A Network of Magnetometers for Multi-Scale Urban Science and Informatics

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Abstract. The magnetic signature of an urban environment is investigated using a geographically distributed network of flux-gate magnetometers deployed in and around Berkeley, California. The system hardware and software are described and initial operations of the network are reported. The sensors measure vector magnetic fields at a 3,960 Hz sample rate and are sensitive to $0.1 \, \mathrm{nT}/\sqrt{\mathrm{Hz}}$. Data from individual stations are synchronized to $\pm 120 \mu s$ using GPS and computer system clocks and automatically uploaded to a central server. We present the initial observations of the network as well as preliminary efforts to correlate sensors. A wavelet analysis is used to study observations of the urban magnetic field over a wide range of temporal scales. The Bay Area Rapid Transit (BART) is identified as dominant signal in our observations, exhibiting both aspects of broadband noise and coherent periodic features. Significant differences are observed in both day/night and weekend/weekday signatures. A superposed epoch analysis is used to study and extract the BART signal.

1 Introduction

The study of fluctuating magnetic fields, commonly referred to as magnetometry, has found widespread application in a variety of disciplines. Understanding geomagnetic fields are important to global-positioning-system (GPS)-free navigation, radiation-hazard prediction, atmospheric modeling, and fundamental geophysics research. Additionally, measurements of the auroral magnetic field are necessary in testing models for space-weather prediction, aiming to mitigate hazards from solar storms (Angelopoulos, 2008; Peticolas et al., 2008; Harris et al., 2008). High-cadence (sampling rate) magnetic field measurements have been used for magnetic-anomaly detection (MAD), which has numerous applications in naval defense and unexploded ordnance detection (Sheinker et al., 2009). Geographically distributed magnetometers operating at high sample rates have been used in atmospheric science to measure the global distribution of lightning strikes using the Schumann resonance (Schlegel

and Füllekrug, 2002). Recently, multi-satellite space missions have used magnetometry to provide multi-point observations of dynamic evolution of plasmas on electron scales (Burch and Phan, 2016; Phan et al., 2018).

Many advancements in magnetometry have been driven by progress in the design of high precision sensor networks. Time synchronized sensor networks are currently being implemented in as diverse disciplines as the search of dark matter (Pustelny et al., 2013; Afach et al., 2018) and localization and monitoring of wildlife in ecology (Wang et al., 2005); perhaps the most notable recent accomplishment of network design is the observation of gravitational waves associated with black hole mergers by the Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo Interferometer collaborations (Abramovici et al., 1992; Abbott et al., 2016, 2017). Indeed, sensor networks have long been used in geophysics to monitor geomagnetic dynamics: e.g. SuperMAG, an international consortium of magnetometer arrays, comprises approximately 300 sensors operated by numerous organizations, providing uniformly processed data in a common coordinate system and timebase (Gjerloev, 2009, 2012).

Here we report on the development of a synchronized magnetometer network in Berkeley, California for the purpose of studying urban magnetic fields over spatiotemporal scales not previously studied. Through applying proven techniques of network design and magnetometry, we aim to complement the growing field of observational urban science and informatics. Only recently have investigators been able to accumulate and analyze data with adequate spatial and temporal granularity to characterize the dynamic evolution of a city. Recent work has shown that broadband visible observations at night can identify patterns of light that can be used to measure total energy consumption and public health effects of light pollution on circadian rhythms (Dobler et al., 2015). Measurements of urban lighting made faster than ∼120 Hz allow for phase change detection of fluorescent and incandescent flicker, which may be used as a predictor for power outages (Bianco et al., 2016). In addition, infrared hyperspectral observations can determine the molecular content of pollution plumes produced by building energy consumption providing a powerful method for environmental monitoring of cities (Ghandehari et al., 2017). In tailoring a synchronized network of magnetometers for an urban area, we explore whether dynamic signatures of urban magnetic fields can contribute to the growing discourse surrounding urban science and informatics.

Our magnetometer array, currently consisting of four sensors, operating at a 3,960 Hz sample rate with high-precision timing (120 μs) for correlation analysis, will make sustained measurements of urban magnetic fields over years, observing dynamic magnetic signatures characterizing a city. Figure 1 shows a map of Berkeley with a sample network configuration. Our hardware, software, and instrumental techniques are described in Sec. 2, Initial network observations are presented in Sec. 3. Observations taken from multiple, geographically separated, stations are analyzed and compared in Sec. 3.1. A wavelet analysis is introduced in Sec. 3.2 to provide an analysis of the different spatiotemporal scales present in the urban magnetic field. Initial results of multi-station correlations are presented. In Sec. 4, we present an initial method to isolate the BART signal.

2 Methods

2.1 Instrumentation and Hardware

Each station consists of a commercially available fluxgate magnetometer, a general-purpose laptop computer, and an inexpensive GPS receiver. We emphasize both our preference for commercially available hardware and additionally highlight the adoption of timing techniques from the Global Network of Optical Magnetometers for Exotic (GNOME) physics project (Pustelny et al., 2013). Our approach, which avoids bulky and expensive hardware in favor of consumer components wherever possible, reduces the cost of the acquisition system and enables portability through battery operation. However, achieving the desired timing precision ($\sim$120 μs) with affordable commercial hardware requires customized timing synchronization algorithm.

Each station is controlled by a computer (PC, ASUS X200M) running the Windows 10 operating system (OS). The PC acquires magnetic field data from the DAQ (Biomed eMains Universal Serial Bus, USB, 24 bit) and timing data from the GPS receiver (Garmin 18x LVC). The DAQ continuously samples the Biomed eFM3A fluxgate magnetometer at a sample rate of 3,960 Hz. Absolute timing data are provided once per second by the GPS receiver, which is connected through a high-speed RS232-to-USB converter (SIO-U232-59). The GPS pulse-per-second signal is routed to the computer through the carrier detect (CD) pin of the RS232 converter with 1 μs accuracy. Data from the DAQ arrive in packets of 138 vector samples approximately every 35 ms. The data are recorded together with the GPS information and the computer system clock and uploaded via wireless internet to a shared Google Drive folder.

2.2 Time synchronization

Time intervals between the GPS updates are measured by the computer system clock (performance counter), running at $\approx$ 2.5 MHz. A linear fit model is used to determine the absolute system time relative to the GPS. The GPS timing data from the previous 120 seconds are used in determining linear fit parameters. When a magnetic-field data packet is received, the acquisition system records the performance counter value. The packet time-tag is determined from interpolating the linear fit GPS time to the performance counter value. Typical jitter of the inferred time stamps is 120 μs and is limited by the USB latency (Korver, 2003).

