H. Becker

Duo- and Quadro-sensor Configuration for High Speed/High Resolution Magnetic Prospecting with Caesium Magnetometer

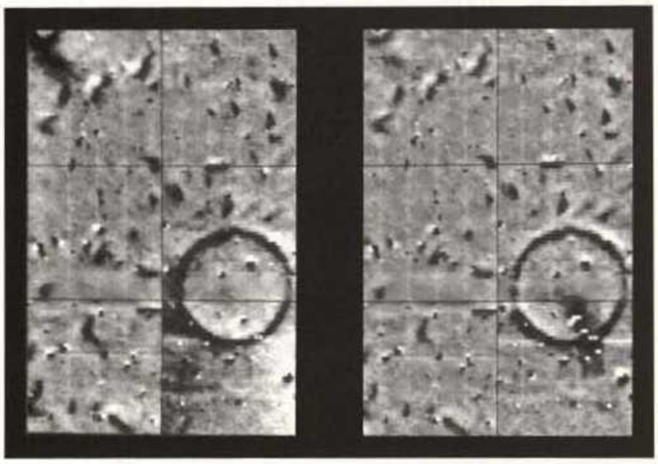
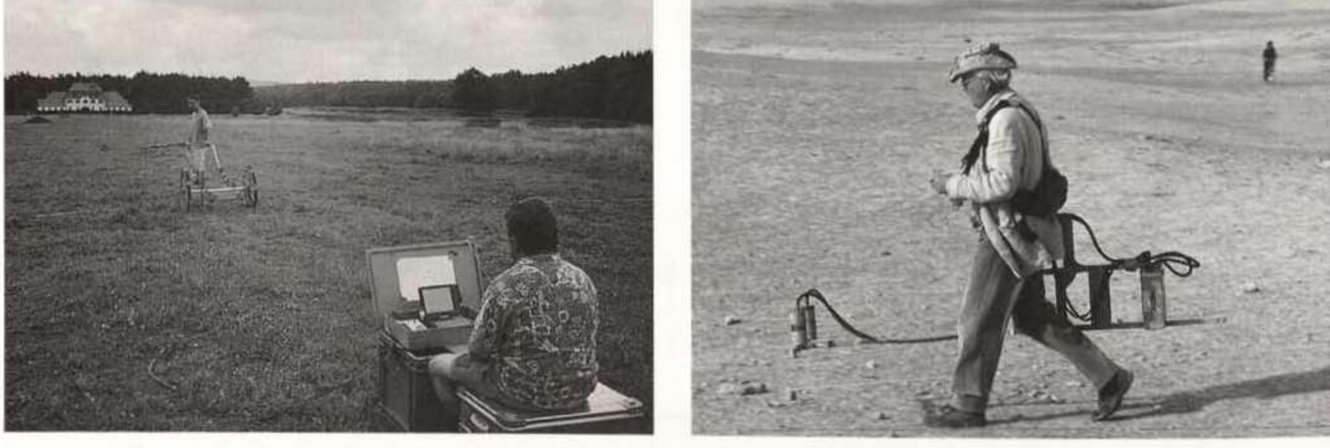


Fig. 1. Wolfertschwenden, Roman burial or mausoleum directly under a power line, duo-sensor configuration of CS2/MEP720 system, digital image of the magnetogram of six 20 m grids, raster 0.25/0.5 m, dynamics -6.4/+6.4 nT in 256 greyscale (white/black). a) reduction of the diurnal variation by the line mean, speed dependent shift correction, no grid edge matching. b) linear reduction of the static field of the high voltage pole in 25 m distance by highpass filtering and desloping, same technical data as a)

The caesium magnetometry with the so-called duo-sensor configuration became the most successful method for magnetic prospection used by the Munich team (H. Becker and J. W. E. Fassbinder). Available since 1996 when the Scintrex SMARTMAG SM4G-Special came on the market, this magnetometer system was nearly exclusively used for our international cooperation work in many countries under most variable climatic and geologic conditions. This paper describes the development of the multi-sensor technique in caesium magnetometry and points out that speed is as important as special resolution and sensitivity for magnetic prospecting in archaeology.

