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ANOMALOUS EM SIGNALS AND CHANGES IN ELECTRICAL RESISTIVITY AT PARKFIELD: COLLABORATIVE RESEARCH BETWEEN THE UNIVERSITIES OF CALIFORNIA AT BERKELEY AND RIVERSIDE AND OREGON STATE UNIVERSITY

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TECHNICAL ABSTRACT

Fluctuations of resistivity and anomalous electromagnetic (EM) signals have often been reported as precursors to earthquakes. Most of these reports are based on anecdotal observations of unusual phenomena associated with distant earthquakes and the signals are often orders of magnitude larger than that predicted from laboratory measurements and expected stress or strain changes, leading to considerable uncertainty in their reliability. In an attempt to assess the validity of these reports and to understand how such signals might be generated, we have been monitoring resistivity changes since 1988 and anomalous EM signals since 1995 at the site of a focused earthquake prediction experiment at Parkfield. Monitoring at a location with many other geophysical measurements allows for correlation of anomalous EM changes with other physical properties such as water level, temperature, strain, and seismicity. Correlation of anomalous variations with other anomalous geophysical signals increases the likelihood that our anomalies are tectonic signals and provides clues to mechanisms. Our goal is to determine whether a moderate (M~6) earthquake can produce anomalous signals at instruments located only 10 km (i.e., at the epicenter) from that earthquake. If observable changes are not seen at such close proximity, then the association of signals with more distant and often smaller earthquakes is much less credible. Based on laboratory and field studies, resistivity variations and anomalous signals of only a few percent of the background levels are expected. Transfer functions

(TFs) between electric fields or between electric and magnetic fields are needed in both cases; resistivity variations will appear directly as changes in the TFs, and small anomalous signals can be detected only after removal of the natural field. To monitor resistivity, stabilities of estimated TFs need to be better than 1%. We have developed techniques to estimate these TFs with errors of less <0.5% between electric fields and ~1-2% between electric and magnetic fields. While these levels represent substantial improvement over standard methods, further work is needed to reduce these errors. The TFs must remove more than 99% of the natural signal in order to detect anomalous EM signals, and we must differentiate between cultural noise and tectonic signals. Mulitvariate processing has been used to characterize cultural noise and natural source complications and to improve residual filters. Complications due to severe cultural noise from the San Francisco area (BART) would be reduced significantly by addition of a third monitoring station near Parkfield. There have been no clear associations yet between the residual fields or the transfer functions and the smaller, local earthquakes. This lack of correlation with earthquakes as large as M5.0 suggests that there is a lower limit of sensitivity; if so, then monitoring EM changes may provide a useful discriminant for large, damaging earthquakes.

NON-TECHNICAL ABSTRACT

There are many reports of anomalous electric and magnetic fields at frequencies from quasi DC to several 10's of Hertz, and changes in ground resistivity, prior to earthquakes. Most reports are devoted to one or another of these phenomena using a variety of measurement configurations and data processing techniques. It is the objective of this study to determine whether significant changes in resistivity, quasi DC electric fields, or ULF electric and magnetic fields occur before earthquakes in California.

Introduction

The primary objective of the UC Berkeley electromagnetic (EM) monitoring array is to identify EM fields that might be associated with earthquakes. The array has consisted of up to three sites since 1995 at SAO, PKD, and PKD1, each of which measures three orthogonal components of the magnetic field and two orthogonal components of the electric field. Such an array is necessary in order to separate the fields of a local source (e.g., an earthquake signal) from the natural EM fields of the Earth. Our approach has been to determine the transfer function between fields at different sites for periods of normal background EM variations and then use this transfer function to predict fields between sites. Differences between the observed and predicted fields are used to search for anomalous local fields.

Analysis of the UCB array has shown that cultural noise from the San Francisco Bay Area (in particular BART) extends over surprisingly large areas, and that natural ionospheric sources may exhibit significant spatial complexity (*Egbert et al*., 2000). The fundamental MT assumption of spatially uniform sources is thus frequently violated in this area. These source complications are highly variable in time, reducing the effectiveness of a single remote site for EM noise cancellation. Multiple remote sites would allow significantly better cancellation of these more spatially complex EM noise fields, and would also reduce bias errors in the inter-station transfer function estimates. It was always the goal of the project to have three stations, but in 1999 the use permit at Haliburton Ranch was lost and PKD1 was removed just one month after PKD was installed. Analysis of data from this one month clearly demonstrates the value of three sites for improving the residual analysis.

Magnetotelluric Array Overview

In 1995 we installed two well-characterized electric and magnetic field measuring systems at two sites along the San Andreas Fault which are part of the Berkeley Digital Seismic Network. Since then, magnetotelluric (MT) data have been continuously recorded at 40 Hz and 1 Hz and archived at the Northern California Earthquake Data Center (NCEDC), Tables 1 and 2. At least one set of orthogonal electric dipoles measures the vector horizontal electric field, E, and three orthogonal magnetic sensors measure the vector magnetic field, B. These reference sites, now referred to as electromagnetic (EM) observatories, are co-located with seismographic sites so that the field data share the same time base, data acquisition, telemetry, and archiving system as the seismometer outputs.