Due to OS limitations some data packets are not processed immediately by the PC. Packets may be delayed by several milliseconds before arriving to the data-acquisition software. The number of the delayed packets depends on the OS load. During normal operation of a magnetometer, about 3% of packets are delayed. The intervals between both GPS pulses and packet arrival times are measured with the performance counter in order to identify the delayed packets. Any GPS pulses which deviate more than 50 μs from the expected arrival time are discarded from the linear-fit model. When a data packet arrives with a 200 μs deviation from the expected time, the associated time stamp is replaced with the expected arrival time inferred from the linear fit.

2.3 Performance characterization

To characterize sensor and data acquisition system timing performance, the four sensors are simultaneously placed in a single
Helmholtz coil system driven by a pulse generator. Each sensor is sampled by a unique DAQ and PC, ensuring that the time
characterization accounts for all delays associated with signal processing and transmission through the system. Sensors are
5 stimulated with a $2\,\mu$T amplitude square wave, with period of 200 ms and duty cycle of 50% (Fig. 2a). The left and right
columns in Fig. 2 represent the data before and after application of the timing-correction algorithm. The inset in Fig. 2a
demonstrates how a delay in retrieving a data packet disrupts the timing of the field pulses. When a data packet is delayed, the
magnetic-field samples are distributed over a slightly larger time period, causing a shift in the observed time of the square wave
zero crossing relative to the other sensors. Figure 2b shows the time discrepancies between the interpolated and expected square
10 wave zero crossings. The zero crossings are recorded with $120\,\mu$s standard deviation from the expected interval; however, a
large number of outliers with up to 10 ms discrepancy exist. Figure 2c shows the histogram of the data from 2b, where the red
curve represents the best fit Gaussian. After the timing correction algorithm is applied to the data, time stamps associated with
outlier packets are replaced with the expected arrival times (Fig. 2 d,e,f). The remaining jitter is a Gaussian distributed with an
error of $120\,\mu$s .

15   Figure 3 shows the instrumental noise floors for each vector axis of the magnetometers. Data were obtained in a two-layer
μ-metal shield for approximately 35 minutes (2^{23} samples at the 3,960 Hz sample rate). Data were separated into an ensemble
of 64 individual intervals of 2^{17} samples. Power spectral densities were calculated for each interval, with the noise floor taken
as the ensemble average of the interval spectra. The noise floor varies between individual axes, with the most noise observed on
the Z-axis. For all three directions, the noise floor is constant between $\sim$ 2-700 Hz. Narrowband spectral features from 60 Hz
20 and harmonics are easily observed in the data. For frequencies above 1 Hz, the noise floor is uniformly below $0.1\ \mathrm{nT}/\sqrt{\mathrm{Hz}}$.
The peak observed in the noise floor, predominately in the Z and Y channels, between $\sim$ 300 Hz and $\sim$1500 Hz, is likely due
to the operation of the fluxgate electronics.

3 Observations of urban magnetic signatures

3.1 Multi-station analysis of urban magnetic fields

25 The spatiotemporal behavior of ultra-low-frequency electromagnetic fields throughout the San Francisco Bay Area has led
to the identification of the Bay Area Rapid Transit (BART) as a source of electromagnetic noise (Fraser-Smith and Coates,
1978). Subsequent measurements at a distance of 100 m of BART suggested periodic bursts of magnetic activity roughly
the periodicity of the BART train (Ho et al., 1979). Given its observability, reliable periodicity, and presence of multi-scale
signatures (e.g. individual train periodicity versus daily operation schedule), the BART is a useful tool in understanding the
30 operation of a magnetometer array in an urban area.

Many magnetic signatures associated with urban activity occur at frequencies where GPS alone provides adequate timing.
To observe the spatiotemporal effect of BART in the urban magnetic field, we decimate our high cadence data to 1 Hz sample

rate using a 3,960 element moving average low pass filter (-3dB cutoff at ≈ 0.44 Hz) to address aliasing. Low-cadence data can provide adequate time resolution and bandwidth for correlating multi-station observations of urban magnetic fields over many days and months. In the subsequent analysis, only data from stations 2, 3 and 4 is used for multi-station comparisons; station 1 served as an engineering unit at the time.

5   Figure 4 shows the fluctuating scalar magnetic field magnitude of three stations on Sunday, 20 March 2016 (PDT). Mean fields for each station are subtracted from the total magnitude. A magnetically quiet period corresponding to BART non-operating hours is consistent with previous observations of the urban magnetic field (Fraser-Smith and Coates, 1978). Each panel additionally shows one-minute-average magnetic field observations from the USGS station in Fresno, CA. Fig. 4(a) demonstrates a general agreement between our observations and the USGS data. Fig. 4(b) shows that urban fluctuations

10 dominate the daytime magnetic field. Additionally, Fig. 4(c) shows a subset of the data from 10-11 AM, revealing several synchronous spikes in each sensor.

    Figure 5 shows distributions of observed magnitude fluctuations binned at $10^{-3}\,\mu$T. The record naturally separates into two intervals, corresponding to the hours when BART trains are running (roughly, from 7:55AM to 1:26AM) and hours when BART trains are inactive. We refer to these intervals as "daytime" and "nighttime" respectively. Different characteristics are

15 observed for daytime and nighttime distributions. The nighttime distribution functions appear as a superposition of several individual peaks, The standard deviations, indicative of a typical fluctuation amplitude, of the measurements are given in order of increasing amplitude as $\sigma_3 = 0.009\,\mu$T, $\sigma_4 = 0.026\,\mu$T, and $\sigma_2 = 0.072\,\mu$T. Computing the amplitude of a typical nighttime fluctuation using the average of standard deviations computed using a 20 minute sliding window throughout the night significantly reduces the estimated fluctuation amplitudes $\langle\sigma_3\rangle = 0.001\,\mu$T, $\langle\sigma_4\rangle = 0.004\,\mu$T, and $\langle\sigma_2\rangle = 0.014\,\mu$T. This

20 suggests that the magnetic field fluctuations during the night are dominated by low amplitude fluctuations, with occasional large jumps in the field leading to a multi-peaked distribution function. Different numbers of discrete peaks (jumps) are observed in the sensors, suggesting that they may not be related to globally observable magnetic events, e.g. the BART.

    From Fig 1, it is clear that both the daytime and nighttime variance of the distributions increases as distance to the BART rail decreases, suggesting that the background noise level observed in each station is set by the distance to BART, even when

25 the trains are not running. Identifying other anthropogenic fields (for example, traffic) is complicated by the presence of the large BART signal. Accordingly, identifying the signatures of additional urban sources requires a thorough characterization of the magnetic background generated by BART.

