



On the Use of Fluxgate 3-Axis Magnetometers in Archaeology: Application with a Multi-sensor Device on the Site of Qasr 'Allam in the Western Desert of Egypt

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**On the use of fluxgate 3-axis magnetometers in
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On the use of fluxgate 3-axis magnetometers in archaeology: application with a multi-sensor device on the site of Qasr ‘Allam in the Western Desert of Egypt.

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Running head: Fluxgate 3-axis magnetometers in archaeology: a multi-sensor device

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Abstract

Fluxgate 3-axis magnetometers are seldom used on archaeological sites due to their lack of precision. Nonetheless, they offer light weight, low power consumption and the ability of compensation of the magnetization of the prospecting device. This study proposes to use calibration and compensation processes developed for space research and aerial measurement to build a multi-sensors and georeferenced device to assess deep and shallow objects for large scale archaeological investigations in Qasr ‘Allam, in a context of heavy sedimentary coverage and uneven surface. The use of the device on the site in combination with potential field transformations of the signal such as the double reduction to the pole and the vertical derivative reveal a vast irrigation system as well as a large cultic facility. A comparison with gradiometric measurements shows a resolution at least as good for shallow sources. The precise positioning allows to perform targeted excavations which validate the geophysical interpretations and offer new archaeological information. These discoveries give enough proof to the local authorities to clearly delimit the area to be protected from the threatening progression of agricultural fields.

Keywords: Magnetometry, 3-axis fluxgate magnetometers, Multi-sensors, Magnetic compensation, Potential field transformations, Vertical vector fluxgate.

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36 Introduction

37 Situated in the Western Desert of Egypt, the oasis of Bahariya (Figure 1) is inhabited
38 since Prehistory (Svoboda, 2006; 2013). The main phases of the ancient Egyptian
39 civilization can be observed in the area. However, they are not as well documented as in
40 the Nile valley because only a few scholars have studied the Bahariya region. This is
41 mainly due to access difficulties until construction of road infrastructure in the mid-20th
42 century. The growing number of investigations took place since the end of the nineties.
43 They revealed the archaeological potential of the area for illustration of a locally badly
44 known period, ranging from the Third Intermediate Period to the Roman times, (i.e.
45 from the 9th century B.C. to the 3rd century A.D. (Colin, 2013a, pp. 151–152)). This
46 paper focuses on the site of Qasr ‘Allam (Figure 1), which integrity is threatened by
47 heavy sedimentary processes and the rapid site destruction by recent increases in
48 agricultural development. Geophysics is used to locate and study the archaeological
49 remains of a historically significant dwelling.

50 The site of Qasr ‘Allam

51 Before any archaeological study, the site of Qasr ‘Allam was known mostly as a
52 rectangular structure emerging from the sand which was interpreted by the inhabitant as
53 an Arabic fort (Colin and Labrique, 2003, pp. 169–170). More than ten years of
54 excavation then revealed facilities buried within sand and mud to be composed of
55 mudbrick buildings of different natures, such as housings, storerooms and workshops
56 (Figure 2, A-B-C). These structures were interpreted as part of a wide religious
57 estate, the “Domain of Amun” according to stamped potteries found in the domestic
58 dump sites of the dwellings. Two periods of occupation can be identified from 9th to 7th
59 centuries B.C. (Colin, 2011, pp. 57–68). A complex network of fossilized irrigation
60 structures can be identified through the traces of wells as well as open and underground
61 channels surrounding the dwelling. In nowadays arid landscape most of these structures
62 are partially or totally covered with sand. Often, only the materials excavated during
63 construction and maintenance are visible on the surface (Figure 2, A-D-E-F).

64 These discoveries might indicate that the site could be a well preserved example of a
65 complete cultic facility with three main components: a cultic core, associated domestic

buildings and its surrounding agricultural domain, of which most parts are still buried within the ground. The structural organization of the excavated buildings suggests indeed that they were only an annex in the periphery of a much larger and central religious facility (Colin, 2011, pp. 65–66; Colin and Duvette, 2012, pp. 161–162). According to this hypothesis, the direction of the access ramp of a cellular foundation platform (Figure 2, A-B), whose typology is well known in the Nile valley (Spencer, 1979a, pp. 116–118; Spencer, 1979b; Traunecker, 1987; Leclère, 2008, pp. 630–636; Malecka-Drozdz, 2014), would indicate that the presumed core is located westwards, where lies a sand dune a few metres thick and where no archaeological traces are visible on the surface.

However, this hypothesis suffers from two uncertainties: 1- the lack of traces on the surface of the complex core; 2- the lack of information on the spatial and chronological links between the buildings and the irrigation system.

Answers to these problems could be gained from a geophysical imaging of the sub-surface. The surveying strategy should then take into account strong constraints: the area is highly threatened from the west by the agricultural development, increasing every year. Therewith, the whole dune shows an uneven topography scattered with dried halfa grass and bushes reaching a height up to 0.8 m. Thus, the prospection of the area must be fast and adapted to the roughness of the terrain.

Choice of the geophysical method

In such a context, the most appropriate solution would appear to be the magnetic methods. Geomagnetism is a popular and effective method for archaeological purposes (Linford, 2006; Gaffney, 2008). The main advantages are: -1- the anthropic traces show usually a strong contrast of magnetization with their surroundings; -2- the rapidity of measurement and light weight of the sensors to allow mapping of large surfaces with a high density of data. In addition, a first prospection using vector gradiometer (Geoscan FM256) was conducted between the sand dune and the platform in 2006 and 2010 by Tomasz Herbich (Herbich, 2011). It revealed irrigation structures as well as walls and foundation trenches (Colin, 2006; Colin, 2010; Herbich, 2011), thus giving evidence of a contrast of magnetization strong enough to identify the archaeological remains. However, the study of Herbich (2011) also revealed some limitations over the sand dune: the topography and vegetation make the implementation of a grid and the

measurements less than 0.8 m above the ground highly difficult without an intense preparation of the field. Moreover, one of the properties of the vertical gradient is to enhance short wavelength and to smooth out large wavelength variations of the magnetic field. This makes gradiometers extremely sensitive to shallow objects but of limited capability to identify deeper sources or lower magnetic contrasts as it is the case for Qasr ‘Allam (Blakely, 1995, pp. 324–326; Fagaly, 2001, pp. 327–328). This paper proposes to overcome these limitations by adapting the measurement of the total magnetic field with 3-axis vector fluxgate magnetometers, usually used in space research or mining exploration (Nabighian *et al.*, 2005), and more recently for the detection of unexploded ordnances (Munsch *et al.*, 2007), to archaeological surveys.

Method

Device

The core of the developed method lies in the measurement of the intensity of the magnetic field with fluxgate magnetometers. Such magnetometers (Figure 3, A) have the advantage of being light (80 g) and consuming low energy (< 1 W). Their three orthogonal sensors allow the measurement of the three components of the magnetic field at rate up to more than 1000 Hz (Primdahl, 1979), from which the total field can easily be calculated. The device developed for this study (Figure 3, C) is built around an in-house developed electronics (Figure 3, B). It powers the rest of the instrument, digitizes and stores the data of 1 to 8 magnetometers as well as 1 to 2 global navigation satellite system (GNSS) antennas. The electronics is mounted on a backpack and 4 magnetometers are placed 0.5 m apart from each other in front of the operator, one metre above the ground. A GNSS antenna is placed at the top of the backpack for the navigation. Both navigation and magnetic data are displayed in real time through a head mounted display (HMD). The device weighs less than 15 kg and can be operated by a single person who follows parallel survey lines set every 2 m and displayed in the HMD. Thus, georeferenced magnetic profiles are acquired every 0.5 m centred on each survey line without any preparation on the field. In Qasr ‘Allam, 5000 m² to 12000 m² of magnetic data were acquired per hour of measurement.

