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Matched filter separation of magnetic anomalies caused by scattered surface debris at archaeological sites

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ABSTRACT

Randomly scattered debris, some of it ferromagnetic, on or near the ground surface regularly degrades magnetic data acquired for archaeological purposes. These sources create short-wavelength high-amplitude dipolar anomalies in total field magnetic intensity maps and they can dominate maps of the vertical magnetic gradient. Thus, we generally wish to separate longer wavelength anomalies created by features of interest, such as foundations or building perimeters, from the shorter wavelength anomalies created by debris on or near the ground surface. Matched bandpass filtering, employed extensively in the aeromagnetic industry, is an effective way to separate magnetic anomalies arising from different depths. It entails fitting the radially averaged power spectrum of the total field magnetic data with a series of power spectra corresponding to simple equivalent layers at the archaeological site. We show that applying matched bandpass filtering to a set of total field magnetic intensity data yields two equivalent layers with excellent separation of near-surface sources from deeper sources of interest. The benefit of this approach over enhancing surface features using magnetic gradiometry, analysis by upward continuation, or the analytic signal is that we isolate the source layers without losing information.

INTRODUCTION

Randomly scattered debris, some of it ferromagnetic, on or near the ground surface regularly degrades magnetic data acquired for archaeological purposes at historic town sites, in particular mining towns. Such debris may include steel cans, lumber, horseshoes, nails, roofing steel, machinery parts and other cultural artefacts such as flower containers in cemeteries. In archaeological work at such sites we typically seek signals from residential foundations, building perimeters, or perhaps corral and stable boundaries. These features of interest usually have a length scale of metres to several metres or more. The lower part of the spatial range is also the upper range of magnetic anomalies from the surface litter. We locate and map the debris when it lies on the surface. Yet the magnetic signal of surface scatter, with its high gradients and high amplitudes, dominates contour scales and obscures more subtle anomalies having longer spatial wavelengths. Often we wish to separate the signals from sources at varying depths with different spatial dimensions.

Separating the longer wavelength anomalies from deeper sources, such as foundations, with respect to shallow sources requires collecting observations of total field magnetic intensity as opposed to magnetic gradiometry. Measuring the gradient of the magnetic field isolates signals from shallow sources, those with high gradient short wavelength anomalies, at the expense of longer wavelength signals. Tabbagh (2003) noted that with appropriate filtering, total field observations can be archaeologically advantageous to measuring the vertical gradient of the magnetic field. Separation filtering of potential fields is a classic topic including techniques in the Fourier domain (e.g, Syberg 1972; Jacobsen 1987) or using wavelet transforms (e.g., Fedi and Florio 2003; Paoletti *et al.* 2007). The filtering we find most appropriate and successful for separating sources on or near the ground surface from those buried in the shallow subsurface is matched filtering (Syberg 1972; Phillips 2001).

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EXAMPLE MAGNETIC DATA

Recent magnetic observations (Fig. 1) from Cinnabar, a historic town site near Yellowstone National Park, USA, provide a representative example of surface debris degrading longer wavelength signals in a map of total field magnetic intensity. We extracted these data (Fig. 1) from a broader survey done during a joint endeavour of The University of Montana, Department of Anthropology and Yellowstone National Park. We acquired these total field magnetic intensity observations at 5 Hz while walking bidirectional transects spaced approximately one metre apart using a Geometrics G858 Cesium vapour magnetometer on a magnetically quiet day. There was neither forecast nor observed sunspot activity sufficient to drive significant magnetic variations during the time in which we completed our survey. Thus we did not correct the data relative to a fixed recording base station.

Initially we planned on integral GPS guidance but antenna failure lead to laying out transects with ropes and a tape measure. Regardless, either method of guidance typically adds noise to the desired signal due to mislocations, variable walking speeds and directionally dependent sampling frequencies.

Our total magnetic field intensity observations (Fig. 1), gridded by kriging, include features with differing character. First, there is corrugation that is typical in ground and airborne magnetic surveys where observations are acquired at relatively high spatial frequency along more widely spaced transects. Despite the usual efforts to keep the sensor a constant distance from the ground, bunch grass, rough surfaces, rocks and wind combine to interfere with the operator and impact the distance of the sensor from the ground while walking and acquiring observations at 5 Hz. This yields short wavelength anomalies along acquisition lines that become linear magnetic anomalies biased in the direction of acquisition on maps. Thus, following removal of a planar regional field (~0.8 nT per metre to the north-east) we decorrugated (Urquhart 1988; Phillips 2007) the data to better isolate the signal from surface debris and deeper sources (Fig. 2).

The numerous small dipolar features on the decorrugated magnetic map (Fig. 2) at the scale of 0.5–2 m result from randomly scattered ferrous sources on or near the ground surface. At the Cinnabar site, these objects include horseshoes, bits of cast iron stoves, scrap sheet metal, nails and the like. Such objects have a combination of induced and remanent (permanent) magnetizations. An induced magnetization would typically cause a dipolar signature that is a paired set of high and low amplitudes with the low amplitude offset towards magnetic north (12.5^{o} east at the study location). If there is a remanent magnetization vector added to the induced magnetization, the dipole signature points in an alternative direction depending on the vector sum of the induced and remanent magnetizations. These differences in direction are not important in the separation of anomalies by matched filtering.