The MT observatories are located at Parkfield (PKD1, PKD) 300 km south of the San Francisco Bay Area and Hollister (SAO), halfway between San Francisco and Parkfield, Figure 1. In 1995, initial sites were established at PKD1 and SAO, separated by a distance of 150 km, and equipped with three induction coils and two 100 m electric dipoles. PKD1 was established as a temporary seismic site, and when a permanent site (PKD) was found, a third MT observatory was installed in 1999 with three induction coils, two 100 m electric dipoles, and two 200 m electric dipoles. PKD and PKD1 ran in parallel for one month in 1999, and then the MT observatory at PKD1 was closed. Data at the MT sites are fed to Quanterra data loggers, collocated at the BDSN stations, synchronized in time by GPS and sent to the Berkeley Seismological Laboratory (BSL) via dedicated communication links.

Site	Net	Latitude	Longitude	Elev (m)	Date	Location
PKD	BK	35.945171	-120.541603	583	1999/02/05 -	Bear Valley Ranch, Parkfield
PKD1	BK	35.8894	-120.426109	431.6	1995/06/06 - 1999/03/08	Haliburton House, Parkfield
SAO	BK	36.76403	-121.44722	317.2	1995/08/15 -	San Andreas Obs., Hollister

Table 1: Sites of MT observatories

Sensor	Channel	Rate (sps)	Mode	FIR
Magnetic	VT?	0.1	C	Ac
Magnetic	LT?	1.0	C	Ac
Magnetic	BT?	40.0	C	Ac
Electric	VQ?	0.1	C	Ac
Electric	LQ?	1.0	C	Ac
Electric	BQ?	40.0	C	Ac

Table 2: Typical data streams acquired at each MT site, with channel name, sampling rate, sampling mode, and FIR filter type. C indicates continuous; T triggered; Ac acausal.

Instrument Responses

As part of the station maintenance, calibrations have been performed on various components of the MT systems and the transfer function information at the NCEDC is updated accordingly.

Station Maintenance 2001-2003

SAO

In 2001, SAO experienced problems with the power supplies for the B-field and E-field equipment. The B-field coils and the EFSC box were removed, calibrated, and returned. The voltage regulator circuit of the B-field power supply was replaced.

In January 2003 the Q4120 datalogger was replaced. In February, the Hx coil was replaced.

PKD

The site at Parkfield continued to have problems with electrodes drying out. Bentonite was added to help retain moisture. The electrodes were pulled in March and the copper-sulfate solution was replaced. In parallel, lead-lead-chloride electrodes were provided by John Booker of the University of Washington. The lead-lead-chloride electrodes appear to be less sensitive to the lack of moisture in the holes.

Last September, lead-lead chloride electrodes from John Booker were installed in the 200 m dipoles. They require less maintenance than the copper-copper sulfate electrodes used in the 100 m dipoles. The addition of bentonite has significantly improved water retention in the electrode holes, increasing electrode longevity. In December the vertical coil was replaced, and in May and June 2003, the batteries powering the electric field pre-amplifiers were replaced.

Data Quality Control

During this year, BSL staff worked in collaboration with Gary Egbert to install his software for automated data processing. The software provides the capability of identifying problems and alerting staff. There is a daily printout of the signal to noise ratios (SNR) in dB for each channel of the array. Currently, SNR's below 10 dB are flagged for inspection or repair by the array operators. Any failures of the UCB MT array are now immediately detected so that corrective action can be taken in a timely fashion. With these improvements in the system, nearly continuous high quality data have been collected.

Routine Data Processing

A major part of the recent effort at Oregon State University has been to develop user friendly computer codes for routine processing of data from the UCB MT sites. The processing system is based on a graphical user interface, written in MATLAB, which allows the user to download MT data from the NCEDC and complete all routine processing steps (including the multi-site). The program also can be used to plot processing results, multi-channel time series and various simple diagnostics of data quality. Results (including daily estimates of MT impedances, inter-station transfer functions, estimates of noise amplitudes, and summaries of frequency and time domain residual amplitudes) are then automatically archived for statistical analysis and correlation in space and time with cluster events at Parkfield. There is now a daily printout of the signal to noise ratios (SNR) in dB for each channel of the array.

Any data in the NCEDC archive can be downloaded, but by default the program gets and processes the most recent unprocessed data. These codes will thus enable more-or-less automatic monitoring of system functionality, and make it easier to maintain a high rate of quality data return. The streamlined processing codes will also make it easier to reprocess existing data with any new schemes that will be implemented in the future. We are presently using the new system to process the backlog of data from the array, and to update analyses of residuals, and of MT impedance stability.

Frequency Domain Processing

The frequency domain analysis using multiple station techniques (*Egbert*, 1977) makes optimal use of data from all sites to estimate stable and reliable transfer functions. The multi-site analysis has also proven to be very useful for better understanding of signal and noise, and for separating coherent signals of differing spatial scales, Figure 2(a). For example, (*Egbert et al*. 2000) used a multiple station analysis to show that the transfer function between SAO and PKD1 is systematically affected by both the DC train system in the Bay Area (BART) and by the non-uniformity of the natural fields in the Pc3 band, Figures 3 a,b. These results demonstrated that cultural noise sources can extend their effect over surprisingly large areas, and at the same time, natural ionospheric sources may exhibit significant spatial complexity. Because of this added spatial complexity, multiple sites are required for complete cancellation of the background (non-tectonic) EM noise. Ideally three stations should be used to avoid bias errors in the transfer function estimates and to maintain better control over cultural noise.