Calibration and compensation

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4 128 The major disadvantage of the fluxgate magnetometers is of being relative devices.
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6 129 This means that the instrument requires a precise calibration before each session of
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8 130 measurements to correct errors of sensitivity, offset and angle. This problem is well
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10 131 known and various techniques of calibration have been developed. In this study the
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12 132 calibration is done using a process developed initially for space research (Olsen *et al.*,
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14 133 2003). It consists in the rotation of the magnetometers (or the whole device) in all
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16 134 direction around a fixed point where the magnetic field can be considered steady. The
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18 135 registered variations of the magnetic field are therefore only due to the different kinds of
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20 136 errors which can then be minimized using a least squares method. The advantage of the
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22 137 process is that it also compensates the remnant and induced magnetization of the device
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24 138 itself (Munsch *et al.*, 2007). This makes the fluxgate the only magnetometer capable of
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26 139 such compensation, allowing compact multi-sensor devices as well as motorized
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28 140 measurements. A typical result of the effect of the calibration and compensation process
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30 141 on a magnetometer is shown in Figure 4, where computed parameters reduce the
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32 142 variations of measurements at a fixed point from around 200 nT to 0.3 nT.

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143 *Time-dependant variations*

144 Another issue with the measurement of the total magnetic field is the correction of
145 the time-dependant variations which may be caused by extra-terrestrial sources or
146 anthropic activities. Additionally, fluxgate magnetometers are not absolute and subject
147 to drift with the change of temperature (0.1 to 0.5 nT/°C according to the manufacturer).
148 In an environment affected by homogeneous but not linear temporal variations, as it is
149 often the case in urban areas, corrections can be made by using a magnetometer
150 installed at a fixed point (base station) during the measurements, thus recording only the
151 time dependant part of the signal. Such solution was not possible in Qasr ‘Allam due to
152 legal and logistical difficulties to have a base station on the site at the time of the study.
153 However, during the surveying hours (6 to 10 a.m.), time-dependant variations are
154 linear and can therefore be easily corrected. They are the result of a combination of
155 effects from a temperature drift as well as from far external sources of which the linear
156 variation is confirmed by using geomagnetic records of one of the nearest
157 INTERMAGNET observatory (Tamanrasset).

158 *Data processing*

The measurement provides the 3 calibrated components of the total magnetic field, from which the total magnetic intensity is calculated. In archaeology the prime interest is to measure/illustrate subtle spatial variations of the magnetic field. This is achieved by observing the anomalies of the total magnetic field's intensity. The anomaly is defined as the difference between the intensity of the measured magnetic field and the regional field (Blakely, 1995, pp. 178-180). The latest is computed using the International Geomagnetic Reference Field (IGRF) (Finlay *et al.*, 2010). The anomaly of the intensity of the total magnetic field can then be displayed either as profiles or as maps after a gridding computerized operation (D'Errico, 2005). The node distance of the grid is usually set as half of the distance between each magnetometer, i.e. 0.25 m in this study. After this procedure, the residual errors can lead to the appearance of a levelling effect between profiles (Fedi and Florio, 2003). To solve this problem, the differences at the crossing points between the values on magnetic profiles (in-lines) and traverses (tie-lines) are measured. Then, a constant to apply to each profile is calculated by a linear inversion to minimize the differences at the crossing points.

Results

The data acquisition over the Qasr 'Allam site took place in April and May 2012. Through 200 km of survey lines, more than 800 km of georeferenced magnetic profiles were recorded over an area about 340,000 m² (Figure 5).

Maps of magnetic anomalies

Usually, magnetic anomalies are represented using maps with a linear colour scale. Those consist in attributing a colour or grey tone to each node of the grid according to its value using a linear scale, as shown in Figure 6. Unfortunately, such a representation is often not sufficient to show accurately all the anomalies of a site, as they can range from a few to hundreds of nano-Tesla. A common solution to this problem is to display multiple maps with different scales to understand the anomalies from the largest to the smallest. Such a process might be time consuming and is not the most practical, as several maps have to be observed at the same time. To overcome this problem, we introduce another approach, the equi-populated mapping. An equi-populated map consists in attributing a shade (or colour) to each node using a non-linear scale in such a

189 way that all the shades are evenly distributed on the map. Thus, both small and strong
190 magnetic anomalies can be represented on a unique map, as shown in Figure 7.

191 From both representations (Figure 6-7), different kind of anomalies can be observed
192 on the site. Depending on their wavelength and shape, they can be ranked as follows.

- 193 - **Dipolar anomalies:** the strongest one in the west is due to a metallic pole; the
194 others are due to pieces of metal which are scattered everywhere on the site,
195 showing no particular distribution.
- 196 - **Short wavelength lineation** (about 1 m and less): they are the most common
197 anomalies and can be sorted in different subgroups. In the southern part, a high
198 concentration of curved lines following roughly N-S and E-W orientations is
199 present. A similar pattern can be seen in the northern part, though in much
200 smaller quantities. In the central part, the lines are straighter and follow an
201 orientation similar to the one of the large wavelength lineation surrounding
202 them.
- 203 - **Large wavelength lineation** (about 10 m): they approximately draw two
204 rectangles of 150 x 100 and 125 x 100 m in the central part of the map. Their
205 orientation is of a few degrees east.
- 206 - **North-south gradient:** the magnetic anomaly field decreases of about 20 nT
207 from north to south. This gradient cannot be explained by the regional magnetic
208 field as the International Geomagnetic Reference Field gives an increase of 3.8
209 nT from north to south. Thus, it is likely that such a gradient is due to a deep
210 local variation of the underlying geology.

211 These anomalies reveal the presence of different kind of magnetic heterogeneities
212 within the ground. Unfortunately, the shape, amplitude and position of an anomaly (as
213 well as the gradient) depend on multiple factor such as the shape, the orientation, the
214 position and magnetization of the source as well as the orientation of the regional
215 magnetic field. To decipher these anomalies, interpretation tools can be found in
216 potential field theory.

217 *Potential field transformations*

218 In any kind of magnetometry, the horizontal position of the sources is situated
219 somewhere in between the positive and negative extrema of a skewed anomaly. When

the wavelength is shorter than the size of the object, as it is often the case for very shallow objects, this is not a problem. Otherwise, as it is often the case in this study, the error can reach up to a few metres, which is not acceptable to locate properly archaeological trenches. Fortunately, the position of the remains can be obtained by using a potential field transformation known as the double reduction to the pole (DRP). The DRP consists in the calculation of the signal when both the magnetization and regional field are set vertical. Thus the anomalies become symmetrical with their maxima above their sources (Baranov, 1957). In the spectral domain, the operation is easily done by multiplying the spectrum of the anomaly by

$$\left[\frac{i\sqrt{u^2 + v^2}}{au + bv + ic\sqrt{u^2 + v^2}} \right] \left[\frac{i\sqrt{u^2 + v^2}}{a'u + b'v + ic'\sqrt{u^2 + v^2}} \right], \quad (1)$$