3.2   Time-frequency (wavelet) analysis

Localizing the temporal distribution of spectral power requires simultaneous analysis in both time and frequency domains. To

30 investigate the time-frequency distribution of low-frequency fluctuations associated with BART we implement a continuous wavelet transform (CWT), using Morlet wavelets (Torrence and Compo, 1998). The unnormalized Morlet wavelet function $\psi(\tau)$ is a Gaussian modulated complex exponential,

$$\psi(\tau) = \pi^{1/4} e^{i\omega_0\tau} e^{\frac{-\tau^2}{2}}, \tag{1}$$

with non-dimensional time and frequency parameters τ and ω_0. A value of $\omega_0 = 6$ is commonly used across disciplines (Podesta, 2009; Torrence and Compo, 1998; Farge, 1992). The CWT of the magnetic field B is defined by the convolution of the time series with a set of self-similar wavelets, scaled by factor s, and normalized to maintain unit energy at each wavelet scale.

$$W(s,t) = \sum_{i=0}^{N-1} B_x(t_i)\psi(\frac{t_i - t}{s}). \tag{2}$$

We implement a wavelet transform with 130 scales logarithmically spaced between $2 \leq s \leq 16,384$, corresponding to a frequency range of 0.58 mHz $\lesssim f \lesssim 0.47$ Hz. Full day wavelet power spectral densities $|W(s,t)|^2$ in units of $(\mu T^2/Hz)$ for stations 3 and 4 on Sunday, 20 March 2016 (PST) are displayed in Fig. 6. These spectrograms prominently display the quiet nighttime period across all scales. Strong power is observed in scales corresponding to a 20-minute period (0.833 mHz) and associated higher harmonics. This 20-minute period coincides with the Sunday BART timetable on the geographically closest BART line (Richmond-Fremont). The black lines display the region subject to edge effects, known as the cone of influence (COI), corresponding to the e-folding time for the wavelet response to an impulse.

A brick-wall bandpass filter (i.e., unity gain in the passband, full attenuation in the stop band) between 0.7-10 mHz is applied to each sensor to isolate the range of observed spectral features. The top panel of Fig. 7 shows the band-passed time series for 10-11 AM on 20 March 2016. The band-passed time series are normalized to their maximum values for the purpose of visualization. These observations suggests that stations 3 and 4 are correlated with each other and respectively anti-correlated with station 2. This verified by the bottom panel of Fig. 7, which shows the cross correlation coefficients $C_{ij}(\tau)$ calculated for the band-passed 24 hour time series:

$$C_{ij}(\tau) = \frac{\sum_{n=0}^{N-\tau-1}(B_i[n+\tau] - \bar{B}_i)(B_j[n] - \bar{B}_j)}{\sqrt{\left[\sum_{n=0}^{N-1}(B_i[n] - \bar{B}_i)^2\right]\left[\sum_{n=0}^{N-1}(B_j[n] - \bar{B}_j)^2\right]}}, \tag{3}$$

where N is the record length, τ is a translation between time series, and n is the sample index (Bendat and Piersol, 1990). The phase correspondence between the stations is consistent with the distribution of stations east/west of the BART line (Fig. 1), and suggests strong azimuthal symmetry around the BART rail. Future work will look to determine the multipole components (e.g. line current, dipole, quadrupole) corresponding to the BART field.

Figure 8 shows full day wavelet spectral densities for station 2 on both Wednesday, 16 March 2016 and Sunday, 20 March 2016. The quiet BART night is much shorter on Wednesday; corresponding with different weekend and weekday timetables. Additionally, Fig. 8(a) demonstrates the absence of a strong 20-minute spectral component in the Wednesday data. The increase in spectral complexity is consistent with increases in train frequency, an additional active BART line, and variability associated with schedule changes for commuter hours. Previously efforts to capture period signatures associated with the BART found bursts of activity corresponding approximately to the train schedule, but with an irregular variation in the waveform (Ho et al., 1979). In contrast, our observations reveal a highly regular signature, with multiple spectral components, occurring at the

BART train period. The periodicity of the coherent BART signature enables for identification and extraction of the time-series waveform associated with BART operation.

4   Extracting a periodic signal

Previous attempts have been made to identify and remove transient features associated with BART from geomagnetic time-series using wavelets (Liu and Fraser-Smith, 1998). Our observations of a highly periodic BART signature suggest that statistical averaging over observations may be used to remove the periodic behavior. The periodic 20-minute signature observed in the Sunday 20 March 2016 time-series from station 2 can be extracted using the technique known as superposed epoch analysis (Singh and Badruddin, 2006). We identified 46 sharp peaks in the magnetic field occurring with an approximately 20-minute period (e.g. Fig. 4). From these 46 peaks, an ensemble $[X(t)_i]$ of intervals is constructed comprising the 3 minutes preceding and 17 minutes succeeding each individual peak. Averaging over the ensemble of intervals $\bar{X}(t) = \frac{1}{N} \sum_{i=0}^{N-1} X_i(t)$ reveals a coherent signature with an approximate 20-minute period, Fig. 9(a). The periodic signal observed in the data has the form of a sharp discrete peak of $\approx 1\mu$T, followed by an oscillation with a period on order of several minutes. A quantitative comparison between each member of the ensemble and the extracted coherent structure is obtained through the Pearson correlation. The average correlation between the extracted signal and observed data is $\bar{\rho} = 0.7$, with ρ_i ranging from 0.1 to 0.85. The cross correlation indicates the fraction of power in each interval derived from the average signature. Figure 9(b) demonstrates high correlation between the extracted average signal with an hour of observations taken from 9-10 AM (PDT). Figure 9(c) demonstrates an interval of data (with $\rho = 0.17$) which includes a transient feature observed in multiple stations, likely due to transient variation in the BART operation. Through extracting periodic magnetic signatures of BART, we enable the identification of globally transient events associated with BART operation which can be used to differentiate local anomalous behavior due to other urban signatures. Measurements from a single sensor allow us to identify events which deviate from the correlated periodic observations; our future work will employ the full network of magnetometers to identify spatiotemporally correlated signals, allowing for identification of magnetic fluctuations local to each sensor.

5   Discussion

An array of four magnetometers has been developed with a sampling rate of ~ 4 kHz and sensitivity better than 0.1 nT/$\sqrt{\text{Hz}}$ for the purpose of monitoring urban magnetic fields. The array has been deployed around Berkeley, CA and subsequently work will report on observations taken in New York City. This array is sensitive to both low frequency variations in the Earth's geomagnetic field, as well as a variety of anthropogenic sources: currents associated with BART, traffic, and 60 Hz power-lines. The broadband spectra of the urban magnetic field is dominated by the BART train system, which also generates coherent narrowband spectral features. Significant variations in spectral signatures are observed between weekends and weekdays, corresponding to differences in the BART train schedule. During the hours for which BART is non-operational, broadband noise is significantly decreased and agreement with the USGS magnetic field measurements is observed. However, the nighttime field

still contains features not attributable to geophysical activity. Further study is required to determine the nature and sources of these features.