Predictions based on data from at least three sites will significantly improve our ability to detect anomalous signals. Source complications, as well as local incoherent noise sources, are highly variable in time (e.g., Figure 3b), making it a challenging task to verify that apparently anomalous signals truly originate in the earth. Thorough calibration and understanding of both local and distant noise sources is essential. This critical step has now been accomplished for the UCB array (*Egbert et al*., 2000; *Eisel and Egbert*, 2001). When a major Parkfield event does occur we will be in a very good position to detect and identify anomalous EM emissions (if there are any) and to avoid the ambiguity of interpretation that has plagued much of the past search for EM precursors.

This analysis has revealed significant diurnal variations in the residual distributions. With a two site array, residuals are smallest between the hours of 0-4 am, making this a particularly good time to look for anomalous signals. Comparison of the temporal distribution of unusually large magnetic residuals to local earthquake catalogs has so far revealed no clear associations, but there have been few earthquakes of significant magnitude in the time period studied.

The MT stations at PKD and SAO can also be used to monitor resistivity changes prior to earthquakes. Unlike the UC Riverside telluric array, the MT impedance can yield depth information because the depth of penetration of the EM waves increases with period. Seasonal changes caused by precipitation would presumably be shallow and affect primarily the shorter periods, while deeper changes would be seen also at longer periods. The amplitude of the MT impedance may fluctuate at all periods in response to shallow changes (the so-called "static" shift problem), but the phase of the response is set by more regional structure at longer periods. Thus, variations in phase should be a sensitive indicator of resistivity variations at seismogenic depths (~10 km). *Eisel and Egbert* (2001) made a study of the stability of the MT impedances at PKD1. Typical deviations of estimates based on a single day of data differed from the long term average transfer function by 2-3% for $T < 300$s and increasing to about 10% for $T=2000$s. Variations between contiguous days were nearly random, so significantly smaller variability can be obtained by longer averaging times. There is some evidence from this analysis for a slow variation of about 1% in impedance amplitude when an 11 day average is applied. Relative resistivity variations are nearly frequency independent, appear anti-correlated between the x-y and y-x modes, and are larger than variations in phase. These features together are suggestive of temporal variations in nearsurface static distortion. Although it is difficult to make a definitive statement on the basis of the data analyzed so far, there does not appear to be any seasonal component to these variations, as might be expected

Time Domain Processing

This year time domain processing codes have been developed and tested on short segments of data by Karl Kappler using a least squares Wiener filter. An effort has been made to do residual analysis purely in the time domain. The data used are the MT measurements on all five channels sampled at 1Hz. Since the station mostly sees noise originating by large sheet currents in the ionosphere, and the distance between sites is only a few hundred km, the input EM signal at each station should be roughly the same. Thus, a transfer function (TF) between two sites should be approximately constant. The relationship between the two sites is determined at a time when no significant seismic activity (SSA) is occurring near the arrays. On a day when SSA is present at one site, we can examine the residuals for anomalous activity.

We use an impulse response operator (IRO) rather than a TF as we are working in the time domain. The current IRO is a Wiener filter computed using least squares. The operator is computed using a day's worth of data (86400 observations). Before computing the operator, the data must be despiked. For this, an automated despiking algorithm has been employed. Time series data are scanned for anomalies which lie more than a user specified number of standard deviations from the sample mean (default is 10). When an outlier is observed, the corresponding channel at the other station is examined within a two minute window about the time of the outlier. If a similar event took place, the anomaly is considered signal. Otherwise it is considered anomalous noise and is replaced. Currently a two minute window about the spike is replaced with a linear fit. Substituting with an ARMA (Auto Regressive Moving Average) model prediction has also been used, but is not yet the standard.

After despiking, the data are detrended using a first order polynomial. Then the IRO is computed. To predict a given channel we use all five channels at the other site. Denoting the channel to be predicted as the time series X_t, we obtain the formula

$$X_t = \sum_{ch=1}^{5} \Psi_{ch} * T_{ch}$$

where ch denotes that the sum is over each channel, and each channel has its own convolution operator. The * then denotes the convolution between the filter and T, the time series.

The length of the IRO can be any odd number. It has been observed that by using a longer IRO, predictions improve. With a long enough operator the least squares fit can be made arbitrarily fine, but such a fine fit is also fitting noise unique to the data segment used to compute the IRO. We choose an IRO length which gives a fit roughly as good as it gives a prediction of future signal. Figure 4 shows the ratio of the RMS signal to residuals as a function of IRO length. As the filter gets longer, the fit is better.

Due to the computing power needed for this approach (inverting a matrix of dimension 5 times the filter length, and mutiplying two large matrices), we can see that the number of calculations rises quadratically with filter length. For day long time segments it is difficult to compute an IRO much longer than 35. An optimization can be performed for a given time segment length to determine the best IRO length. These may include a constrained least squares inversion using support vector machines, or ARMA approaches. For simply reducing one channel to residuals through modeling, invertible ARMA methods yield reduction as good or better. The disadvantage to this type of modeling, however, is that it is difficult to use in predicting one station from another. Furthermore, the method is expensive on computing power and can only model short segments, say of order one hour, with the current computing system and software.