Finally, there are some longer wavelength (~10 m east-west) signals that trend north-south through the area. These features correlate with subtle drainages apparent on satellite imagery. Therefore at least some of the anomalies may result from variable concentration of magnetic minerals in old fluvial deposits. Yet, in the final analysis, there is some suggestion that a few may be cultural fea-

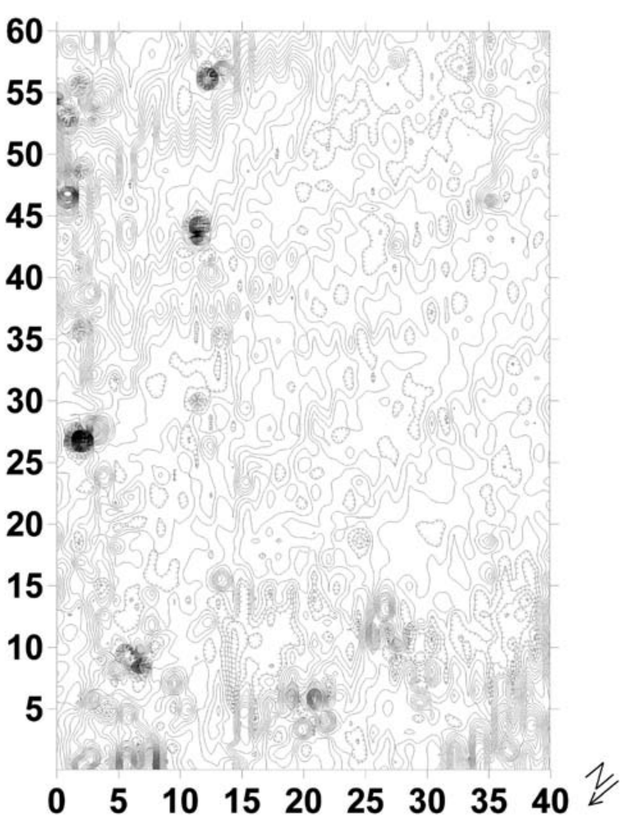

FIGURE 1
Total field magnetic intensity, contour interval is 5 nT, the range is 447 nT and horizontal dimensions are in metres. The bidirectional acquisition direction, with one metre spacing, is vertical in the figure. Tightly packed near circular contours illustrate effect of debris on or near the ground surface.

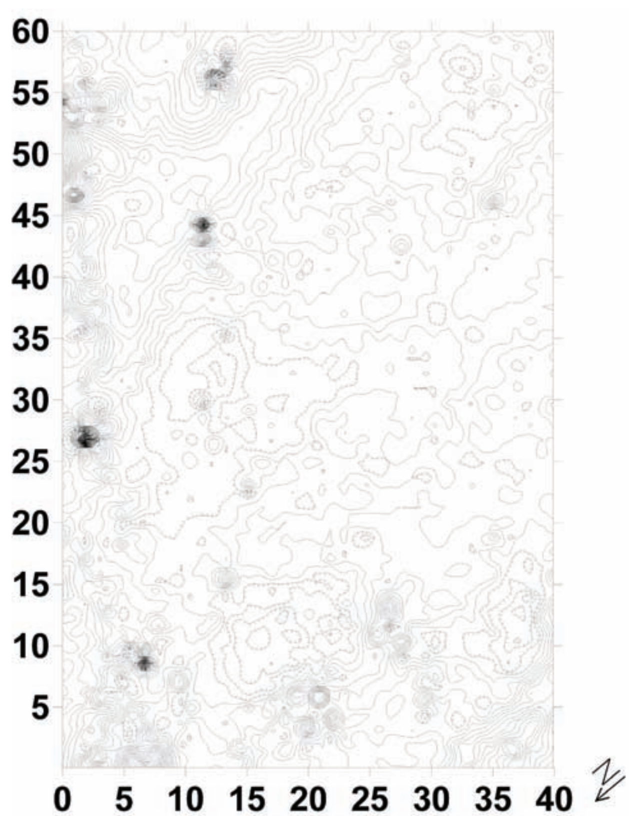

FIGURE 2
Decorrugated total field intensity with planar regional field of about 54 000 nT removed. The contour interval is 5 nT; horizontal dimensions are metres.