For geophysical prospecting in archaeology the three 's' are required: sensitivity, speed and spacial resolution. These principles for magnetic prospecting are followed in Vienna (Melichar 1990, Neubauer 1990, Eder-Hinterleitner et al. 1996) and Munich (Becker 1990, 1995, 1996, 1997, 1998) by high resolution caesium magnetometry, but other groups are following. The developments in the Munich laboratory with caesium magnetometers V101 (Varian, Scintrex) and CS2/MEP720 (Picodas/Scintrex) met most of the three 's' requirements, but could be still improved in speed (Becker 1997). Fluxgate gradiometers which are widely used in the UK are limited in sensitivity especially applied at most of the low susceptibility contrast sites in Europe (Becker, Jansen 1996). There exists also a five sensor fluxgate gradiometer system (delta Z) developed in Kiel (Stümpel 1995), but this may be also insufficient regarding sensitivity at low susceptibility soils. The V101- and CS2/MEP720 caesium magnetometer systems have been developed for one track gradio- or variometer configuration of the sensors, which ideally compensates the outer geomagnetic variations. It took the author almost two years realizing, that the two sensors of the gradiometer CS2/MEP720 could also be moved parallel in fieldwork covering two tracks for total field measurement at same hight above ground. This simple "trick" doubles the sampling-speed. Every sensor added to the system multiplies the survey speed and opens a wide range for magnetic prospecting over large areas with limited time.

Fig. 2a, b. Duo-sensor on wheels with CS2/MEP720 system (application at Seehof, Photo J. W. E. Fassbinder) and one man carried SMARTMAG SM4G-Special (H. Becker in Resafa 1999, first use by H. Becker at Monte da Ponte in 1995)



