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Temporal versus spatial geomagnetic variations along the west coast of Greenland

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Abstract

Information about the intensity and spatio-temporal characteristics of geomagnetic activity is of interest to aeromagnetic surveyors because a successful magnetostatic anomaly survey relies on the ability to distinguish between spatial and temporal magnetic variations. The latter are usually recorded at a fixed reference magnetometer station. We examined about six months of data collected with the Greenland west coast magnetometer chain at 1-s sampling rate and investigate to which extent temporal geomagnetic variations in selected frequency bands (1, 10 and 100 mHz) are correlated between neighboring sites (which are spaced by 190 km on the average). It appears that the differences between geomagnetic total field variations recorded at neighboring stations are significantly smaller than the magnitudes of the variations themselves. We further set a threshold of 20 nT for very quiet conditions and find that in general broadband total field variations exceed this threshold almost twice as often as the differences between geomagnetic variations at neighboring sites.

Keywords: Geomagnetic field; Greenland magnetometer chain; Aeromagnetic survey; Spatio-temporal magnetic variations

1. Introduction

Quantitative information about the intensity and spatio-temporal characteristics of geomagnetic activity is of interest to aeromagnetic survey teams who depend on measurements from a remote reference magnetometer in order to assess the usefulness of the survey data. For the surveyors, it is essential to know whether their measurements – which have the objective of mapping the spatial distribution of magnetostatic anomalies – are collected during geomagnetically quiet periods or, if taken during more disturbed times, can be corrected for the effect of temporal geomagnetic variations. During the survey such variations are recorded at a fixed base station (the remote reference station). Geomagnetic variations of large spatial scale – for instance the magnetic field of the auroral electrojets (e.g., Friis-Christensen et al., 1985) – leave rather similar records on the moving airborne and the remote reference magnetometers. This allows, in principle, for correcting the survey data by separating temporal from spatial variations. Geomagnetic variations of small spatial scale – such as field line resonances (e.g., Samson, 1972; Pilipenko, 1990) and traveling convection vortices (Friis-Christensen et al., 1988) – do not easily allow for survey data correction from remote reference stations (unless they are in close vicinity) and can thus render the magnetic anomaly survey useless.

We therefore investigate the possibility of categorizing magnetic field variations with respect to the expected level of spatial variability. One possible approach builds on the assumption that spatial and temporal scales are systematically related. In this case one can use statistical methods to establish a quantitative relation between the temporal and spatial frequency content of geomagnetic variations. For given geomagnetic variations the temporal frequency distribution can then be used as a proxy for the most probable spatial wavelength distribution which eventually permits

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an assessment of the accuracy and reliability of correcting survey results with remote reference measurements.

Our study is a first step toward this goal. We focus on a specific area, the Greenlandic west coast, where the Danish Meteorological Institute (DMI) operates a dense chain of magnetometers (for a description see http://www.dmi.dk/projects/chain/greenland.html) and where the Geological Survey of Denmark and Greenland (GEUS) has an ongoing collaboration with the Greenland Home Rule Authorities on magnetostatic anomaly mapping (Rasmussen and van Gool, 2000). From the analysis of more than six months of high resolution magnetometer data we determine the mean intensity and spatial variability of geomagnetic variations in selected frequency bands.

2. Magnetostatic anomaly survey parameters

An aeromagnetic survey of the kind conducted along the west coast of Greenland is usually performed with small specially equipped aircraft which proceed at a speed of 30–70 m/s at an altitude of 60–300 m above the ground. They fly a sequence of parallel lines, frequently north–south oriented, at 100–500 m line separation, and connect them by cross lines at larger spacing. Under normal conditions a total length of 1000–1500 km is mapped during one shift. During a typical survey period (which lasts a few months) a total flight length of the order of 100,000 km is surveyed. Until now only total magnetic field variations were recorded (at 10-Hz sampling rate) and stamped with a reference signal from a GPS receiver.

