Magnetic Field Variations in Alaska: Recording Space Weather Events on Seismic Stations in Alaska

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ABSTRACT

Seismometers are highly sensitive instruments to not only ground motion but also many other nonseismic noise sources (e.g., temperature, pressure, and magnetic field variations). We show that the Alaska component of the Transportable Array is particularly susceptible to recording magnetic storms and other space weather events because the sensors used in this network are unshielded and magnetic flux variations are stronger at higher latitudes. We also show that vertical-component seismic records across Alaska are directly recording magnetic field variations between 40 and 800 s period as opposed to actual ground motion during geomagnetic events with sensitivities ranging from 0.004 to 0.48 (m/s^2)/T. These sensitivities were found on a day where the root mean square variation in the magnetic field was 225 nT. Using a method developed by Forbriger (2007, his section 3.1), we show that improving vertical seismic resolution of an unshielded sensor by as much as 10 dB in the 100–400 s period band using magnetic data from a collocated three-component magnetometer is possible. However, due to large spatial variations in Earth's magnetic field, this methodology becomes increasingly ineffective as the distance between the seismometer and magnetometer increases (no more than 200 km separation). A potential solution to this issue may be to incorporate relatively low-cost magnetometers as an additional environmental data stream at high-latitude seismic stations. We demonstrate that the Bartington Mag-690 sensors currently deployed at Global Seismographic Network sites are not only acceptable for performing corrections to seismic data, but are also capable of recording many magnetic field signals with similar signal-to-noise ratios, in the 20–1000 s period band, as the observatory grade magnetometers operated by the U.S. Geological Survey Geomagnetism Program. This approach would densify magnetic field observations and could also contribute to space weather monitoring by supplementing highly calibrated magnetometers with additional sensors.

KEY POINTS

- Unshielded broadband seismometers are sensitive to magnetic field changes.
- Magnetometer data can be used to reduce the noise floor of long-period seismic records up to 10 dB.
- Collocated magnetometers could both improve seismic data quality and contribute to geomagnetic monitoring.

Supplemental Material

INTRODUCTION

In addition to ground motion, seismometers are well known to be sensitive to several nonseismic drivers including temperature (Doody *et al.*, 2017) and pressure changes (e.g., Beauduin *et al.*, 1996; Zürn and Wielandt, 2007). Instrument manufacturers mitigate the influence of these noise sources in several ways including using thermally compensating mass suspension springs with low coefficients of thermal expansion and low coefficients of elastic modulus. However, the ferromagnetic materials used to reduce thermal sensitivity have been shown to respond to changes in Earth's magnetic field (e.g., Forbriger, 2007). The sensitivity of a seismometer to magnetic field variations is not limited to terrestrial applications. In fact, the broadband seismometer from the Seismic Experiment for Internal Structure project on Mars also was collocated with

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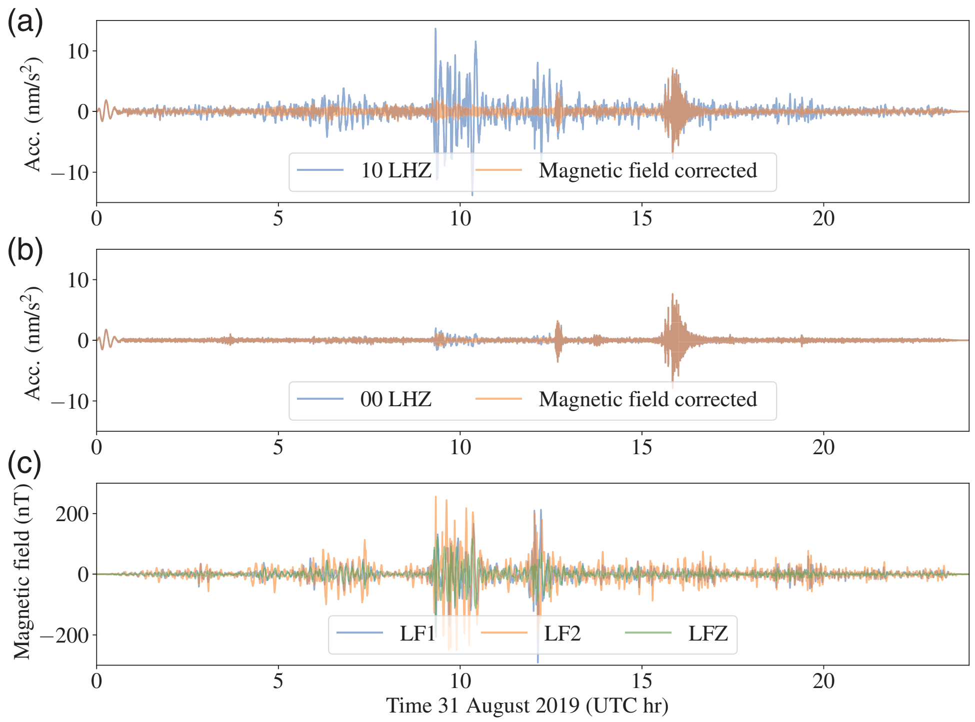


Figure 1. (a) Vertical seismic data beginning at UTC 00:00 on 31 August 2019, from Incorporated Research Institutions for Seismology (IRIS) and U.S. Geological Survey (USGS) station COLA (College, Alaska) from the secondary sensor before correcting for the magnetic field (blue) and after correcting for the magnetic field (orange). (b) Same as (a), but for the mu metal shielded primary sensor. (c) Mean-removed magnetic field data from the magnetometer at COLA. All traces were band-pass filtered from 40 to 800 s period. The 31 August 2019 M_w 5.4 Burma event can be seen on both sensors at approximately 15:20 UTC.

a magnetometer to help distinguish magnetic field variations from seismic activity (Lognonné *et al.*, 2019, Introduction). In addition, magnetic field variations coming from cultural activity, such as trains, can possibly produce unwanted magnetically induced noise (Lowes, 2009, Introduction). Although sensitivities to magnetic fields vary between different sensors, Forbriger *et al.* (2010) demonstrated that even during times of exceptionally low fluctuations of magnetic flux density, multiple Streckeisen STS-2 seismometers in the German Regional Seismographic Network were limited by magnetic field noise at long periods (>300 s).