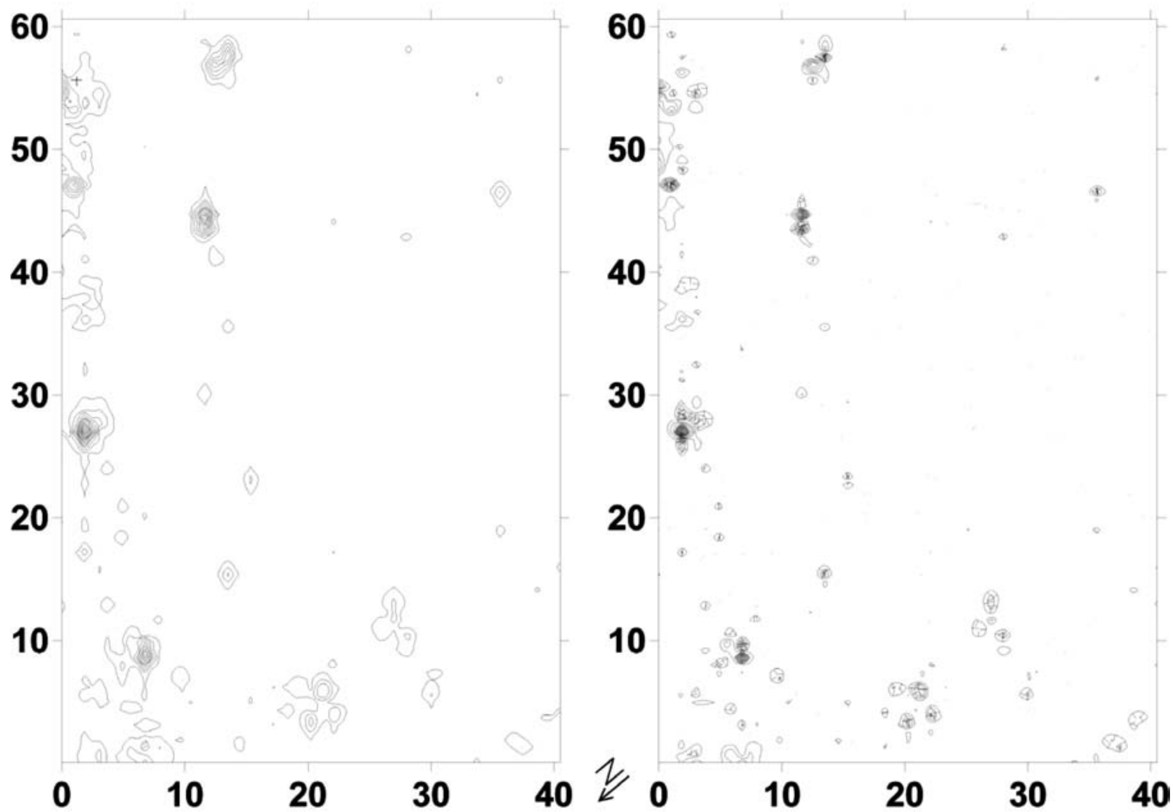

FIGURE 3
Enhanced signals from causative sources on or near the surface; horizontal dimensions are in metres. Left: analytic signal of the total magnetic intensity. Right: synthetic vertical gradient calculated by differencing the total field intensity with an upward continuation of 0.2 m; the zero contour is suppressed for clarity.

tures. Generally, we wish to separate these longer wavelength anomalies and the shorter wavelength dipolar anomalies.

SEPARATING THE MAGNETIC EFFECTS OF SURFACE DEBRIS

Numerous potential field methods (e.g., Blakely 1995) exist to attenuate or enhance signals of interest in a magnetic data set. Most of those methods make use of the spatial frequency (or wavenumber) domain following a Fourier transformation of the data. For example, evaluating successive upward continuations (e.g., Jacobsen 1987) of the total field anomaly to a height of around one to two times the survey's line interval will typically remove the dipolar expression of surface debris at archaeological sites. Upward continuation involves multiplying the power spectrum of the total magnetic field by a filter, which decreases exponentially in the spatial frequency domain. Unfortunately, this upward continuation also attenuates high spatial frequency (short wavelength) content beneficial to resolving other features. Differencing successive upward continuations approximates the vertical gradient of the field and isolates shallow sources (Fig. 3). Alternatively, one can enhance the dipolar features by calculating the analytic signal of the total field (Roest *et al.* 1992). If one is searching for the sources of those dipolar anomalies missed in a surface survey, publically available Magpick© software by Tchernychev (2008) allows one to interactively pick, locate and number dipolar anomalies on a magnetic map. Unfortunately, none of these three techniques (analytic signal, differencing upward continuations or locating dipolar sources) provide a way to remove their contribution to the total field map. Another technique, threshold filtering, removes components of a signal whose amplitudes are below a specified level (the threshold) regardless of their position on the wavenumber axis. White ($1/f^0$) noise is flat in the wavenumber domain. Thus, applying successive threshold filters with increasing thresholds to the data allows one to remove increasing amounts of white noise, sometimes bringing out features not otherwise seen. Threshold filtering decrements the signal at a constant level across the spatial frequency spectrum but the dipolar anomalies typically have high power due to their shallow depth. Therefore, the dipolar anomalies are not effectively isolated with threshold filters. Removing components across the frequency spectrum also lowers resolution in edge detection of larger-scale features.

Matched bandpass filtering is an effective way to separate magnetic anomalies from different depths. The method is based on equivalent sources (Pedersen 1991) that are fictional layers below the observation surface where the distribution of magnetization produces the observed magnetic field. Spector and Grant (1970) showed that equivalent source layers at different depths yield radially averaged logarithmic power spectra, from gridded magnetic data with segments of constant slope. These linear segments in the power spectrum represent magnetic sources at similar depths and characterize features at the principal depth ranges of causative sources. Syberg (1972) proposed matching bandpass filters, in the spatial frequency domain, to the characteristic parts of the power spectrum for different features. Filtering the total field magnetic data with the matched bandpass filter extracts the frequencies corresponding to these principal depth ranges. For example, the spectrum of a layer of magnetic dipoles is linear at high spatial frequencies but becomes concave down and achieves a maximum at low spatial frequencies (e.g., Phillips 2001). Fitting a line to the high-frequency end of the spectrum and removing that component separates the dipole layer from the remaining signal.