where u and v are the wavelengths associated with x and y directions, $i^2 = -1$, (a, b, c) the components of the unit vector in the direction of the regional magnetic field, and (a', b', c') the components of the unit vector in the direction of the magnetization (Bhattacharyya, 1965). The direction of the regional field is given by the IGRF while the direction of magnetization is either set as the same as the regional field when the ratio remnant/induced magnetization is near zero or obtained through successive iterations until the signal become symmetrical. In Qasr 'Allam, as the buildings are made in mudbricks, the orientation of magnetization was set equal to that of the regional field. In Figure 8, the anomalies become symmetrical, confirming this induced-only magnetization hypothesis. It must be noted that a simple reduction to the pole (only one vector set vertical) does not give the position of the source (Figure 8). The calculated DRP map gives therefore the position of sources visible or not on the surface (Figure 9). The archaeological interpretation stays difficult due to the presence of a very large wavelength anomaly most probably due to the geology. An easy way to enhance the shortest wavelength while smoothing the largest ones is the use of the vertical derivative. The operation is straightforward in the spectral domain and corresponds to the multiplication of the spectrum of the map by

$$\left(\sqrt{u^2 + v^2} \right)^n, \quad (2)$$

where u and v are the wavelengths associated with x and y directions and n is the order of derivation. Figure 10 corresponds to the map obtained after computing the vertical gradient of the DRP. It can be observed that the different lines are indeed enhanced and, most importantly, new lineations appear, especially in the central area.

Comparison with gradiometry

To assess the quality of the data for archaeological interpretation compared to gradiometry, the area surveyed by Herbich (2011) with a fluxgate gradiometer (Geoscan FM256) was also covered with the device developed in this study. The comparison of the results (Figure 11) shows that the proposed method reveals at least as many information as a vector gradiometer, even though the magnetometers are more distant from the ground (1 m). The vertical derivative map (Figure 11, A) appears more blurred than the gradiometric map (Figure 11, B) because it corresponds to a more distant acquisition from the sources.

Discussion

Interpretation of magnetic anomalies

The different maps give important information on the sources of the magnetic anomalies. The different linear anomalies can be interpreted as highly probable archaeological remains and are divided into three categories: long wavelengths, straight and non-straight short wavelengths. The non-straight linear elements with short wavelengths follow the same rough orientation pattern and shape as the irrigation structures visible on the ground surface. Some of them directly follow the traces of the irrigation structures observed on the ground surface. They are also mostly connected to an area of visible wells in the south eastern part of the site (Figures 2 and 5). This strongly suggests that those anomalies can be interpreted as irrigation structures, present not only under the sand dune, but also within the harder ground in the whole area (Figure 12). A targeted excavation of such a structure within the sand dune (Figure 12, area 15) confirmed open irrigation channels under 1.2 m of sediments (Colin and Duvette 2012, pp. 163-164). The filling sediments of one segment contained artefacts (potteries, terracotta figurines) of a well-attested type, according to the local typology of the 8th or the 7th century B.C. (Colin and Duvette, 2012, p. 164). This information validates the hypothesis that at least one part of the irrigation network was

277 contemporary to the cultic complex and that these farming devices most probably
278 belonged to the religious estate.

279 The two other types of linear anomalies can be interpreted differently. They are
280 situated in front of the access ramp of the platform, where the rest of a religious facility
281 can be expected. They show angular shapes, and display an orientation similar to the
282 one of the already excavated constructions. It can therefore be stated that they most
283 likely correspond to ancient buildings, thus enlarging the surface of the whole facility
284 from 40 000 m² to 150 000 m² (Figure 12). The variability of wavelengths can be
285 explained as different depths of sources, either due to the variability of the post-
286 abandonment sedimentary deposits, to different sizes of structures or to successive
287 archaeological periods. This is verified by two targeted excavations which started in
288 2013 and 2014 and are still in progress (Figure 12, areas 16 and 17). They revealed the
289 presence of cultic buildings corresponding to the magnetic anomalies at different depths
290 from 0.15 to 2.4 metres (Figure 12, area 16 and 17 respectively) which are related to
291 different occupations from at least the 8th or the 7th century B.C. to the 2nd century A.D.
292 and are affected by an environmental change (Colin, 2013b; Colin *et al.*, 2014). The
293 stratigraphy of the tested areas revealed that the sedimentary processes followed two
294 successive patterns. The ruins of the last occupation period (Roman times) are mainly
295 covered by aeolian sand in an arid context, but the remains of the former periods (from
296 Third Intermediate Period until Late Period or later) are filled with alluvial earthen
297 sediments, in a seemingly more humid context.

298 *The 3-axis fluxgate magnetometer total field approach*

299 In addition to the interpretation results, the study reveals the potential of the use of 3-
300 axis fluxgate magnetometers for large scale archaeological surveys. The light weight of
301 the magnetometers and their compensation ability allow the construction of a compact
302 multi-sensors device which can be operated by a single technician. At least four
303 simultaneous georeferenced magnetic data without any preliminary preparation of the
304 site can be acquired. The position of the magnetometers 1 m above the ground surface
305 allow to cover areas with more vegetation or a more uneven topography than with a
306 gradiometer device. Using vertical gradiometry, the lower probe is usually situated 0.2-
307 0.3 m above the ground surface. Thus, the proposed approach proved to be capable to
308 survey 5000 to 12000 m² per hour with a 0.5 m spacing and reveal at least as many

information on archaeological remains as a gradiometer through the use of the vertical derivative of the signal (Figure 11). The application of the DRP gives theoretically the exact horizontal position of the sources, unlike a single reduction which leads to a residual skewness. If the difference or even the use of a reduction can be negligible for very shallow sources, it is not the case with deeper sources, as shown in Figure 8 and the comparison between Figure 7 and 9.

Conclusion

The study both validates the application of an innovative approach to magnetic prospections in archaeology and reveals important information on the site of Qasr ‘Allam.

The use 3-axis fluxgate magnetometers and associated potential field transformations proved to be efficient to reveal information on both deep and shallow archaeological sources at a large and rapid scale. The results obtained in Qasr ‘Allam offer two prospects for further development: 1- doubling the speed of acquisition by doubling the number of magnetometers; 2- using the compensation ability to develop a smaller device which allows a few centimetres spacing between sensors for high precision small scale surveys.

In Qasr ‘Allam, the geophysical survey strengthens the hypothesis of the archaeologists. It locates remains of large scale buildings positioned in the expected area, whose general plan and direction are consistent with the hypothesis of a religious complex which combines a main cultic centre (totally covered by sediments) with economic and domestic facilities (of which parts were previously excavated). The accurate positioning of probable archaeological structures has allowed setting up targeted excavations that led to important results: parts of the irrigation network were already used from the 8th or 7th century B.C. in the vicinity of the buildings, the site was used for cultic purposes to at least the 2nd century B.C. and was impacted by a rapid environmental change from humid to arid in the latest periods of occupation. Without the results provided by the magnetic mapping, the thickness of the sedimentary deposits would have discouraged any attempt to explore the underground by means of the classical archaeological digging methods. A next step would be to investigate further the supposed cultic centre and the associated environmental change to find further chronological and functional data. According to its size and the thickness of sediment,

the study would need the combination of archaeological excavations and a more detailed geophysical method. In consequence, these conclusions encouraged the Egyptian Supreme Council of Antiquities (SCA) to delimit an area to be protected in 2014 to avoid the destruction of remains by the fast progression of agricultural fields.