These observations rely on the implementation of the network presented in Sec. 2. Our network relies on low-cost commercial hardware as well as a customized time synchronization algorithm which allows cross-correlating the sensors at high

5   frequencies. This algorithm additionally corrects for latency issues associated with the use of commercial, non-precision, hardware. Our synchronization procedure, which has been verified through simultaneous simulation of sensors, is precise to ≈120 μs. Though many sources of urban magnetic fields operate at much slower time scales, this precision enables studies of high frequency urban magnetic anomaly detection and sensor cross-correlation. Additionally, this synchronization algorithm may be implemented across other sensor networks built with cost-effective hardware.

10   We provide a proof-of-concept deployment of what, to our knowledge, is the first synchronized network of magnetometers specifically designed for observing the effects of human activity on the magnetic field in an urban environment. Further development of algorithms to characterize and extract the BART signal, as well as other magnetic signatures, is necessary. These algorithms may take advantage of other data sources–e.g. realtime BART arrival/departure data–and machine learning techniques. In analyzing magnetic observations of a city, we demonstrate that urban magnetic fields can reflect identifiable

15   aspects of human activity; further work will look to identify other sources of urban magnetic fields with multi-scale signatures, (e.g. traffic and energy consumption). This work may prove useful to the identification and reduction of noise in geophysical sensor networks which measure magnetic fields and seismic activity. Several additional courses for future work are evident: the study of high frequency signals such as the 60 Hz power-line; exploration the long term behavior of magnetic fields taken from single station observations; and comparative measurements of urban magnetic fields between cities.

20   *Data availability.* The datasets generated during and analyzed during the current study are available from the corresponding author on reasonable request. Public release of the data has not been approved at this time. Our time filtering algorithm and data acquisition software are publicly available on GitHub at https://github.com/lenazh/UrbanMagnetometer.

Author contributions. E.Z., A.W., and V.D were responsible for hardware development. E.Z., A.W., V.D., and T.A.B. participated in network characterization. T.A.B. conducted analysis of magnetometer data. A.W., V.D., and T.A.B. generated figures. V.D., T.A.B., and E.Z.

25   contributed most portions of the manuscript. D.B., J.W., G.D., C.P., and A.W. generated initial concept for network and study. D.B. and J.W. were responsible for the project management and coordination. All authors participated in discussion and direction of work as well as review of manuscript.