Since 1992 a number of aeromagnetic surveys (short name “Aeromag”) have been conducted by various specialized companies on behalf of GEUS in a 200–300 km wide strip along the southwestern coast of Greenland, see Fig. 1. Several electromagnetic surveys (abbreviated AEM) have also been performed, but they are not of concern to this paper because here we deal only with airborne magnetic surveys. We have analysed reports from surveys performed between 1998 and 2001, kindly made available to us by GEUS (T.M. Rasmussen, private communication). They comprise a total of 331 field days (including aircraft maintenance and pilot rest time). The reports revealed that the most frequent deviation from schedule (flight shortening or even cancellation) is caused by adverse terrestrial weather. This situation occurred on 43% of all survey days. The next frequent cause for deviations from the original operations plan is excessive geomagnetic activity, i.e., adverse space weather (which occurred on 8% of all days). Technical problems and equipment malfunctioning take the third place (4% occurence rate).

Geomagnetic activity is usually considered too high if the temporal variations recorded at the reference station exceed 10 nT during a 1-min time segment. However, this is only a rule-of-thumb, the survey manager has a certain liberty in judging whether the level of geomagnetic activity is acceptable or not.

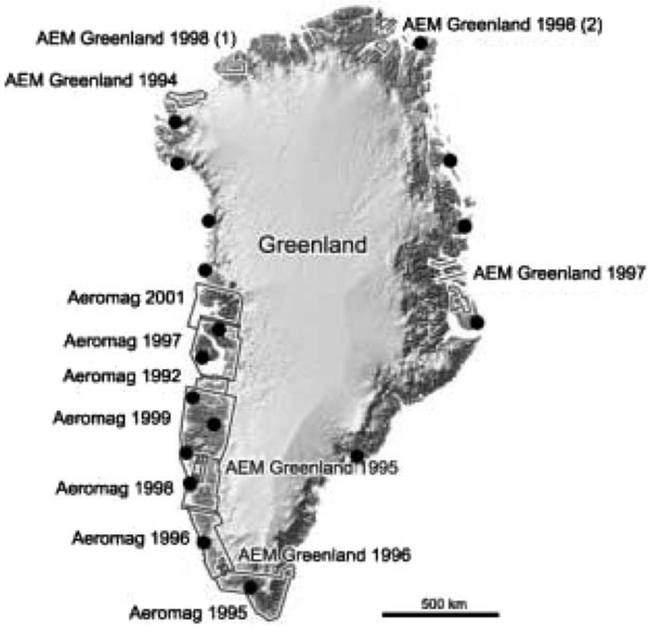

Fig. 1. Map og Greenland where the areas of recent aeromagnetic surveys (Aeromag) and electromagnetic surveys (AEM) are indicated. Aeromagnetic surveys along the coast are expected to continue in the coming years. DMIs magnetometer stations (•) are densely spaced along the west coast and wider apart on the east coast (figure courtesy of GEUS, adapted from http://www.geus.dk/).

In order to quantify more objectively the acceptable level of geomagnetic variations we investigate how to make use of measurements from DMIs Greenland magnetometer chain and develop guidelines for assessing the conditions under which remote reference magnetometer measurements can be used to improve the accuracy of aeromagnetic survey data.

3. Data analysis: Method

Since 2003 DMIs Greenland coastal magnetometers are running at 1-s sampling rate. The level of broadband noise amounts to about 0.1 nT for most instruments and up to 0.2 nT for some older sensors. In this study we consider solely the west coast magnetometers because they are – at an average distance of 190 km – more densely spaced than the east coast stations and also because they are nearly aligned along the same geomagnetic meridian. In order to ensure that data from different magnetometers were taken under the same geomagnetic conditions and are thus compatible we use only those days in 2003 during which all west coast stations were running and collecting usable data without interruption except for gaps of less than 10-s duration. This reduces the number of usable days to 167.

The data were corrected for spikes and jumps, and individual missing data points and short gaps (less than 10 s) were filled through interpolation. All vector time series were filtered with several bandpass filters (1, 10 and 100 mHz center frequencies, respectively). The bandpass filtered time series are centered (i.e., have zero mean) by definition. The three sets of bandpass filtered time series were then divided into 20-min segments. Significantly shorter time segments would result in data which are, at least in the 1-mHz band, no longer independent from those in adjacent intervals. Our bandpass selection assures that Sq variations do not enter the analysis because at subauroral, auroral and polar cap latitudes usually only the 24-, 12-, 8-, 6-h and possibly the 4.8-h spectral components are detectable in the geomagnetic background activity (Junge-Tiersch, 1986).