Employing matched bandpass filtering for anomaly separation has a long history (Nabighian *et al.* 2005) in the application of aeromagnetic data to tectonics, structure and resource exploration but not in archaeology. Anomaly separation by matched bandpass filtering in the spatial frequency domain is successful when the signal (feature) of interest dominates one spectral band of the magnetic field's power spectrum. Generally, there may be a noise layer with low-amplitude high-frequency noise related to acquisition, a layer that corresponds to the surface (or near-surface) magnetic sources and one or more additional layers from deeper magnetic sources. In an archaeological study these may correspond to acquisition and instrument noise, debris on or near the surface, somewhat deeper sources such as foundations or compact living surfaces and possibly a deeper signal from underlying geological sources. Shallow and deeper magnetic sources dominate the high and low spatial frequency ends of the power spectrum respectively.

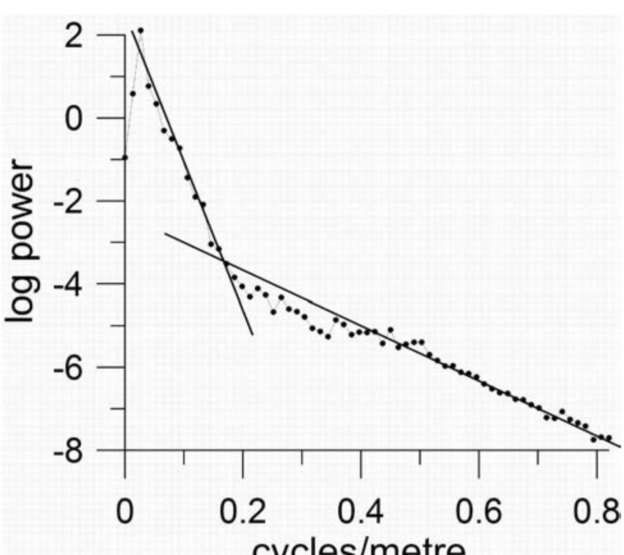

FIGURE 4
Radially averaged power spectrum of the total field magnetic intensity. The symbols show the power spectrum and the solid lines illustrate the separation of two equivalent layers forming the basis for matched bandpass filters, as discussed in the text.

MATCHED FILTERING OF THE EXAMPLE DATA

The general idea in matched filtering is to fit the radially averaged power spectrum of the total field magnetic data (Fig. 4) with a series of power spectra corresponding to simple, equivalent layers at the archaeological site. One then uses the equivalent layer information to construct bandpass filters, which separate the original magnetic field data into wavelength groups that contain the magnetic anomalies in each equivalent layer. As noted by Spector and Grant (1970) and later workers, the power spectra of these equivalent layers are linear segments in the log power spectrum of the data. Existing software (Phillips 1997, 2007) based on the contributions of Syberg (1972) facilitates the calculations.

For an example, consider a two-layer case consisting of a magnetic dipole layer with amplitude spectra A_1 and average depth d_1 overlaying a deeper magnetic half-space at depth d_2 with amplitude spectra A_2. The depth terms will dominate the spectrum and, ignoring any noise, the total magnetic intensity, which is their sum, will have two independent linear segments in its radially averaged log power spectrum. Let their intercepts, at wavenumber (k) = 0, have values of c_1 and c_2 for the dipole layer and deeper half-space, respectively. Then, the amplitude spectra for the components look like:

$$A_1(k) = c_1 \exp(-d_1 k)$$
$$A_2(k) = c_2 \exp(-d_2 k).$$

Their combined power spectrum is:

$$E(k) = [A_1(k) + A_2(k)]^2, \text{ or}$$
$$E(k) = [A_1(k) * (1 + A_2(k)/A_1(k))]^2.$$

Substituting for $A_1(k)$ and $A_2(k)$,

$$E(k) = [c_1 \exp(-d_1 k) * (1 + (c_2/c_1) \exp((d_1–d_2)k)]^2.$$

The inverse of the second factor in the previous expression is

$$F(k) = 1/(1 + (c_2/c_1) \exp((d_1–d_2)k).$$

$F(k)$ is the filter to separate the shallow magnetic dipole layer from the deeper magnetic half-space. Multiplying the Fourier transform of the total magnetic intensity by the filter and then applying the inverse Fourier transform to the product separates the components. The constants c_1 and c_2 are the intercepts of the appropriate linear segments read off the log radial power spectrum versus wavenum-