Across the Global Seismographic Network (GSN) and other networks designed to make long-period observations, the sensor is often isolated from magnetic field changes by surrounding it in mu metal (a nickel–iron alloy, annealed in a way that provides a path for the magnetic field lines around the shielded area). The exceptionally high-magnetic permeability of mu metal attenuates the magnetic field by a factor of 18–30 (Pálinkás *et al.*, 2003, their fig. 6; Forbriger, 2007, his section 5.2). However, the high cost of mu metal shielding often prohibits its use in temporary and regional seismic networks. Furthermore, for stations installed in shallow postholes, such as the Incorporated Research Institutions for Seismology (IRIS) Alaska Transportable Array (TA), the addition of mu metal shielding could further complicate field logistics by requiring costly additions to the instrumentation and larger diameter postholes.

The Earth's magnetic field extends far above the Earth's surface, interacting with the solar wind to form the magnetosphere. Charged particles in the magnetosphere are directed toward the poles, in which they increase ionospheric conductivity and allow strong electric currents to flow only a few hundred kilometers above the Earth's surface. These currents cause enhanced geomagnetic activity at high latitudes (e.g., Love, 2008). Therefore, the high-geomagnetic latitude of Alaska TA coupled with the lack of magnetic shielding around the sensors may make this network particularly susceptible to recording space weather events. Magnetic flux variations generally increase in amplitude with increasing periods (e.g., Baumjohann and Nakamura, 2007; Constable, 2016). The irregular micropulsations (called pi's) associated with high latitudes have periods of 1–150 s (Saito, 1969), and magnetic storms show elevated amplitudes in magnetic field variations from 60 s to periods as long as a day (Constable, 2016; Fig. 1). Although this phenomenon was not observed at TA stations in the lower 48 states, geomagnetic storms are likely to appear in Alaska TA seismic records. Furthermore, these geomagnetic storms have frequency content similar to bands used to study mantle structure from surface waves (Kovach, 1978; Laske and Widmer-Schnidrig, 2015) and ambient noise tomography (e.g., Porritt *et al.*, 2011; Gao and Shen, 2014).

The purpose of this work is twofold. We demonstrate that during space weather events, unshielded seismic stations in Alaska are recording magnetic field variations in addition to actual ground motion. Although the methodology of Forbriger (2007, his section 3.1) for correcting out magnetic fields from seismic data in Alaska is successful if a magnetometer is collocated with the seismic station, this approach becomes less useful as the distance between the magnetometer and seismometer increases. We then show that collocating relatively low-cost magnetometers at each high-latitude seismic station could be a tractable solution to improving seismic data quality

TABLE 1
Variance Reductions in Percentages, Sensitivities, and Coefficients for the Different Components at COLA

Component	Location Code	Variance Reduction %	Sensitivity $(m/s^2)/T$	$a_z (m/s^2)/T$	$a_1 (m/s^2)/T$	$a_2 (m/s^2)/T$
LH1	10	3.31	0.098	−0.038	−0.0038	0.09
LH2	10	2.67	0.15	−0.14	−0.053	−0.0087
LHZ	10	92	0.096	−0.09	−0.016	0.00012
LH1	00	0.38	0.0031	0.0026	−0.0009	−0.0014
LH2	00	0.48	0.005	0.0028	0.004	−0.0019
LHZ	00	8.2	0.0071	−0.0071	−0.00022	−0.000019
LHU	10	2.28	0.11	−0.078	−0.076	0.00075
LHV	10	4.73	0.151	0.032	−0.093	−0.11
LHW	10	3.51	0.079	0.032	−0.07	0.02
LHU	00	0.61	0.0028	−0.00031	0.0028	0.000089
LHV	00	0.43	0.0024	−0.0015	0.00089	−0.00178
LHW	00	1.44	0.0087	−0.0015	0.0013	0.0085

The 00 (Streckeisen STS-6) and 10 (Streckeisen STS-5) sensors are installed at Incorporated Research Institutions for Seismology and U.S. Geological Survey (IRIS and USGS) network station COLA (College, Alaska). The components LH1, LH2, and LHZ refer to the output components of the seismometer, whereas LHU, LHV, and LHW refer to the rotated physical components of the sensors.

at these sites while simultaneously recording high-quality magnetic field data. These Bartington three-component magnetometers cost approximately $700 (as of April 2020). Using the second set of three channels on a Quanterra Q330, digitizing these data in a fashion similar to how seismic data are digitized is possible. This is a very cost-effective solution compared to mu metal shielding. It costs approximately $2000 to shield a sensor using mu metal. These units have reported noise levels of less than 400 pT^2/Hz at 1 s period with a bandwidth out to DC. An additional benefit to this approach is that it would aid in densifying the existing sparse network of magnetic observatories and could improve our ability to monitor space weather hazards in real time (Love and Finn, 2017) as well as aid in the understanding of how spatially variable the Earth's magnetic field is (Love *et al.*, 2016, their section 7).

