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From Nanotesla to Picotesla — a New Window for Magnetic Prospecting in Archaeology

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ABSTRACT The first use of a picotesla (1 pT = 0.001 nanotesla) sensitivity on the ground is reported for magnetic prospecting in archaeology. The instrument consists of two caesium magnetometers, CS2 (Scintrex, Canada), and a magnetometer processor, MEP720 (Picodas, Canada), which is interfaced to a subnotebook computer for control and data logging. Time mode sampling every 0.1 s allows resampling at 10 cm intervals. Digital image processing techniques are used for the visualization of data. The system opens a new window for magnetic prospecting in archaeology, especially by detecting archaeological structures with an extremely weak magnetization contrast, caused by biogenic magnetite.

Key words: magnetic prospecting; caesium magnetometer; picotesla (pT); resampling procedure; magnetogram; digital image processing.

Introduction

Magnetic prospecting has been established over three decades as an important method in archaeological research (Aitken, 1974; Clark, 1990; Scollar et al., 1990). Owing to the variety of magnetization processes in archaeological structures, most features of archaeology are imaged above ground as anomalies of the earth's magnetic field. Primarily the properties enabling the dectection of archaeological structures has been explained by the Le Borgne effect (Le Borgne, 1960, 1965). However, this effect cannot apply to magnetic anomalies caused by non-burnt wooden posts or palisades, which are in the range of some 0.1-0.001 nanotesla (nT) and only detectable by high sensitivity caesium magnetometry (Becker, 1990a,b). Recent investigations concerning the magnetic properties of archaeological soils have shown a magnetization process due to magnetic bacteria, which contain single domain magnetite crystals acting in the soil forming process by the decomposition of organic material (FaBbinder and Stanjek, 1993; FaBbinder 1994). Under different conditions biogenic greigite (Fe_3S_4) is formed (FaBbinder and Stanjek, 1994), which could be the explanation for magnetic anomalies within archaeological contexts.

The problem of the visualization of this latent image had been solved as a combination of high sensitivity and high-resolution magnetics in the field with digital image processing of data in the laboratory (Becker, 1983). This technique plays an important role in the Bavarian State Authority for Monument Protection and Archaeology (Bayerisches Landesamt Denkmalpflege, Abteilung Vor-Frungeschichte), where aerial archaeology is combined with magnetic prospection on the ground on a digital image computer (Becker, 1990a). The combined prospection allows the documentation of archaeological monuments without destruction — even without touching the ground. The large area coverage of Bavaria is done by aerial photographs with hand-held cameras through the open window of an aircraft (Cessna 172) taking 20 000 to 40 000 photographs per year during a total of 500 flight hours. Magnetics on the ground concentrates on

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important sites of specific archaeological interest. Only sites with stone structures in the ground, e.g. a Roman villa, are measured additionally using resistivity meters (RM15, Geoscan, England). The two caesium magnetometer systems allow the prospection of about 40 ha (400000 m^2) with 0.5 m sample intervals per year. The costs per hectare for the instrument are negligible compared with costs for personnel. Not using the best instrument available for archaeological prospection results in a severe loss of information about archaeological features because of the weak magnetization contrast, and the inevitable waste of time and money.

A new dimension for archaeological prospection was attained recently by an optically pumped caesium magnetometer with a sensitivity in the picotesla range (1 picotesla (pT) = 0.001 nanotesla (nT)). It is the first time that magnetic prospecting has been used on the ground with picotesla sensitivity.

Magnetic prospecting system with caesium magnetometers, V101

For more than 10 years a magnetic prospecting system has been used in Bavaria and elsewhere consisting of caesium magnetometers, V101 (Varian and Scintrex, Canada), on a wheeled device, optoelectronic positioning, and data recording on hand-held computers (Figure la and b). Over sites with rough surfaces, such as Troy, the sensor configuration can be carried; in this case the positioning is managed by a fisherman rope which is pulled from a wheel with an optoelectronic slot disk producing 2 cm pulses. The system allows the coverage of 1 ha at 0.5 m intervals (40 000 readings) in one or two days. The magnetometers have a sensitivity of 0.1 (±0.05) nanotesla (nT) at 10 Hz cycles. The sensors can be freely configured as a gradiometer magnetometer (vertical configuration of two sensors 0.3 and 1.8 m above ground) or a variometer magnetometer (one sensor at a fixed-base position and the moving sensor at 0.3 m above ground). For near-surface structures these configurations differ in amplitude by a factor of 1.8 (Becker, 1990a). Normally the vertical gradiometer mode over 1.5 m on the cart is used for easy field operation, because there is only one cable set between the sensors and the

