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Characterizing Potential Earthquake Signals on the Stanford-USGS Ultra-Low Frequency Electromagnetic (ULFEM) Array

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Introduction

Anomalous ultra-low frequency (0.01-10 Hz) electromagnetic signals have been reported prior to M ≥ 6.0 earthquakes, most notably prior to the 1989 Ms 7.1 Loma Prieta earthquake in California. Stanford University, in conjunction with the USGS and UC Berkeley, has maintained five ULFEM recording stations along the San Andreas Fault in order to test the hypothesis that ULFEM signals are related to earthquakes.

ULFEM Array

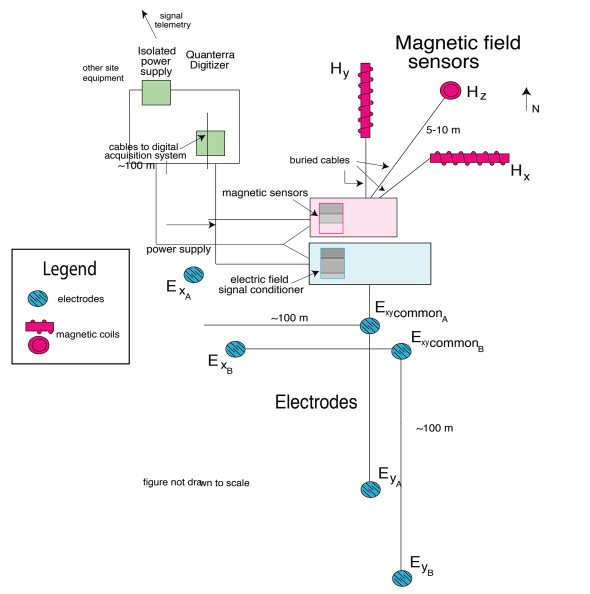
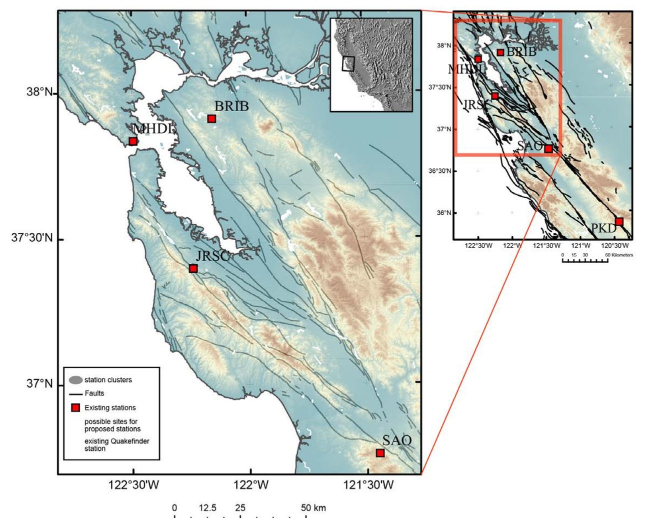


Figure 1: *Schematic typical site (Karakelian et al., 2002)*

Typical ULFEM station: three orthogonal magnetometers (N, S, W-E, vertical; 0.01 to 100 Hz) and two 100-m orthogonal electrodes; collocated with broadband seismic station to allow separation of telluric and ground-motion-induced EM signals. Data are recorded at 40 Hz.

Figure 2: *Maps of the ULFEM sites*



Initial Work

Previous reports of possible ULFEM precursors, or their absence following exhaustive searches of available data, define a crude distance-magnitude relationship in which larger-closer earthquakes would be capable of producing detectable precursors. No earthquake exceeding this distance-magnitude relationship has yet occurred within 500 km of our network; therefore our study is as yet mostly an attempt to develop appropriate methodologies.