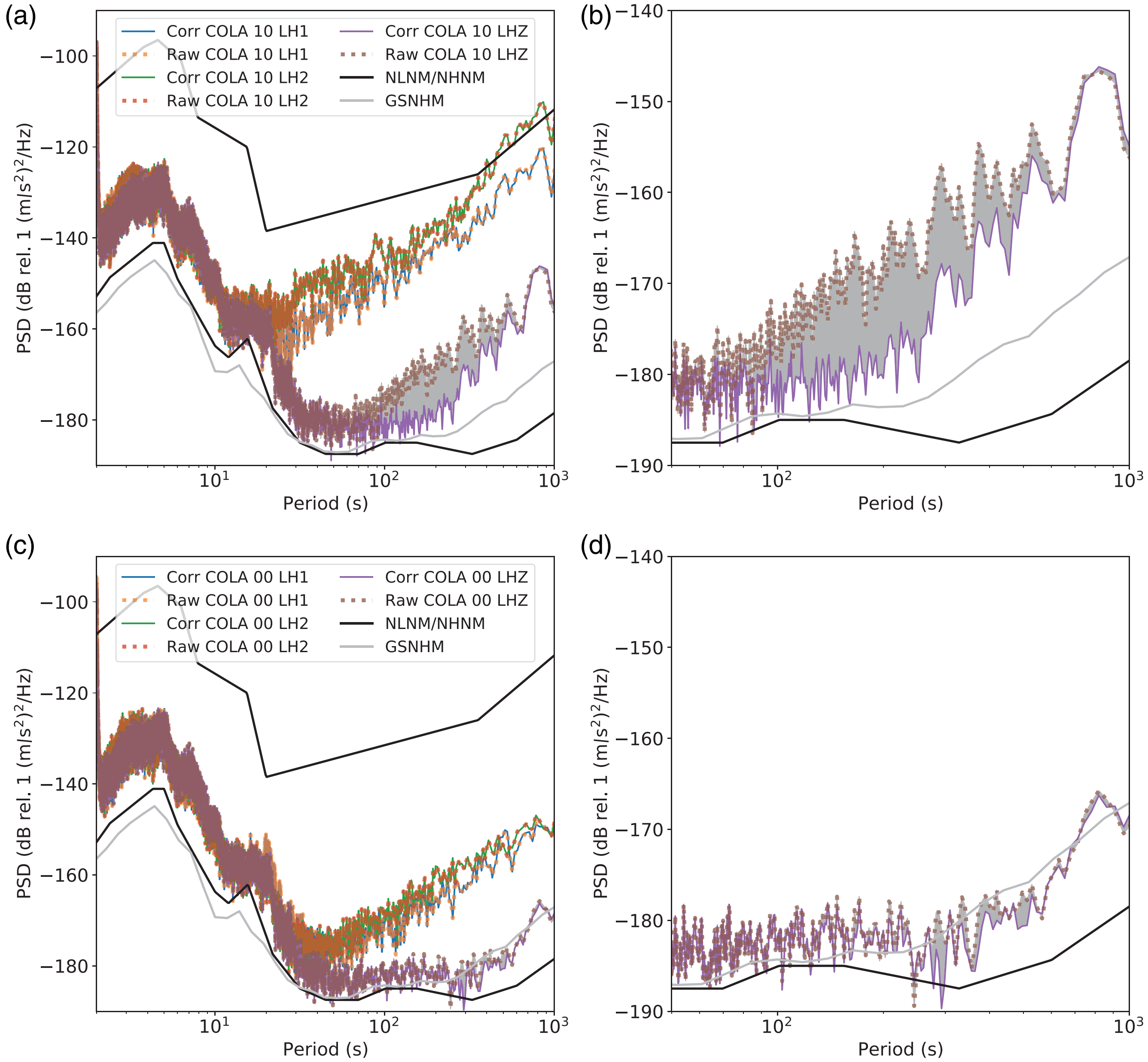
REMOVING MAGNETIC FIELD VARIATIONS FROM SEISMIC DATA

IRIS and U.S. Geological Survey (USGS) seismic station COLA (College, Alaska), near Fairbanks, provides a prime location to understand the contribution of magnetic field changes to noise levels at a seismic station and explore the effectiveness of correcting out this nonseismic signal. This is because it is at a relatively high latitude (64.87° N) and is collocated with a three-component Bartington Mag-690 magnetometer. Let $x(t)$ denotes the output of one of the sensitive axes of a seismometer at time t given in units of acceleration. If $y_1(t)$, $y_2(t)$, and $y_3(t)$ denote the output of the three orthogonal magnetometer components, then we wish to remove any signals that are common to both the magnetometer and the seismometer. This is done by estimating coefficients a_1, a_2, and a_3 that minimize R, the energy of the residual, in a least-squares sense:

$$R = \min_a ||x(t) - a_1 y_1(t) - a_2 y_2(t) - a_3 y_3(t)||_2. \quad (1)$$

We estimate these coefficients after band-pass filtering all traces from 40 to 800 s using data from 31 August 2019. This is similar to the method developed by Forbriger (2007, his section 3.1) with the coefficients a_i having units of acceleration per magnetic flux density (e.g., $(m/s^2)/T$). These coefficients have been found to be relatively stable over time and represent the sensitivity of the seismometer to the different components of the magnetic field (Forbriger, 2007). The reduction in variance gives a measurement on how limited a particular sensor is to magnetic field variations (Table 1). That is, a sensor could be sensitive to magnetic field variations, but the resolution is limited by another nonseismic noise source. In Figure 1, we show an example of vertical seismic data from COLA both before (blue) and after (orange) correcting for the contribution of the magnetic field for both the Streckeisen STS-5 (Fig. 1a; location code 10) and the mu metal shielded Streckeisen STS-6 (Fig. 1b; location code 00). Our estimates of the coefficients were done for the same time period as the correction shown. We note that the waveforms of an M_w 5.4 earthquake in Burma do not appear to be affected by these corrections on either sensor. Figure 2 shows the spectra of all components of these instruments before and after performing the magnetic field correction. The difference in noise levels on the horizontal components at periods greater than 20 s is likely a result of the Streckeisen STS-5 being installed at 10 m depth, whereas the Streckeisen STS-6 is installed at 117 m depth (Hutt *et al.*, 2017, their fig. 7). These differences in installation depth could also explain why the vertical component of the Streckeisen STS-6 shows improved resolution over the Streckeisen STS-5 at periods greater than 100 s. That is, the Streckeisen STS-6 is likely better thermally isolated (Doody *et al.*, 2017, their fig. 10).

From Figure 1, the unshielded STS-5 at COLA is clearly sensitive to changes in the magnetic field on its vertical component. However, we can correct for these transient events using



a collocated recording of the magnetic field. For this day, we are able to attain a reduction in variance of 92% on the vertical component of the unshielded STS-5 (Fig. 1a) and a reduction of 8% on the vertical component of the shielded STS-6 (Fig. 1b). Despite having similar magnetic sensitivities as the vertical components (Table 1, column 4), our reductions in variance for the horizontal components of both sensors are significantly lower at ~3% for the unshielded STS-5 and <1% for the shielded STS-6. This suggests that magnetic field variations are limiting the resolution, and ultimately the quality of the data, for the vertical component, but not for the horizontals of the STS-5. We note that this is in contrast to Forbriger (2007, his fig. 14), in which the study identified that the horizontal components of the STS-2 at Black Forest Observatory

Figure 2. (a) Power spectral density (PSD) estimates for the secondary sensor (location code 10) on 28 September 2019, at IRIS and USGS (network code IU) station COLA (College, Alaska) before magnetic field corrections (Raw, dashed lines) and after magnetic field correction (Corr, solid lines). The gray-shaded area denotes the frequency band in which magnetic field correction coefficients were estimated and showed improvement over the raw PSD. The corrected and raw horizontal components (LH1 and LH2) overlay very closely, whereas the vertical raw and corrected components show a difference of as much as 10 dB at 100 s period. (b) Same as (a) but zoomed in to the vertical component in the 50–1000 s period range (same colors as (a)). (c) Same as (a), but for the magnetically shielded primary sensor at COLA (location code 00). (d) Same as (c) but zoomed in to the vertical component in the 50–1000 s period range (same colors as (d)). For reference, we include the Peterson (1993) New Low-Noise Model and New High-Noise Model (NLNM and NHNM) in black as well as the Berger *et al.* (2004) Global Seismographic Network (GSN) Horizontal Low-Noise Model (GSNHM) in light gray.

(Schiltach, Germany) were very sensitive to magnetic field variations. This could be due to the sensors having a different form factor (the STS-5 is a posthole sensor) or it could be a result of differences in installations. Both the STS-2 and the STS-5 are Galperin suspension instruments (three orthogonal sensing components in which each component is sensitive to both horizontal and vertical motions). The final sensor output is a "mixed" signal, which yields a vertical component as well as two horizontal components (Wielandt, 2002). For completeness, we have also included the sensitivity of the Galperin suspension components for both the STS-5 and STS-6 (Table 1). As with most seismic stations, we attribute sensor tilt in response to changing atmospheric pressure as the dominant source of long-period noise on the horizontal components (e.g., Tanimoto and Wang, 2018).

With the unshielded STS-5 at COLA, we are able to improve vertical-component noise levels between 100 and 400 s period by approximately 10 dB (Fig. 2b). Because the spectrum of Earth's magnetic field tends to increase with increasing period (e.g., Constable, 2016, her fig. 1) and the Earth's natural seismic field is strongly excited by oceanic microseisms between approximately 5 and 30 s period (e.g., Peterson, 1993), we do not anticipate space weather strongly impacting seismic observations at these shorter periods. At periods longer than 400 s, noise improvements from the magnetic correction become less substantial as thermal and pressure variations likely become the dominant source of vertical-component noise (Steim, 2015, his section 1.02.3.2.1).

We note that the magnetic field corrected and uncorrected horizontal-component spectra are nearly identical for each respective sensor at COLA. However, the two sensors do show different noise levels due to installation at different depths. This again supports our hypothesis that sensor tilt noise as opposed to magnetic field variations is the dominant noise source on the horizontal components, or that Newtonian attraction of fluctuating atmospheric masses could be introducing noise at similar levels (Klügel and Wziontek, 2009). Although Zürn and Wielandt (2007) limit their discussion to vertical data, a consistent minimum on horizontal components possibly occurs at some partially fixed frequency. Further limitations in horizontal seismic noise are discussed in Zürn *et al.* (2007). We note that the unshielded STS-5 at COLA is installed at 10 m depth in a borehole and likely experiences less tilt than surface vaults and similar tilt to many posthole installations (e.g., Hutt *et al.*, 2017). Therefore, we anticipate that performing magnetic corrections will not improve horizontal-component data for most seismic stations at high latitudes under moderate magnetic field variations. However, although our analysis was restricted to a time period in which variations were relatively large (225 nT root mean square [rms]), days with larger magnetic storms could greatly exceed this, and the corrections could potentially improve horizontal data. Although most of our reduction in magnetically induced noise was isolated to the vertical component, we are unable to identify if the steel casing is changing the flux lines of the magnetic field. In other words, our magnetometer is not directly installed in the posthole, so the vertical magnetic field could be amplified from the steel casing. Therefore, we do not know how different the magnetic field is at the seismometer versus our magnetometer location. This also prevents us from further testing the compass-needle effect proposed by Forbriger (2007, section 4.2), in which the suspension spring of the sensor acts as a compass needle.