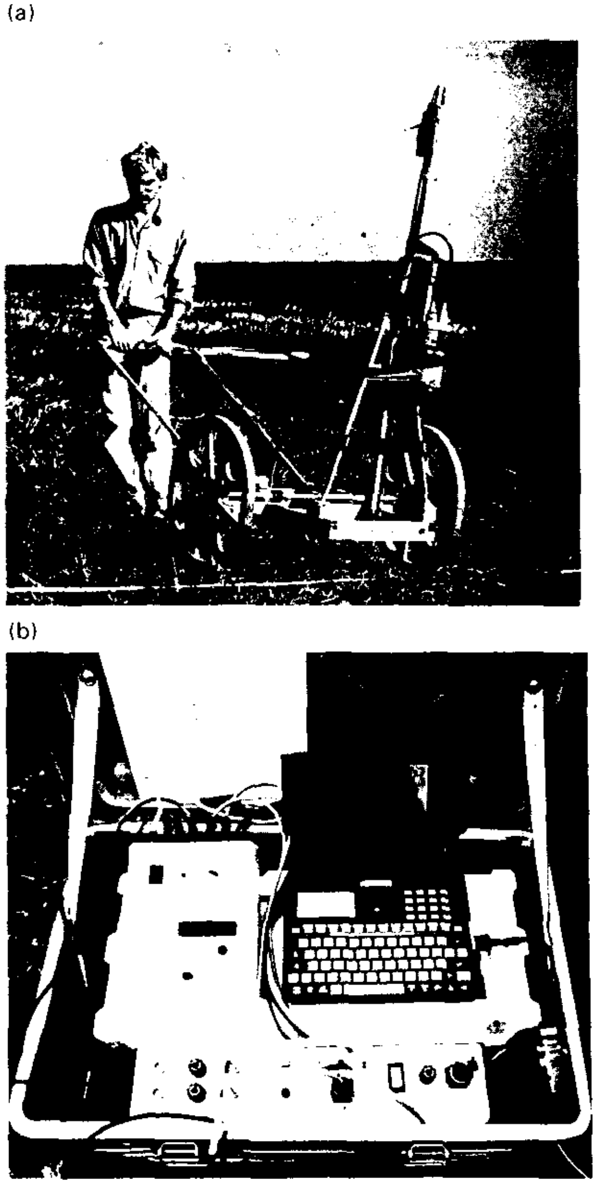


Figure 1. Magnetic prospecting system on a non magnetic cart in gradiometer mode (0.3 and 1.8 m) of caesium sensors V101 (Varian and Scintrex) or CS2 (Scintrex). Distance triggers are given by the rotation of the wheels via an optoelectronic device with 2 cm resolution. (b) Aluminium box with magnetometer processor MEP720 (Picodas), interface electronics, power supply and subnotebook computer, which is connected to the sensor unit by a 50-100 m cable set.

readout–data storage unit. Only when higher sensitivity is needed for deeper structures or for easier operation by carrying the sensor, the vanometer mode is preferred.

A vertical sensor separation of 0.5 m, which is used for most fluxgate gradiometers, reduces the amplitude of the magnetic anomaly by a factor of five. Compared with the sensitivity of the V101 caesium magnetometer (±0.05 nT) for a total field, the sensitivity of fluxgate gradiometers for the vertical component of the magnetic field without digital averaging is about 10 to 20 times less. Therefore almost all archaeological structures with biogenic magnetite are not detectable by fluxgate gradiometers.

Although the V101 caesium magnetometer gives an output of data every 0.1 s, only discrete values were sampled every 0.5 m, because of insufficient speed and capacity of the first hand-held computers. A 20-m grid with 0.5 by 0.5 m samples (1600 data points) was first logged in the core of the computer and then written on a microcassette. Sample intervals of 0.25 m caused a severe loss in speed of operation. Fast operation of the sensors in zigzag mode results in a shift of linear anomalies over adjacent lines. This shift effect changes a linear structure to a zigzag feature even after perfect positioning on the line (Figure 2b). The reason for this phase shift lies in the windowing technique of V101: the determination of the Lamor frequency for a sensitivity of ± 0.05 nT in 0.1 s is only achieved by the determination of a ± 0.035 Hz signal out of 300 MHz. Unfortunately this phase shift cahnot be corrected easily for V101 systems, because it is non-linear and amplitude dependant. This problem could be avoided in parallel mode, but this means a double speed reduction, which is never acceptable; especially for the large areas involved and the limited time available for field work

Nevertheless many projects, such as Assur in Iraq (Becker, 1991), Munbaqa in Syria (Becker and Jansen, 1994), Troy in Turkey (Becker et al., 1993; Becker and Jansen, 1994) (Figure 2a) and various sites in Bavaria (Becker 1990a) (Figure 3a), have demonstrated the archaeological impact of this technique. However, the possibilities for archaeological prospection were still limited by the sensitivity of the magnetometers and insufficient spatial resolution. In particular, sites consisting of small features, such as postholes with very low contrast in susceptibility, or deeply buried structures showed these limitations.