Figure 5 shows the result of five 11-point Wiener filters applied to the five channels of Parkfield data on day 228 in 1996. This day was chosen for its good signal to noise ratios in the raw data, and the fact that a M4.0 earthquake occurred one month later near the Parkfield array. The IRO was computed using this day's data, so this is essentially a least squares fit. The edges are imperfect, but the fit is generally excellent. The RMS ratio is around 12.2; however, if we neglect the edges (5000 s to either side), the RMS is 14.

In Figure 6, the day 228 filters are used for prediction of day 230. We can see that the shape of the fit is again excellent, but there are some long period effects, which leave the prediction higher than the signal in some places and lower than the signal in others.

In the raw data there have been some long period instrument related diurnal effects in the magnetic data. A high pass filter has been designed for this job. Care is required in filtering out the long period signals, as the MT precursors we are looking for could be low frequency.

Summary

The residual analysis in time domain is free of the frequency domain inherent errors. The Gibbs phenomenon and effects due to discrete modeling are non existent. The time domain residuals can be computed and scanned for anomalous activity. Bandpass filtering of the raw data will likely remove some of the prediction misfit. Also, cutting the data into smaller parcels (one-three hours) and detrending each of these segments individually may reduce some of the long period noise. High frequency noise also leads to misfits in data. Low pass filters need to be employed to decimate signal to about 0.03 Hz, as we are looking for signals with duration greater than half a minute. Cleaning out this high frequency noise will likely improve predictions. The code is in place to begin the filtering this fall. Experiments with other prediction methods (such as constrained LS and ARMAs mentioned earlier) will continue as well. The plan is to have an automated system which reads in data from the array, despikes, computes residuals, and then scans the residuals for RMS anomalies in place over the next 4 months.

Acknowledgements

Frank Morrison directs the MT program, and collaborates closely with Gary Egbert of Oregon State University and Steve Park of UC Riverside. Karl Kappler is developing time domain processing techniques. Sierra Boyd, John Friday, Lind Gee, and Doug Neuhauser also contribute to the operation of the MT observatories.

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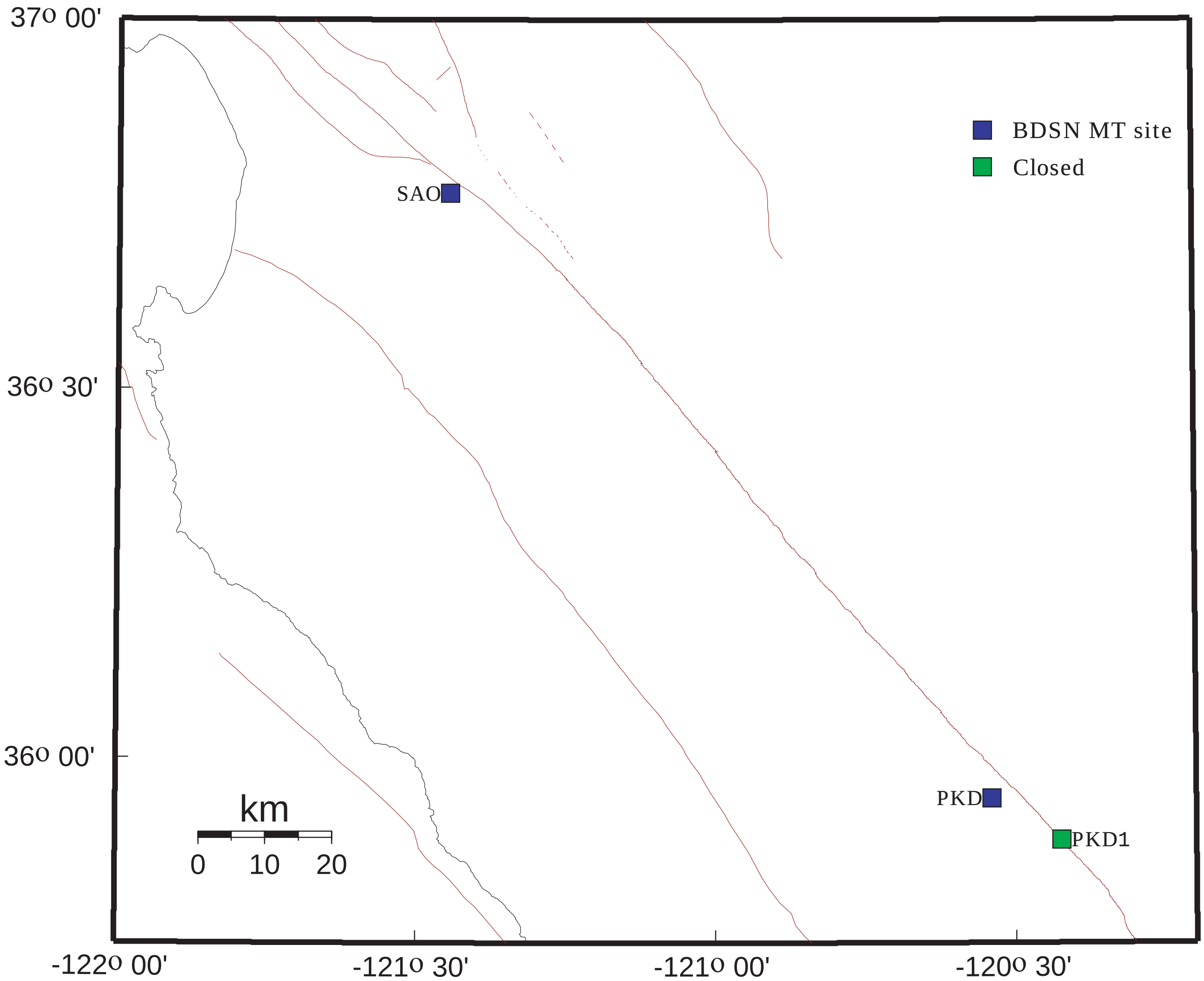

Figure 1. Map illustrating the location of operational (filled squares) and closed (grey squares) MT sites in central California.

