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Role of regularized derivatives in magnetic edge mappers evaluation

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INTRODUCTION

In qualitative and quantitative interpretation of archaeomagnetic data (total field and/or vertical magnetic gradient), the use of so-called edge mappers (detectors, delineating methods, transformations) can bring additional information on the shape, size and character of archaeological features. Edge mappers enhance the anomalous features of the magnetic fields on the edges of explored structures and help to improve the interpretation. In past decades, several types of edge mappers have been developed and tested (a good review is given in Stampolidis and Tsokas 2012). Most of these methods are based on the evaluation of various ratios of derivatives of different kind, mostly horizontal and total derivatives and their components. Among them, transformations that are used the most are: vertical and horizontal gradients, total gradient (called also analytical signal, when calculated from the total magnetic field), so called tilt-derivative, theta-derivative, balanced horizontal gradient (TDX) and TDX multiplied by analytical signal, that is, the so called TDXAS transformation (Stampolidis and Tsokas 2012).

METHOD

When using edge mappers, one has to be very careful with the numerical evaluation of higher derivatives of the interpreted magnetic field due to their inherent weakness; they strongly enhance noise, remaining processing errors, edge effects, etc. These operations belong to the so-called ill-posed problems of mathematical physics, therefore there is a need for their stabilization, in other words, their smoothing. There exist several approaches to this problem, from simple moving-window smoothing filters in the space-domain to more sophisticated methods, built upon the concept of Wiener optimum filtering (Pawlowski and Hansen 1990), enhanced derivatives evaluation (Fedi and Florio 2001) and Tikhonov regularization (Pašteka *et al.* 2009).

The lattermost approach will be applied in this contribution. It is based on the application of a specially derived low-pass filter in the Fourier domain (derived in Appendix A in Pašteka *et al.* 2009). This filter is managed by the value of a regularization parameter (*alpha*), which is changed in a large interval

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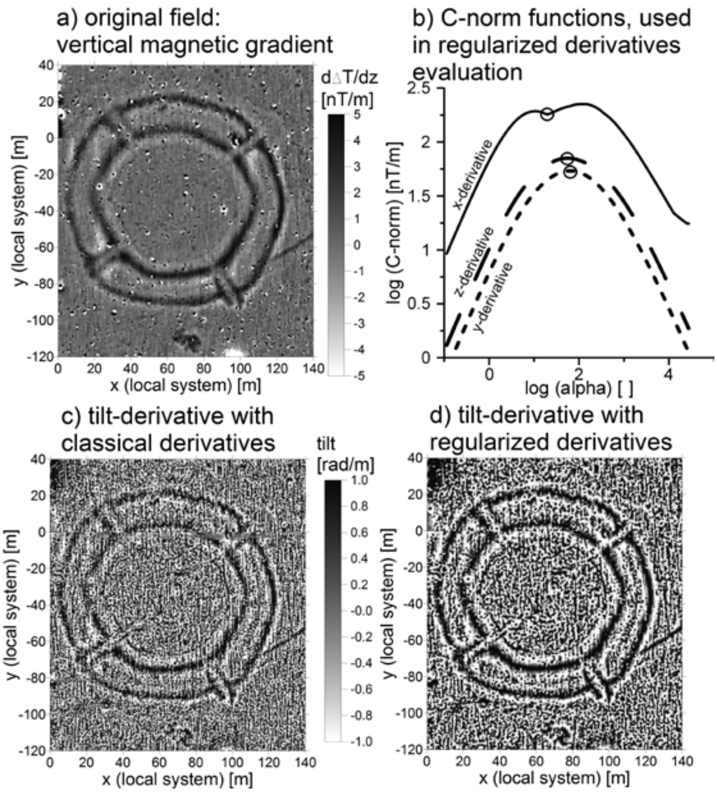

Fig. 1. Results of the transformation by means of regularized derivatives incorporation into edge mappers evaluation: Milovice site (Czech Republic). a) Original field: vertical magnetic gradient; b) C-norm functions: x-derivative (solid line), y-derivative (short-dash line), z-derivative (long-dash line), circles detect the values of optimum regularization parameter; c) tilt-derivative with classical derivatives (non-regularized, Fourier domain); d) tilt-derivative with regularized derivatives (Fourier domain)

(in a geometrical sequence) and the obtained solutions for the numerical derivative are compared to describe their "closeness" by means of the evaluation of special C-norms functions (Fig. 1b). Properties of such a C-norm function (local minima close to their global maximum or global maximum itself, circles in Fig. 1b) define the optimum regularization value, a solution where equilibrium between a correct and smoothed solution has been achieved. This processing step can be automated and more reliable solutions can be achieved; this was used during the analysis of several case studies.

SELECTED CASE STUDIES

The first presented site is a site close to Milovice (Czech Republic) with a Lengyel culture roundel structure (Milo *et al.* 2015). The roundel has a nearly circular shape and consists of an internal palisade trench and two parallel ditches. Magnetic field data acquisition was achieved by means of a fluxgate magnetometer Ferex 4.032 DLG Foerster with four sensors (line distance: 0.5 m, sampling interval: 0.25 m). Numerical derivatives of the interpreted magnetic field (Fig. 1) were performed by means of the proposed method; the C-norm function has been evaluated (Fig. 1b) for a geometrical sequence of the regularization parameter and analyzed with the aim to find the best (optimum) solution (circles in Fig. 1b). Evaluated tilt-derivative maps with classical derivatives (without regularization) (Fig. 1c) and with incorporated regularized derivatives (Fig. 1d) show the great advantage of this kind of derivative stabilisation. In the map with regularized derivatives utilisation (Fig. 1d), the high frequency content was removed permitting better analysis of the interpreted structures. In this transformed field (Fig. 1d), the palisade in the central part of the roundel is well recognisable and it seems to have some kind of continuation into its centre at two of the four entrances.

