waves in the Pc3 band.

We have clear evidence that magnetic fields generated by DC train activity are seen at distances of at least 300 km. Given this large length scale it is almost certainly necessary to include the conducting ionosphere (only 100 km above) in any analysis of EM propagation. This conclusion is strongly supported by the distinct asymmetry between early morning and late evening bias in the T_{yy} component of the interstation TF (Figure 1, (7)). We have shown that bias at these local times almost certainly results from BART, so this asymmetry suggests that propagation of the EM fields from their ultimate source in the Bay Area to Parkfield is influenced by the spatial pattern of conductivity in the ionosphere. But can this be treated as a passive conductor as in solid earth induction studies? Or might the sort of HM dynamics which allow for Alfven waves be relevant to the description of such long distance propagation of large scale anthropogenic EM sources? Does BART actually excite geomagnetic pulsations?

MT impedances from sites within 100 km of the SF Bay Area have been previously observed to be seriously biased by the finite spatial scales in the BART sources [Egbert, 1997]. Very subtle biases in MT impedances have also been detected at Parkfield [Eisel and Egbert, 1999]. The nature of the bias (a steep increase in apparent resistivity with period, phases dropping to near zero) is consistent with the impedance expected in the near field of a grounded electric dipole. This source model seems reasonable for BART, a DC train system with an electrified third rail. Currents flowing in the system vary in space and time in a complex manner, due to the motion of the trains and to cycling of motors used to control speed. Although nominally the return path for currents is in the running rails, significant current leakage into the ground seems inevitable. As a whole the system is a complex network of very long grounded dipoles with temporally varying geometry and current inputs. A complete understanding of how BART generates magnetic fields over such a large area will require accounting for return path currents leaking into the conductively heterogeneous earth and ocean, as well as currents, and possibly HM oscillations, induced in the ionosphere by these telluric currents.

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