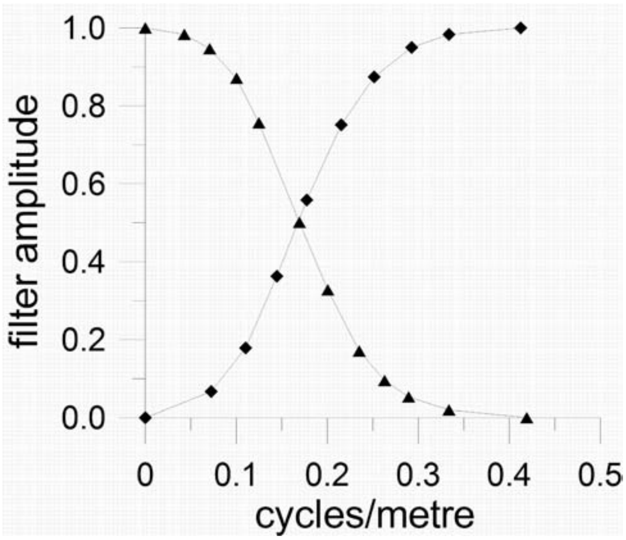

FIGURE 5
Matched bandpass filters in the spatial frequency domain. Triangles show bandpass for long wavelength signal and diamonds indicate bandpass for short wavelength signals. Parameters for the filters are determined empirically as discussed in the text.

ber plot at $k = 0$. We obtain the depths d_1 and d_2 from the slopes of the linear segments with depth = –slope/4*pi when the horizontal axis is cycles/wavelength (Blakely 1995). Phillips' (2007) implementation, as used in this study, utilizes a non-linear least squares refinement to the initial observational fits of line segments on the log power spectrum.

The radially averaged log power spectrum of our example data has two obvious linear segments (Fig. 4). The segment with steeper slope at longer wavelengths (fewer cycles per metre) results from relatively deeper sources. The segment with lower slope at shorter wavelengths (more cycles per metre) is from the scattered debris on or near the surface. The matched bandpass filters (Fig. 5) for separating equivalent layers are calculated as the quotient of the spectrum of each single layer divided by the spectrum of the total field (Syberg 1972). Applying the matched bandpass filters (Fig. 5) to the Fourier transform of the total field magnetic intensity data (Fig. 2) separates the magnetic anomalies by their apparent depth to causative sources (Fig. 6). In this case the equivalent layer for the shallow sources is at 0.5 m and that for the deeper sources at 3.0 m. These depths indicate adequate separation but it is worth recalling that there is no inherent depth information in magnetic observations. Adding the two

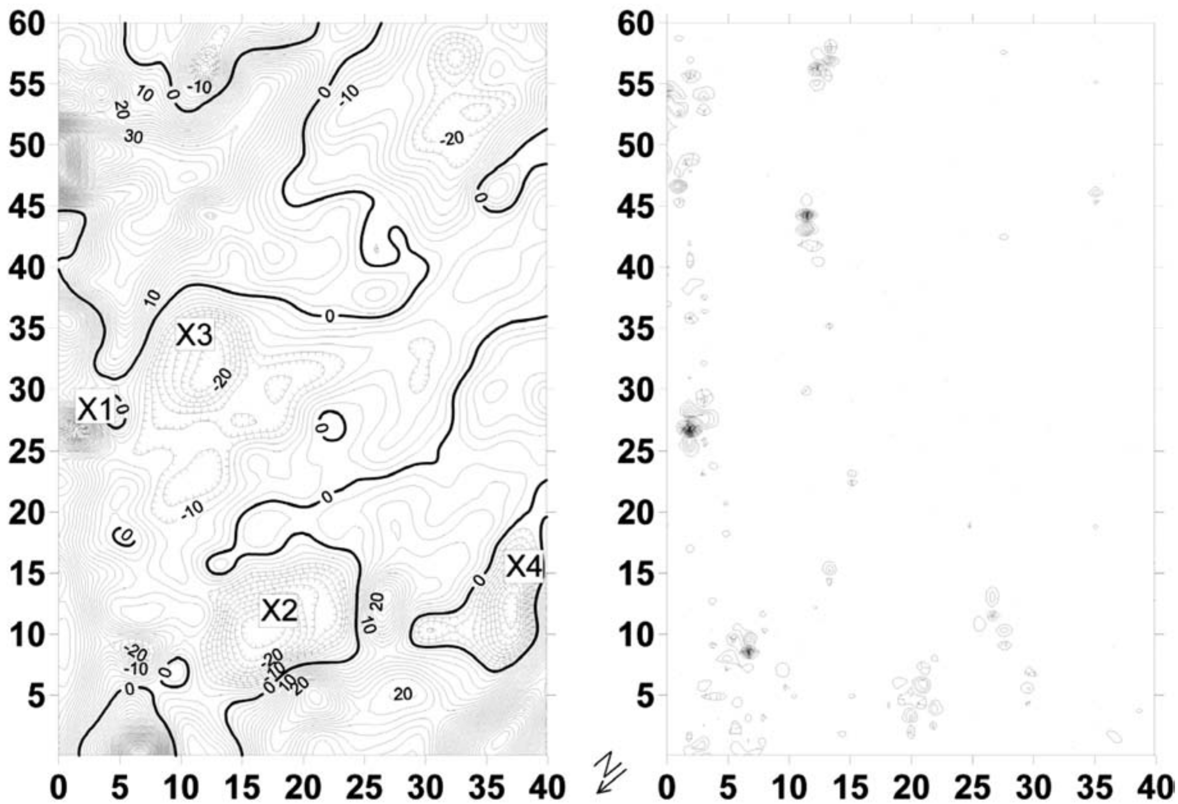

FIGURE 6
Total field magnetic intensity separated into two equivalent layers; horizontal dimensions are in metres. Left: magnetic field from the deeper equivalent layer separated by applying the long wavelength bandpass filter to total field intensity; contoured at 2 nT. Right: anomalies from on or near-surface sources contoured at 10 nT; the zero contour is removed for clarity. The sum of these two maps equals the original decorrugated data (Fig. 2); X1– X4 mark locations mentioned in the text.

