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Precision of Geomagnetic Field Measurements in a Tectonically Active Region

M. J. S. JOHNSTON,* R. J. MUELLER,* R. H. WARE,** and P. M. DAVIS***

**U.S. Geological Survey, Menlo Park, CA 94024, U.S.A.*
***CIRES, University of Colorado, Boulder, CO 80309, U.S.A.*
****Department of Earth and Space Sciences, University of California, Los Angeles, CA 90024, U.S.A.*

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A linear regression on standard deviations of differential proton magnetometer measurements at distances from a few meters to 50 kilometers indicates a standard deviation of hourly means that varies with site separation as $\sigma = a + bd$ where $a = 0.07 \pm 0.08$ nT, $b = 0.01 \pm 0.003$ nT/km and d is the site separation in kilometers. At a few meters separation, for sites with low cultural noise in both seismically inactive and active regions, the standard deviation of hourly mean data has a mean of 0.12 ± 0.03 nT for instruments with 0.25 nT sensitivity and 0.07 ± 0.01 nT for instruments with 0.125 nT sensitivity. The least-count noise contributions are expected to be less than 0.06 nT and 0.03 nT, while undetermined instrument noise appears to contribute 0.10 and 0.06 nT respectively. Instrument temperature sensitivity does not exceed 0.001 nT/°C over a range from −6°C to 21°C. For typical site separations of 10 to 15 km throughout the San Andreas fault, estimates of σ for hourly mean data range from 0.15 to 0.3 nT depending on local magnetization characteristics. Spectral density estimates indicate difference field noise power decreases with increasing frequency at about 3 db/octave. Dominant spectral peaks occur at diurnal harmonics and at the tidal M_2 frequency. Geomagnetic difference-field noise limits measurement capability at all frequencies below about 2 c.p.h. Where instrument precision starts to limit detection capability, instruments of higher sensitivity may be useful.

1. Introduction

Local magnetic field perturbations are expected to accompany changes in tectonic activity and, in particular, to result from the stress drops occurring with moderate to large magnitude earthquakes. This general field of study is termed tectono-magnetism (NAGATA, 1970) while the subset of co-seismic or earthquake related phenomena are known as seismomagnetic effects (STACEY, 1964). Although serious attempts to detect these events are being made in most countries where earthquake hazards are a problem, the most extensive efforts are concentrated on the San Andreas fault system in California (JOHNSTON *et al.*, 1976). Since 1973, the U.S. Geological Survey has been monitoring local magnetic fields at several hundred locations near active faults in this system.

This report concerns the determination of both the instrument precision (or instrument noise) and the precision of measurement of local magnetic fields with pairs of these instruments as the instrument separation is increased. To make these determinations, we first investigated instrument precision and temperature sensitivity using data recorded on pairs of closely spaced instruments in both seismically quiet (Colorado) and seismically active (California) regions. During these experiments the ambient temperature varied by several tens of degrees Celsius. Similar measurements at increased instrument separation were then used to determine spatial coherence and measurement precision for typical monitoring operation of the U.S.G.S. network of instruments.

2. Instrumentation

The instruments used in this study are total-field proton precession magnetometers operated at 0.25 and 0.125 nT sensitivity. They are commercially available (Geometrics model G-826 or G-816) except for the addition of a more accurate temperature-compensated reference oscillator. The U.S. Geological Survey permanent magnetometer network consists of 27 of these instruments in a general linear array along the San Andreas fault from just south of San Francisco to the Salton Sea (MUELLER et al., 1981). All instruments sample synchronously every 10 minutes and the data are transmitted digitally to a mini-computer in Menlo Park for routine analysis and display.

In order to conduct the experiments on instrument precision, a portable version of the standard or permanent magnetometer installation was used, the only difference being that the data were recorded on-site with digital printers. All magnetometers were operated in regions of low local magnetic gradient, typically less than 5 nT/m, in order that small sensor displacements would not result in apparent local field offsets.

In all cases, the sensor was mounted in a cylindrical cavity in the top of a wooden post at a height of 1.8 m above ground. The post was set in concrete to a depth of about 1 m. The accuracy of relocation of the sensor was less than ± 5 mm.

