Noise Reduction in Electromagnetic Time Series to Improve Detection of Seismic-Induced Signals

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A method is described for removing the ionospheric-induced electromagnetic signals from electromagnetic time series in order to improve the detection of signals caused by oceanic, industrial, environmental, or seismic activity. The method is based on transforming the ionospheric-induced signals at a remote site to the local site using smoothly varying transfer functions. This assumes the remote site is relatively free of the non-ionospheric-induced signals. The transformed ionospheric-induced signal is then subtracted from the local time series. The method is tested on data recorded at Hollister and Parkfield that have been provided by F. Morrison. The sites are both near the San Andreas fault in California. Parkfield is used here as the remote site because it will be less contaminated by man-made sources since it is in a remote part of central California. The electric dipoles are approximately 100 m long with electrodes buried about 3 m deep and the magnetic sensors are three buried coils.

1. Introduction

Recent review papers (Johnston, 1989; Park et al., 1993; Park, 1994; Johnston, 1996) discuss the possible mechanisms for seismic-induced electromagnetic signals and the various experimental efforts to detect seismic-induced signals and interpret them as pre-cursivce or co-seismic events. Overall there appears to be some evidence for seismic-induced signals, but many experimental results are ambiguous. Johnston (1996) state that further improvements are needed for noise-reduction procedures. A method is therefore presented here for removing the ionospheric-induced signals using a remote site for observing the ionospheric signals.

The method is based on computing transfer functions and using them to transformed the ionospheric-induced time series from the remote reference site to the local site. This transformed time series is subtracted from the local time series yielding the non-ionospheric-induced signals at the local site. The remote site is assumed to be relatively free of non-ionospheric-induced signals. The method is based on Larsen (1989) and Larsen et al. (1996), which describe a robust method for deriving smoothly varying transfer functions.

The method is tested here on electromagnetic time series from Hollister and Parkfield which are about 150 km apart (Fig. 1). The time series from these sites are being collected to determine whether significant changes in resistivity, quasi-dc electric fields, or ULF (0.01 Hz to 10 Hz) electromagnetic fields occur before earthquakes in California (Morrison et al., 1996). These examples show that the noise reduction method works quite well for the 1-Hz and 40-Hz data from Parkfield and Hollister. Results are presented for the 1-Hz data using Parkfield as the remote site because it is in a fairly remote region and there are no other remote sites distant from the San Andreas fault for this data set.

2. Method

The local observations can be a horizontal component of $E$, a horizontal component of $B$, or the vertical component $B_z$. The remote observations can be the horizontal electric components of $E^R$ or the horizontal
Fig. 1. Location of Hollister and Parkfield electromagnetic observing sites (stars), major faults (solid and dashed lines), and volcanoes (dots) adapted from Richter (1958).
magnetic components of $B^R$. The simplest method for removing the ionospheric-induced signal is to assume that it is the same at the remote and local sites. Then the remote electric observations $E^R$ can be subtracted from the local $E$ and the remote magnetic observation $B^R$ can be subtracted from the local $B$. However, the observed ionospheric-induced signals will, in general, differ between the local and remote sites due to spatial changes in geology and source, and errors in alignment and calibration. Alignment and calibration errors were a problem in earlier studies of noise reduction for the simple time domain subtraction method (Nichols et al., 1988). Here, these errors are not a problem if one uses the following frequency domain electromagnetic relationship between a local component $F$ ($F = E_n, E_e, B_n, B_e, B_z$) and the remote electric horizontal components of $E^R$ where $n$ is north, $e$ is east, and $z$ is up

$$F(\omega) = T_n^{FE}(\omega)E_n^R(\omega) + T_e^{FE}(\omega)E_e^R(\omega) + R^{FE}(\omega)$$

or between local $F$ and the remote magnetic horizontal components of $B^R$

$$F(\omega) = T_n^{FB}(\omega)B_n^R(\omega) + T_e^{FB}(\omega)B_e^R(\omega) + R^{FB}(\omega)$$

where the $T$'s are the transfer functions and the $R$'s are the frequency domain residuals.