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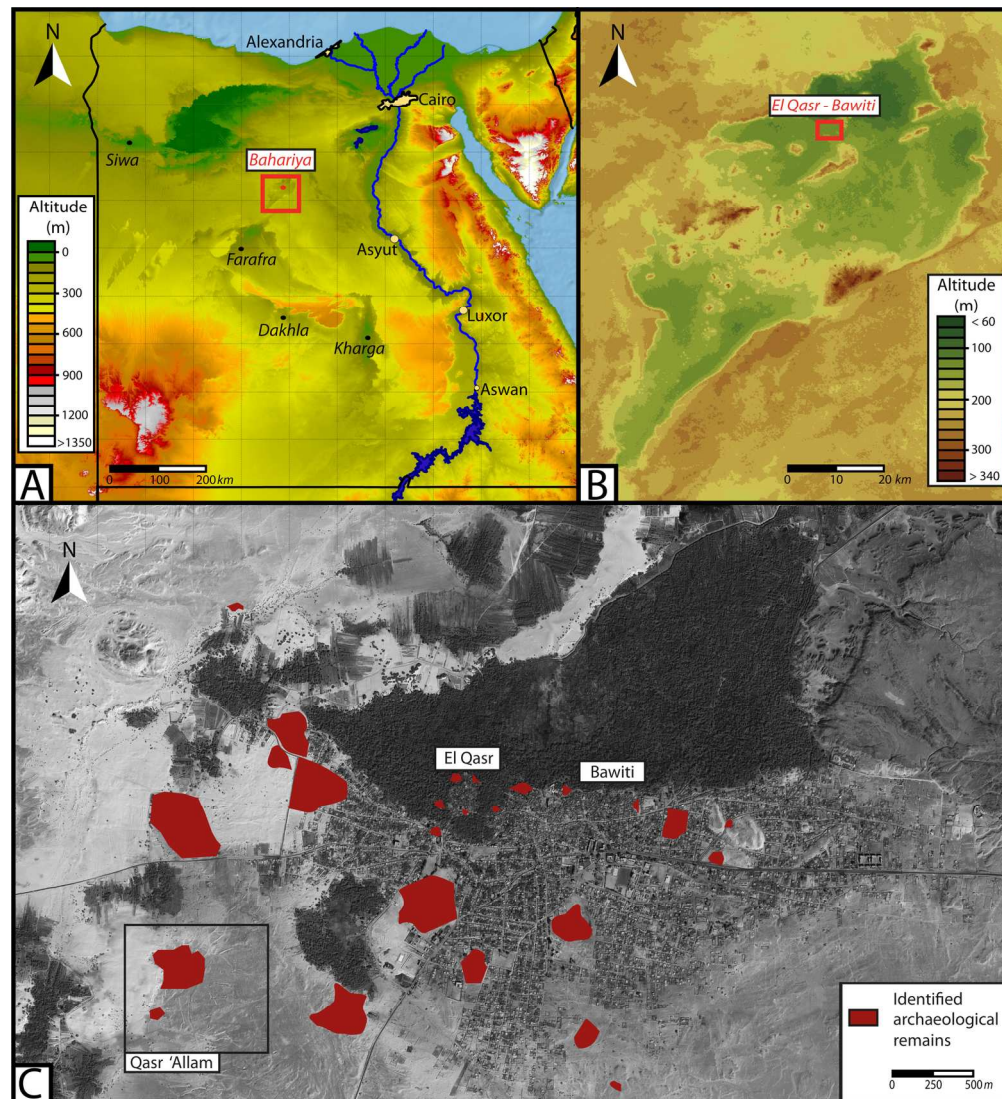
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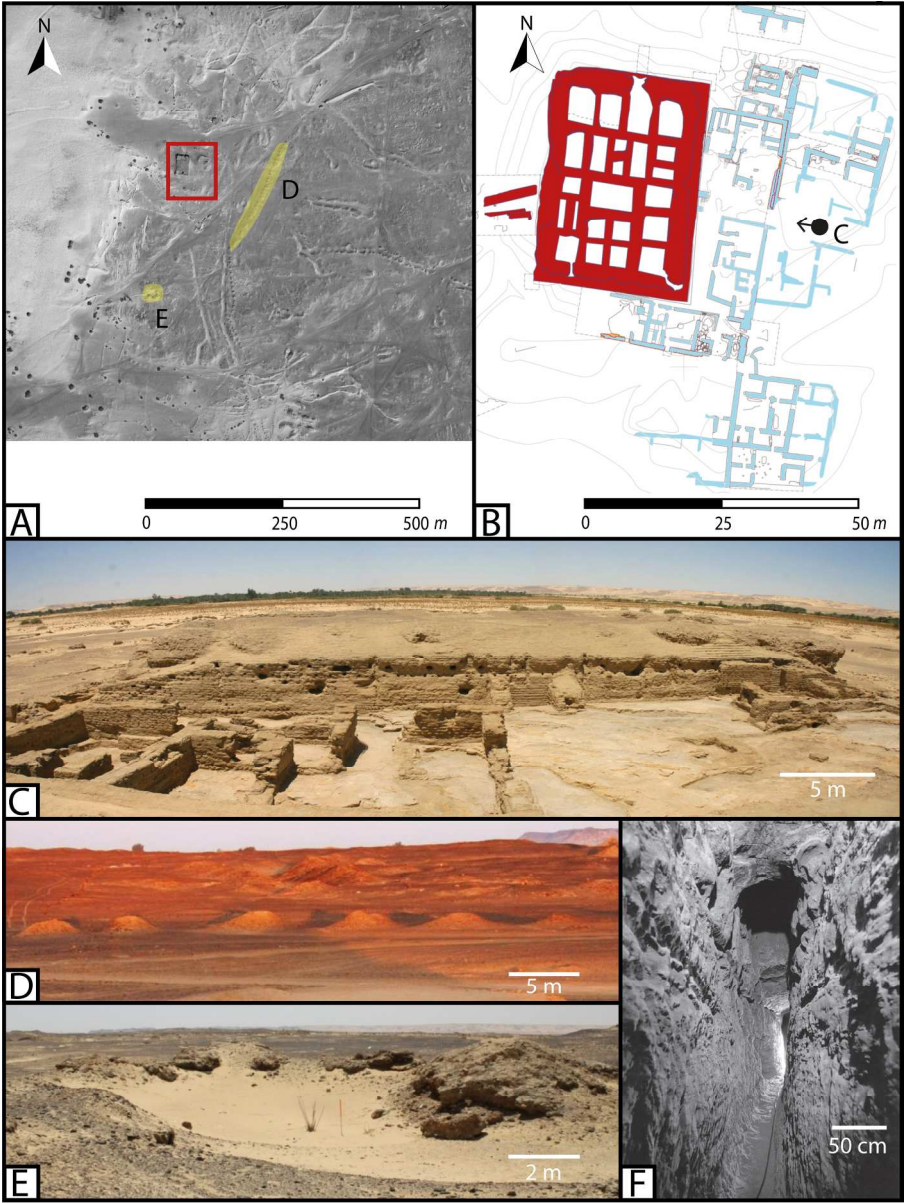
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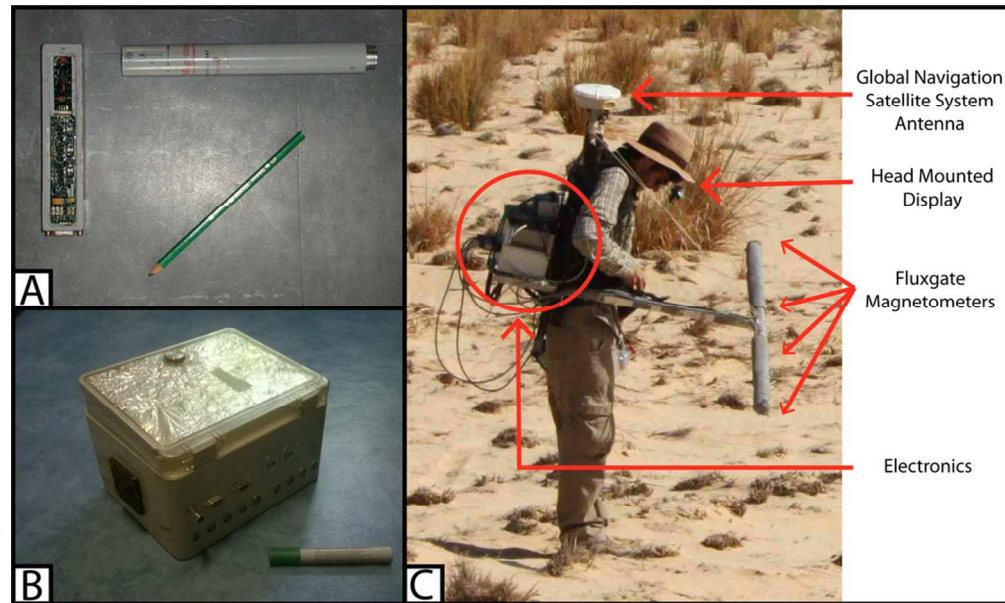
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A- Localization of the oasis of Bahariya on a topographic map of Egypt. B- Localization of El Qasr-Bawiti on a topographic map of Bahariya. C- Localization of the site of Qasr 'Allam on a satellite image of El Qasr and Bawiti. Topography from SRTM90 data available at <http://srtm.csi.cgiar.org/> (Jarvis et al., 2008). Satellite image from the satellites Quickbird taken in 2003 (DigitalGlobe Incorporated, Eurimage SPA licence). 164x180mm (300 x 300 DPI)