Aeromagnetic surveys in Greenland have until now been conducted with total field sensors. We therefore refer in our analysis to the total magnetic field in order to remain consistent with survey conditions. Since the Greenland variometers are oriented such that the eastward magnetic field component is approximately zero the total field computation involves only the northward (H) and downward (Z) components.

Within each 20-min segment (variable i) and for each station (index k) we determined the maximum absolute total field deviation from the quiet level

$$\mathrm{Dev}_k(i) = \max\{\mathrm{abs}[\delta H_k(i)\cos(I_k) + \delta Z_k(i)\sin(I_k)]\} \tag{1}$$

and the maximum absolute difference between neighboring sites (identified by indices k and m)

$$\begin{aligned}\mathrm{Diff}_{km}(i) = \max\{&\mathrm{abs}[\delta H_m(i)\cos(I_m) + \delta Z_m(i)\sin(I_m) \\ &- \delta H_k(i)\cos(I_k) - \delta Z_k(i)\sin(I_k)]\},\end{aligned} \tag{2}$$

where I_k and I_m denote the magnetic inclinations at sites k and m, respectively.

Deviations and differences were binned into eight classes the widths of which double from one to the next higher (note that we chose bin limits for deviations and differences individually and independently). The results provide us with information about the variance and spatial correlation of geomagnetic variations at certain frequencies.

In order to contrast the magnitude of variations at auroral and polar cap latitudes against those at lower latitudes we have included data from the Danish geomagnetic observatory at the subauroral site Brorfelde (BFE). They were recorded and processed the same way as the Greenland data, and magnetic field deviations were computed in the same manner. However, we have not computed differences between the southernmost Greenland station (NAQ) and BFE since it appears that they are too far apart and their data (in the selected frequency bands) are almost entirely uncorrelated.

4. Data analysis: Results

The distributions of maximum deviations (according to Eq. (1)) obtained from the binning are represented in Fig. 2 as heavy black histogram bars. The right panel of Fig. 2 (1-mHz band) shows that the amplitudes increase slightly from auroral latitudes (NAQ) to cusp latitudes (ATU) and decrease when entering the polar cap and going up to very high latitudes (THL). While all stations equatorward of UPN show the highest occurrence frequency in the 4–8 nT bin it is ATU where the uppermost bins are more filled and the lower bins are more depleted than at any other station. The subauroral observatory BFE shows – not unexpectedly – substantially lower values than all the Greenland stations (most often we see BFE maximum amplitudes below 0.5 nT).

It should be noted that the substantial decrease towards very high latitudes can only be partially attributed to smaller magnetic field amplitudes. We have indeed seen this effect when computing the full vector magnetic field variations at the Greenland sites (results not shown here). But that is the minor cause. The larger part of the observed weakening is due to the fact that the total field at very high latitudes (inclination near 90°) is dominated by the vertical magnetic field variation which has proven to be generally smaller than the horizontal variation.

The distribution seen in the left panel (100-mHz band) is much more irregular. This is explained by excessive noise at some sites, most obvious at UMQ but also being noticed at KUV and STF. It is due in part to instrument noise, in part to non-optimal sensor location and interference with other external signals and in part to irregularities in the supplied electric power. Most of these technical problems have recently been rectified. Because of the small amplitudes prevailing at the higher frequencies (typically 10 times less than in the 1-mHz band) the noise stands out very clearly. It is reassuring to note that the sites where our variometers are colocated with our geomagnetic observatories (THL, GDH, NAQ and BFE) are among those with the lowest noise level.

The latitude dependence of the distribution in the 10-mHz band (center panel) follows largely that of the 1-mHz band but has generally smaller amplitudes (roughly one third). One notices an indication of the higher system noise at stations KUV and UMQ. The change in bin ranges from one frequency band to the next reflects the fact that the amplitudes increase roughly with the square root of the inverse frequency.