Picotesla magnetometer
MEP720/CS2

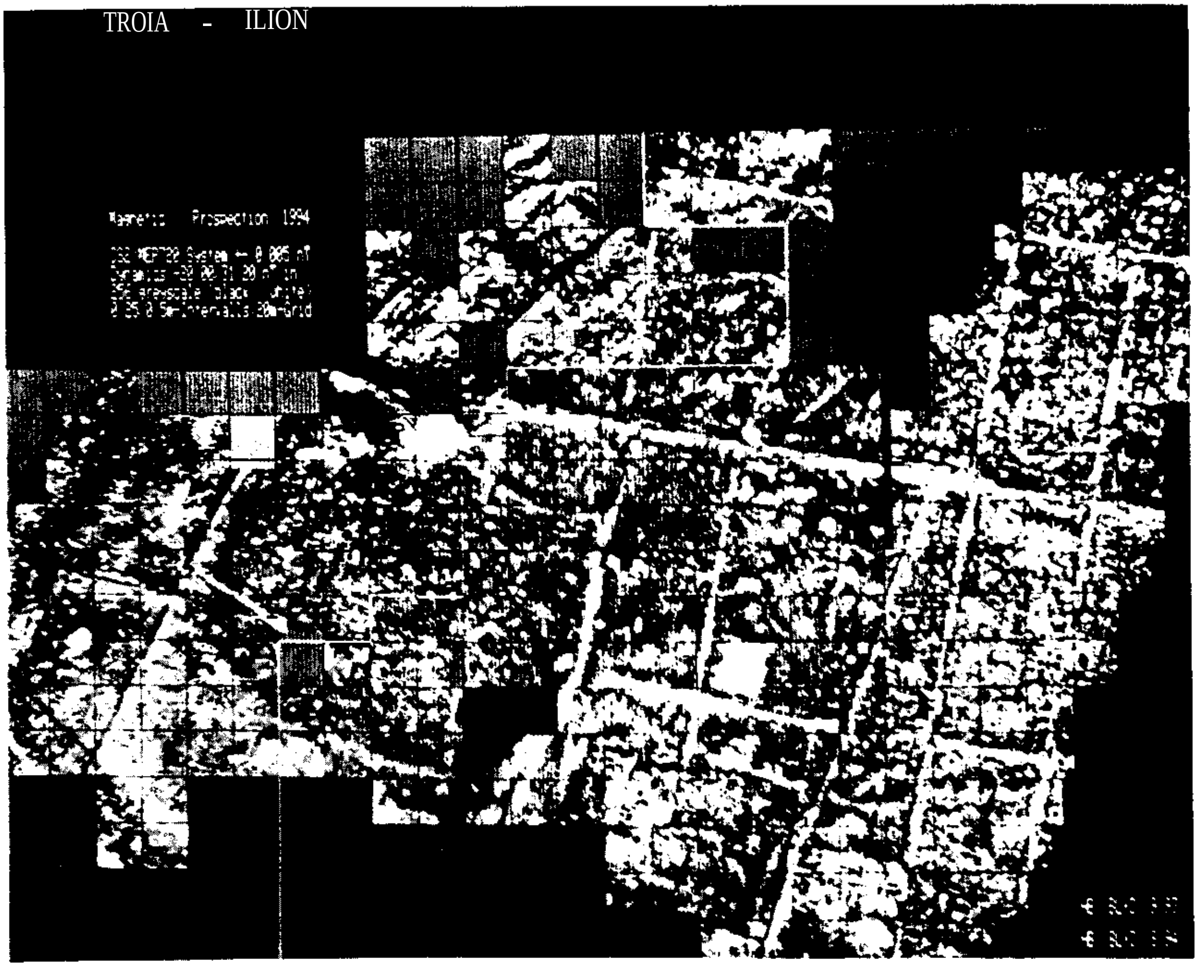
In collaboration with Picodas (Canada), a new magnetometer system has been developed consisting of CS2 sensors (Scintrex) and MEP720 magnetometer processors (Picodas) with a sensitivity of ± 0.001 nT and again at 10 Hz cycles. Built-in filters allow complete cancellation of, 50 and 16 2/3 Hz signals, which opens the possibility for operation directly under power lines or near electric railways. MAGGRAD software (Picodas), originally designed for aeromagnetics, has been especially modified for the purpose of archaeological prospection on the ground. The sensors and sensor electronics are interfaced by a cable via the magnetometer processor with a subnotebook computer which controls the process and storage of data. Data from the two magnetometers, with gradiometer or variometer configuration of the sensors 0.3 m (1.8 m) above ground, are sampled in time mode (every 0.1 s) on separate channels. Other channels are used for distance positioning, status of the magnetometer, time, etc., which allows resampling up to 0.1 m intervals. The system is powered by a 12 V car battery the whole day. For field operation, two people are necessary: one push/pulls the cart with the sensors in a 20 m grid, the other controls the magnetometers and data storage under MAGRAD (Picodas). A graphic display of all on-line values and an acoustic warning in the case of magnetometer problems are a great help in controlling the sampling process in the field.

GRIDPLOT software (Picodas) gives a graphic plot of a 20 m grid on the screen of the subnotebook computer used in the field. REPLOT software (Picodas) outputs the data (line, distance, magnetometer 1, magnetometer 2, magnetometer gradient, magnetometer status, ext. status, time, etc.) for every 0.1 s in ASCII format, which defines the base for the resampling programme (RESAM). One of the important steps in the resampling procedure is the shift correction, which is necessary because of the fast operation of the system in zigzag mode. Time mode sampling every 0.1 s allows a speed dependent shift correction, which results in a rather 'sharp' image of magnetic alignments. This procedure would have not been applicable for the previous V101 system because of a non-linear phase shift, which is dependent on the amplitude of the signal (Figure 2).