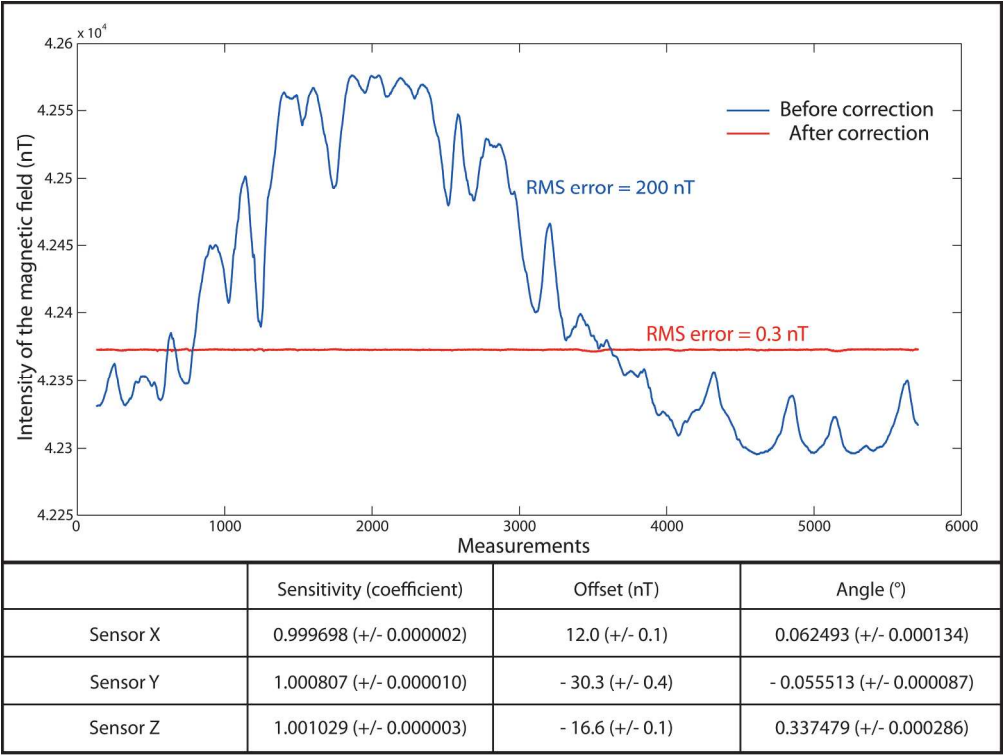


A- Localization of the excavated dwelling (red) and the irrigation structures of the pictures D and E (yellow) on a satellite image of Qasr 'Allam (DigitalGlobe Incorporated, Eurimage SPA licence). B- Architectural plan of the excavated dwelling and orientation of the picture C. Blue and red colours corresponds to buildings of a first and second period of occupation. C- Lateral view of the cellular foundation platform of the second period of occupation. D- Traces of an underground channel. E- Traces of a well. F- Inside of an underground channel similar to the ones of the site and excavated in the oasis of Kharga (Wuttman et al., 1996). 199x265mm (300 x 300 DPI)

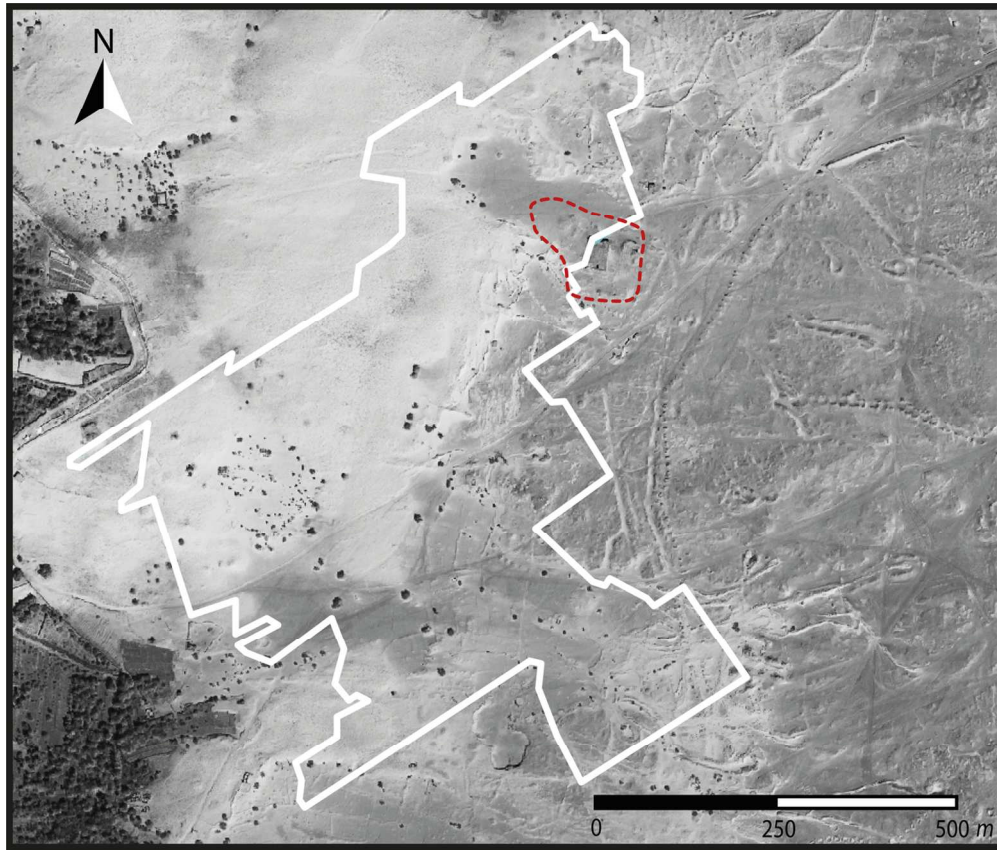


A- 3-axis fluxgate magnetometer (Bartington Inc., Mag-03 MC). B- Custom electronics with 8 magnetometer inputs developed by Institut de Physique du Globe de Strasbourg (IPGS). C- Multi-sensor device developed by IPGS.