grids (shallow and deep) would yield the original data set. The benefit of this approach is that the source layers are isolated without losing information as is the case with enhancing surface features using magnetic gradiometry, analysis by upward continuation, or the analytic signal.

The shallow source components of the magnetic data are well separated from the total field data and obviously distinct from the deeper sources (Fig. 6). The shallow sources are more concentrated to the left (north-east) of the map, which parallels a long-lived road through the study area. Most of the shallow sources lie on the ground surface and are more reasonably found by visual inspection than by magnetometry. The map of shallow sources bears strong resemblance to the analytic signal of the total field intensity and the synthetic vertical magnetic gradient created by differencing upward continuations (Fig. 3). Any of these three methods serves to isolate and locate the shallow causative sources. The advantage of separating the shallow sources with matched bandpass filtering is that no information is lost; the remainder of the information remains in the map of deeper sources (Fig. 6).

Following separation, the magnetic signals from the randomly distributed sources littered on and near the ground surface cause much less degradation of the deeper sourced anomalies (Fig. 6). There is some spectral overlap in the signals and the filters (Fig. 5) and areas with apparently larger concentrations of surface debris still have some expression on the map of deeper sources (e.g., X1 labelled on Fig. 6) but the deeper source layer is now easier to interpret. In particular, magnetic lows labelled X2, X3, X4 have edges, as judged by high magnetic gradients, at distinct angles to the dominate north-south trend of the underlying fluvial sediments. These three anomalies are strong candidates for future archaeological excavations.

CONCLUSION

Matched bandpass filtering entails fitting the radially averaged power spectrum of the total field magnetic data with a series of power spectra corresponding to simple equivalent layers at the archaeological site. It is a very effective way to separate magnetic signals from sources on or near the ground surface from signals arising from deeper sources. A major advantage of the technique over magnetic gradiometry, differencing upward continuations, or employing the analytic signal, is we separate the source effects without losing any signal. That is, we are not limited to only collecting signals from the shallowest sources nor do we lose information from deeper sources when we isolate the signal from shallow sources.

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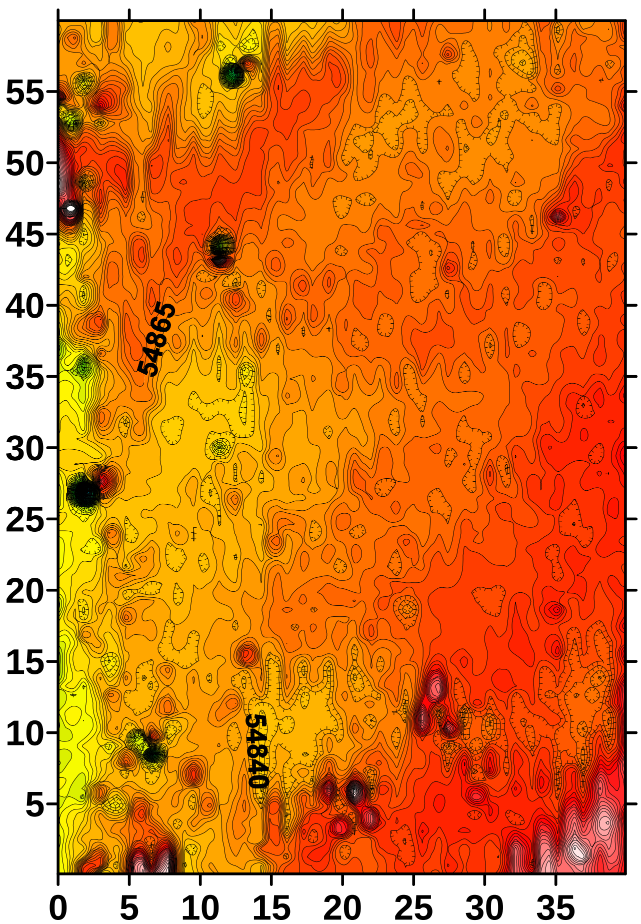