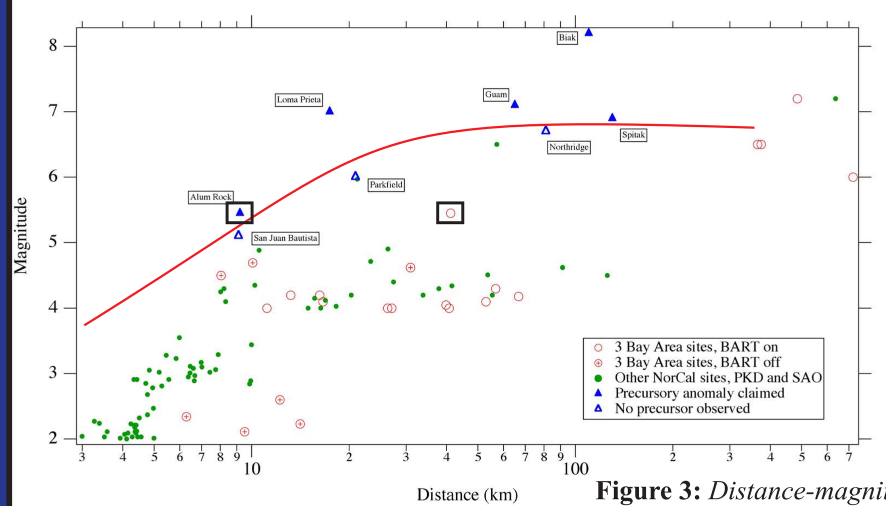
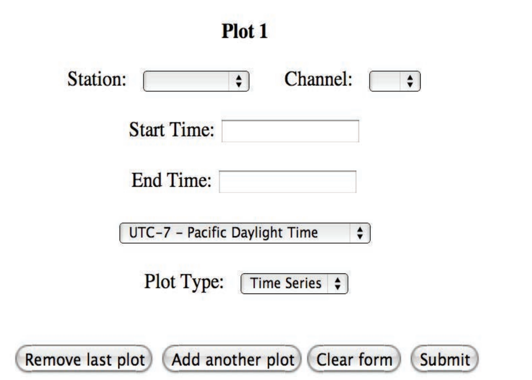


Figure 3 shows the distance-magnitude relationship of certain earthquakes. We chose to examine JRSC EM data proceeding the Alum Rock earthquake, as anomalous signals were seen by QuakeFinder on one of their sites close to the epicenter (see black boxes on graph indicating the relationship of Alum Rock earthquake to the site recording it).

Figure 3: *Distance-magnitude plot of studied earthquakes in relation to ULFEM sites, as well as earthquakes studied in other papers*

Data Availability

All data are available via our website (Neumann et al, 2008):
http://ulfem-data.stanford.edu



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Tom Bleier, Clark Dunson of QuakeFinder

Data Analysis

Co-seismic Signals

Fifteen earthquakes were selected because of their close proximity to a site or because of their large magnitude. We compared the electromagnetic channel data with seismic data to see which EM channels registered the earthquake arriving at the site, with the hypothesis that in order to see pre-seismic signals, we should at least see co-seismic signals. Four earthquakes of the fifteen were seen to have visible co-seismic EM signals. We hope to use the delineation between where co-seismic EM signals are observed and not to establish a lower limit, below which we would not expect to see any pre-seismic EM signals.

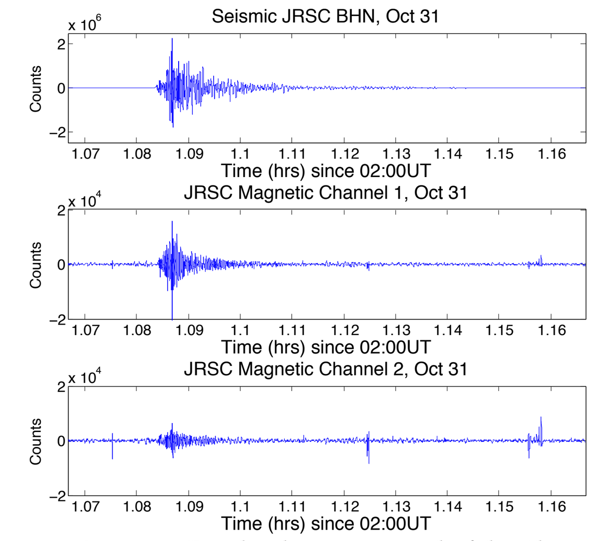


Figure 4: *Graphs showing arrival of the Alum Rock earthquake on one seismometer and two magnetometers at JRSC*

Pulsations

Bleier et al. (2009) report anomalous electromagnetic signals, that they call pulsations, prior to the 10/31/2007 Alum Rock M 5.4 earthquake, with "strong" amplitudes, greatly exceeding the local background noise. Therefore, we examined 40 Hz EM data around the arrival time of the largest/closest earthquakes to our array, focusing on co-shaking signals and pulsations as have been described preceding the Alum Rock earthquake. Our analysis compares results from 4am-2am (corresponding to normal operating hours of the Bay Area Rapid Transit electric train) with those from the 2am-4am period when BART is not in service.