In addition to the maximum deviations we show the maximum absolute differences between total fields from neighboring stations (according to Eq. (2)) in the same panels, with the respective bin range numbers printed along the bottomside axes. The differences are displayed as thin gray histogram bars laid over the deviation results (heavy black bars). For instance, the gray bars in the SVS row of the right-hand panel indicate the distribution of differences between THL and SVS in the 1-mHz band. In the 1-mHz band the bin limits used for the differences (bottom axis) are only half of those used for the deviations (top axis) while they are 2/3 of the deviations in the 10-mHz band and identical to the deviations in the 100-mHz band. This demonstrates that geomagnetic variations at longer periods (where the overall amplitudes are larger) are to a certain degree correlated between neighboring stations, in contrast to

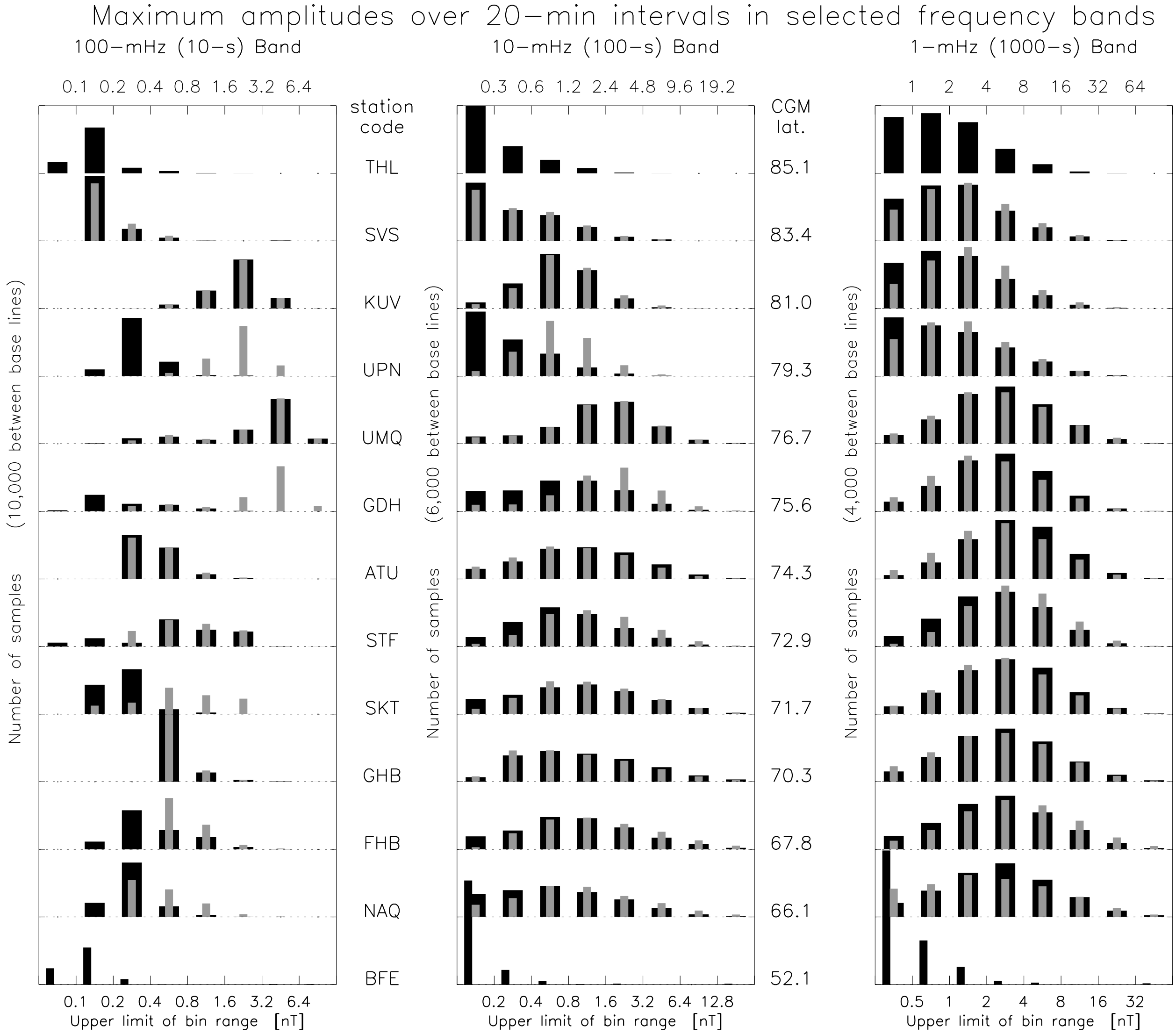

Fig. 2. Distribution of maximum absolute total magnetic field deviations (thick black bars) and maximum absolute total field differences between neighboring stations (thin gray bars) along the Greenlandic west coast, recorded within 20-min intervals and filtered according to three selected frequency bands. The scales at the top refer to the deviations and the scales at the bottom to the differences. The bin width always doubles from one bin to the next. Note that the ordinate scaling changes from one column to the next in order to use the full space while not to let bars from neighboring stations overlap.