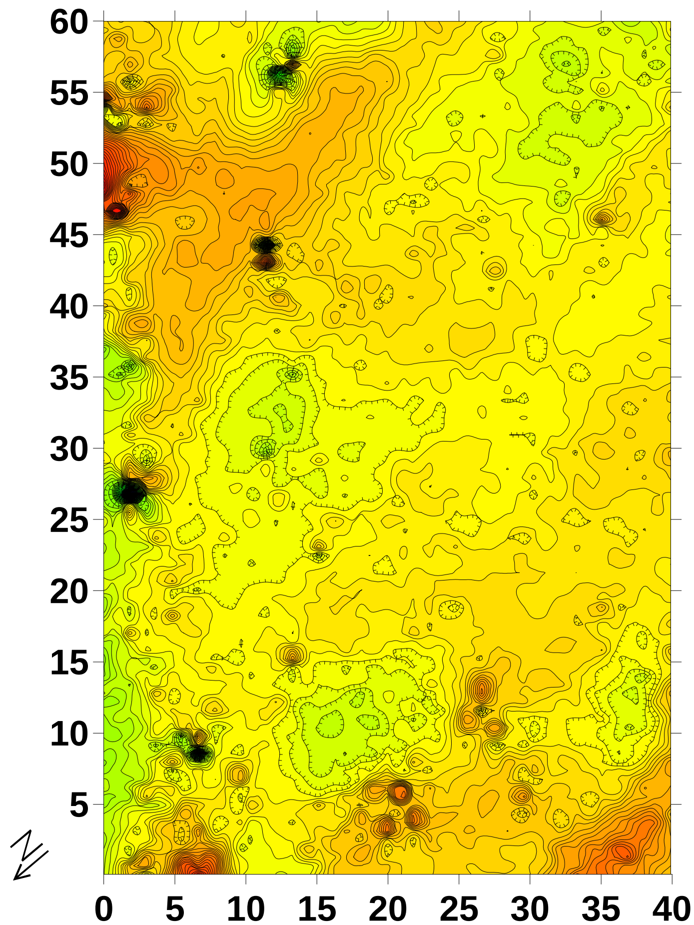

FIGURE 1. Total field magnetic intensity, contour interval is 5 nT, the range is 447 nT and horizontal dimensions are in metres. The bidirectional acquisition direction, with one metre spacing, is vertical in the figure. Tightly packed near circular contours illustrate effect of debris on or near the ground surface.

FIGURE 2. Decorrugated total field intensity with planar regional field of about 54,000 nT removed. The contour interval is 5 nT; horizontal dimensions are metres.

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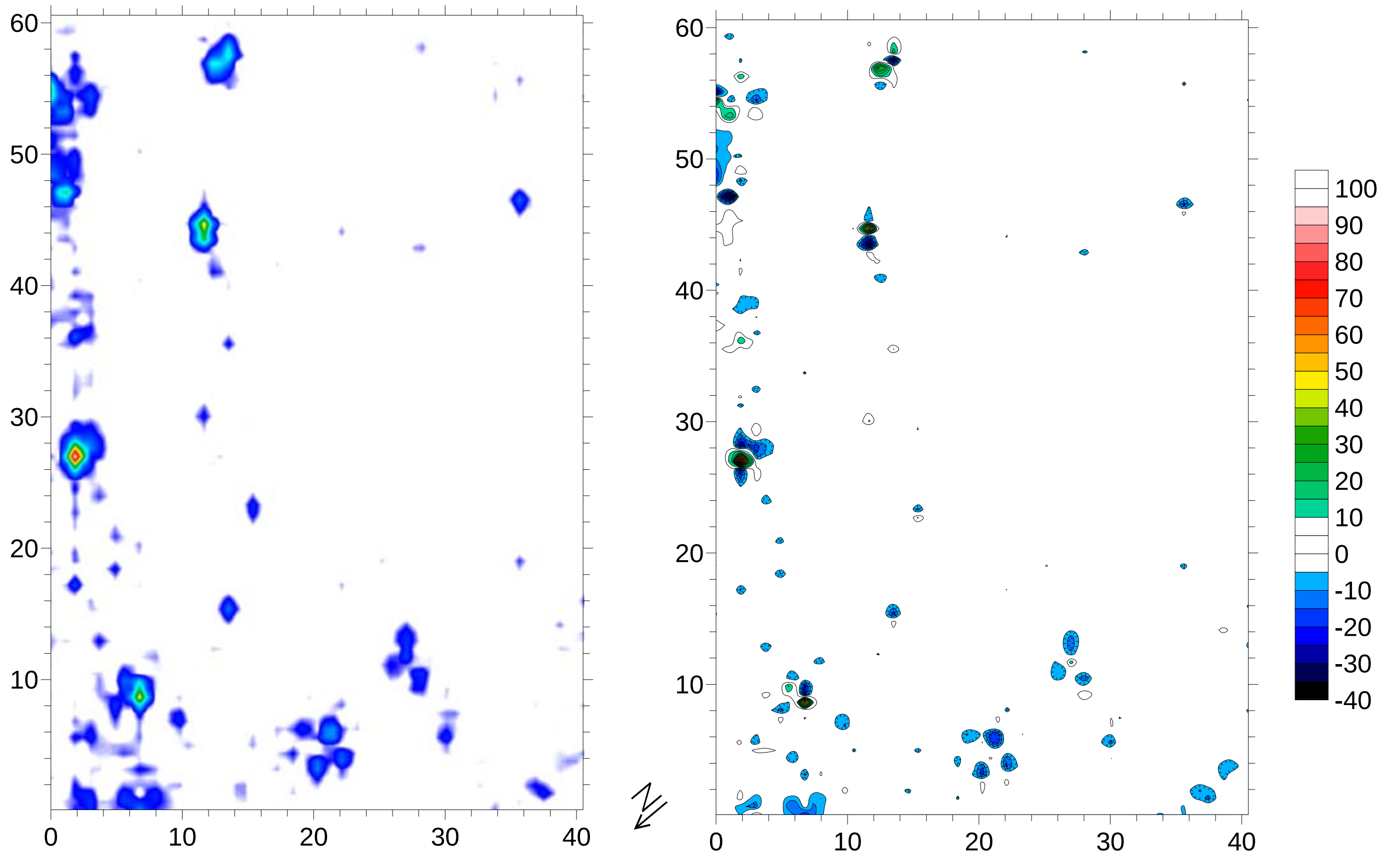