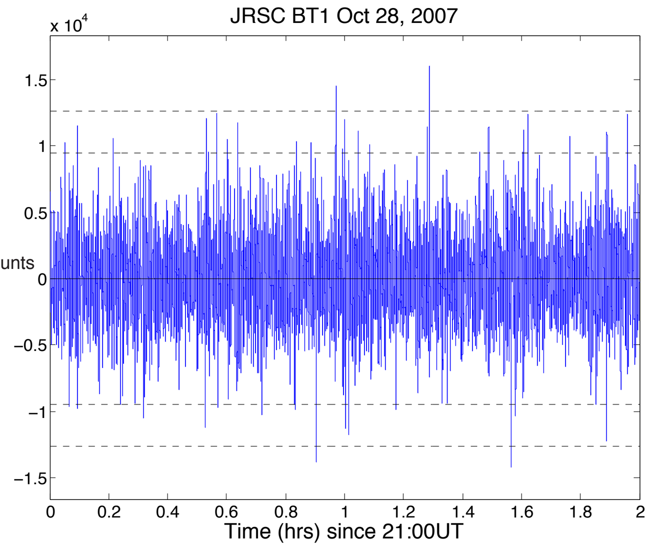


Figure 5: *Two hours of EM data with dotted lines indicating 3 and 4 standard deviations from the mean of the two hour window of data being examined*

We defined a pulsation to be any spike in the data that exceeded 3 standard deviations. We distinguish between 3 different types of pulses: bipolar, unipolar (+), and unipolar (-). Figure 6 shows a typical pulsation we observed. Figure 7 is a comparison of two channels recording the same pulse.

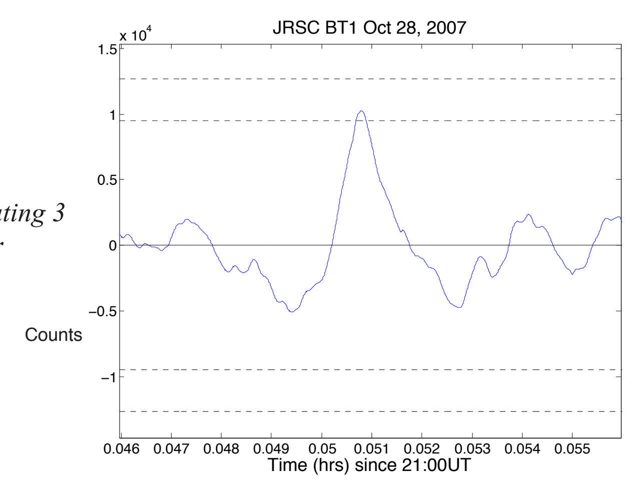


Figure 6: *Typical unipolar + pulse exceeding 3 standard deviations*

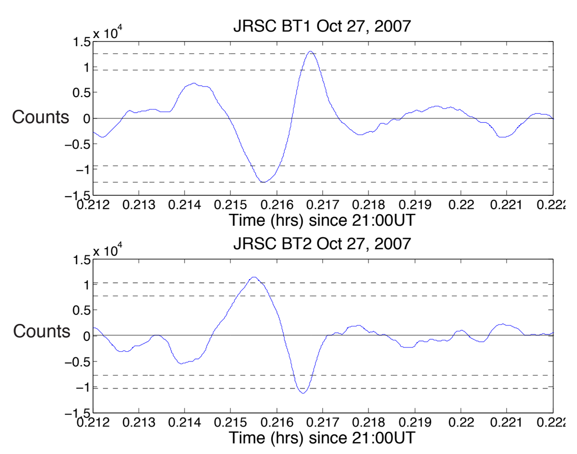


Figure 7: *Bipolar pulse seen on two channels*

We counted the number of pulsations in the week prior to the October 30, 2007 Alum Rock earthquake, located 41 km from our site. Four hours of data were examined each day (2 hours BART on, 2 hours BART off). Table 1 shows the average number of pulse types seen in two hours of data examined for a day.