MAGNETIC FIELD-INDUCED NOISE ACROSS ALASKA TA

Although we observe the strong magnetic event shown in Figure 1 on many of the Alaska TA vertical-component seismograms (Figs. S1–S4 available in the supplemental material to this article), the signal is not coherent across the entire network. This is likely due to the high spatial variability of Earth's magnetic field (Pulkkinen *et al.*, 2006, section 5) and inhibits our ability to perform magnetic corrections on seismometers not collocated with the magnetometer at COLA. We used the aforementioned magnetic-correction methodology on the vertical components of four additional Alaska TA sensors located at various distances from COLA (Table S1). In general, we found that variance reductions decreased with distance from the magnetometer. For example, we were still able to attain an 89% reduction in variance for the station 33 km away at Poker Flat. However, at station J25K, which is 122 km away from COLA, we observe only 58% variance reduction and find magnetic corrections to be unreliable at stations more than 200 km away from COLA. For example, at B20K, which is 695 km, we observe only a 2.9% variance reduction.

As an alternate approach to determining the extent to which Alaska TA stations record magnetic field variations, we estimate power spectral densities (PSDs) for all stations with network code AK and TA in Alaska during days with substantially different magnetic field activity as measured by the A_p index. The daily A_p index values were retrieved from the GeoForschungsZentrums German Research Centre for Geosciences and are calculated using data from The International Real-time Magnetic Observatory Network (INTERMAGNET) Higher A_p indices indicate days with enhanced geomagnetic activity.

For our analysis, we used data from 29 August 2019, a day with little magnetic field activity (A_p index of 3), as well as 1 September 2019, which is a day in which the magnetic field was much more active (A_p index of 39). For each seismic station, we compute PSDs in 1 hr increments using 2^{10} samples (1024 s windows) with 75% overlap. For each window, we remove the linear trend, the mean, and apply a Hann taper. From our PSD estimates, we take the 10th percentile statistics from 40 to 400 s. The mean of this value provides a noise estimate with each circle in Figure 3a being a single station noise estimate. Between 40 and 400 s period, we see that many of the stations in the AK and TA networks have higher vertical noise levels