The inherent precision or noise of proton magnetometers is set by the combination of the least-count or digitization noise, σ_D, and sources of noise, σ_A, which are dependent on the proton signal-to-noise ratio (MUDIE, 1963). Currently available low noise circuits and techniques for maximizing the proton signal allow noise which is dependent on the proton signal-to-noise ratio to be less than 0.1 nT. The standard deviation due to least count noise, σ_D, has been shown by ZURN (1974) to be given by:

$$\sigma_D = \frac{q}{\sqrt{12}} \qquad (1)$$

where q is the least count or quantization interval.

The instrument precision, σ_I, in a constant field is given by:

$$\sigma_I^2 = \sigma_D^2 + \sigma_A^2. \qquad (2)$$

Measurement precision for synchronized differential magnetometer measurements is determined by the net effect of instrument precision, σ_I, external field noise, σ_E, which increases with instrument separation, and digitization noise, σ_d, arising from digitizing and differencing two almost synchronized field measurements. The maximum value of σ_d is $q/2$.

The measurement precision, σ_T, of differenced data from two synchronized, but separated, magnetometers is therefore given by:

$$\sigma_T^2 = \sigma_E^2 + 2\sigma_I^2 + \sigma_d^2. \qquad (3)$$

For close spaced measurements, almost complete coherence would be expected between data recorded on each instrument. The measurement precision, σ_T, of differences between instruments would then be given by:

$$\sigma_T^2 = 2\sigma_D^2 + 2\sigma_A^2 + \sigma_d^2 \text{ as } \sigma_E \to 0. \qquad (4)$$

If the magnetometers were perfect and the field was constant, then both σ_A and σ_D would approach 0 and

$$\sigma_T^2 \approx \sigma_d^2. \qquad (5)$$

For $q = 0.25$ nT

$$(\sigma_T)_{max} \approx 0.12 \text{ nT}. \qquad (6)$$

For $q = 0.125$ nT

$$(\sigma_T)_{max} \approx 0.06 \text{ nT}. \qquad (7)$$

So, for the close-spaced tests the observed total standard deviations, σ_T, reflects the instrument precision and the degree to which these exceed the values in (6) and (7) is a measure of instrument noise σ_A. On the other hand, estimates of σ_T as the instrument separation is increased, reflect the measurement precision of the magnetometer system.

Measurement and instrument precision tests were conducted at a seismically active and a seismically quiet region shown in Fig. 1. The active region is about 100 km south of San Francisco, California, and the quiet region is about 40 km northwest of Denver, Colorado.

2.1 *Instrument precision tests*

At each of the two test areas, the magnetometers were operated from 10 to 50 m apart at sensitivities of 0.25 nT and 0.125 nT respectively. The magnetometers and

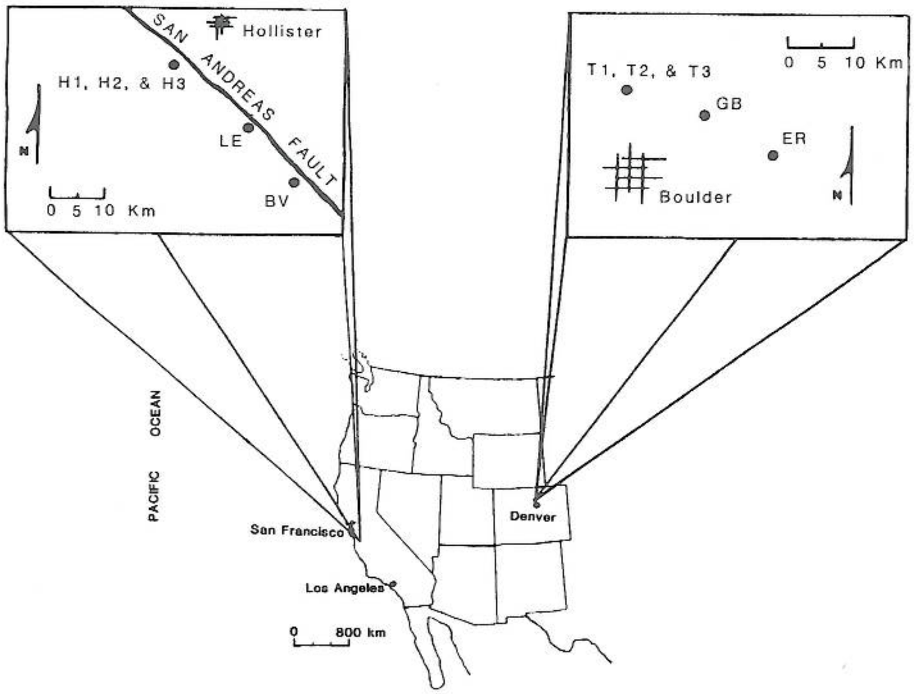

Fig. 1. Test site locations in California and Colorado.