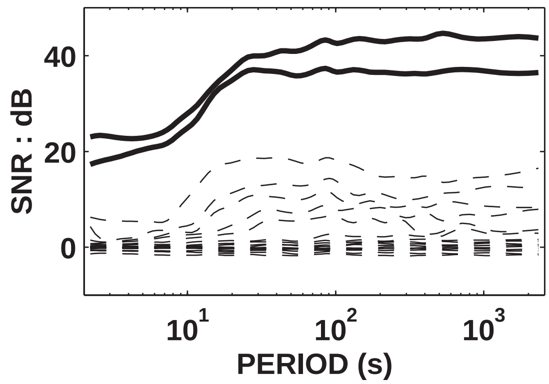

Figure 2(a). Eigenvalues of the scaled Spectral Density Matrix (SDM) for the three site PKD1/PKD/SAO array, computed following the methods described in Egbert, (1997). Briefly, cross-products of Fourier coefficients computed from short time segments of all 17 data channels are averaged for the 30 days. For idealized quasi-uniform MT sources, there should only be two eigenvalues significantly above the 0 dB noise level. Additional large eigenvalues, as seen here from 10-300 s, are a clear indication of coherent noise or temporally varying complications in source geometry. For the two dominant eigenvectors, the horizontal magnetic components are roughly uniform across the array, consistent with the usual MT assumptions. Eigenvectors three and four are dominated by gradients in the EM fields.

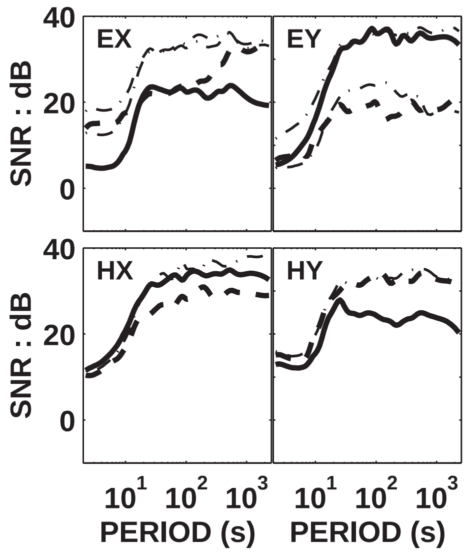

Figure 2(b). The magnitude of incoherent noise power is estimated for each channel, and these are used to non-dimensionalize the SDM. Eigenvalues of the 17x17 scaled SDM then give signal-to-noise (power) ratios of independent coherent EM sources.