the shorter periods where the differences are more dominated by local station noise and thus uncorrelated between neighboring stations.

The implication of the comparison between deviations at individual stations and differences between neighboring stations for aeromagnetic surveys under magnetically disturbed conditions is discussed in more detail in the following section where we consider constraints imposed by the survey specifications.

5. Implication for aeromagnetic surveys

Since the survey manager requires, among other conditions, that the total field variation within any 1-min interval does not exceed a certain threshold we pose the following two questions.

- How many 1-min intervals, relative to the number of all 1-min intervals collected, experience a total magnetic field deviation which exceeds a threshold of 20 nT for at least one data point within the respective minute?
- How many 1-min intervals, relative to the number of all 1-min intervals collected, experience a total magnetic field difference between neighboring stations which exceeds a threshold of 20 nT for at least one data pair?

To answer these questions we used the following procedure. We applied a 100-mHz (10-s) lowpass filter with subsequent subtraction of the daily mean to the time series in order to clean the time series from some of the worst instrument- and station-specific local noise prevailing at some sites. We then determined the number of occurrences of those 1-min intervals in which the 20-nT threshold was exceeded. We have chosen 20 nT rather than 10 nT for the threshold (the latter was once quoted by a surveyor) because a 10-nT threshold, when applied to Greenland data, resulted in an almost 100% rejection of the deviations and even of the differences. One must not confuse these results with those displayed in Fig. 2 because we are considering in this section broadband time series, in contrast to narrowband time series displayed in the previous section.

The results are shown in Fig. 3 where the Greenland magnetometer sites are plotted along the abscissa, positioned according to their respective corrected geomagnetic latitude. The figure shows the relative occurrence of threshold excesses of total magnetic field deviations at the individual stations (triangles at the top limit of the light gray area) and the relative occurrence of threshold excesses of total magnetic field differences between neighboring stations (diamonds between sites at the top limit of the dark gray area).

The deviations themselves do not exhibit site-specific peculiarities, they follow a smooth trend, rising from the equatorward side (NAQ) to the center and decreasing again toward the poleward side (THL). The differences show a somewhat rocky distribution. It is obvious that larger differences are more often encountered when the station spacing is larger (cf. the peaks between the sites FHB-GHB, UMQ-UPN and KUV-SVS). This observation indicates that the spatial correlation decreases with increasing distance. In order to counteract this effect we have divided the distribution of differences by the square root of the normalized site separation. The result is shown as a dashed line laid over the solid line. It is smoother and indicates a trend for the differences to decrease from auroral sites to polar cap sites. The trend possibly reflects the fact that dawn-, dusk- and nightside ionospheric electric currents are more dynamic and variable in the auroral zone (up to about 75° geomagnetic latitude) than deep in the polar cap. The dayside ionosphere, on the other hand, exhibits IMF-dependent high-latitude ionospheric currents poleward of 80° geomagnetic latitude (Friis-Christensen, 1981).

However, the general trend of decreasing numbers (both deviations and differences) towards the northernmost sites certainly (and probably mostly) reflects the fact that the total field is more dominated by the vertical component if the geomagnetic latitude is higher.

The simple but important implication of these results for areomagnetic surveys is the following. If survey data are deemed unusable because of too high magnetic activity at the remote reference station (in our case more than 20 nT deviation from the base line) then about 90% of all survey measurements would be invalid (triangles in Fig. 3). If survey data were corrected with measurements from a remote reference station in those cases when a second station at some distance recorded rather similar magnetic field variations than only about 50% of the survey data would be invalid (diamonds in Fig. 3).