	BART off	BART on
unipolar +	19	17
unipolar -	26	9
bipolar	17	7

Table 1: *Average number of pulses/2hr window measured over the 7 days preceeding the earthquake*

Comparisons

Figure 8 shows a two hour window of our EM data (in blue) from JRSC, at 41 km away from earthquake with the red lines indicating when pulsations were observed at a QuakeFinder site located only 2 km from the epicenter (Bleier et al. 2009). (Expanded plots of the same data shown in Figure 9)

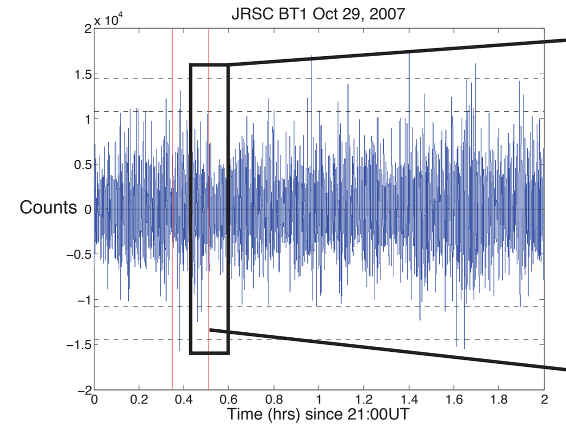


Figure 8: *2 hour window of EM data from JRSC when BART was on. Red lines indicate times when Bleier et al. (2009) reported pulses*

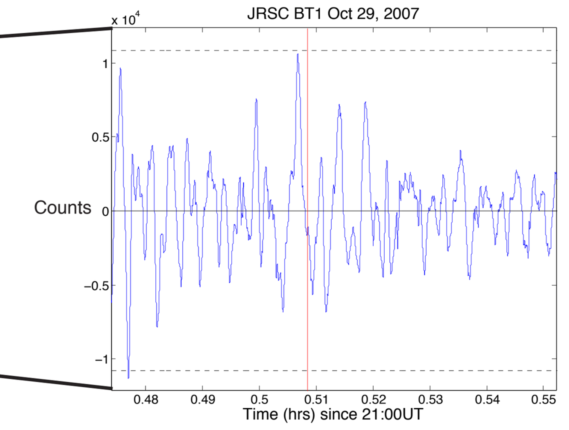


Figure 9: *Figure 9 zoomed in to show Bleier pulses in relation to our data*

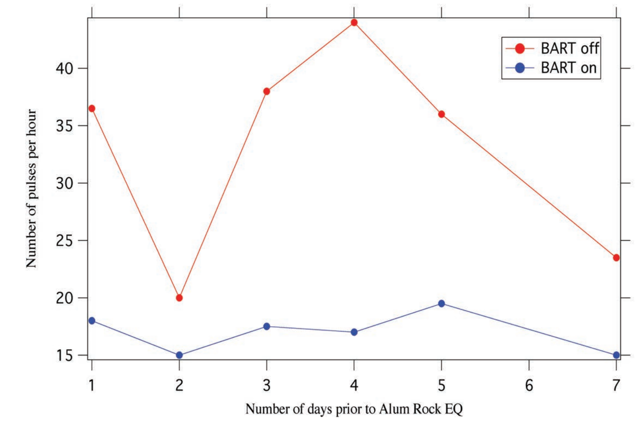


Figure 10 shows the average number of pulses per hour from the two hour window time segment that was studied for each day in the week before the Alum Rock earthquake. We don't see any trend of increasing number.