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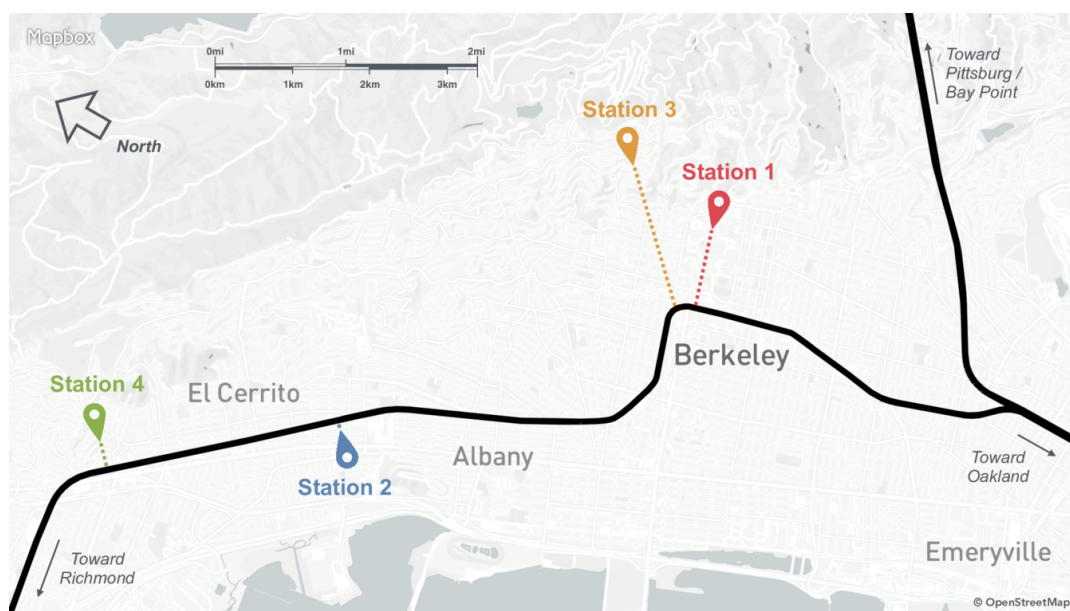
Figure 1. Map of Berkeley and location of the stations. The colored pins identify the locations of the magnetometers in our network. The black line shows the different paths of the BART trains. The shortest distance from each magnetometer station to the nearby BART line is represented by the dashed lines. Stations 1 to 4 are respectively located 1 km, 0.13 km , 2 km , and 0.36 km from the BART rail.
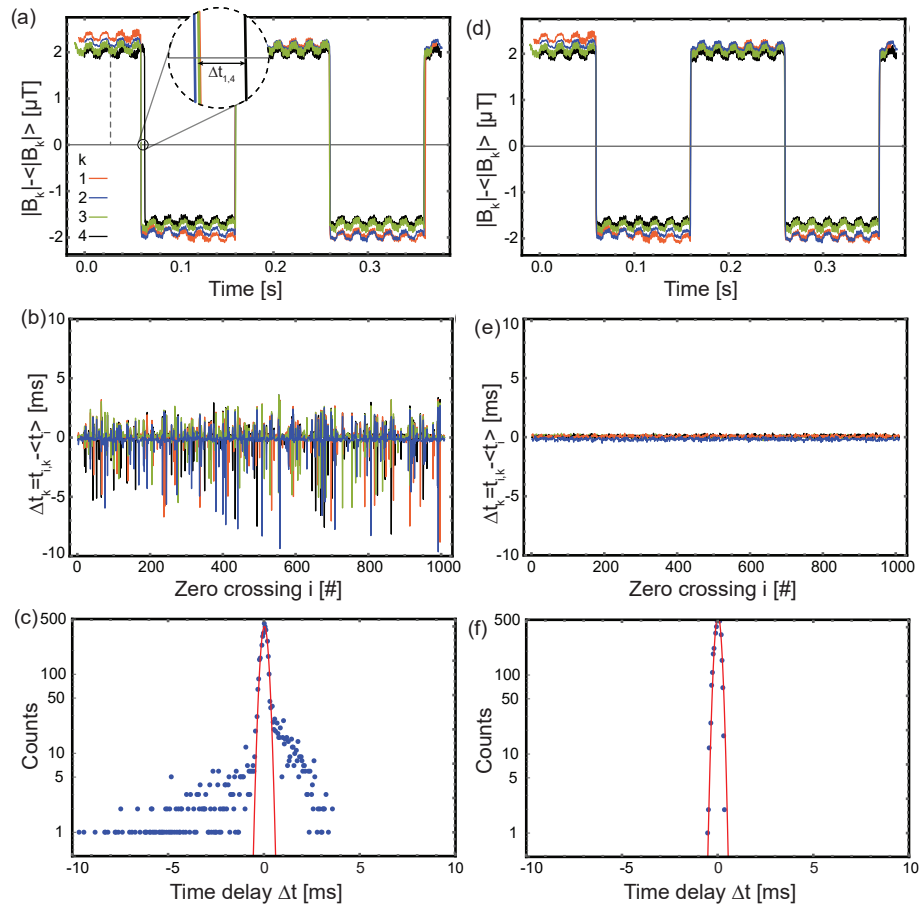
Figure 2. Characterization measurement of the time synchronization algorithm. The four magnetometers are subjected to a square-wave-modulated magnetic field. The left column (a-c) shows measurements with unprocessed time tags. The right column shows the time tags after processing. (a) Time series of the four magnetometer traces. The inset shows a discrepancy in magnetometer 4 at the zero crossing. (b) The difference of the mean zero crossing time of the square wave and the individual zero-crossing time for each magnetometer for two minutes of data. (c) Histogram of the data in (b), with the red curve representing the