recording systems were operated without thermal protection on the ground surface. The temperature range for the 0.25 nT test in Colorado was from −8 to 21°C with an average diurnal change of 13°C. The range for the 0.125 nT test was from −6 to 21°C with an average diurnal change of 15°C. Each test was conducted over a 4.2 day period. During this period digital records of synchronized data were obtained at 1 minute intervals. The data were later decimated to allow comparison with data from telemetered instruments in these areas.

Figure 2a shows six comparative plots of 10 minute differenced data from magnetometers operated at a 0.25 nT sensitivity. The upper three plots with labels containing the letter "T" are from the Colorado test site. Those with the letter "H" are from the California test site. Estimates of standard deviation range from 0.20 to 0.30 nT and have an average value of 0.25 nT. Substitution of this value and Eq. (6) in Eq. (4) indicates the existence of instrument noise σ_A of about 0.13 nT. Missing data result from malfunctions of the digital data recorder.

The most obvious feature of these plots, other than the rough equality of the standard deviations, is the indication of least-count noise together with some high-frequency fluctuations which were found to be normally distributed about the mean. To reduce these high-frequency fluctuations, a 6-point or hourly average was calculated. Figure 2b shows plots of these data. Estimates of standard deviation σ_T

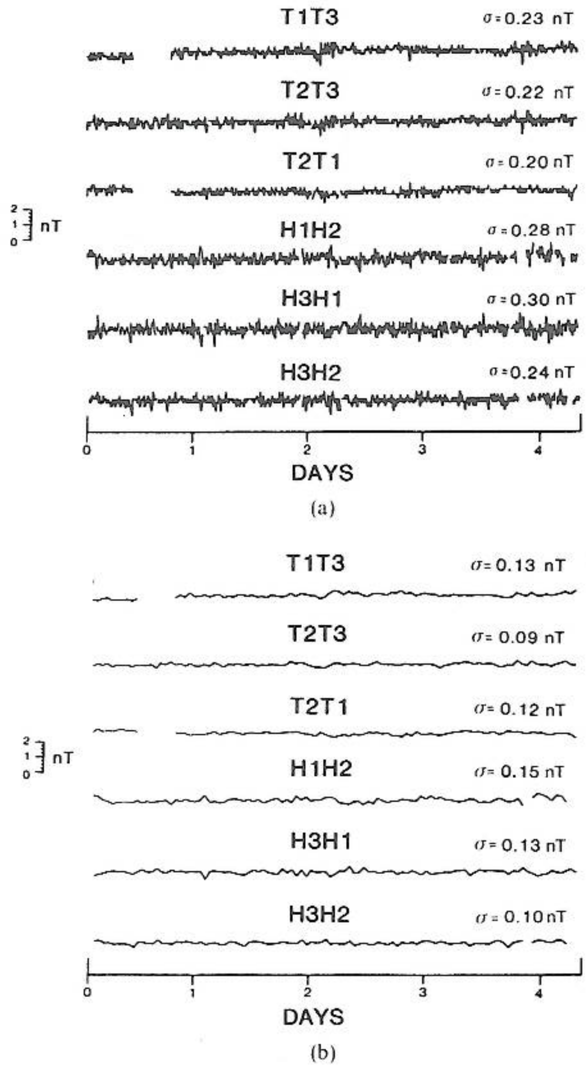

Fig. 2a. Comparison between field differences for close-spaced stations with 0.25 nT sensitivity in Colorado (upper three) and California (lower three) at a 10-minute sample rate. The standard deviation σ is shown with each set.

Fig. 2b. Hour averages and corresponding standard deviations of the data shown in Fig. 2a.

range from 0.09 to 0.15 nT and have an average value of 0.12 nT. Using Eq. (4) this indicates instrument noise σ_A (hr) of 0.04 nT.