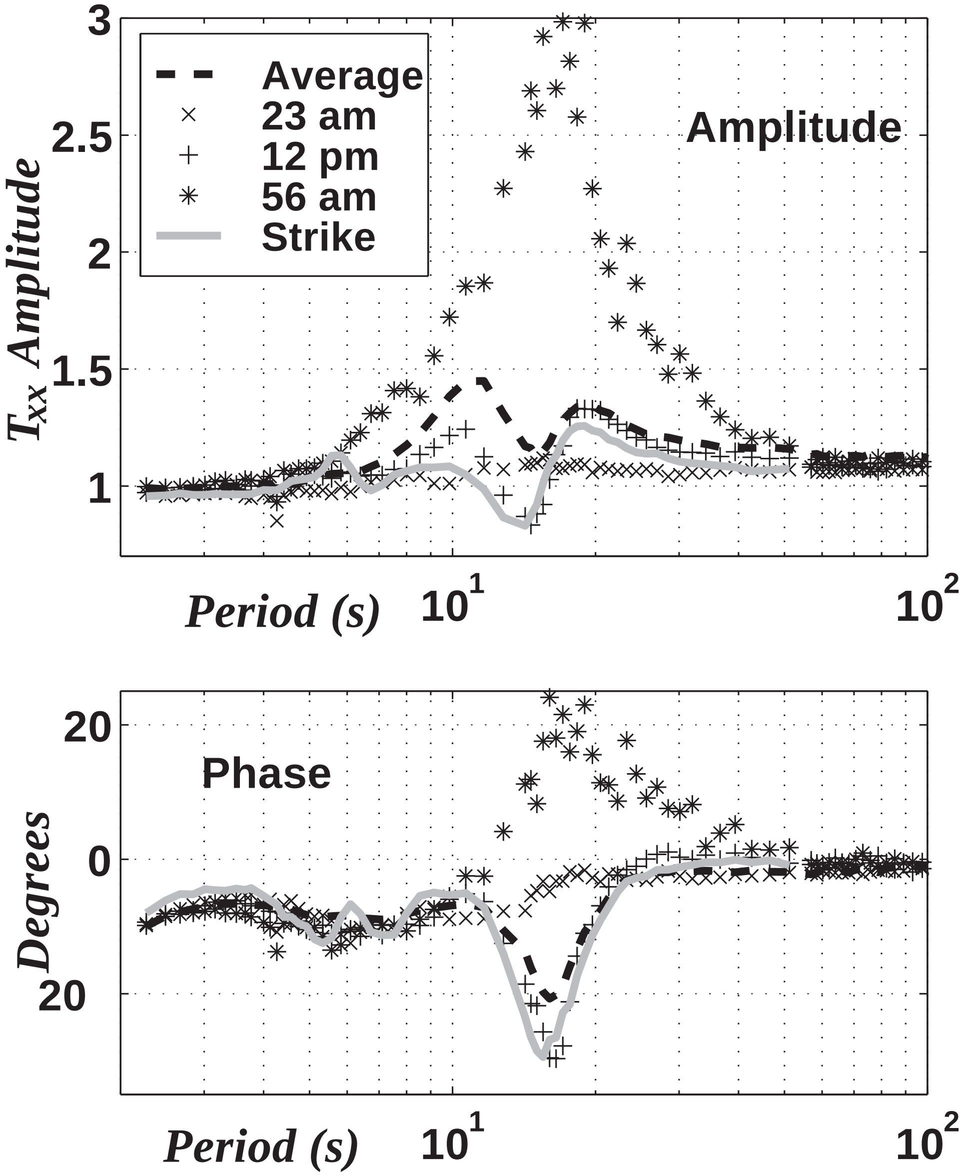

Figure 3(a). Amplitude and phase of the Hx/Hy transfer function (TF) between PKD1 and SAO. Curves marked by symbols correspond to TFs estimated for different local times, as indicated in the legend. The heavy dashed line is the TF computed from all data (days 140-199, 1997), and the heavy grey solid line is the TF computed from the data collected druing a strike by BART workers (days 150-156, 1997; see Egbert et al., (2000)). For periods outside of the band plotted, TFs computed for different data subsets are in close agreement.

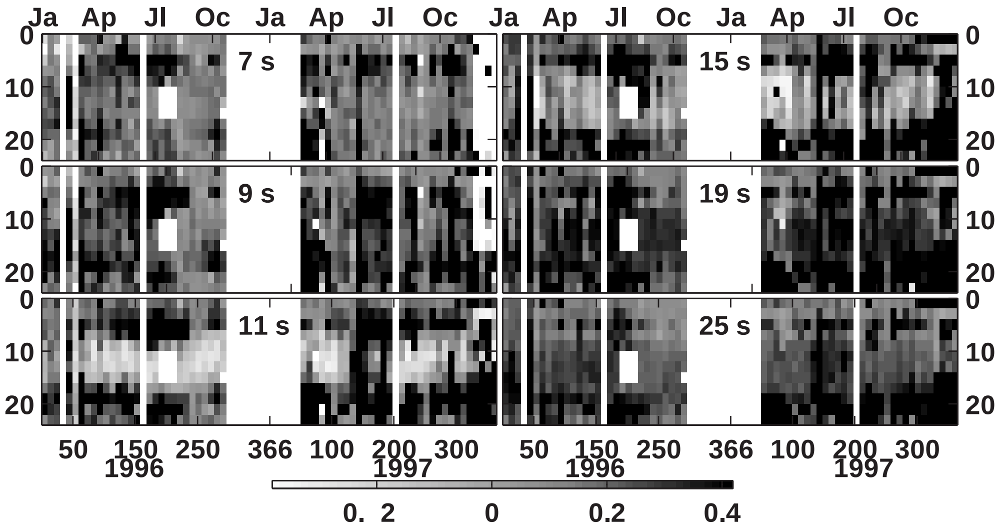

Figure 3(b). Variations in the real part of the Hx/Hx TF as a function of local time and time of year, for data grouped into 10 day-long 2 hour bands.