The residual time series $r(t)$, which contain the non-ionospheric-induced signals, are found by taking the inverse Fourier Transform of the frequency domain residual $R(\omega)$. These residuals will be automatically independent of alignment errors because both horizontal components of the remote observations are used and the residuals will be independent of calibration errors because the calibration is time invariant and therefore contained in the estimates of the transfer functions. The alignment and calibration errors merely change the amplitude of the estimated transfer functions.

There are two statistical methods for computing the transfer functions. One is the least squares method which finds $T^{FE}$ or $T^{FB}$ by minimizing, respectively, the variance of the frequency residuals $R^{FE}$ or $R^{FB}$. The other method is the remote reference method, which finds $T^{FE}$ and $T^{FB}$ by minimizing the real part of the covariance between the frequency residuals $R^{FE}$ and $R^{FB}$ (Larsen, 1989; Larsen et al., 1996). For these methods to work, the remote site should be relatively free of the non-ionospheric-induced signals. Generally, the remote reference method yields superior estimates of the transfer functions because they are not biased by uncorrelated noise. Time dependency $\exp(-i\omega x)$ assumed.

The robust method for determining these transfer functions is described in Larsen (1989) and Larsen et al. (1996). The robust method generates, by an iterative process, frequency, time and section weights so that the frequency and time weighted residuals are approximately normally distributed in both the frequency and time domain and the weighted data sections have approximately the same variance. This is found to yield more stable estimates of the transfer function. A pi prolated window is used and the jackknife method is used to estimate the transfer function errors.

3. Observations

The data used were collected near Parkfield and Hollister, California (Fig. 1) by F. Morrison and his group at U. C. Berkeley using the EMI (Electromagnetic Instruments, Inc.) system and recorders. The electromagnetic array consists of horizontal 100-m-long electric dipoles and three magnetic components from buried coils. The electrodes are buried at 3 m depth and consist of a coiled copper sheet within a 1-m-long ceramic tube containing a saturated solution of CuSO$_4$.

The time series can be corrected for the instrumental filters but this is not necessary, because the focus here is on the residual time series and not on the interpretation of the transfer functions. Therefore, the units of the time series are left in counts. The conversion to SI units is approximately 1 mV/km = $10^4$ counts and 1 nT = $10^5$ counts at 1 Hz. The 1-Hz magnetic time series in counts is approximately equal to the first difference of the actual magnetic time series because the magnetic variations are recorded by coils.
The 1-Hz data are examined by 1-day intervals that are divided into 24 approximately 1.1-hour sections having 2048 values per section with an overlap of 248 values (approximately 13 percent of the section length). Two days are examined: 1996 Julian day 79, which corresponds to March 19 (Tuesday) with starting time at 12 UT or 4 am local time (UT = universal time; local time = UT - 8 hours), and 1996 Julian day 109, which corresponds to April 18 (Thursday) with starting time at 16 UT or 8 am local time.

4. Results

Results are presented for the 1-Hz north magnetic time series $b_n(t)$ at Hollister using Parkfield as the remote site. The transfer functions are estimated by the remote reference method. It is found that $E_R$ is less noisy than $B^R$ at Parkfield and remote $E_R$ is therefore used to compute the residual time series that are used to examine the non-ionospheric-induced signals. The dominant component of $T^{FE}$ (with $E$ in direction 97° west of north) is shown in Fig. 2 for Julian days 79 and 109. Figure 2 shows that the transfer function for Julian days 79 and 109 are nearly the same with discrepancies that are mostly less than the estimated errors. The number of outliers rejected to get these estimates is less than 4 percent. The overall coherence squared for Julian day 79 is 0.96 and for Julian day 109 it is 0.98. These high coherences indicate that the ionospheric-induced field is quite coherent between Hollister and Parkfield.

The signal cancellation ratio (S.C.R.) is a useful parameter for quantifying the amount of ionospheric-induced signals that can be removed from the observations. It is defined by $10 \log \left( \frac{\text{observed spectrum}}{\text{residual spectrum}} \right)$ (Nichols et al., 1988) and is shown in Fig. 3 for Julian days 79 and 109 where it is found to be higher than 20 db for some frequencies.