The second test was conducted at both sites using two magnetometers operated with a 0.125 nT sensitivity. The sampling interval, duration of operation, and recording equipment are identical to those previously described. The two differences derived from 10 minute data at each location have standard deviations of 0.16 and 0.17 nT respectively and are shown in Fig. 3a. Substitution of this value and Eq. (7) in Eq. (4) again indicates the existence of instrument noise σ_A of about 0.11 nT. Hour averages of these data with standard deviations of 0.07 and 0.08 nT respectively are shown in Fig. 3b. If 1 minute samples of these same data are used to create 60 point hour averages, the standard deviations are 0.033 and 0.038 nT respectively.

2.2 *Instrument temperature sensitivity*

Each magnetometer was tested in the laboratory over a temperature range from $-10°C$ to $40°C$ with a constant frequency input signal. No variation with temperature was observed within the least count noise. Of more importance for precise geomagnetic field measurements is a temperature test of the complete field system. Since the temperature during the testing period ranged from -6 to $21°C$ with at least a $13°C$ diurnal variation, these data can be used to place an upper limit on the temperature sensitivity of magnetometers operated in a differential mode. The mean standard deviation of hour averages of the 1 minute difference data is 0.036 nT. Since neither trends nor diurnal fluctuations are observed in these data, the temperature sensitivity of these differential operated magnetometers must not exceed 0.001 nT/°C.

2.3 *Effect of station separation on measurement precision*

The recording magnetometer systems were operated at station separations from 10 m to 50 km at both test sites in order to determine the effects of station separation on differenced total field data. Plots of 6 point averages of difference field data at various station separations from the two test sites are shown in Fig. 4. The station

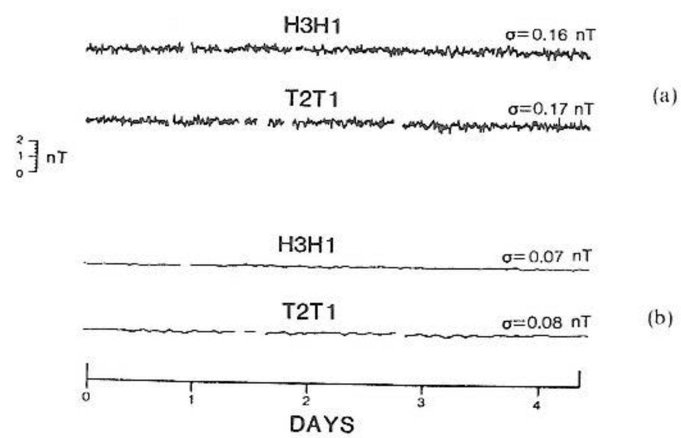

Fig. 3a. Comparison between field differences for close-spaced stations operating at 0.125 nT sensitivity in California (upper) and colorado (lower) at a 10-minute sample rate. The standard deviation σ is shown with each set.

Fig. 3b. Hour averages and corresponding standard deviations of the data shown in Fig. 3a.

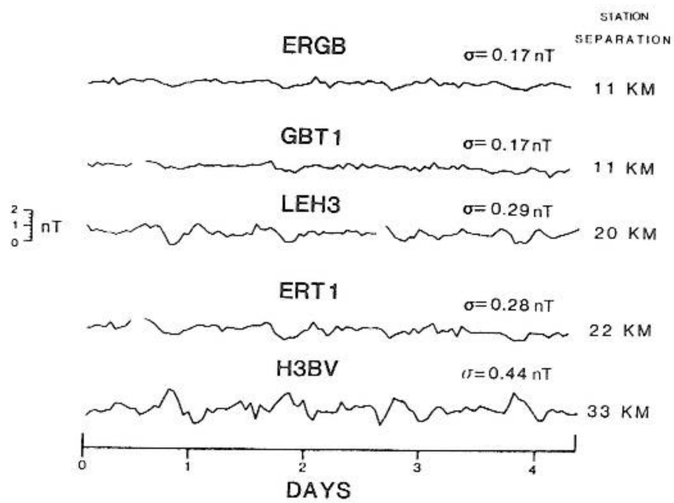

Fig. 4. Hour averages of field differences with increasing station separation with their corresponding standard deviations. The first, second and fourth traces were recorded in Colorado and the third and fifth trace in California.

separation in kilometers and the estimates of standard deviation are shown on each plot. Higher levels of noise resulting from less complete cancellation of magnetic field fluctuations, with increasing station separation, become increasingly evident in these data. As the station separation increases, the amplitude of these fluctuations largely determine the increased standard deviation with increased station separation.