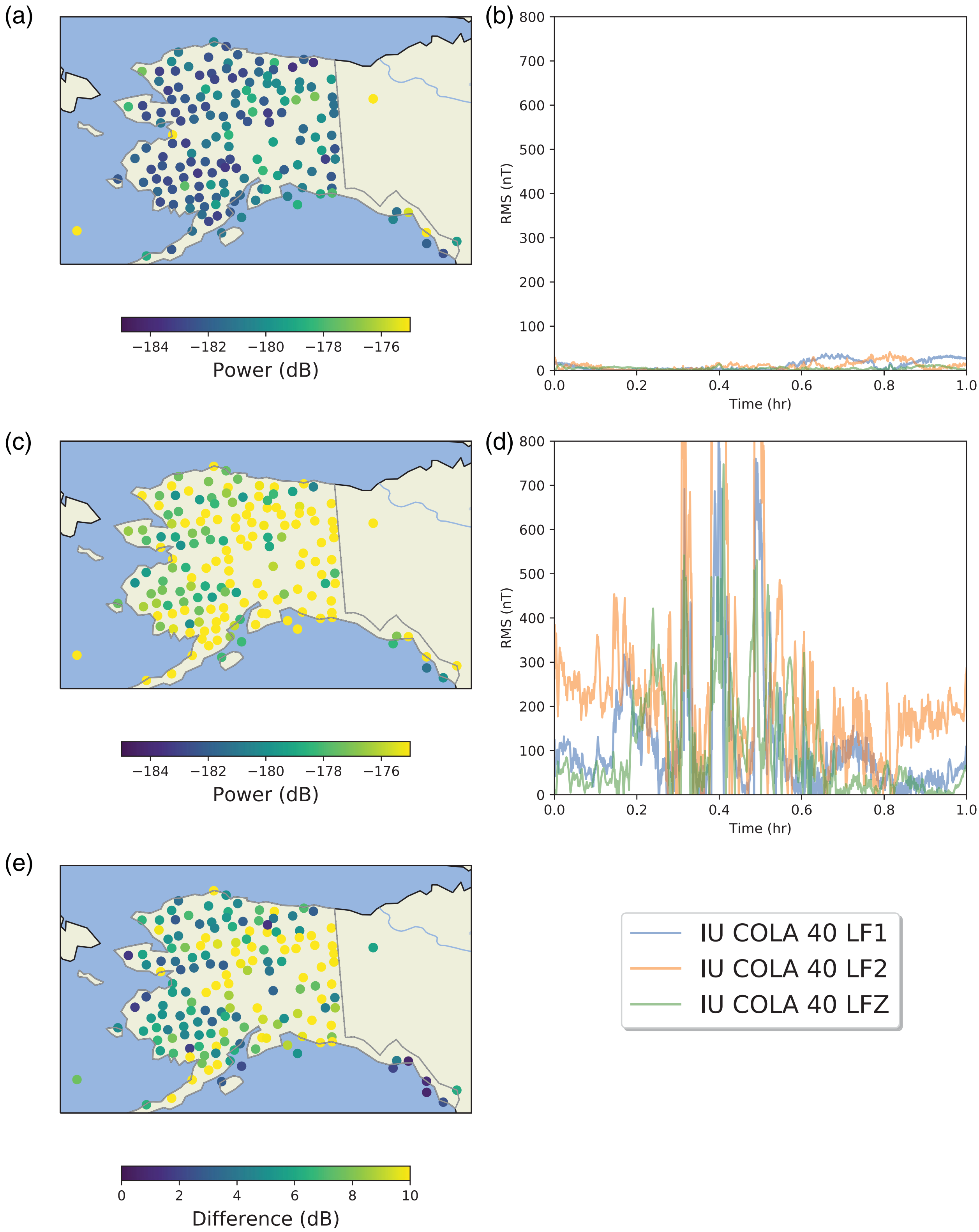


Figure 3. (a) 10th percentile background vertical noise levels in decibels (dB) relative to 1 $(\mathrm{m/s}^2)^2/\mathrm{Hz}$ in the 40–400 s period band on 29 August 2019, for broadband stations in Alaska. (b) Root mean square (rms) magnetic field values in nT for 29 August 2019, at IRIS and USGS (network code IU) station COLA (College, Alaska). (c) Same as (a), but for a day with an active magnetic field (1 September 2019). (d) Same as (b), but for 1 September 2019. (e) The difference in dB between the 10th percentile PSD estimates during the magnetically active day and the magnetically quiet day. Positive dB differences indicate that the station is noisier on 1 September 2019.

during days with large magnetic field activity (Fig. 3). Many stations show increases in noise levels that exceed 10 dB. This increase in signal is also present when comparing the rms amplitude for these 2 days. In Figure 4, we see that the rms amplitudes tend to increase for almost all stations in the TA and AK networks. As our study makes use of only one magnetometer, ascertaining how much of the variability in elevated noise levels is coming from different magnetic field amplitudes is not possible. However, sensors with elevated sensitives to magnetic field variations were unlikely to be preferentially installed in the eastern half of Alaska. This suggests that better spatial resolution of the variability of the magnetic field could help to better constrain things like the geographic distribution of auroral activity.

AN OPPORTUNITY FOR SPACE WEATHER OBSERVATIONS

The geomagnetic community has been working toward improving real-time space weather monitoring (Love and Finn, 2017, section 3.1). Their goals have been to expand the geographic distribution of magnetometer stations, increase acquisition and sampling rates, improve data quality, increase promptness of data transmission, and facilitate access to real-time magnetometer data. Although the magnetometer used in this study does not meet the standards set by INTERMAGNET for observatory quality data (Love and Chulliat, 2013), it does provide a very local recording of Earth's magnetic field and provides data suitable for a magnetic variometer station. We also see from Figure 5a that the dynamic range between the USGS INTERMAGNET stations (gray) and the seismic stations operating Bartington Mag-690s (black) have very similar dynamic ranges in this period band. That is, both USGS INTERMAGNET and the Bartington Mag-690s have similar lower and upper noise levels. Although these additional magnetometer installations at seismic sites might not be calibrated to a level that makes them useful for secular variation measurements (Jackson *et al.*, 2000), they do provide additional spatial resolution and could help to improve our understanding of space weather phenomena. That is, only a few USGS INTERMAGNET stations have lower noise in the period band of 20–1000 s, so these data are largely consistent with magnetic field observations in this period range. At periods less than about 5 s, we see that the dynamic range of the deployed Bartington Mag-690s gets smaller than that of the USGS INTERMAGNET sites. This could be a result of a frequency-dependent response on the Bartington Mag-690 units or antialiasing in the digital filter of the USGS INTERMAGNET sites. We have not compared differences in long-term drift or other parameters that are important for INTERMAGNET station specifications. Finally, we should point out that many INTERMAGNET stations are sensitive to ground motion caused by large seismic events (Stacey and Westcott, 1965). Understanding the seismic sensitivity of geomagnetic observatories could help to reduce uncertainty at time periods in which geomagnetic storms and large earthquakes are synchronous. For example, the 7 September 2017 M_w 8.2 earthquake in Tehuantepec, Mexico (Melgar and Ruiz-Angulo, 2018) and a large magnetic storm occurred at the same time (Dimmock *et al.*, 2019).

IMPROVED RESOLUTION AND SAMPLE RATES

Although the needs and specifications for seismic data and magnetic field data are different, seismology has been very successful in recording high-sample rate data in near-real time and having the data openly accessible to all seismologists via IRIS (Trabant *et al.*, 2012). Collocated magnetometers at seismic stations could help to improve space weather monitoring by allowing for higher sample rate data in near-real time, as well as helping to improve resolution at many seismic stations. This is analogous to how microbarographs are providing additional insight when collocated with seismometers (Tanimoto and Wang, 2018). Similarly, the seismic community could benefit from improved calibration techniques and standards, which have been adopted and standardized by INTERMAGNET for geomagnetic observatories. Adopting such standards in the seismic community could help to improve calibration practices and data quality (Davis and Berger, 2012, their discussion). For example, the GSN has yet to meet the calibration design goal of accuracy to within 1% (Lay *et al.*, 2002, Functional Specification 5; Ringler *et al.*, 2015, their discussion).