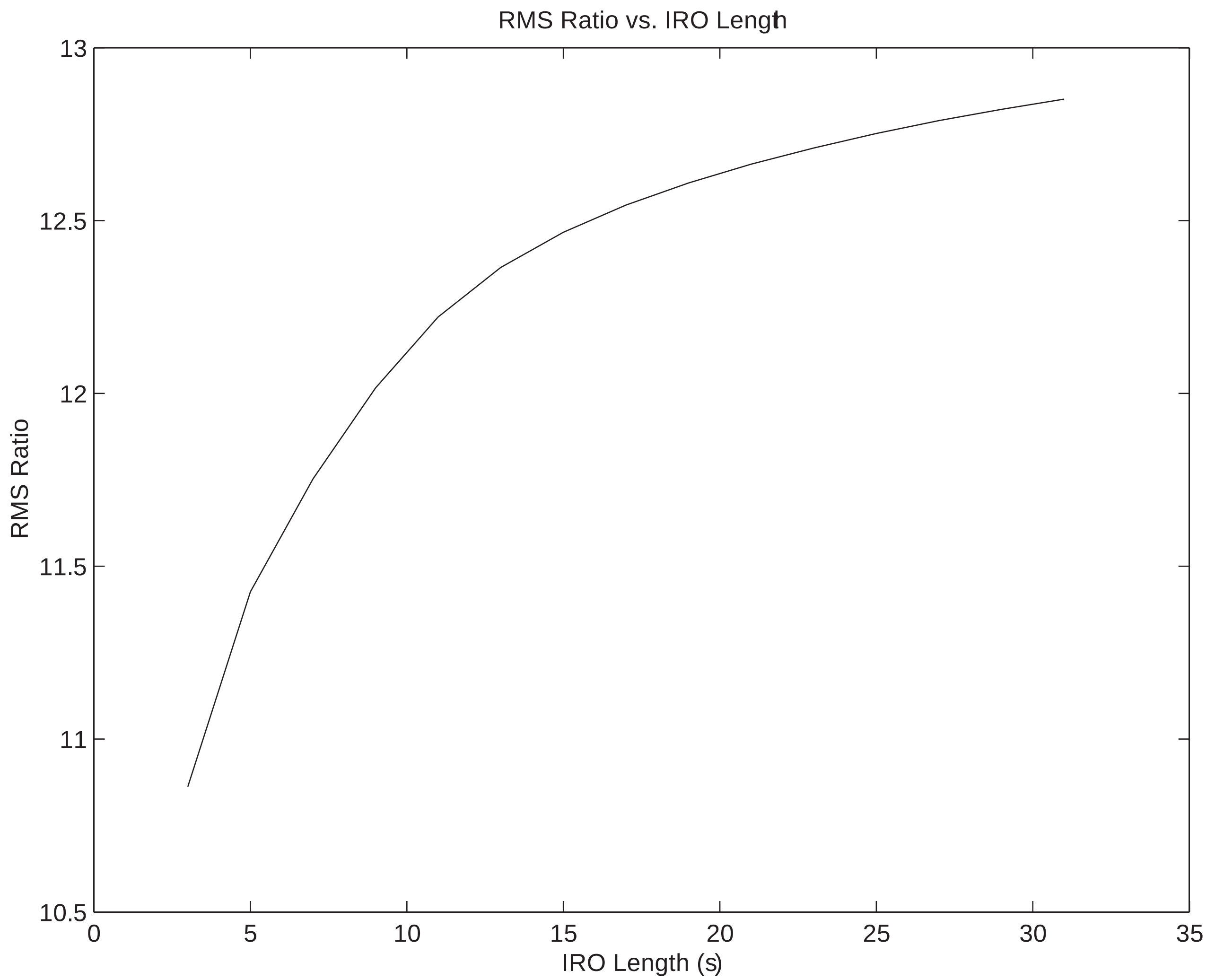

Figure 4. The ratio of the RMS signal to residual as a function of IRO length. As the filter gets longer, the fit is better.