90x54mm (300 x 300 DPI)

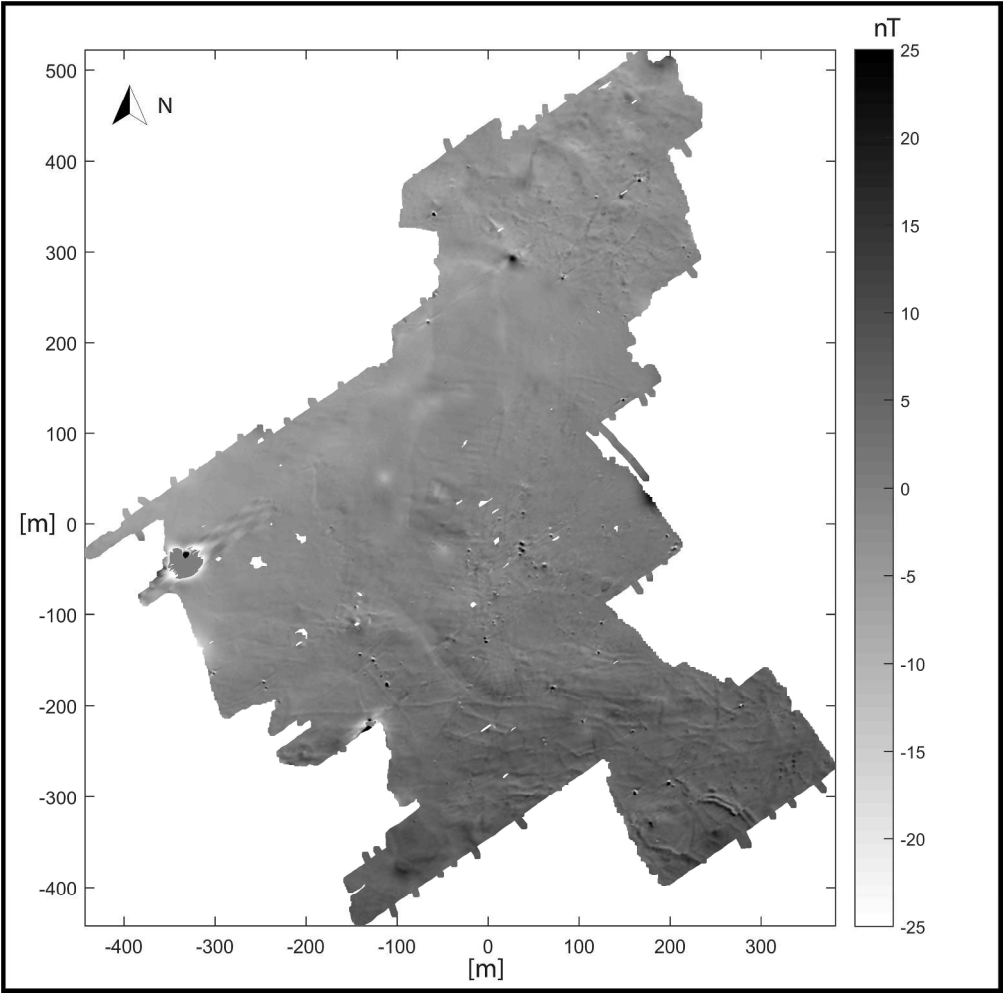


Intensity of the magnetic field measured by one magnetometer during the calibration and compensation process of the device before (blue) and after (red) corrections. Computed error parameters are given in the lower part of the figure.
112x85mm (600 x 600 DPI)

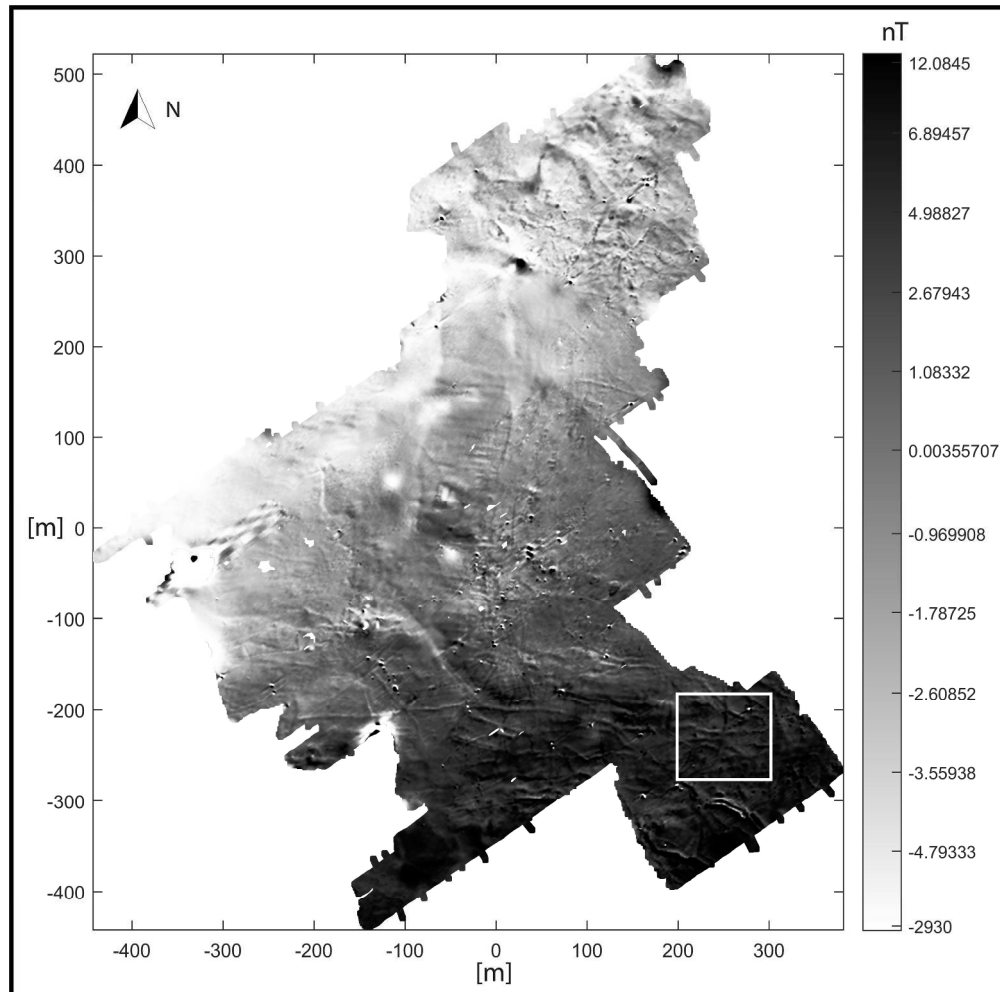


Satellite image of Qasr 'Allam (DigitalGlobe Incorporated, Eurimage SPA licence). The area of the geomagnetic prospection is delimited by the white line. The area of the excavated dwelling is delimited by the red line.