To better understand how magnetic field variations could limit the resolution of vertical seismic data, we estimated both high- and low-magnetic field noise models for the stations in the GSN that operate magnetometers (six stations, Fig. 5a). For each station, we estimated a 10th percentile (blue) and 90th percentile (orange) PSD (McNamara and Buland, 2004, e.g., Fig. 5). Certainly, time periods have PSD levels outside of these ranges, but the 10th and 90th percentiles give a good estimate of the background operating range. We then take the pointwise minimum and maximum as a function of period. These curves are similar to those developed by Peterson (1993, his fig. 15) for seismic data. For reference, we have also developed noise models for the USGS-operated geomagnetic observatory stations (gray, Fig. 5a). For further details on the processing methods, we refer the reader to the supplemental material. Using the magnetic field minimum and maximum curves obtained from seismic stations operating magnetometers, we are able to produce equivalent seismic noise as a function of period for different values of seismometer sensitivity to magnetic field variations (Fig. 5b). In Figure 5b, we see that sensors with coefficients less than 0.01 $(m/s^2)/T$ are likely not limited in resolution by magnetic field changes (yellow), whereas coefficients near 1.0 $(m/s^2)/T$ (purple) could be limited, at periods greater than 300 s, even at locations with small magnetic field variations. For instruments that are not magnetically shielded, for them to have sensitivities in the range of 0.01–1 $(m/s^2)/T$ is not uncommon, with Forbriger *et al.* (2010) reporting some instruments having sensitivities as high as 1.3 $(m/s^2)/T$. Therefore, seismic stations at low latitudes could potentially have vertical-component data

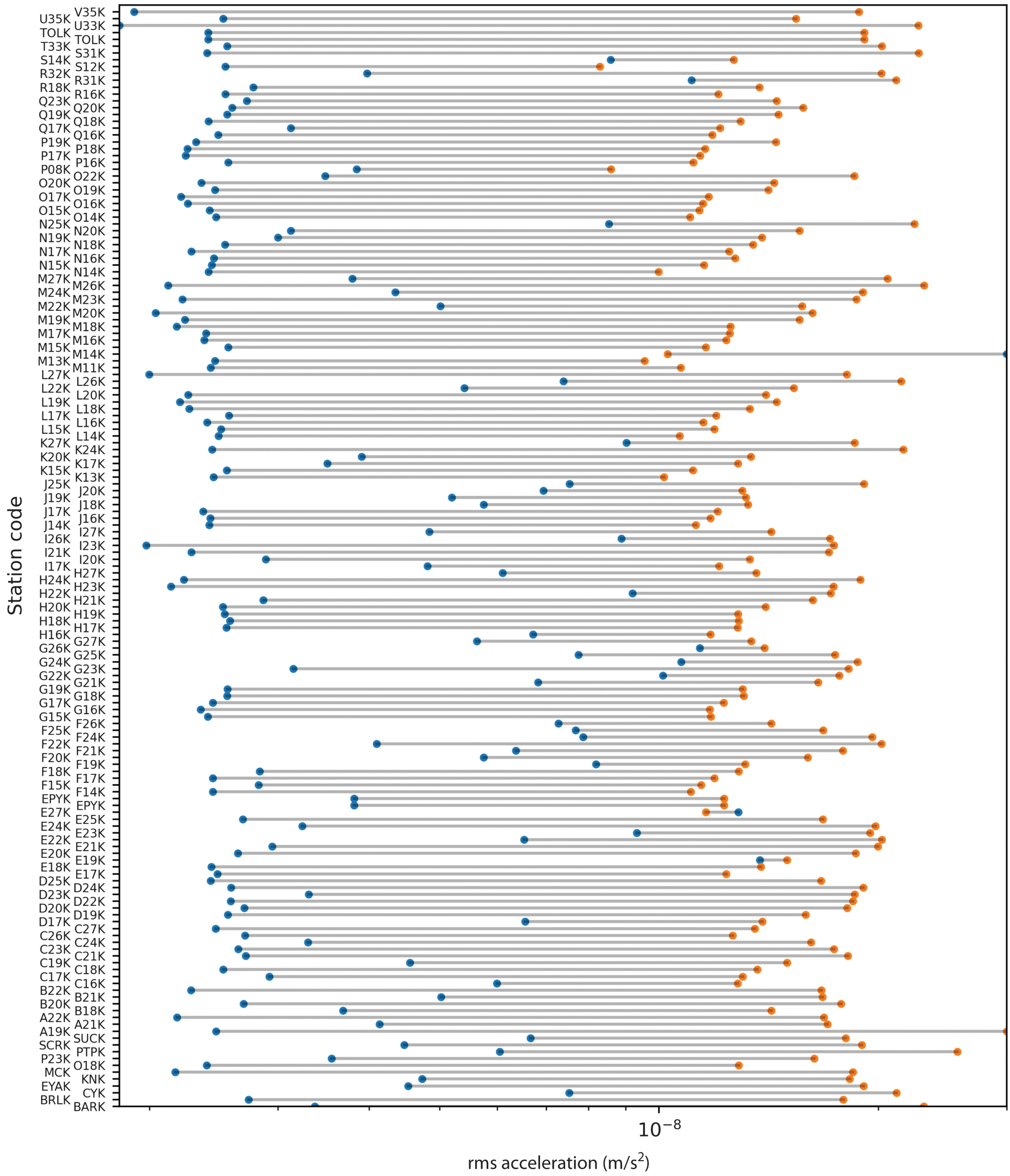


Figure 4. |Rms amplitudes in m/s^2 in the 40–400 s period band for all stations in the Alaska (network code AK) and Alaska Transportable Array (network code TA) on 29 August 2019 (blue circles), in which the mean rms magnetic field at College, Alaska, was 11 nT and on 1 September 2019 (orange circles) was 225 nT.