GEOPLOT software (Geoscan, England) can be used after resampling for preliminary data processing directly in the field. Final data evaluation and visualization is made by digital image processing in the laboratory.

Digital image and graphical data processing

The identification of extremely weak magnetic anomalies of archaeological structures, such as palisades or single post-holes, is achieved only by digital image processing (Becker, 1983). The idea of this technique, which can be applied to all two-dimensional geophysical data, is very simple. The measured point in the field is considered as a pixel (picture element) and the measured value is transformed to a grey value between 0 (black) and 255 (white). The rather coarse raster structure of the image may be eliminated by bilinear interpolation or median filtering. Several techniques of contrast enhance-



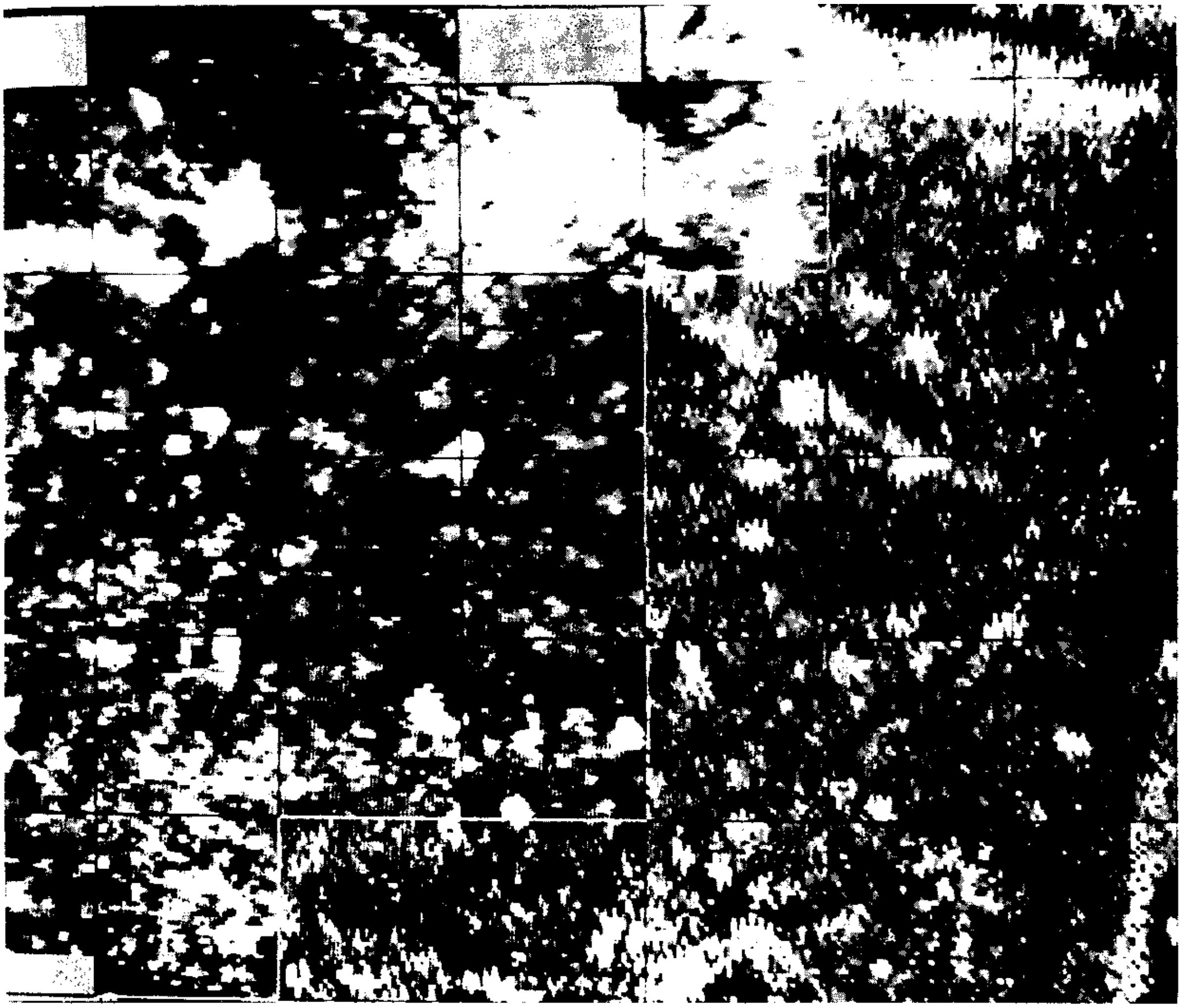


Figure 2. Magnetic prospecting in Troy 1992-1994 using caesium magnetometer V101 (0.1 nT) at 0.5 by 0.5 m intervals (9 ha, 1992 + 1993 on the right-hand side) and using the CS2-MEP720 system (0.005 nT) with 0.5 by 0.25 m intervals (5 ha 1994 on the left-hand side); both in variometer mode; sensor height above ground 0.3 m; magnetogram in digital image processing technique; dynamics -10.0 to +15.5 nT in 256 greyscale (black to white), 20 m grid. (b) Magnetic prospecting in Troy 1993-1994. Detail of Figure 2a, which shows the 'sharper' positioning of the CS2-MEP720 system (left side) after speed-dependent shift correction. Technical data for V101 (right-hand side) and CS2-MEP720 same as Figure 2a.