best-fit Gaussian. While most zero-crossing events have the correct timing within the 120 μs standard deviation of the Gaussian fit, there are a significant number of outliers. (d), (e) and (f) show the same data after implementing the time synchronization algorithm.
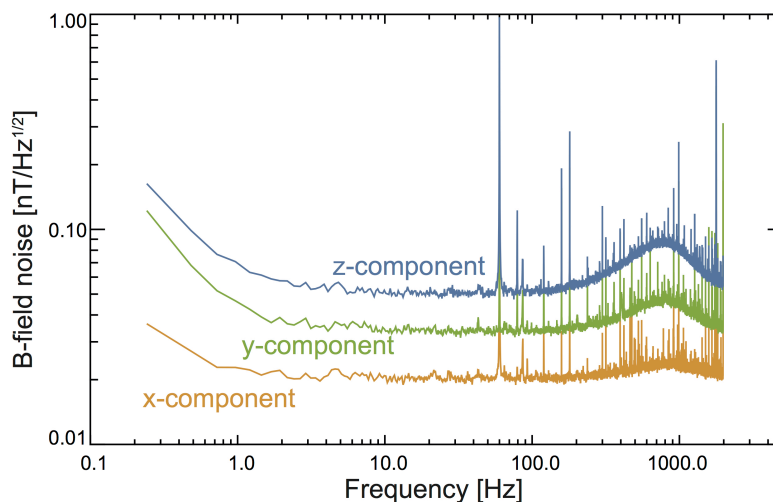
Figure 3. Instrumental noise floors for each vector axis of a Biomed magnetometer.
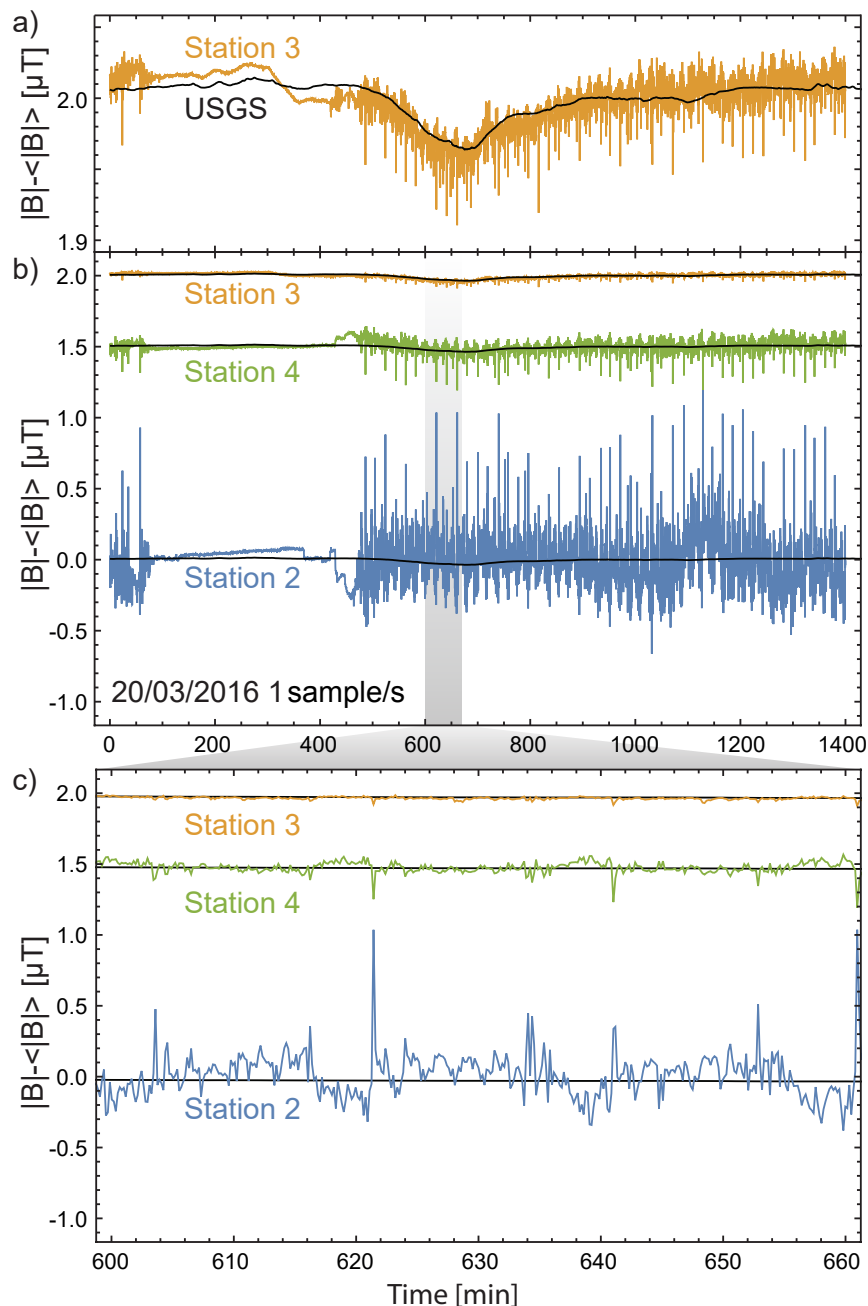
Figure 4. Magnetic field magnitudes for three stations at 1 sample/s cadence on 20 March 2016. Panel (a) shows close agreement between the geomagnetic field measured by a USGS station in Fresno, CA and sensor 3. Panel (b) 24 hour scalar magnitudes (DC values were adjusted for plotting purposes) for the three active sensors; the magnitude of fluctuations decreases with increasing distance from the BART train line. The grey bar represents one hour of data from 10-11 AM (PDT), a better visualization of that region can be seen in Panel (c). The one-minute averaged USGS geomagnetic field data are shown in each plot as a black line.
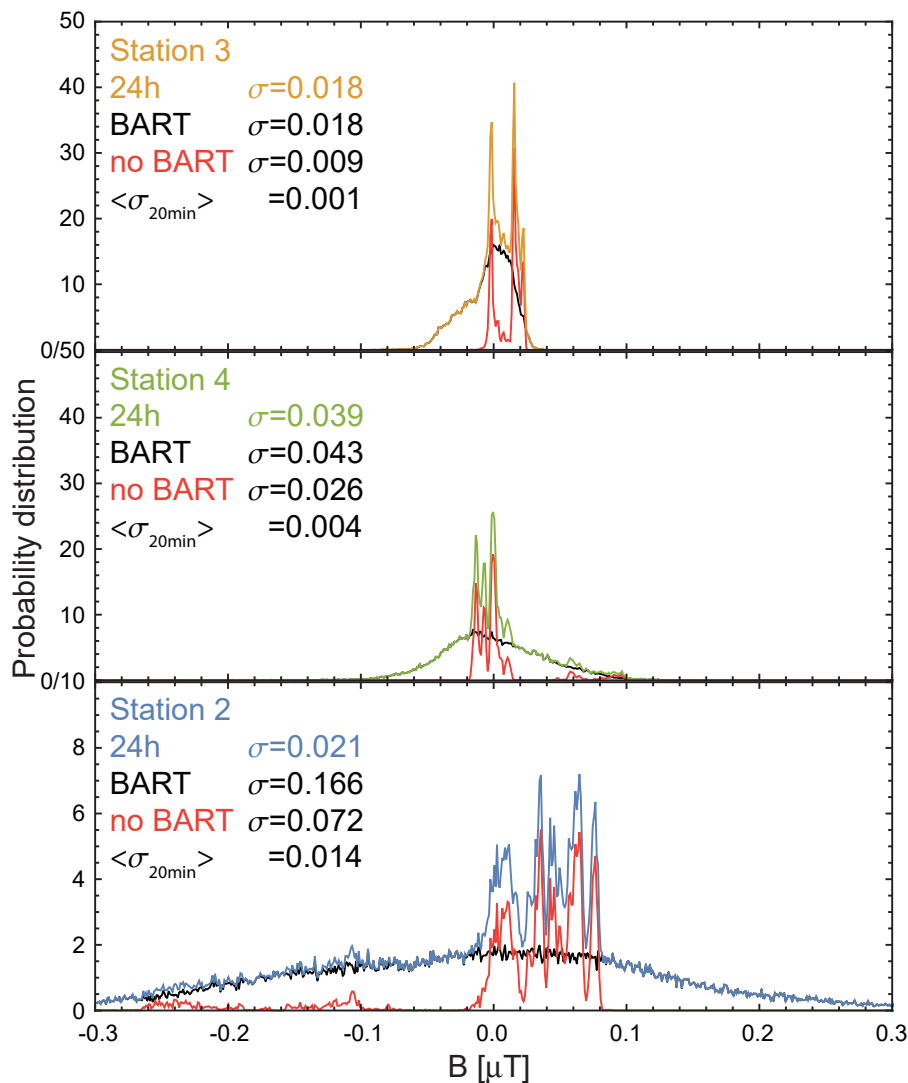