Figure 5 is a plot of the standard deviation (in nanoteslas) versus station separation in kilometers for differenced data from the test sites and other stations in California. Each point on the plot represents a minimum of four days (96 samples) of hourly averaged data. A linear regression of these data indicate:

$$\sigma_{<50\text{km}} = 0.07\ (\pm 0.08) + 0.01\ (\pm 0.003)\ d$$

where $\sigma_{<50\text{km}}$ equals the standard deviation in nanoteslas of differenced data with station separation less than 50 km and d equals the separation distance in kilometers. Also plotted on Figure 5 is the estimate of instrument precision for the 0.25 nT sensitivity instruments.

While the general form of the increase in standard deviation with station separation is quite well determined, the various points scatter about the least squares line by up to 0.1 nT. This results from the variation in magnetic induction, electrical induction, and magnetization directions at the various sites. Various filtering techniques have been developed which attempt to define and correct for these differences in local site response. Using predictive filtering techniques, Davis and Johnston (1983) have shown that a reduction in standard deviation of up to a factor

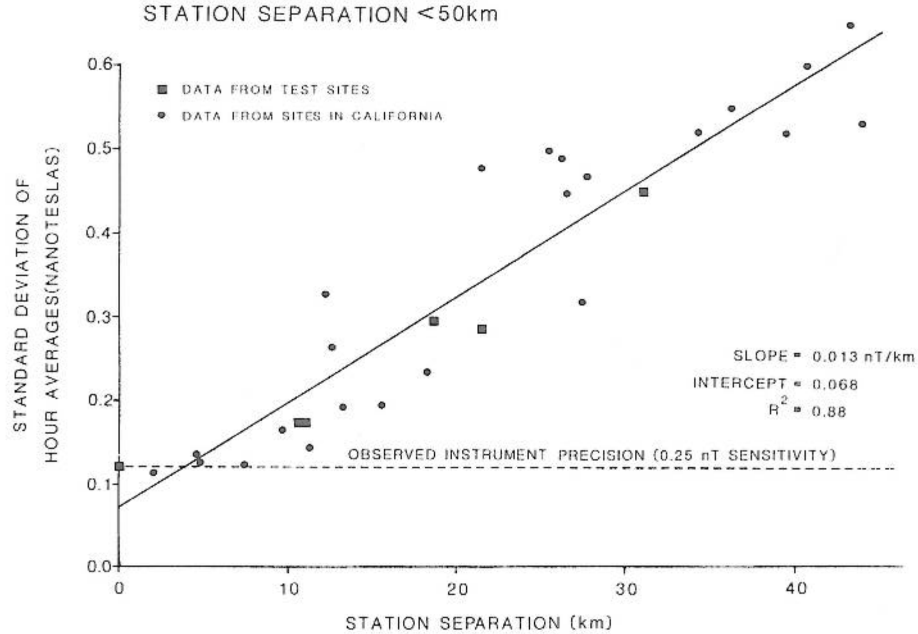

Fig. 5. Summary plot showing the increase in standard deviation of hour averages of all field differences with increasing station separations up to 50 km. The observed instrument precision limit is shown which correspond to a sensitivity of 0.25 nT.

of five can be obtained at noisy sites. However, little improvement is obtained at quiet sites (where cancellation of mangetic storms is quite complete).

Data from the array of magnetometer stations in California (Fig. 6) can also be used to determine effects of station separation, particularly at greater separations where effects of distant sources such as those occurring in the earth's core and magnetosphere are easily detectable. Figure 7 is a plot of standard deviation versus station separation in kilometers for data from this array. Each point on the plot represents a minimum of 4 days (96 samples) of hourly averaged differenced data. A linear regression of these data indicate:

$$\sigma_{>50\text{km}} = 0.57\ (\pm 0.2) + 0.007\ (\pm 0.002)\, d$$

where $\sigma_{>50\text{km}}$ is the standard deviation in nanoteslas of hourly averaged differenced data with station separation greater than 50 km and d equals the separation distance in kilometers.