ment and false colour transformation help in identifying archaeological structures. However, magnetic alignments of palisades or narrow wall ditches of houses are identifiable only in grey-shading images. False colour results in slicing of linear features, which disturbs their context.

Local anomalies are ideally visible after a combination of median and contour filtering. Edge detecting or contour filtering transforms the grey shading into a drawing; after the subtraction of these contours from the median filtered image even single posts become detectable (Figure 3c). However, the application of any filtering must be carefully adjusted to the wavelengths of the archaeological features and must be controlled on the image monitor so as not to lose the important information.

Software routines for the transformation of the highly dynamic picotesla data into the 256 grey scale for final digital image processing are not yet finished. At the present time only linear transformations in the window technique or non-linear arctan functions are available.

Digital image processing is also used for recti-

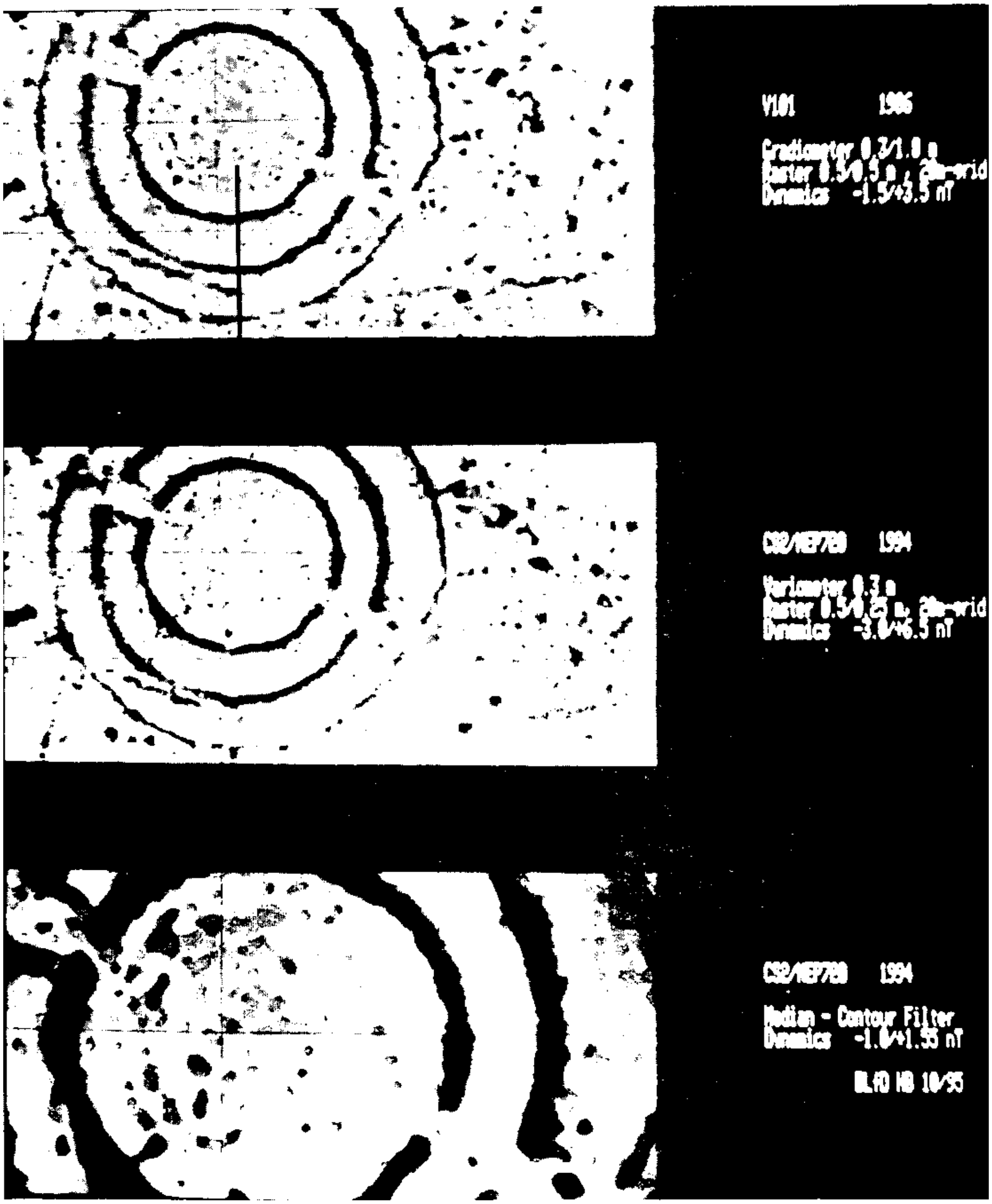


Figure 3. Neolithic ring ditch site near Schmiedorf in Lower Bavaria (5th millenium Bc), a neolithic ditch (6th millenium ac) and a Hallstatt period rectangular enclosure (1st millenium so). Magnetic prospecting in 1986 with caesium magnetometer V101, gradiometer configuration (0.3 