The observed spectra of $B_n$ and residual spectra of $R_n^{FE}$ are shown in Fig. 3 for Julian days 79 and
109. They show that the residual spectrum is significantly smaller than the observed spectrum, which makes it possible to detect a peak in the residual spectra, especially for Julian day 109, in the period range of 12 to 18 seconds. This peak is found to be related to an increase in the non-ionospheric signals between 9 am and 5 pm local time which corresponds to data sections 6 to 13 in Fig. 6. The peak disappears during the other hours of the day for Julian day 109. In addition, this spectral peak is found to be larger in the magnetic field than in the electric field, which suggests noise due to ground motion. However, the peak is unlikely to be due to microseisms because there is no primary peak around 6–8 seconds (Donn and Naini, 1973; Webb, 1992). Since the residual noise level is larger during daytime, this suggests a man-made source or environmental influences linked to daytime hours. One possibility is electromagnetic signals from the San Francisco Bay Area Rapid-Transit system (BART) (Fraser-Smith and Coates, 1978; Ho et al., 1979), but Hollister is about 150 km south of the southern terminus of BART, so this residual spectral peak is probably not due to BART. Furthermore, the size of the peak ought to be the same for the two days (Tuesday and Thursday), but it is not.
Fig. 4. Observed Hollister north magnetic time series in counts by 1.1-hour sections from 1996, Julian day 109, hours 16 UT (8 am local time) through Julian day 110, hour 2 UT (6 pm local time). Data sections overlap by 248 values. Long-term trends have been removed. Dates are start of individual sections in UT. These time series correspond to data sections 5 to 14.
Fig. 5. Residual Hollister north magnetic time series in counts by 1.1-hour sections using Parkfield electric field from 1996, Julian day 109, hours 16 UT through Julian day 110, hour 2 UT. Data sections overlap by 248 values. Long-term trends have been removed. Dates are start of individual sections in UT.
Fig. 6. Diagnostic plot of 1.1-hour data sections with first section starting at 12 UT (4 am local time). Top panel shows high coherence squared for all data sections. Second panel down shows that the number of lines in the residuals is less than 3 percent for all sections. Third panel down shows that the number of outliers is less than 10 percent for all sections. Section 4 has the most outliers. Fourth panel down shows that the amplitude (log gain) of the transfer function has been relatively constant. Fifth panel down shows minor changes in phase of the transfer function. Sixth panel down shows that the residual variance relative to the signal is mostly less than 10 percent, except for section 23, which has been eliminated and labeled by an open box. Bottom panel shows the residual variance relative to its median is largest for sections 6 to 13.
The observed time series $b_n(t)$ and the residual non-ionospheric time series $r(t)$ from 8 am to 6 pm local time are shown, respectively, in Figs. 4 and 5 where the long-term trend has been removed. These plots show that the increase in the residuals is a daytime effect that occurs between 9 am and 5 pm local time. The increase is seen in the observed data but more dramatically in the residuals, which show isolated burst, offsets, and ramps. The top and bottom residual sections in Fig. 5 are representative of the nighttime values.

A diagnostic plot using remote $E_R$ is shown in Fig. 6. It shows, for each data section, the coherence squared, the number of lines (periodic variations) and outliers, the relative changes in amplitude and phase of the transfer function, and the changes in the residual variance relative to the signal variance and relative to its median value. For example, the relative flatness of the changes in the amplitude and phase of the transfer function shows that the transfer function has not significantly changed over the one day of observations. The residual variance relative to the signal is less than 10 percent, except for section 23 that has been excluded from the analyses. The large value is due, most likely, to low signal level. The residual variance relative to its median shows a significant increase for sections 5 to 13 (9 am to 5 pm local time), indicating a daytime increase in the non-ionospheric signals.

5. Conclusions

The noise reduction method works well for the Hollister and Parkfield electromagnetic time series and provides a means for improving the detection of non-ionospheric-induced signals. It also provides a means for examining the data quality and identifying sources of noise. The latter is an important feature for any long-term monitoring effort. The isolated burst, offsets and ramps seen in the residual time series indicates that experimental work is needed to identify and exclude these types of signals, mostly likely due to man-made sources, environmental changes, or instrumental errors, before the site can be used for detecting seismic signals.

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