In the second case study (Fig. 2), the proposed approach was analyzed on vertical magnetic gradient data, acquired over an early medieval settlement at Witsum on the island of Föhr (northern Germany), this within the frame of an Erasmus LLP summer school (INCA International Course on ArchaeoGeophysics). For the data acquisition, the equipment of the University of Kiel, MUSELOGG-1 with six Foerster sensors, was used (line distance 0.5 m). In the anomalous magnetic gradient field, several well developed features can be observed (Fig. 2a displays a selected part of the measured area): pit-houses, ditches, boundaries of fields(?), road, graves and wells(?). When we compare the maps of the horizontal gradient evaluated with classical derivatives in the Fourier domain (Fig. 2b) and with regularized derivatives utilisation (Fig. 2c), we can see that several disturbing (high-wavelength) features, originating in the close vicinity of high amplitude anomalies (Fig. 2b) have been removed (Fig. 2c). In the TDXAS transformation, the shape of the detected objects is well defined (mainly houses, wells and graves) (Fig. 2e) due to the "loss" of the dipolar character, typical of magnetic fields. Here the comparison between classical derivatives and regularized derivatives did not give any significant differences (this fact speaks for the high quality of the acquired dataset with high signal-to-noise ratio).

CONCLUSIONS

We understand the use of the edge mappers as an additional tool in qualitative archaeomagnetic data interpretation. In the prevailing majority of cases, we could recognize the anomalous features directly in the original magnetic field (total field and/or vertical magnetic gradient), but edge mappers helped us in their better understanding and determination. The introduction of regularized derivatives have improved the signal-to-noise ratio on the evaluated derivatives and, in effect, also the properties of the discussed edge mappers (detectors). In general, we are not able now to recommend the "best" edge mapper (in most cases the tilt-derivative and TDXAS transformation delivered the best results). It is rational to evaluate several of them and then to confront the obtained results with the original magnetic field.

The presented concept was realized in the MATLAB programming environment and the script REGTILT is free for potential users upon request.

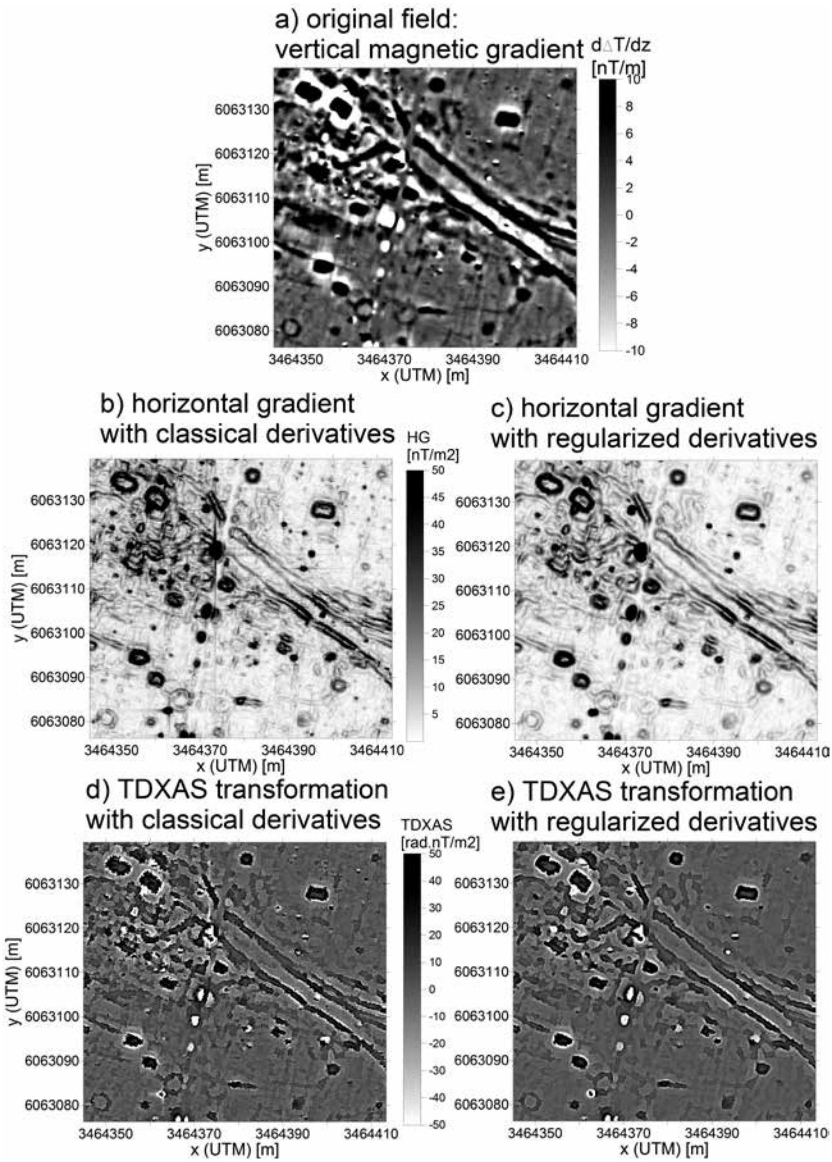

Fig. 2: Results of the transformation by means of regularized derivatives incorporation into edge mappers evaluation: Witsum site (Germany). a) Original field: vertical magnetic gradient; b) horizontal derivative with classical derivatives (non-regularized, Fourier domain); c) horizontal derivative with regularized derivatives (Fourier domain); d) TDXAS transformation with classical derivatives (non-regularized, Fourier domain); e) TDXAS transformation with regularized derivatives (Fourier domain)

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