A further improvement of survey results (which has not been discussed in this paper) can be gained if the chain of magnetometers were not only used to identify quiet intervals and otherwise employ a single reference magnetometer for correction of temporal variations of large spatial scale, but to construct, through interpolation, magnetic field variations approximately valid at the actual location of the survey aircraft. This approach is similar to the method

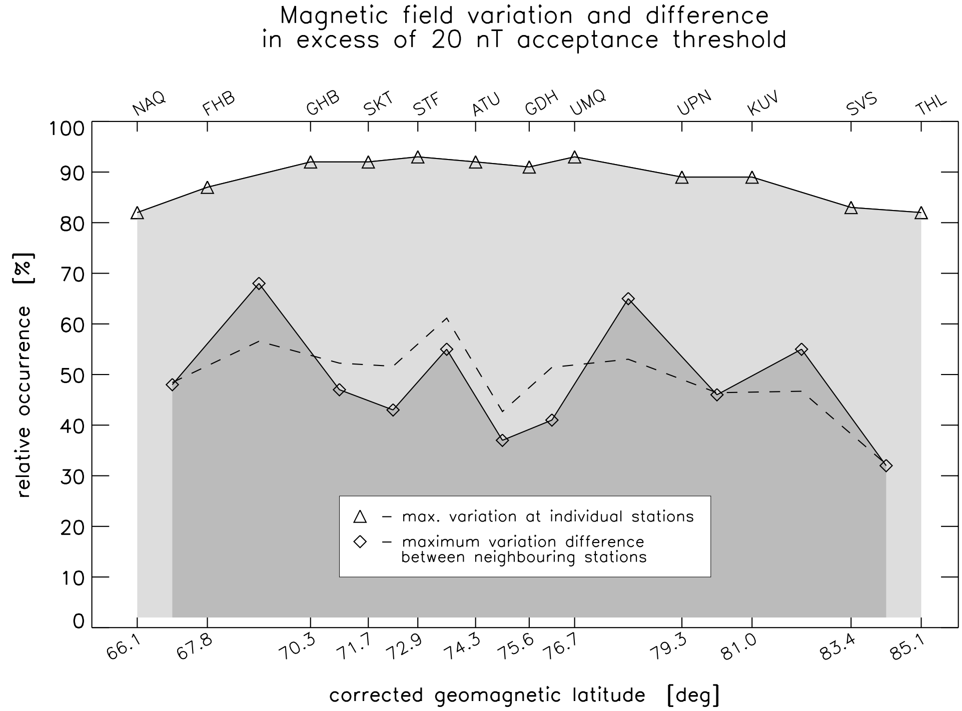

Fig. 3. Relative occurrence of 1-min intervals during which a threshold of 20 nT is exceeded by at least one data point by: (i) the magnetic field deviation at the respective station (light gray); (ii) the magnetic field difference between neighboring stations (dark gray). The dashed line is derived from the differences by scaling them with the square root of the normalized distances between neighboring stations.

of interpolated in-field-referencing (IIRF) which has been employed by the offshore drilling industry in various parts of the world, and notably in the North Sea (Clark and Clarke, 2003).

The correlation is actually even better than the percentage points seem to tell. This can be seen from the following argument (although it is only an approximate assessment). Let us assume that the total magnetic field deviations, Dev_k, are Gaussian distributed with zero mean and the same standard deviation σ_k at all stations. It will happen on the average once every 60 samples (i.e., once every 1-min interval) that a datum exceeds the 2.4-σ limit. The two-dimensional Gaussian distribution consisting of differences between deviations at neighboring sites, Diff_{km}, has a standard deviation $\sigma_{km} = \sqrt{(\sigma_k^2 + \sigma_m^2)}$ if the time series at neighboring sites are stochastically independent. That means that on the average one out of 60 samples exceeds $2.4\sigma_{km} = 2.4 \cdot \sqrt{2}\sigma_k = 3.4\sigma_k$. Consequently, the expected maximum differences between neighboring stations recorded at each station should be about $\sqrt{2}$ times or 40% larger than the variations at the stations themselves. Instead they were observed to be 40% smaller which suggests a significant correlation between the sites.

We conclude that the use of a chain or an array of fixed reference magnetometers can greatly reduce errors in aeromagnetic surveys which result from geomagnetic activity during the survey flights.

Acknowledgements

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