and 1.8 m), sensitivity 0.1 nT, raster 0.5 by 0.5 m. section of the magnetogram as digital image, dynamics -1.5 to +3.5 nT in 256 grey-scale (white to black), raw data, 20 m grid. (b) Magnetic prospecting in 1994 with caesium magnetometer CS2-MEP720 in variometer mode (one sensor at fixed base, the moving sensor 0.3 m above ground), sensitivity 0.001 nT (1 pT), raster 0.5 to 0.25 m, same section of the magnetogram as digital image (Figure 3a), dynamics -3.0 to +6.5 nT in 256 grey-scale (white to black), raw data. 20 m grid. (c) Same as Figure 3b, but subtraction of the contour filter from the median filtered image, which results in the traces of some individual posts of the wooden palisade, dynamics -1.00 to 1.55 nT (10 pT per grey value from white to black).

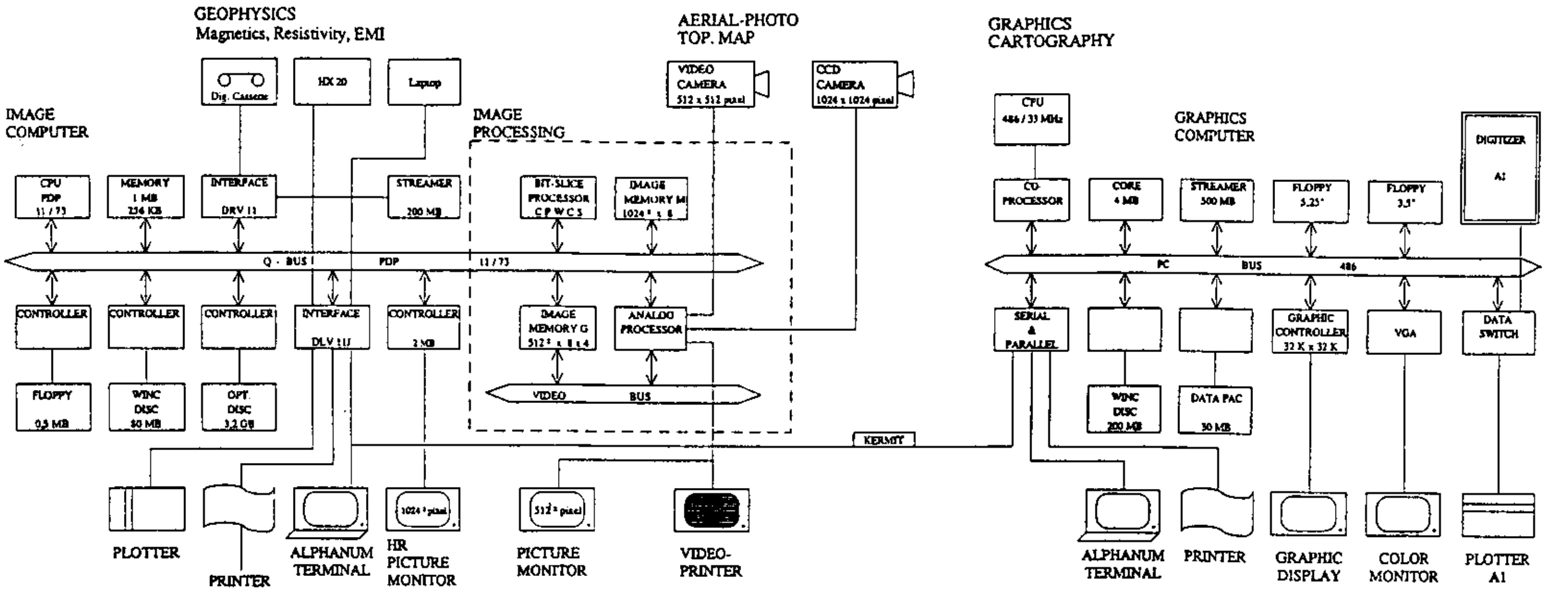


Figure 4. Computer system for digital image and graphic-cartographic data processing at the Bayerisches Landessamt far Denkmalpflege in Munich (stage 9/94).

fication of oblique aerial photos and the compilation of aerial archaeology with ground geophysics (Becker, 1990a). Any archaeological interpretation is done directly on the screen of the digital image computer in a graphic overlay, which can be defined in several colours. The archaeological features traced are stored as polynoms and transformed to a graphic-cartographic computer system for final processing and plotting of the plan (Becker, 1990c) (Figure 5).