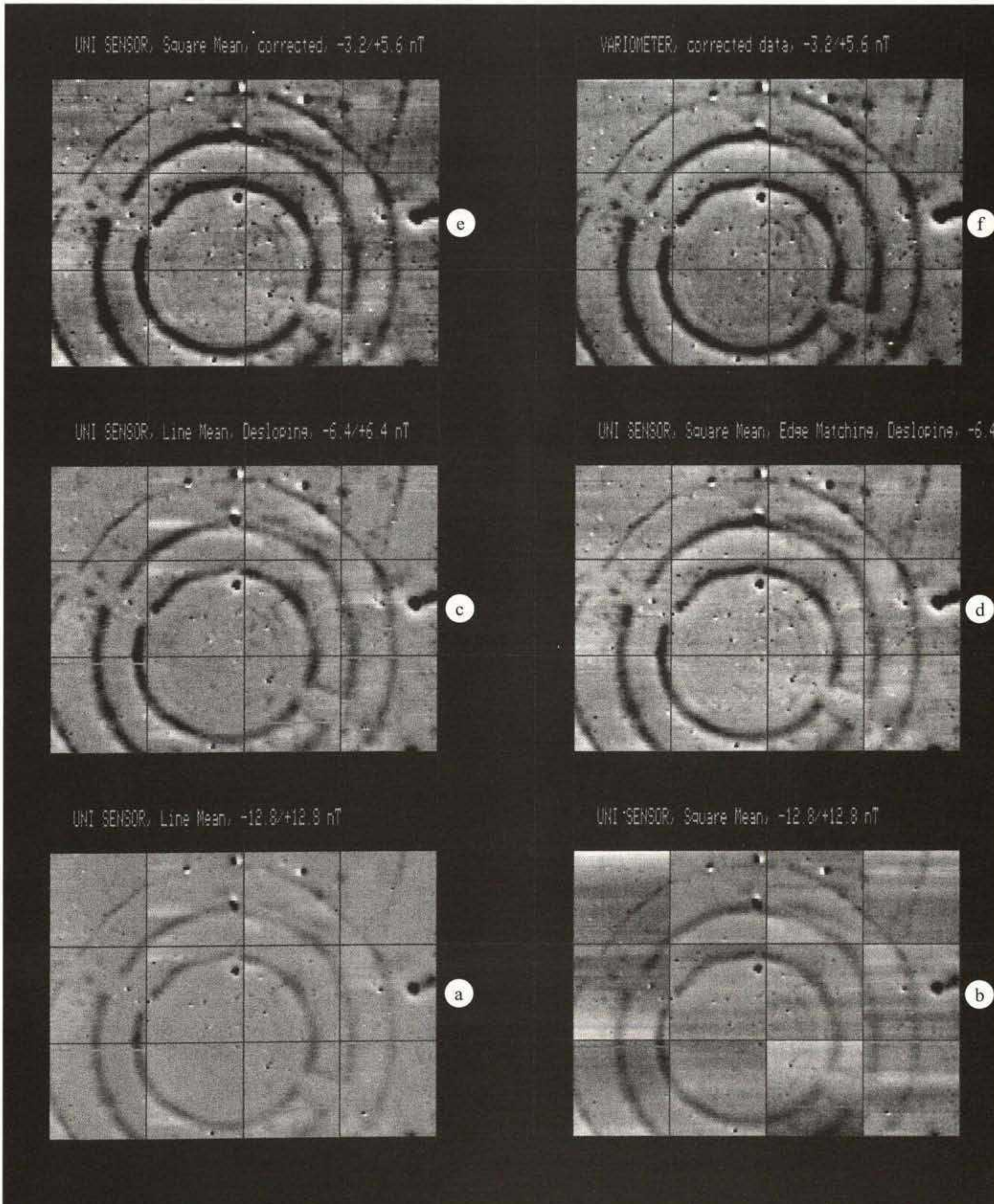


Fig. 3a–f. Reprocessing uni-sensor Schmiedorf-Osterhofen 1986. Caesium magnetometer Scintrex/Picodas CS2/MEP720, sensitivity 0.001 nT, raster 0.5/0.25 m, 20 m grid. a) uni-sensor, line mean reduction, dynamics -12.8/+12.8 nT. b) uni-sensor, square mean reduction, dynamics -12.8/+12.8 nT. c) uni-sensor, line mean reduction, edge matching and desloping, dynamics -6.4/+6.4 nT. d) uni-sensor, square mean reduction, edge matching and desloping, dynamics -6.4/+6.4 nT. e) final result, uni-sensor, square mean reduction, corrected, dynamics -3.2/+5.6 nT to be compared with f) variometer mode, corrected data, same dynamics -3.2/+5.6 nT

Duo-Sensor configuration for caesium magnetometer CS2/MEP720

Every student in geophysics was trained that the base for high sensitive magnetic prospecting is the complete reduction of the natural and technical temporal geomagnetic variations (micropulsations, diurnal variation, powerlines, etc.) by measuring the difference between two sensors in vertical gradio- or variometer mode. However first tests with the CS2/MEP720 Picotesla sys-

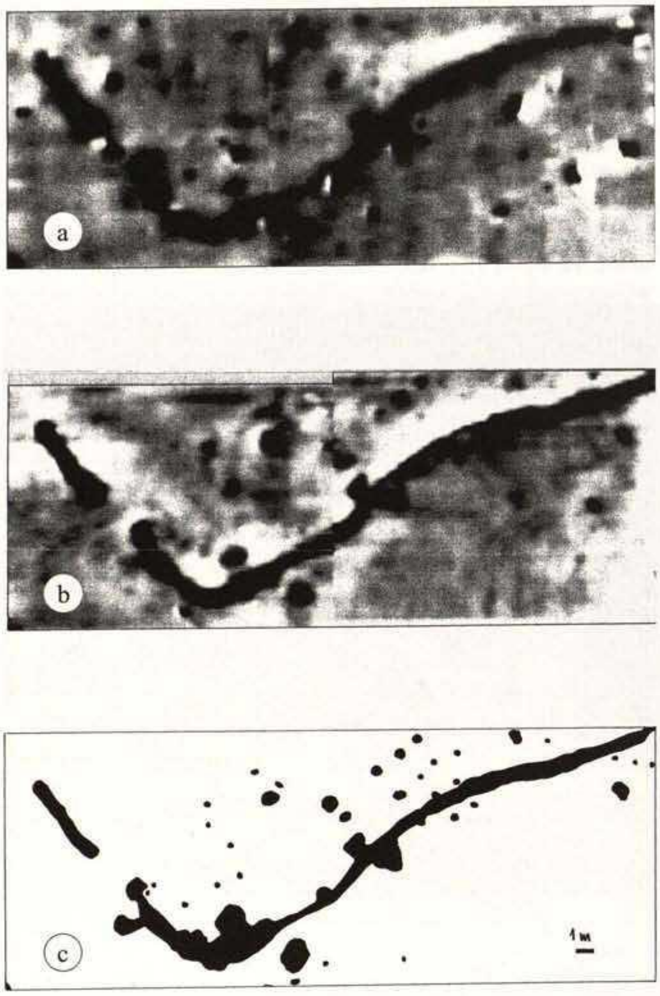


Fig. 4a–c. Murr 1995–1996. Example for surface- and open trench prospecting with duo-sensor on wheels (CS2/MEP720) and man carried application (Smartmag SM4G-Special). (a) Sureface measurement with CS2/MEP720 on wheels; raster 0.5/0.25 m; dynamics -3.2/+3.2 nT. (b) Open trench measurement with hand carried SMARTMAG SM4G-Special, raster 0.25/0.125 m, dynamics -3.2/+3.2 nT. (c) Archaeological findings in the excavation