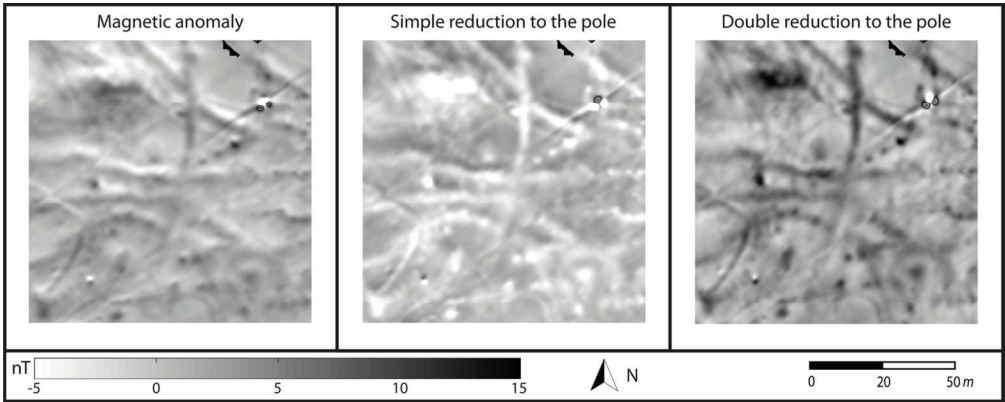
126x107mm (300 x 300 DPI)



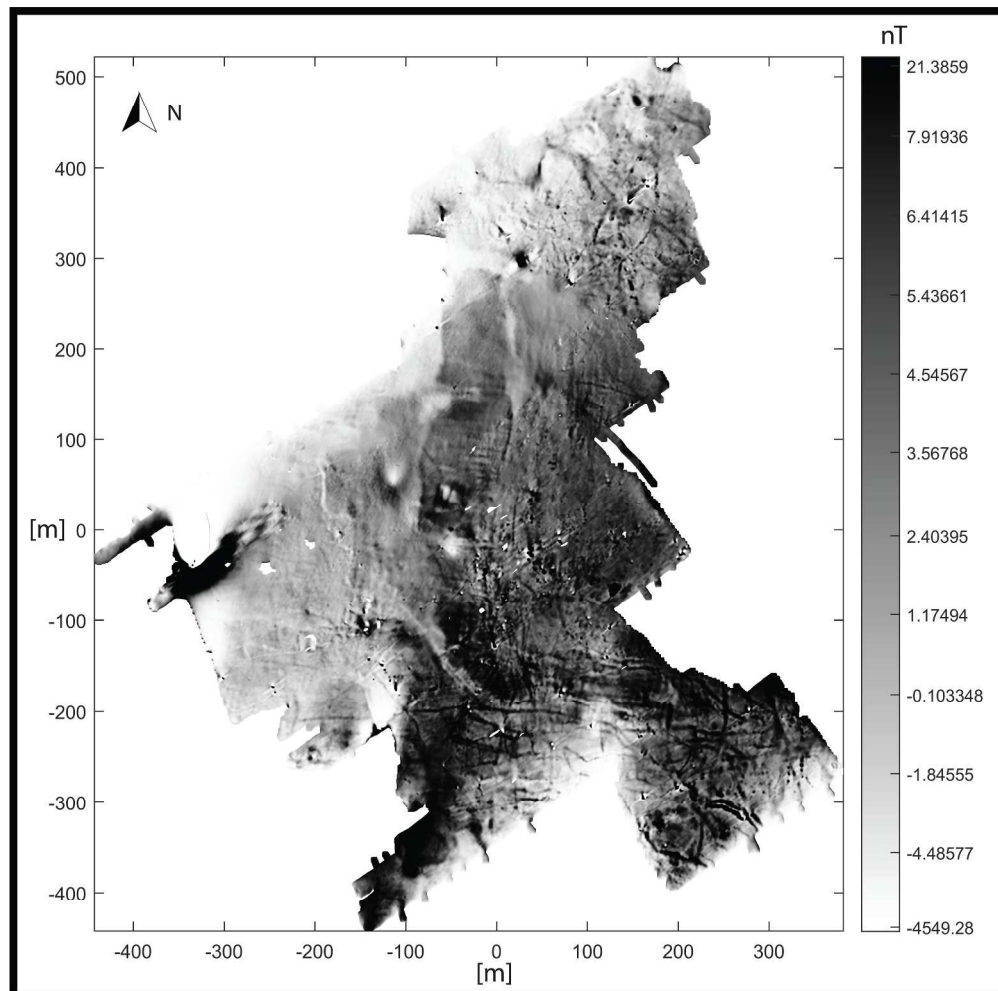
Map of the magnetic anomaly represented with a linear grayscale bar ranging from -25 to 25 nT.
148x147mm (600 x 600 DPI)



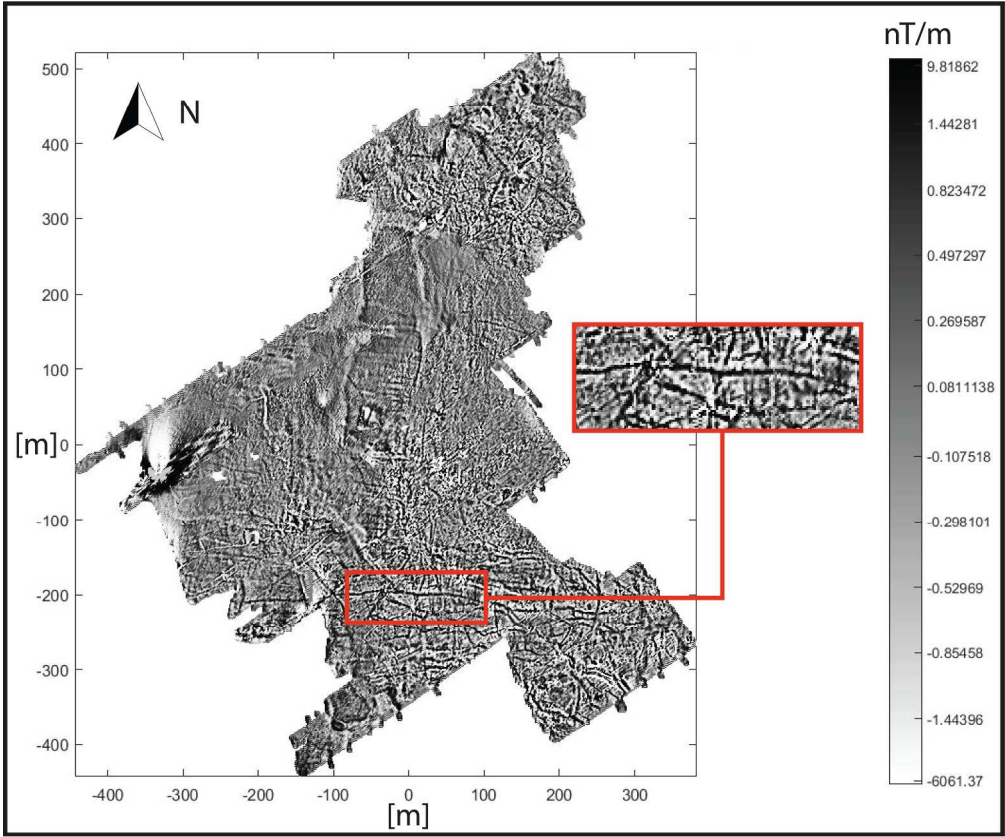
Map of magnetic anomalies represented with an equi-populated greyscale bar. The area delimited by the white line corresponds to the area displayed in Figure 8.
148x147mm (600 x 600 DPI)