Comparison between the nanotesla and the picotesla systems

First tests of the Picotesla system in Turkey (e.g. Troy, Figure 2a and b) and Bavaria (e.g. Schmiedorf, Figures 3b, 3c and 5a) in 1994 show somewhat optimal results in archaeological prospection. In Troy the high sensitivity of the picotesla system could not be used because of the extraordinarily high content of geological magnetite in the cultural debris, but the instrument was even faster in the field than the previous V101 system. In 1992 and 1993 about 4 ha each (160 000 samples at 0.5 m intervals) were measured with that V101 system over 10 days. In the same time in 1994 the MEP720-CS2 system allowed a coverage of 6 ha at an even higher spatial resolution (600 000 samples at 0.5 by 0.2 m intervals). The sample rate had been reduced from 0.1 to 0.2 s because of storage problems of the pre-processed ASCII data. With the picotesla system there seems to be hardly any non-linear phase-shift in the zigzag-mode sampled data. The speed dependent resampling procedure results in an almost sharp image, even after fast sampling in the field (Figure 2a and b).

The advantages of the new picotesla system become even more evident in the case of the neolithic site near Schmiedorf in Lower Bavaria, which is possibly a sun temple from the fifth millenium BC (Figure 3a-c). Soil marks in aerial photographs and a sondage in 1986 have shown that the site is directly under the plough. The magnetization, especially of the double palisades, is due to biogenic magnetite only, which causes anomalies in the range of several 0.01 to 0.3 nT. The site had been surveyed first in 1986 with caesium magnetometer VI01 (0.1 nT sensitivity) with 0.5 by 0.5 m line-spacing/intervals in gradiometer mode, when an almost complete plan of the three ring ditches with the double palisade in the interior could be established exclusively on the basis of magnetic prospecting. The ring ditch site, of 80 m diameter, is surrounded by a large settlement which is also enclosed in a double ditch system 250 m in diameter. There is also a simple ring ditch of 40 m diameter, which may be of the same neolithic age. The neolithic temple site is overlain by a Late Iron Age (Hallstatt period) squared enclosure (Becker, 1990b).

The centre of the three-ring ditch enclosure was remeasured in 1994 using the CS2-MEP720 magnetometer system, with 0.001 nT sensitivity in variometer mode and 0.5 by 0.25 m raster after resampling with almost the same surface conditions of the corn field. A comparison between the surveys in 1986 and 1994 demonstrates clearly the amount of erosion during 8 years. Only the deep middle (D2) and inner ring ditch (D3) seem not to be affected: also, in the model calculation, one can find only small differences between the anomalies of 2.8-m- or 2.6-m-deep ditches. However, the anomaly of the outer ring ditch (Dl) and the Iron Age ditch (Hal) has been reduced since 1986 to half amplitude. The anomalies of the interior double palisade are no longer detectable in this profile presentation (Figure 6).

In consideration of the fact that at least 10-20 cm of the surface soil has been removed due to deep ploughing and erosion by wind and rain in this period, the clearer image of the interior double palisades is due only to the higher sensitivity and higher spatial resolution of the new instrument (Figures 3a and 6). This structure was almost invisible even in the open trench of a sondage, which was excavated in 1986 by an archaeology team from Edinburgh University. For the picotesla magnetometry a content of biogenic magnetite of less than 10^{-6} per cent may be sufficient, which causes no change at all in colour of the soils. This means that there may be a wide range of archaeological structures detectable only by magnetic prospection. The dynamic range of the new magnetogram in the digital image technique ranges from -1.00 to +1.55 nT, with 256 grey values, which makes 10 Picotesla anomalies visible. After the application of gradient filtering to the median filtered data and the subtraction of the two filtered data sets, some anomalies of individual posts of the palisades are detected (Figure 3c).

Single post-holes also became visible in the neolithic settlement near Riekofen-Regensburg, where the complete plan of some neolithic houses with all interior posts and wall ditches became identifiable only by the magnetogram (Figure 5a and b).

Future developments

Further developments of the picotesla system

Figure 5. Neolithic settlement near Riekofen-Regensburg (section). Magnetogram of caesium magnetometer CS2-MEP720, gradiometer mode (0.3 and 1.8 m), sensitivity 5 pT, raster 0.5 by 0.25 m, dynamics -3.0 to +3.4 nT in 256 grey-scale (40 pT per grey-value from white to black), subtraction of median-contour filtered images, 20 m grid. (b) Plan (detail) of the neolithic settlement near Riekofen-Regensburg with the complete layout of neolithic long-houses on the basis of the magnetogram (Figure 5a) after graphical data processing.