FIGURE 3. Enhanced signals from causative sources on or near the surface; horizontal dimensions are in metres. Left: analytic signal of the total magnetic intensity. Right: synthetic vertical gradient calculated by differencing the total field intensity with an upward continuation of 0.2 m; the zero contour is suppressed for clarity.

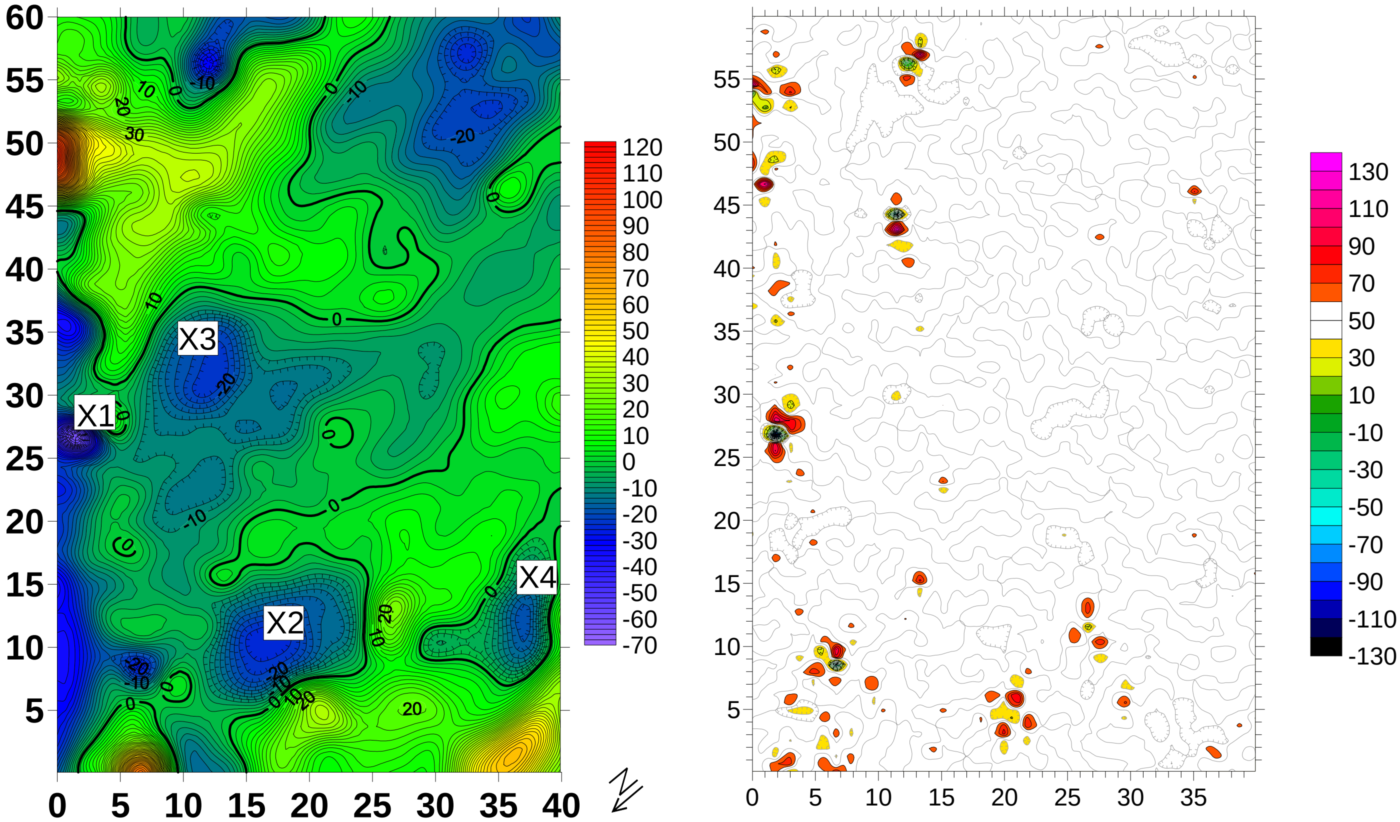

FIGURE 6. Total field magnetic intensity separated into two equivalent layers; horizontal dimensions are in metres. Left: magnetic field from the deeper equivalent layer separated by applying the long wavelength bandpass filter to total field intensity; contoured at 2 nT. Right: anomalies from on or near-surface sources contoured at 10 nT; the zero contour is removed for clarity. The sum of these two maps equals the original decorrugated data (Fig. 2); X1– X4 mark locations mentioned in the text.