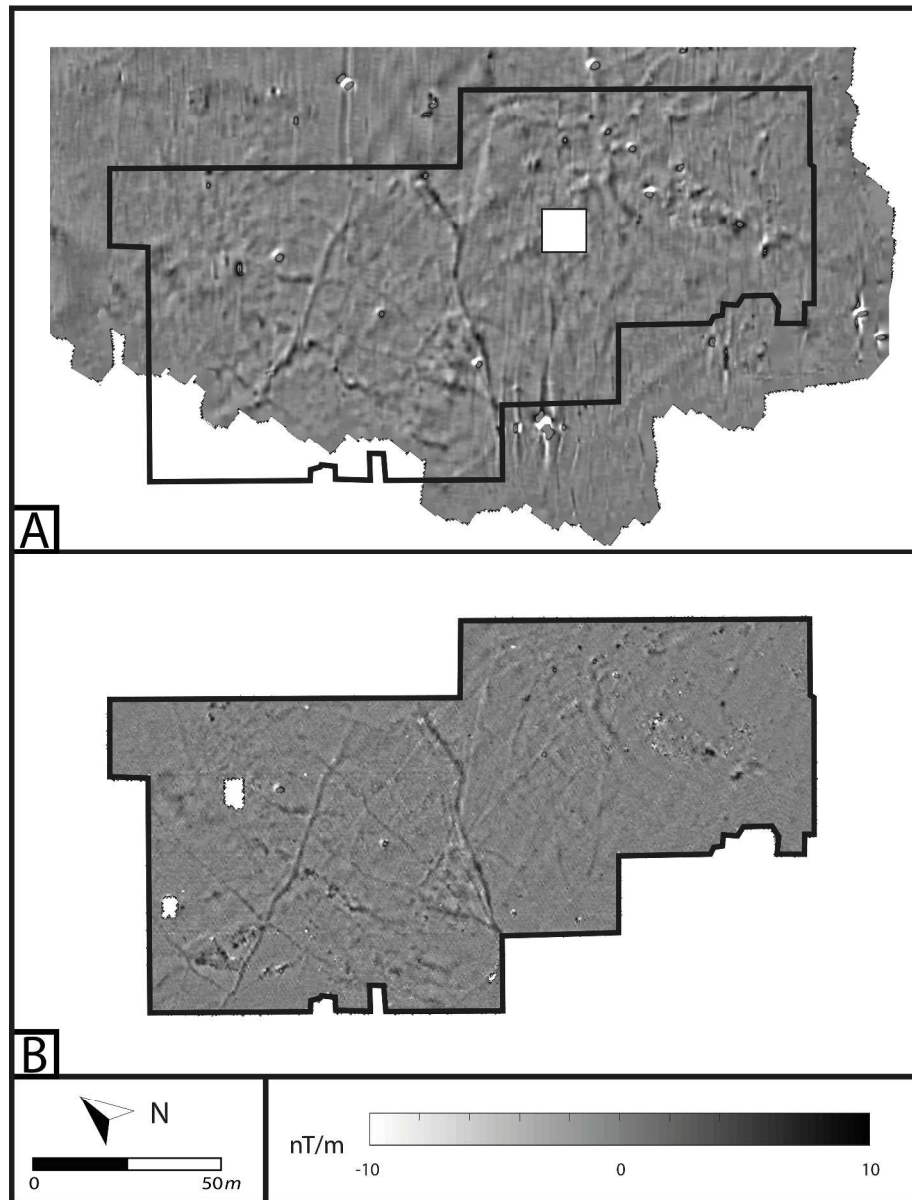
From left to right, map of the magnetic anomaly for a sampled zone of Qasr 'Allam (Figure 7), reduction to the pole of the regional magnetic field and double reduction to the pole. The IGRF-11 was used to obtain the direction to the regional magnetic field and the magnetization direction is set equal to the IGRF direction. 59x23mm (600 x 600 DPI)



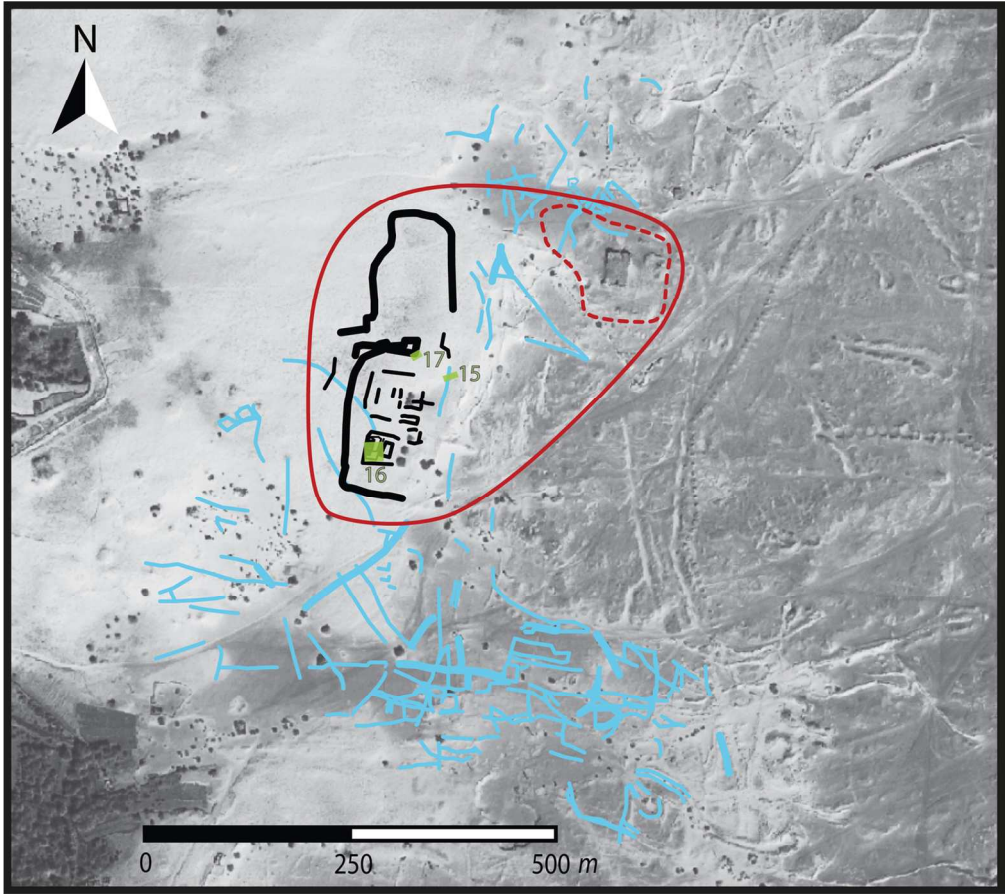
Map of the magnetic anomaly after double reduction to the pole represented with an equi-populated greyscale bar.
148x147mm (600 x 600 DPI)



Map of the vertical derivative of the magnetic anomaly after double reduction to the pole represented with an equi-populated greyscale bar. The enlargement corresponds to the area delimited in red.
125x104mm (600 x 600 DPI)



A- Map of the vertical gradient computed from the data measured with the device developed by Institut de Physique de Globe de Strasbourg (using a vertical derivative). B- Map of the vertical gradient computed from the data measured by teams directed by Tomasz Herbich with a vector gradiometer Geoscan FM256 during previous surveys (Herbich 2011).
196x257mm (600 x 600 DPI)



Interpretative map of the archaeological remains from the geomagnetic prospection. The hydraulic structures are represented in blue, the buildings in black. The dotted and plain red lines mark the minimal limits of the dwelling known before and after the study. The areas highlighted in green correspond to three excavations numbered 15, 16 and 17.
133x119mm (300 x 300 DPI)