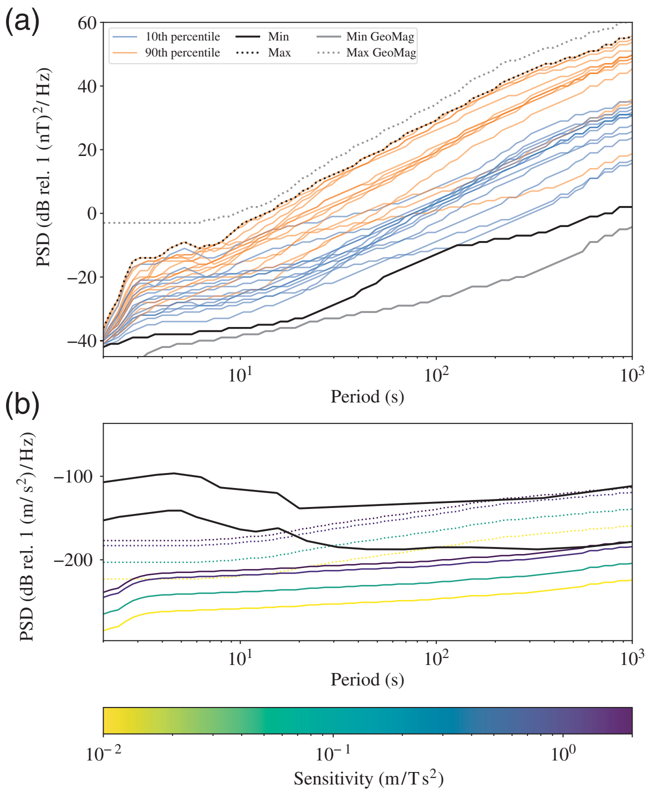


Figure 5. (a) 10th percentile (blue) and 90th percentile (orange) PSD estimates from all seismic stations (station codes: ANMO, CASY, COLA, QSPA, SBA, and SFJD) with collocated three-component magnetometers from 7 October 2016 to 7 October 2019. Each curve represents one component of the three-component magnetometer. The black curves represent the pointwise minimum (solid) and maximum (dashed) noise levels of the 10th and 90th percentiles. For reference, we include the pointwise minimum of the 10th percentile (solid gray) and the maximum of the pointwise 90th (dashed gray) from all USGS Geomagnetic Observatories. (b) Minimum (solid) and maximum (dashed) noise levels from part (a) converted by varying sensitivities as 0.01 $(m/s^2)/T$ (yellow), 0.1 $(m/s^2)/T$ (teal), 1.0 $(m/s^2)/T$ (blue), and 2 $(m/s^2)/T$ (purple). For reference, we include the Peterson (1993) NLNM and NHNM in black.

biased by magnetic field variations and could benefit from collocated magnetic field data.

CONCLUSIONS

The sensitivity of seismometers to Earth's magnetic field has been previously shown to limit long-period seismic resolution (Forbriger, 2007; Forbriger *et al.*, 2010). Although many stations designed for long-period studies (such as the GSN) use mu metal shielding to reduce the effects of Earth's magnetic field (Fig. 1), this is not a viable solution at many stations. When using collocated magnetic field data to reduce noise in seismic data due to variations in the magnetic field, we found the greatest noise reduction between 100 and 400 s periods. Although this methodology did not substantially improve noise levels on the horizontal components, we were able to decrease the noise by as much as 10 dB on the vertical component. The instruments in this study had a sensitivity in magnetic field variations ranging from 0.004 to 0.48 $(m/s^2)/T$. These sensitivities were found on a day in which the rms variation in the magnetic field was 225 nT. We found we were unable to apply magnetic field corrections, with good reductions in variance, for stations located farther than 200 km away from our magnetometer. The period dependence along with complicating factors such as the distance of the station to the magnetic field measurement and other factors such as temperature or pressure variations that may limit seismic resolution could additionally complicate the effectiveness of these corrections.

Although we do observe direct increases in noise levels across Alaska TA for days in which the Earth's magnetic field was active (Fig. 3), we are unable to correct out this signal due to limited magnetic data across Alaska. This suggests that the spatial variability of the magnetic field necessitates more densely deployed magnetometers if we hope to remove the noise introduced by magnetic field changes. We demonstrate that adding low-cost magnetometers to high-latitude seismic stations could allow for both improvements in vertical-component seismic data quality as well as contribute to improving space weather observations by densification. Although these units appear to be promising for densification, it will be necessary to completely characterize the long-term performance of these units. These units should be viewed as supplemental to observatory grade INTERMAGNET sites because they are not calibrated routinely and could have limited dynamic range at periods greater than 1000 s.

DATA AND RESOURCES

All seismic data and magnetometer data at Global Seismographic Network (GSN) stations are freely available at the Incorporated Research Institutions for Seismology (IRIS) Data Management Center (DMC) under network codes AK (Alaska Earthquake Center, University of Alaska Fairbanks, 1987), IU (Albuquerque Seismological Laboratory (ASL)/U.S. Geological Survey [USGS], 1988), and TA (IRIS Transportable Array, 2003). The facilities of the IRIS data services, and specifically the IRIS DMC, were used for access to waveforms, related metadata, and/or derived products used in this study. IRIS data services are funded through the Seismological Facilities for the Advancement of Geoscience and EarthScope (SAGE) Proposal of the National Science Foundation under Cooperative Agreement EAR-1261681. All data from the USGS Geomagnetism Program are available from the Geomagnetism website https://www.usgs.gov/natural-hazards/geomagnetism. All codes used in this analysis are freely available on GitHub: https://github.com/aringler-usgs/magnetic_field. All websites were last accessed in December 2019. The supplemental material to this article contains additional estimates of the sensitivity of various TA stations to variations in the magnetic field.

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