tem in July 1995 have shown, that the two sensors can be arranged horizontally measuring the total intensity of the geomagnetic field at two parallel tracks at same hight above ground (typically 0.3 m) (Fig. 2a). The survey time in the field is reduced to half. A 20 m grid in 0.5/0.1 m raster can be measured in less than 10 min, an hectar in the same raster (200,000 samples) in 4 to 6 hours.

The key to this new technique is given by the magnetometer processor MEP720 (Picodas, Canada) with electronic bandpass filters selectable for 0.7, 1 and 2 Hz for cancellation of high frequency magnetic disturbances. Similar filters are used with Smartmag SM4G-Special (Scintrex). This offers also the opportunity for magnetic prospecting with Picotesla sensitivity directly underneath powerlines (Fig. 1) or beside electric railways. Also the natural temporal high frequency geomagnetic variations (micropulsations) are cancelled by the same method of electronic bandpass filtering. Only the diurnal geomagnetic variation is reduced by the calculation and differentiation of the line means in a 20 (40) m grid, which follow the main course of the geomagnetic field (Fig. 3a–d). At the moment the diurnal geomagnetic variation shows a extremely smooth curvature because of the minimum of sunspot activity in 1996. For control one has to calculate also the square mean over a 20(40) m square because the line mean would cancel a magnetic alignment in line direction. The square mean reduction might be also important for the detection of deeply buried features. Only temporal variations with a wavelength compatible to the measuring time for a 20 m line (15–20 sec) can not be cancelled by this method. But for the identification of archaeologically relevant anomalies there may be no problem, because these long wavelength disturbances will not show up in the next line and can be identified easily (e. g. Fig. 4).

The first example for a duo-sensor measurement with CS2/MEP720 system shows the magnetic prospecting in July 1995 for a Roman villa near Wolfertschwenden/Bavaria. The area containing a ring ditch possibly of a Roman burial or mausoleum is situated directly under a 500 kV powerline. The high frequency noise had been completely cancelled by electronic filtering with 1 Hz bandwidth, and the diurnal geomagnetic variation by numerical reduction on the line means in the 20 m grids. Only the strong static magnetic anomaly of a huge steel carrier in 25 m distance had been removed by highpass filtering (10 x 10 points) and desloping. Today this archaeological monument is partly covered by a cement paved road which can be identified in the magnetogram by its low noise signature (Fig. 1).

Fig. 5. Ostia Antica 1996. "Magnetoscanner" on its first run, magnetic prospecting with two SMARTMAG SM4G-Special in quadro-sensor configuration on a non magnetic cart (total weight = 48 kg)

In order to show the validity of the used software for the line mean and square mean reduction of the temporal geomagnetic variations a reprocessing of the magnetic prospecting of the Neolithic ring ditch site of Schmiedorf-Osterhofen in Lower Bavaria was made for a uni-sensor configuration. This site had been measured in 1994 with the CS2/MEP720 system in variometer mode (one sensor fixed as base station) in 0.5/0.25 m raster and had been published for demonstrating the magnetic anomalies of palisades in the Picotesla range (Becker 1995). Despite this rather disadvantageous case of a uni-sensor reprocessing with temporal geomagnetic variation up to 20 Nanotesla over the measuring time of a 20 m grid, the result after line mean reduction of the moving uni-sensor is almost compatible with the magnetogram in variometer mode (= difference of the moving sensor and the base station) (Fig. 3a–d).

In the meantime the duo-sensor configuration is applied as the standard method for magnetic prospecting carried out by the Munich team. The limits of this powerful method for large coverage in archaeological prospection are found on areas with nearby moving strong magnetic sources like trucks, caterpillars or tank lorries. But for "normal" applications in agricultural areas the duo-sensor configuration for caesium magnetometers with selectable bandpass filters may be used for double speed or double spacial resolution.