Figure 5. Distributions for 24hr, daytime, and nighttime magnetic field observations with typical fluctuation amplitudes, σ, computed for each period. Additionally, the amplitude of typical nighttime fluctuations is computed using a 20 minute sliding window, $\langle \sigma \rangle$, and demonstrates that nighttime observations is non-stationary with several discrete peaks. Daytime fluctuations follow broad distributions. The variance of the distributions increases as the distance from the BART train line decreases.
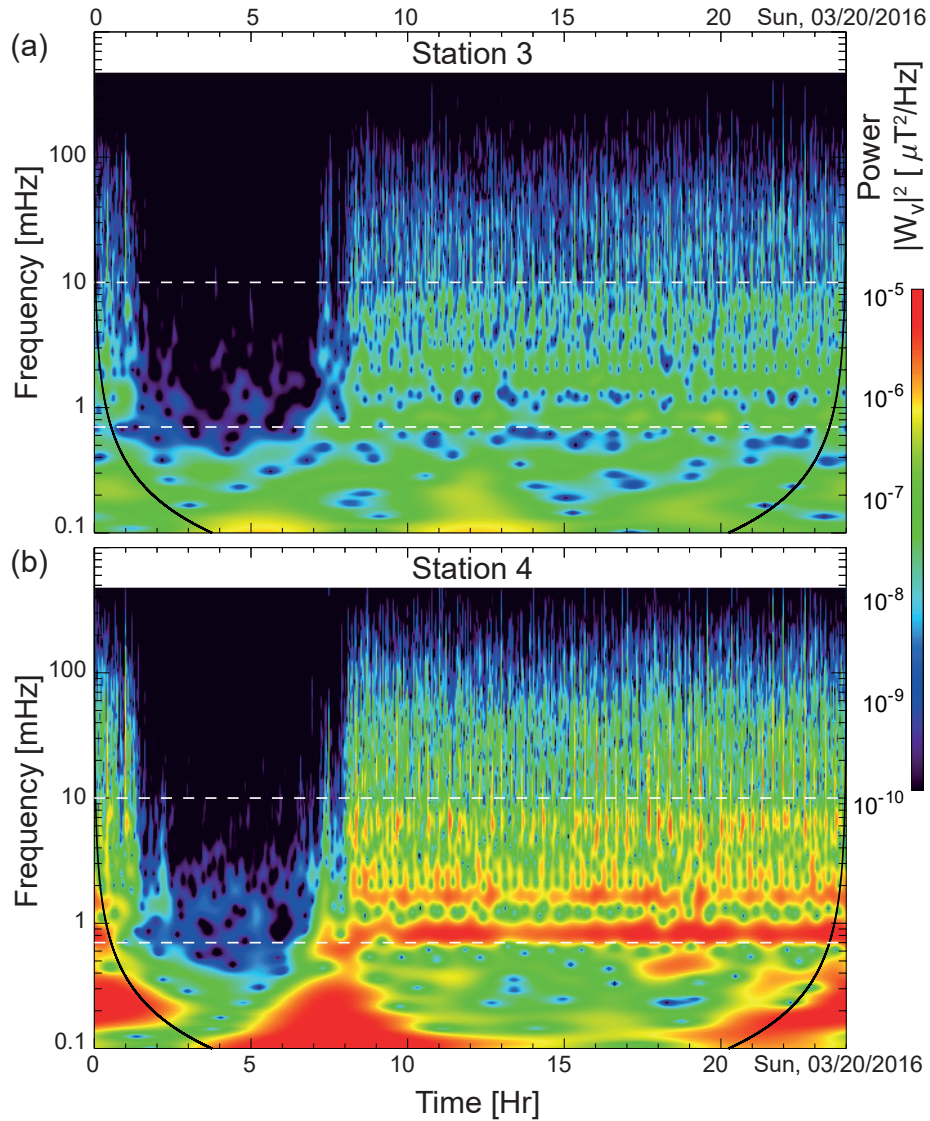
Figure 6. Time-frequency analysis of scalar magnetic field. Continuous wavelet transform power spectral densities (μT^2/Hz) for stations 3 (a) and 4 (b). The spectrograms reveal power in several bands, including the 0.83 mHz frequency corresponding to a 20 minute train period, common to both sensors. White dashed lines show the frequency range of a brick-wall filter (0.7 -10 mHz) applied to isolate these narrowband features. Black lines show the region where edge effects may impact the wavelet transform, frequently called the cone of influence.
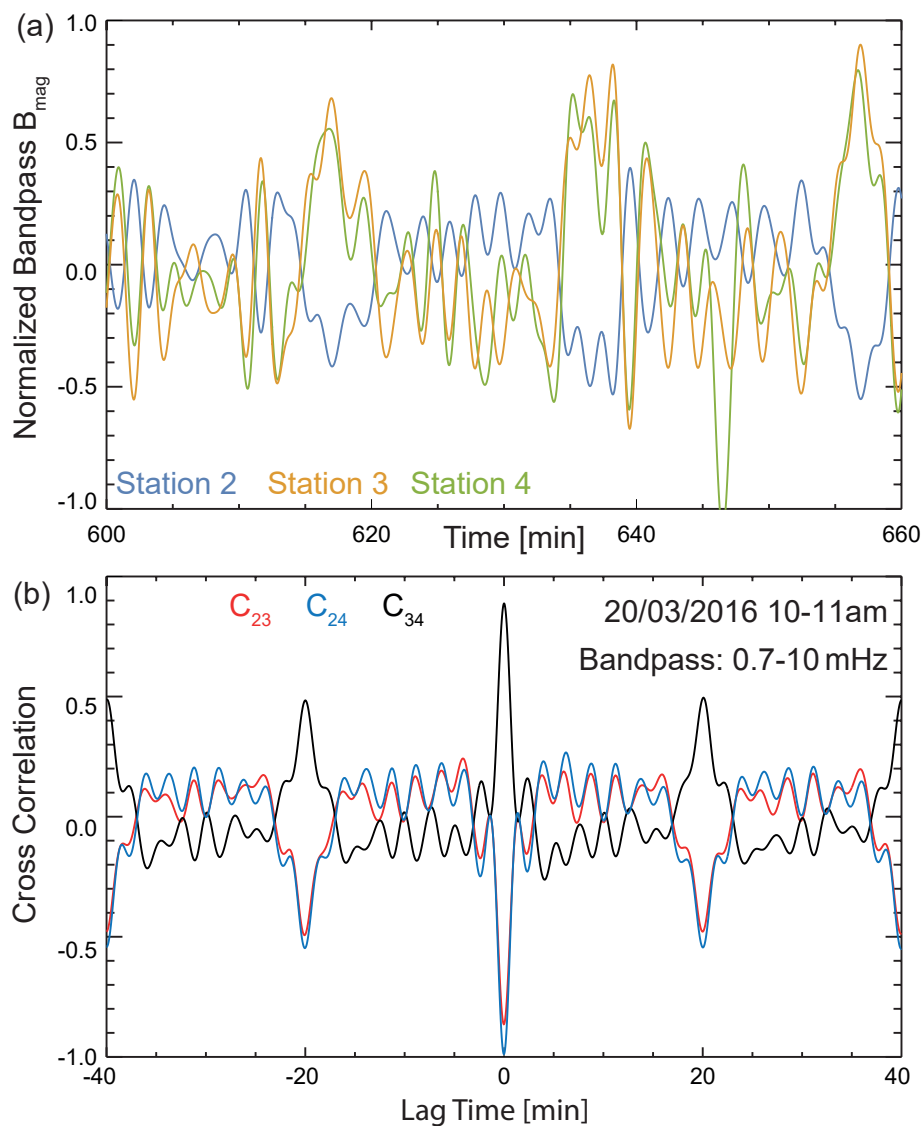