Station separation clearly affects the quality of differenced magnetic field data. These data indicate a general increase in the standard deviation of differences with increased station separation as shown for separation distances < 50 km and distances > 50 km, but the slope of linear fits to these data is less for the larger station

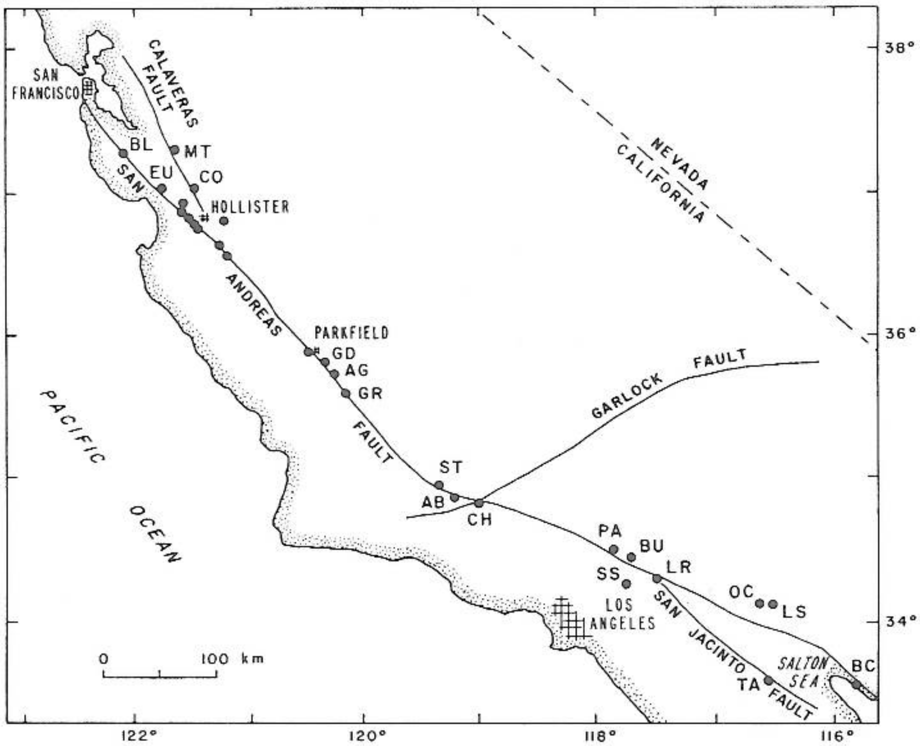

Fig. 6. Location of telemetered proton magnetometers along the San Andreas fault in California.

separations. This could reflect differences in ionospheric sources and geology for the various sets of stations. The data plotted in Fig. 5 for separation distances <50 km also shows that, for magnetometers operated at a 0.25 nT sensitivity, the instrument precision level is approached or equaled in the differenced data for separation distances up to about 9 km. This indicates that, at this sensitivity, station separations of 9 or 10 km are the best compromise of spatial coverage and instrument capability. We note that source dimensions for earthquakes in California with $M_L = 6$ vary from 5 km to 40 km (THATCHER and HANKS, 1973). It is also clear that to obtain higher resolution in these data sets requires closer station spacing and higher sensitivity instruments but many more instruments would be required to define sources with scales of several tens of kilometers.

3. Difference Field Noise Spectrum

A question that still remains concerns how well the instruments can resolve local signals of different durations. At one end of the spectrum are co-seismic events, or seismomagnetic effects. At the other end are long-term changes that might relate to