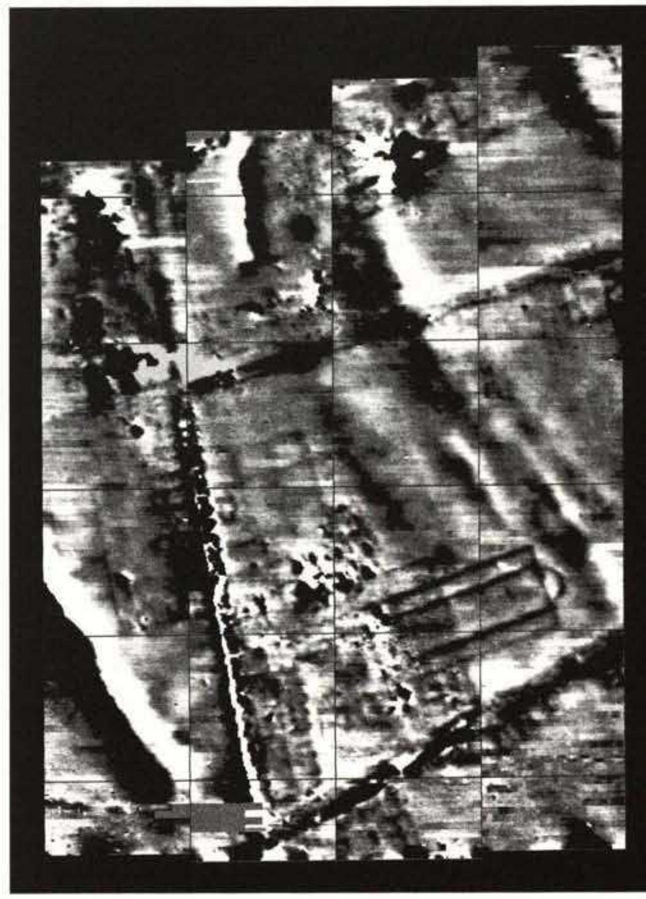


Fig. 6. Ostia Antica 1996 Magnetogram (detail with the basilica of Constantinus I.) in greyshading, dynamics -50.00/+50.00 nT in 256 greyscale (white/black), sensitivity ± 10 pT, raster after resampling 0.5/0.25 m, 1 Hz bandpass-filtering, reduction on 40 m line means, 40 m grid, Mag Nr. OS96-A

Duo-sensor configuration for Caesium magnetometer Scintrex SMARTMAG SM4G-Special

Since 1996 there are two new caesium magnetometers as gradiometer (or variometer) systems available: SMARTMAG SM4G (Scintrex, Canada) with 10 pico Tesla (0.01 nT) sensitivity at 0.1 sec cycle and G586 (Geometrix, Canada) with 0.5 nT at same speed. On request Scintrex made some modifications for archaeological prospecting and a SMARTMAG SM4G-Special caesium gradiometer was extensivly and successfully tested in the duo-sensor configuration on the Copper Age site of Monte da Ponte (Portugal) in March 1996 covering about 7 ha. The same site was already used as a test area for CS2/MEP720 system in variometer mode in 1994 and 1995, which covered about 4 ha (Becker 1997). Because of the rough topography of the site the instruments were used only in a carried application with a manual distance triggering at 5 m intervals. The quality of the data was found to be better with the SMARTMAG than CS2/MEP720 because of improvements of the resampling program with a perfect speed dependent shift correction. Due to the rather strong magnetisation contrast of the site the difference of the sensitivity by a order of 10 between the two systems was not significant.

Another direct comparison of duo-sensor configurations of CS2/MEP720 and SMARTMAG was carried out in the Neolithic settlement near Murr, Bavaria in July 1996 (Becker 1996). The whole site and the vicinity (about 10 ha) was surveyed in July/August 1995 with CS2/MEP720 system in duo-sensor configuration on wheels with 0.5/0.25 m raster. A small area was remeasured with SMARTMAG in a man carried duo-sensor version with 0.25/0.125 m resolution over the open trench of the excavation, after the top soil had been removed by a caterpillar tractor. The comparison between the high resolution magnetograms with the excavation illustrates the main problems of such prospecting work especially of detecting the detailed structure of prehistoric houses (postholes) (Fig. 4a–c). The correspondence of the high resolution SMARTMAG magnetogram over the open trench with the archaeological features in the ground is almost perfect. Even the magnetic anomalies of the postholes of a Neolithic house show up clearly. These anomalies are also visible in the magnetogram of the closed surface, but they are badly disturbed by magnetic features in the top soil. Therefore it may be rare detecting a single posthole from the surface because of the noise of the surface and the top layer. Only typical houses are identifiable in high resolution magnetograms over big areas, when the whole layout of houses become visible.