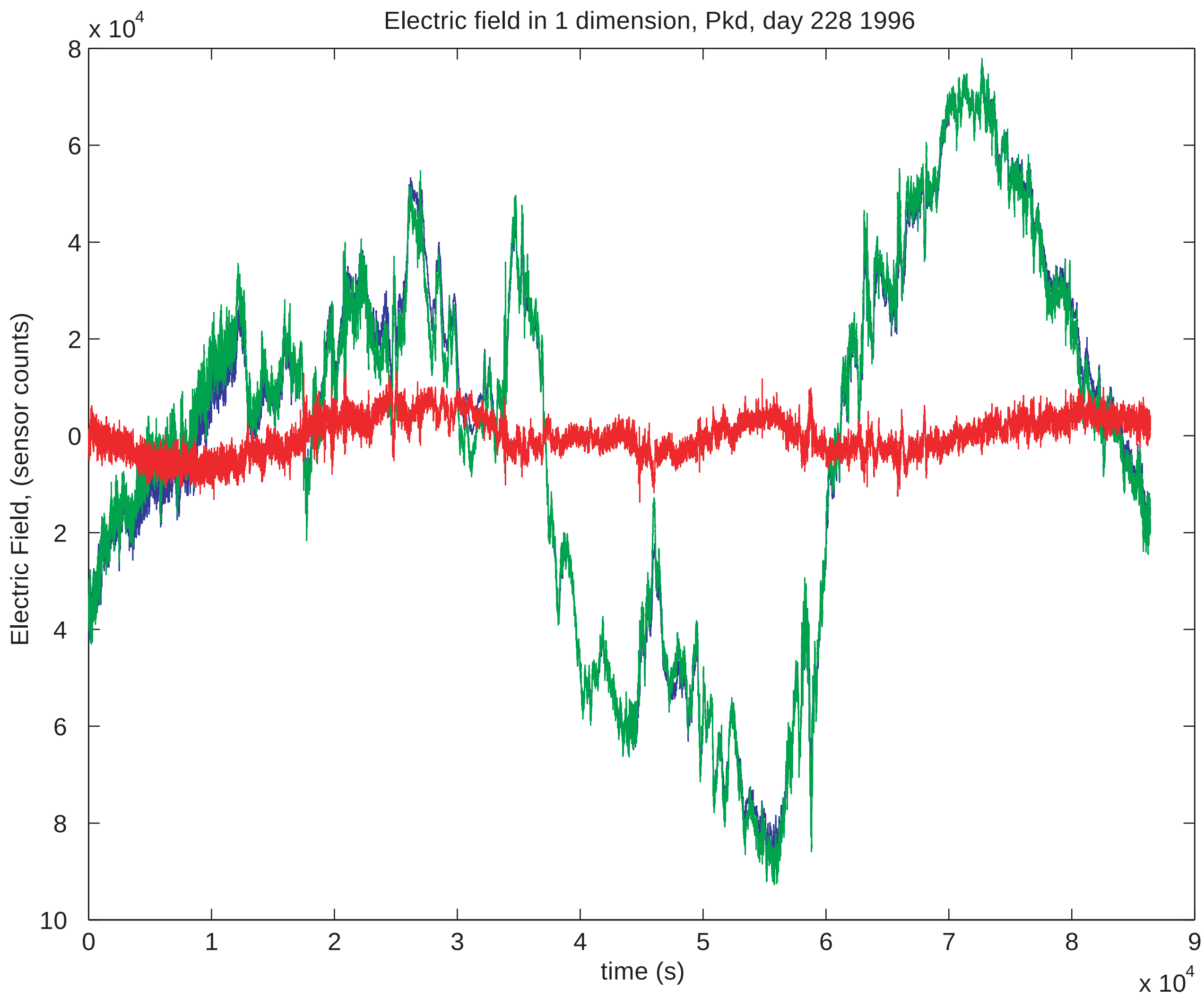

Figure 5. A least squares fit (green) to the signal (blue), and the residual (red), using an 11 point filter to the PKD data of day 228 in 1996.

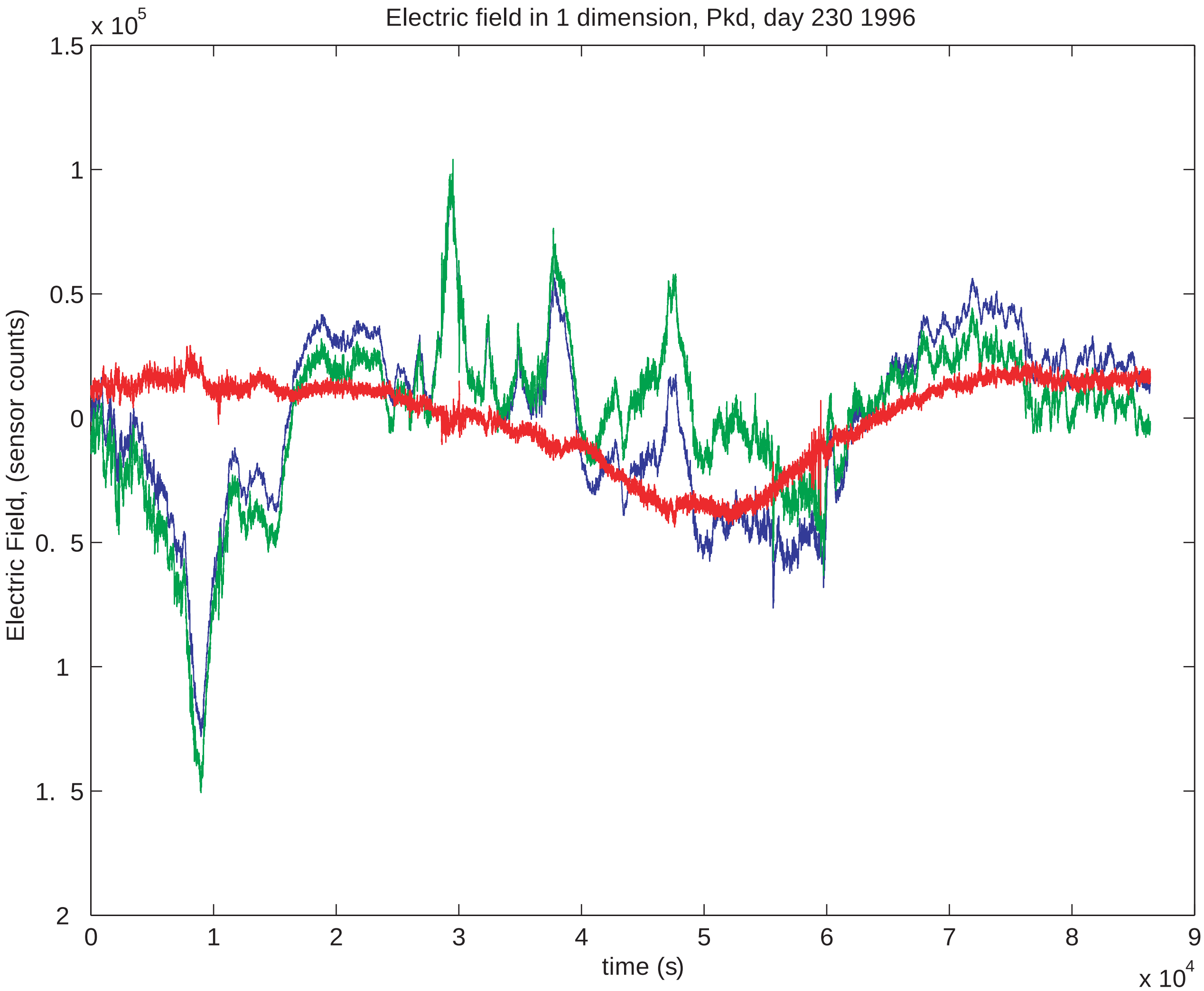

Figure 6. Signal(blue), prediction (green), and residual(red) from using the day 228 filters to predict day 230. Note the change in scale from Figure 5.