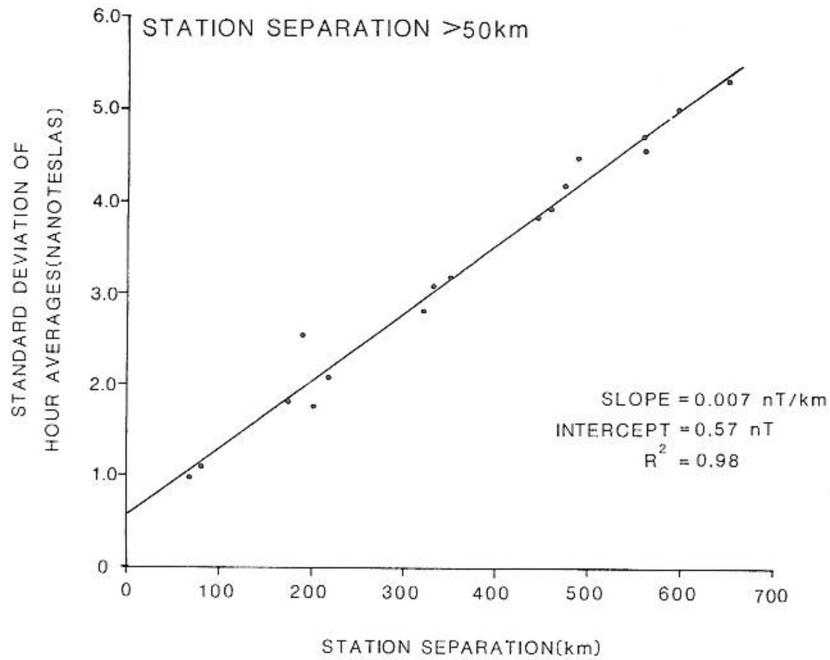

Fig. 7. Summary plot showing the increase in standard deviation of difference-field hour-averages with station separations between 50 km and 700 km.

long-term crustal deformation (JOHNSTON, 1978). The geomagnetic field noise spectrum and the instrument precision determine this capability.

Power spectra have been obtained from eight site pairs with similar site separations between 8 and 15 km. Six months of hour averages of these difference data were used to obtain these spectra. The 95% confidence limits are 7.2 db and −4 db respectively. Figure 8 shows the average of these eight spectra and the observed measurement precision limits for instruments with 0.25 nT sensitivity and a 10 km station separation (Fig. 5).

It is clear from these spectra that the dominant noise peaks result from the diurnal variation, its harmonics, and tides. These peaks limit the resolution at these periods. The tidal peak apparently results from ocean induction rather than earth tides (JOHNSTON *et al.*, 1983). Both the tidal and diurnal-related peaks can easily be removed by filtering these signals from the raw difference records or by using predictive filtering techniques (DAVIS *et al.*, 1981) before obtaining the power spectra. The resulting spectra, without these peaks, are fairly flat and, in the period range from 2 hours to 100 days, decrease at about 3 db/octave.

If decreasing noise power with increasing frequency continues for another octave of frequency, the measurement precision of these instruments would limit spectral estimates. This would occur at frequencies of about 30 c.p.d. (50 minutes) and higher. Short-period transient signals such as might occur minutes before a large

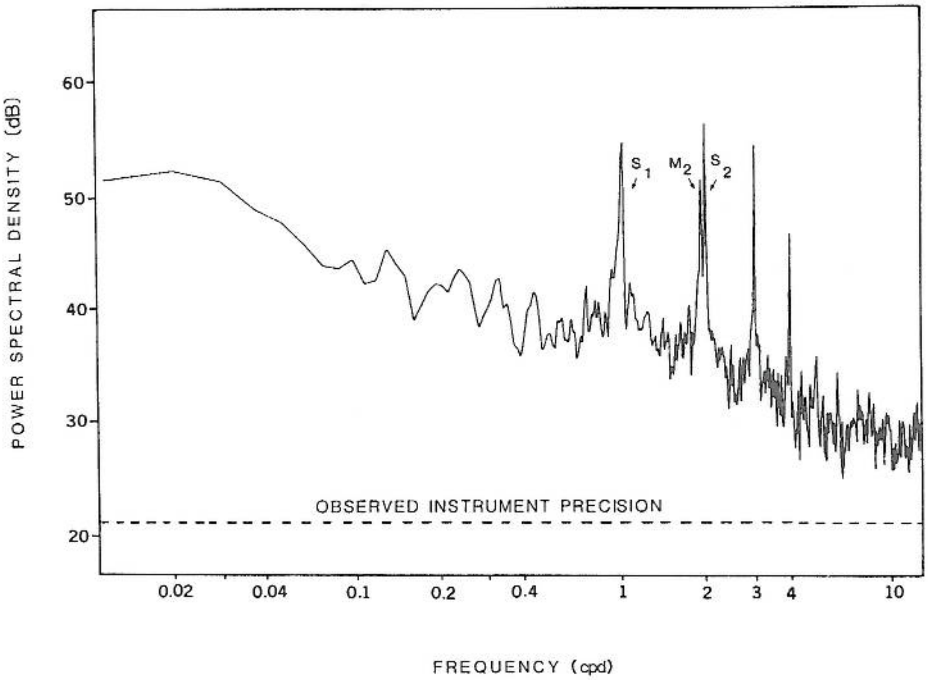

Fig. 8. Average of eight geomagnetic difference-field noise spectra in dB where station separation is from 10 to 15 km. Solar spectral peaks, S_1 through S_6, and the lunar tidal peak, M_2, are the dominant periodic signals in these data. The observed instrument precision limit obtained with the test data sets for 0.25 nT instruments is shown also.