The main advantage of the SMARTMAG system compared with CS2/MEP720 is the fact that it can be operated as a one man carried application due to less battery weight and miniaturisation of the electronics and data storage which is kept in a small console (Fig. 2b). For the CS2/MEP720 system two persons were necessary because of the separation of the sensor unit and the magnetometer-processor/data storage/battery unit. The long cables between these 2 units caused lots of problems espe-

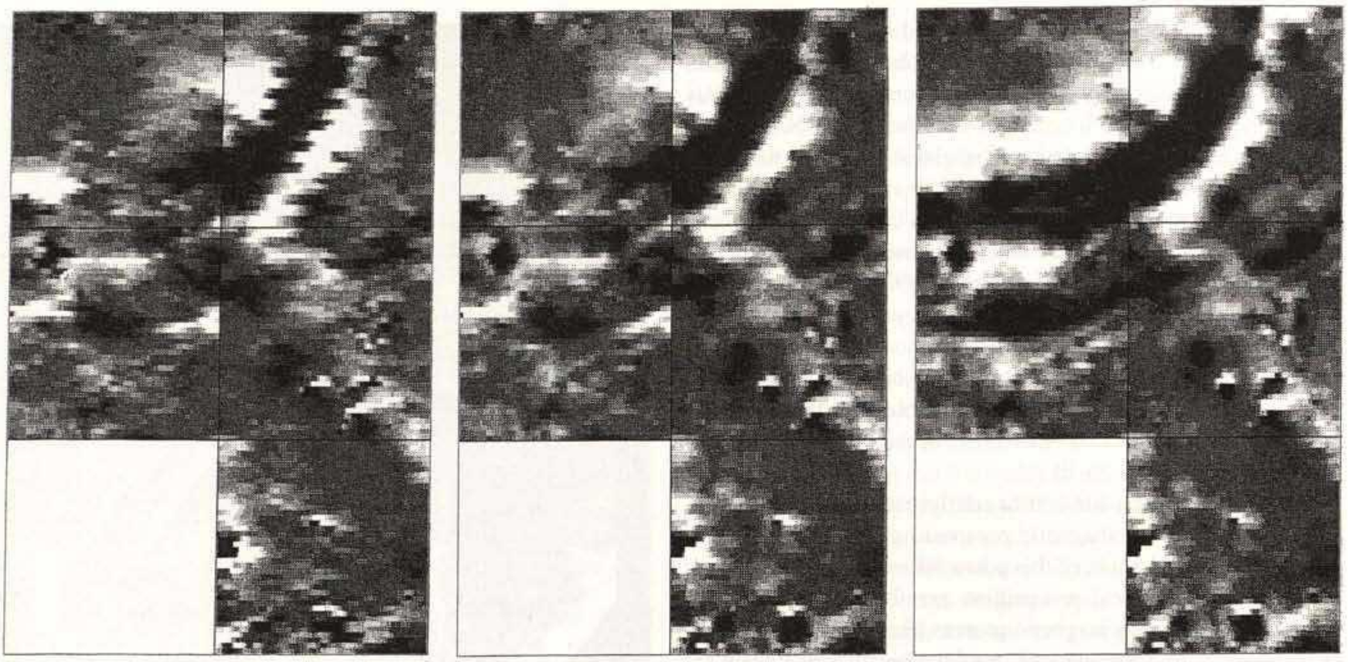


Fig. 7. Monte da Ponte. Speed dependant shift correction and influence of the line mean and square mean reduction of the temporal geomagnetic variation. Magnetogram of five 20 m grids at the second wall (see Fig. 4), raw data (left), speed dependant shift correction with reduction on the line mean (middle), same with reduction on square mean (right), which shows the complete trace of the second wall

cially under rough surface conditions, where a third person was needed only for clearing the cables. With SMARTMAG even as one man carried application with duo-sensor configuration 1.5 ha per day at 0.5/0.1 m spacial resolution (200,000 samples) can be covered easily. On large areas 40 m grids are used instead of 20 m which again improves the survey speed. Some modifications of the data acquisition program of SMARTMAG with automatic increment of line number and reset of station number after stop still could speed up field operation. The limits of ground coverage for high sensitivity/high speed/high spacial resolution caesium magnetometry are no more set by the instrument but only by the walking persistence of the operator.