Figure 7. (a) Band-passed 0.7-10 mHz time-series for all three stations on 20 March 2016 between 10-11 AM (PDT). The bottom panel shows the correlation coefficients between pairs of stations as a function of lag. Stations 3 and 4 are highly correlated (in phase), while station 2 is respectively anti-correlated (out of phase).
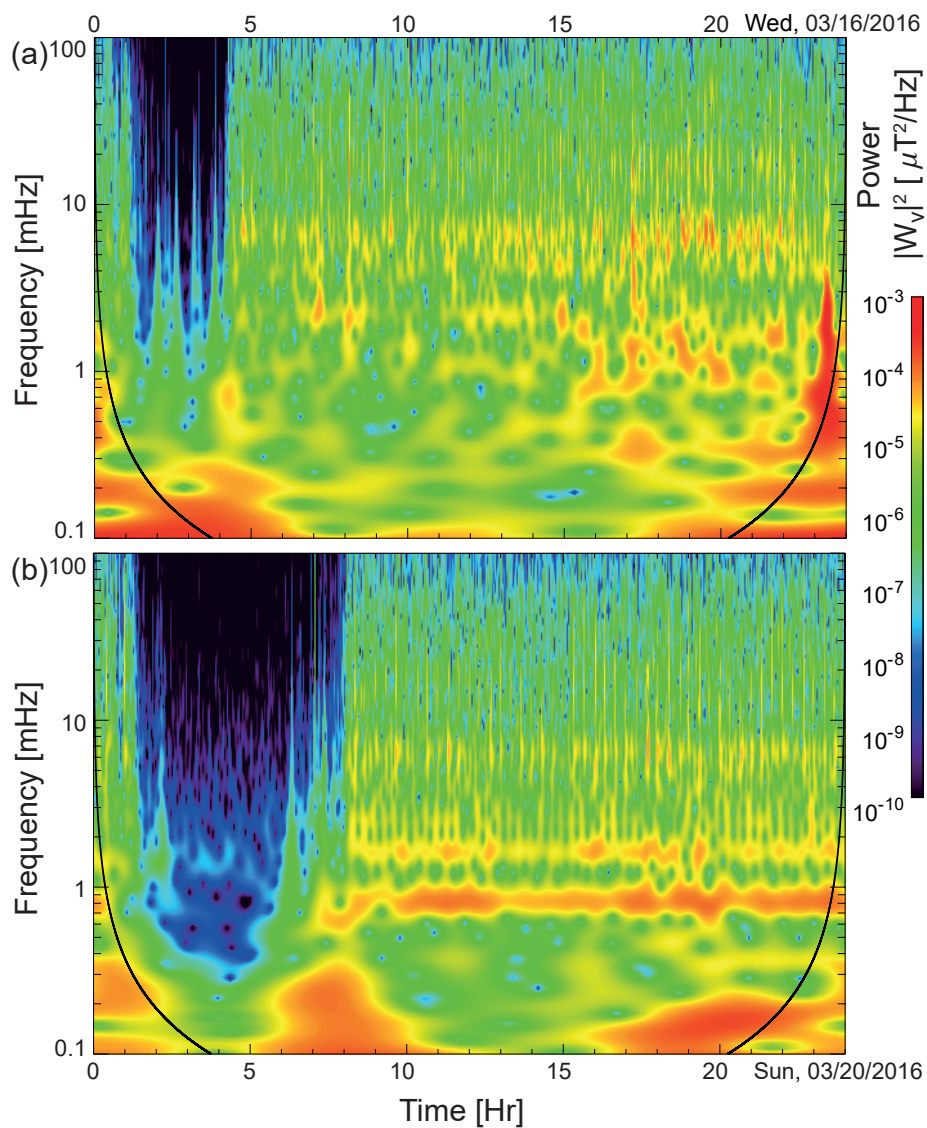
Figure 8. BART night signatures. Continuous wavelet transform of 1 sample s^{-1} magnetic field magnitude data from station 2 on Wednesday, 16 March 2016 (a) and Sunday, 20 March 2016 (b). The nighttime signature is significantly shorter in the data taken on Wednesday, this corresponds with BART operating hours. Additionally, the strong power-bands observed on Sunday are not present in the Wednesday data.
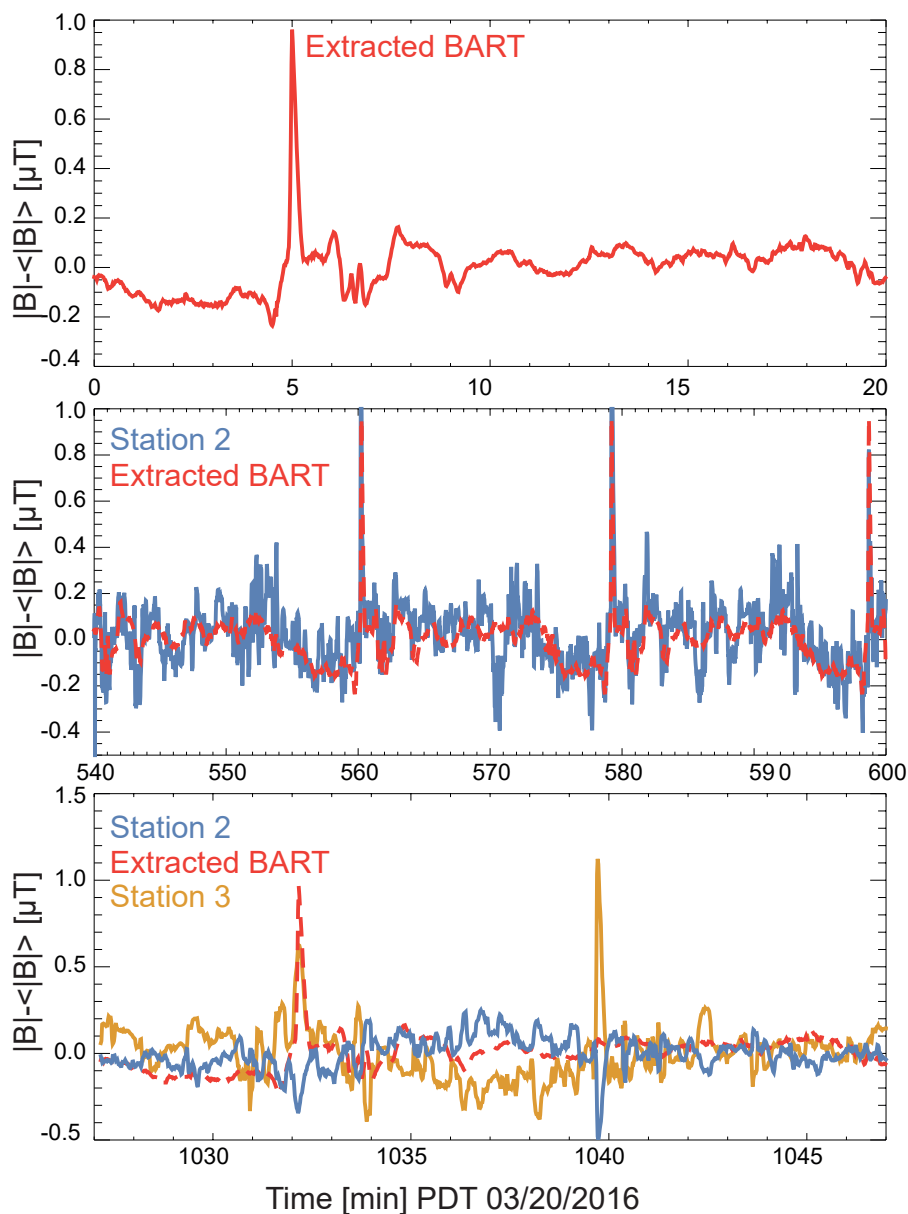
Figure 9. Extraction of BART signal. (a) 20-minute periodic signal of the BART extracted from an ensemble average of 46 intervals from station 2. (b) Comparison of the extracted average signal with an hour of observations from station 2 taken from 9-10 AM (PDT). (c) Comparison of extracted average signal with an interval containing global magnetic anomaly likely due to variation in BART operation.