Figure 10: *Average number of pulses seen in the window studied for each day in the week before the Alum Rock earthquake*

Planetary K-index

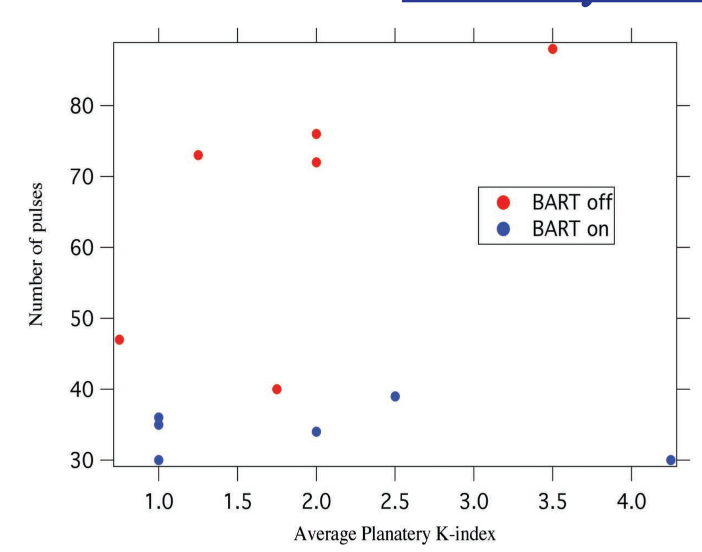


Figure 11 shows the average planetary K-index examined for each day before the Alum Rock earthquake plotted against the total number of pulses seen within the 2-hour periods that were examined for that day. The BART-off results show a general positive trend between the number of pulses and K-index, suggesting the pulses may be externally sourced. However, more days of data should be analyzed to better characterize any possible correlation.

Figure 11: *Graph comparing the number of pulses versus the average planetary K-index for each day in the week before the Alum Rock earthquake*

Conclusions

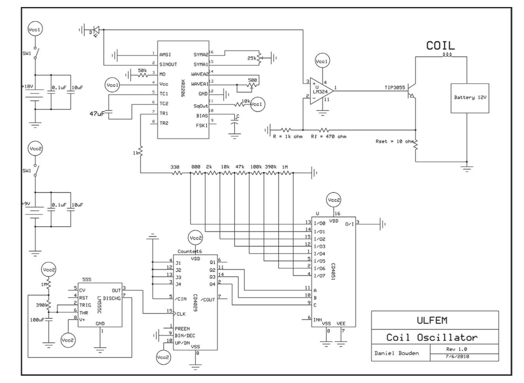
- In the week prior to the Alum Rock M5.4 earthquake, our closest station (JRSC, 41 km from the epicenter) recorded pulsations of similar duration and polarity to those identified by Bleier et al. (2009) in records from a station 2 km from the epicenter (~9 km from the hypocenter).
- The pulsations seem to be part of a natural continuum of signals and are otherwise not distinguishable from other signals of similar frequency in the time series. In addition, the amplitudes of our pulses are much less than that amplitude of the pulsations Bleier saw compared with his site background noise.
- The pulses we have been examining in our data do not appear to show any relationship to the earthquake (e.g., more frequent or larger pulses, or a change in the type of pulse, nearer in time to the EQ) as has been reported by Bleier et al. (2009).
- The difference in our findings from those of Bleier et al. (2009) may result from the fact that our station was significantly further from the epicenter than theirs. Other factors may include that 1) we had significantly fewer pulse events to analyze, 2) we had studied a shorter window of time prior to the earthquake.

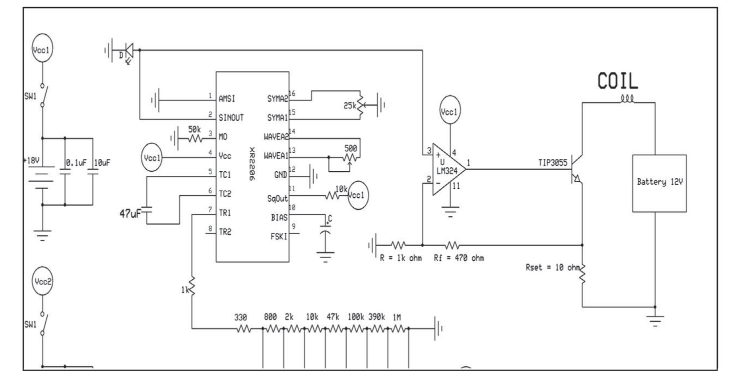
New Hardware Developments in the Stanford-USGS ULFEM Array

To establish and maintain the integrity of the intruments in our ULFEM array, a permanent calibration method is being designed and implemented. The calibration system is an air-core magnetic coil producing a magnetic field generated by an in-house built waveform generator.