Quadro-sensor configuration for caesium magnetometer SMARTMAG SM4G-Special

The experiments with the duo-sensor configuration may have demonstrated that modern caesium magnetometers like SMARTMAG offer the opportunity also for a quadro-sensor configuration simply by arranging the four sensors of two gradiometer systems horizontally. The whole setup of such a system consisting of the four sensors A, B, C, D with four magnetometer/sensor electronics, two consoles AB and CD and four batteries have been mounted on a non magnetic cart. The quadro-sensor system on wheels reach a total weight of 48 kg (non magnetic cart = 18 kg, batteries = 14 kg and 4 magnetometer systems = 16 kg) and can still be operated in the field by one person (Fig. 5).

A first test of a quadro-sensor system was carried out in August 1996 at Ostia Antica, the ancient harbour of Rome. An test area of 15 ha was measured in the regio V of Ostia during seven days of field-work. In the meantime under smooth surface conditions the prospection of 1 ha with 0.1/0.5 m spacial resolution may be done with the quadro-sensor chariot in 2 hours. The project in Ostia resulted in the discovery of the basilica of Constantinus I. (Fig. 6, for details refer to Becker 1999 later in this volume).

A compensated quadro-sensor configuration was also tested 1996 in the prospection for a Roman road station near Oberdrauburg/Austria, where the fifth magnetometer was successfully used as base station in variometer mode for monitoring the temporal geomagnetic variations. No difference was found between this compensated (4 + 1 sensor) configuration and the double duo-sensor processing.

Resampling procedure and data processing

Fast moving sensor systems need special procedures for sampling and data processing. The major advance for fast field measurements with high spacial resolution is the time mode sampling instead of the event triggered sampling at distinct sample intervals at 0.5 m. Modern magnetometers allow ten measurements per second with picotesla (pT) sensitivity (MEP720/-CS2, Picodas/Scintrex), 10 pT sensitivity (SMARTMAG SM4G, Scintrex) and 50 pT sensitivity (G586, Geometrix). The high frequency geomagnetic time variations are canceled by bandpass filtering 0.7, 1, 2 Hz for Picodas MEP720 or 1,2,8 Hz for Smartmag SM4G. As mentioned above the diurnal variation is reduced to the mean value of a 40 m line and also to the mean value of a 40 m square to be sure not canceling anomalies directly in the line. The cycle of Picodas MEP720 and Scintrex SMARTMAG SM4G can be set to 0.1 sec (10 measurements per second) which means a spacial resolution of 10 – 15 cm at normal to fast walking speed. With rather fast sensor moving systems the problem of a data shift must be solved, this means in zig zag mode a displacement of the sensor's position even after exact distance triggering. The measuring time of the magnetometer should be known for exact distance triggering, which is also dependent to the walking speed. This shift correction must be calculated with a time constant, which is typical for specific magnetometer types (0.25 for MEP720/CS2 and 0.75 for SMARTMAG). Only a speed dependent shift correction results in a 'sharp' image for the magnetogram (Fig. 7a–d).

Conclusion and future aspects

In 1996 an area of about 80 ha, but in 1997 an area of 140 ha with 0.5/0.1 m spatial resolution (70 Million readings) had been measured with CS2/MEP720 and two SMARTMAG SM4G-Special systems. The prospecting program in Bavaria was handicapped by restrictions for transportation of the equipment on site for the two survey teams. The development of the basic instrumentation for high speed/high resolution magnetic prospecting even for routine application in the archaeological monument conservation programmes has been finished now. Possibly a compensated multi-sensors configuration (4+1 sensor) will get more importance in the future after the sunspot minimum in 1996. Automatic positioning systems consisting of GPS for beginning and end of a line combined with wheel-triggers for exact distances on the line may speed up field procedure even more. The two MEP720 systems with four CS2-sensors and five SMARTMAG SM4G-Special caesium magnetometers with three consoles which can be operated as 2 complete compensated quadro-sensors systems, which will attribute a important part in archaeological research and archaeological monument conservation.

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