seismic event which just exceed the background level of geomagnetic noise might therefore not be detected by the present array. Any co-seismic or seismomagnetic offset would, however, not be hidden in this way.

An improvement in sensitivity of these instruments (to 0.01 nT or better) might be productive if small signals of crustal origin occur at high frequencies (i.e., greater than about 30 c.p.d.). A more compelling reason for increasing instrument sensitivity would arise if noise reduction techniques are successful in reducing noise power across the entire spectrum.

4. Conclusions

The instrument and array measurement precision of the U.S.G.S. network of magnetometers along the San Andreas fault has been determined for instruments operated at 0.25 nT sensitivity. The instrument precision determined from 6-point hour averages ranges from 0.09 to 0.15 with a mean of 0.12 ± 0.03 nT. Least count noise accounts for about 0.06 nT of this. The rest (0.10 nT) apparently results from noise within the instrument. For instruments operated at 0.125 nT sensitivity, the standard deviation determined from 6-point hour averages is 0.07 ± 0.01 nT. In this case, about 0.02 nT results from least count noise and 0.06 nT is again due to noise within the instrument.

Noise generated by thermal sensitivity of the instruments operated in a differential mode is generally insignificant. We have determined an upper limit on the temperature sensitivity of the instruments of 0.001 nT/°C. The instrument electronics for routine array measurements typically operate in vaults at a depth of about 2 m where annual temperature variations are not more than 15°C and daily temperature variations are less than 1°C. Pre-amplifier malfunctions and other causes which result in marginal signal-to-noise ratio can generate apparent temperature sensitivity. Routine on-site thermal cycling of the magnetometer electronics with portable heaters allows easy detection of an acquired thermal sensitivity once it is suspected. Thermal stability of the crystal reference oscillator is better than ±0.1 ppm over the range 4°C to 25°C.

When the simple difference technique is used to reduce effects of external disturbances from the ionosphere and magnetosphere, measurement precision of the array generally decreases with increasing instrument separation due to incomplete canceling of these disturbances. For separation distances less than 50 km, typical of most of the array, the standard deviation, σ, of hour averages of field differences is given by

$$\sigma_{<50\text{km}} = 0.07\ (\pm 0.08) + 0.01\ (\pm 0.003)\ d$$

where d is the separation distance in kilometers and $\sigma_{<50\text{km}}$ is in nanoteslas. At a 10 km to 15 km separation common to most site pairs, the measurement precision approaches 0.2 nT. For smaller site separations, instruments of higher sensitivity could potentially detect signals below this level. The operation of instruments at a 0.01 nT sensitivity appears warranted if site separations of only a few kilometers are used with a total array scale of many tens of kilometers. This could well be the case for aftershock monitoring following a moderate to large earthquake. At a separation distance of 10 km, the present precision of 0.25 nT appears about optimum for both signal detection and spatial coverage except at frequencies greater than 1 c.p.h.

At separation distances greater than 50 km where external and core fields are poorly canceled, the standard deviation of hour averages is given by

$$\sigma_{>50\text{km}} = 0.57\ (\pm 0.2) + 0.007\ (\pm 0.002)\, d$$

where d is in kilometers and $\sigma_{>50\text{km}}$ is in nanoteslas.

The geomagnetic noise spectra for field differences from a 10–15 km station separation decreases with increasing frequency at about 3 db/octave over the frequency range of 0.01 c.p.d. (100 days) to 12 c.p.d. (2 hours). If power continues to decrease at frequencies above 1 c.p.h., the present instruments will not adequately monitor this end of the spectrum. From about 1 c.p.h. to D.C., however, these instruments appear to be capable of detecting magnetic fields of local origin whose amplitudes exceed the background noise.

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