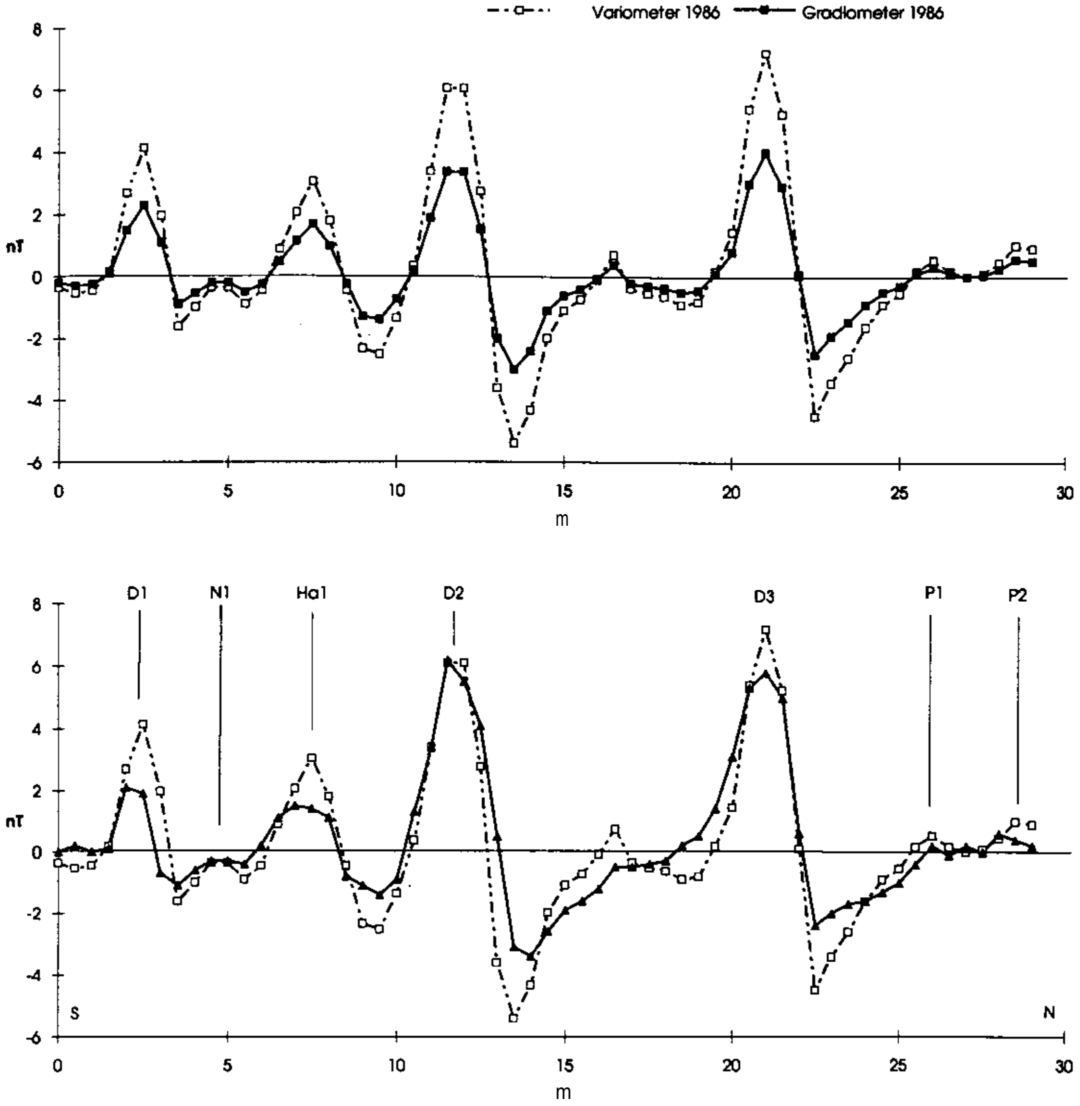


Figure 6. Comparison of caesium magnetometer V101 (1986) and CS2-MEP720 (1994) on a south-north profile crossing the ditches (D1, D2, D3) and palisades (P1, P2) of the neolithic ring ditch site, a neolithic ditch (N1) and the Hallstatt period rectangular enclosure (Hal) near Schmiedorf (for location see Figure 3a). (a) Original data of V101 in gradiometer mode (0.3 and 1.8 m, solid line) and calculated values for variometer mode (dashed line). (b) Original data of CS2-MEP720 survey in variometer mode at 0.3 m above ground (solid line) and calculated data of V101 in variometer mode for the same hight above ground (dashed line) showing the effect of erosion after 8 years.

MEP720-CS2 are planned by using an array of four sensors rather than a pair for higher spacial resolution and time reduction in the field, which is necessary because of the limitations due to intensive agricultural use. Line spacing of 0.25 m would be no problem for detection, even of the small anomalies of wooden posts, which form the majority of archaeological structures in central Europe. The MEP730-760 magnetometer processors (Picodas) for three to six optically pumped sensors are already available for field use on the ground. On the other hand, special software routines for the digital image processing of the data should be developed, allowing a higher dynamic range for better identification of weak anomalies. The limits of magnetics on the ground for archaeological prospection have now been reached with the physical limits of the method itself. The high sensitivity and spatial resolution of the picotesla magnetometer will cover almost the whole range of the wood–earth archaeology in humid areas with biogenic magnetite which documents most of the archaeological heritage of central Europe.

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