Developed technique to calibrate magnetometers:

- Built Air-core Magnetic Coil
- Designed & built waveform generator powered by an Arduino Microcontroller & XR2206 IC





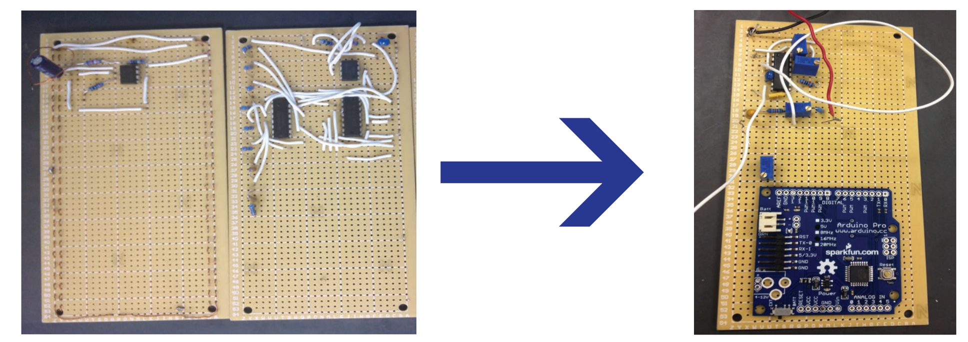


Figure 12: *Progression of the design of the in-house built waveform generator. Implementation of the Arduino Microcontroller replaces hardware of previous desgins*

Coil Design

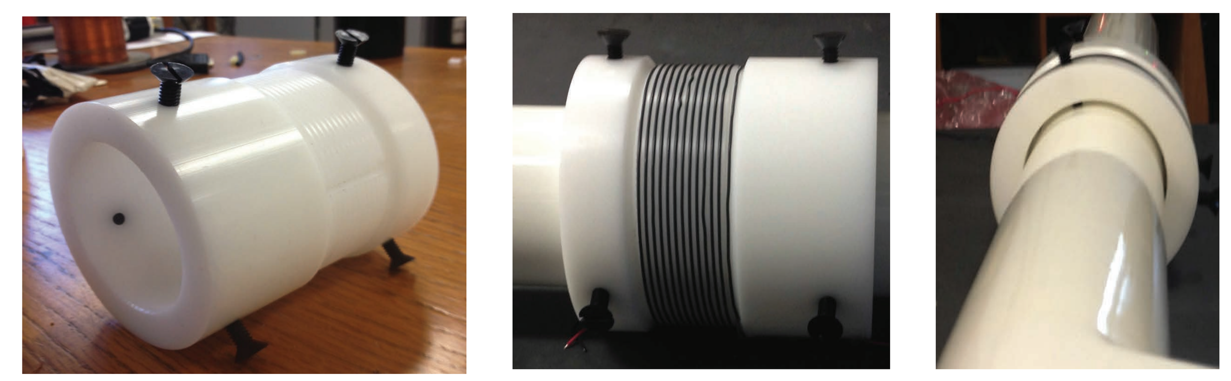
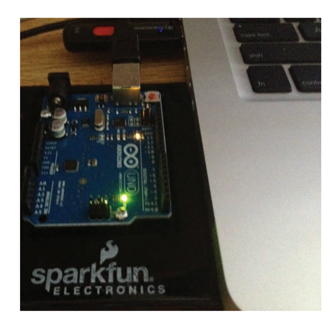


Figure 13: *Coil Design Feartures: 15-turn solenoid, slip-on design, grooved coil form for wire placement. Electric current driven through wire coil generates magnetic field parallel to the coil axis*

In-House Waveform Generator



- Automatic sweep through discrete frequencies (range 0.12 - 10 Hz)
- Manual, automatic and remote control

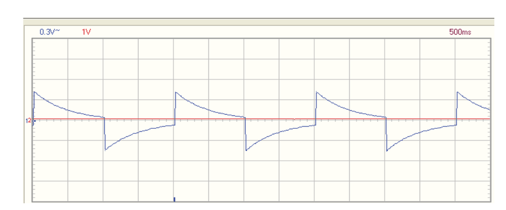


Figure 14: *Screen capture of the signal produced by the Arduino Microcontroller*

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