ANNALS OF GEOPHYSICS, VOL. 45, N. 2, April 2002

A high-resolution aeromagnetic field test in Friuli: towards developing remote location of buried ferro-metallic bodies

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Abstract
High Resolution AeroMagnetic surveys (HRAM) are a novel tool experimented in several countries for volcano and earthquake hazard re-assessment, ground water exploration and mitigation, hazardous waste site characterization and accurate location of buried ferrous objects (drums, UXO, pipelines). The improvements achieved by HRAM stem from lower terrain clearance coupled with accurately positioned, real-time differential navigation on closely spaced flight grids. In field cultural noise filtering, advanced data processing, imaging and improved interpretation techniques enhance data information content. Development of HRAM approaches might also contribute to mitigate environmental hazards present throughout the Italian territory. Hence an HRAM field test was performed in July 2000 in Friuli, North-Eastern Italy to assess the capabilities and limitations of HRAM over a buried pipeline and a domestic waste site. A Cesium magnetometer in towed bird configuration was used on two separate grids. Profile line spacing was 50-100 m and bird nominal ground clearance was set to 50 m. Microlevelled total field magnetic anomaly data forms the basis for subsequent advanced processing products including 3D analytic signal, maximum horizontal gradient of pseudo-gravity and 3D Euler Deconvolution. The magnetic signatures we detected and enhanced over the environmental test site area in Friuli are also compared with similar but more extensive HRAM signatures recently observed in other countries.

Key words *HRAM applications – environmental hazards – Italian test site*

1. Introduction

Environmental characterization and hazard studies may benefit from improvements in the resolution power of relatively low cost aeromagnetic surveys. The increased capabilities of HRAM (High Resolution AeroMagnetic) surveys compared to reconnaissance campaigns stem from lower terrain clearance, tighter line spacing, more accurate real-time magnetic and positioning data acquisition, and enhanced data processing and display techniques. The main advantages of airborne geophysical surveys over ground based studies relate to improved access to remote, hazardous and contaminated areas coupled with extensive, yet rapid sampling (Raymond and Blakely, 1995).

HRAM surveys are based upon preprogrammed flight lines which assist pilot navigation during airborne or helicopter-borne surveys. HRAM terrain clearance is typically of 50-200 m,

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profile line spacing is of 50-200 m, with tie lines spaced less than 500 m. Differential Global Positioning System (DGPS) techniques have been the key to widening applications of high-resolution airborne geophysics. Real-time differential GPS pseudorange navigation ensures that the horizontal positional accuracy is 5 m or better and that the vertical positioning is accurate at least to 10 m (Grauch and Millegan, 1998). Laser and radar altimeter systems with much higher accuracy (about 10 cm) can also be added as part of integrated airborne platforms. Improved positioning implies that magnetic errors related to location can now be reduced to about 1 nT over many terrains allowing for more confident recognition of subtle, low-amplitude anomalies. Optically pumped magnetometers have a resolution of 0.001 nT and cycle at 10 Hz so ground sampling rate can be reduced to 2-5 m. This leads to precise delineation of much shorter wavelength magnetic anomalies related to shallow-source, man-made or natural, geologic features. However, high-resolution aeromagnetic applications demand detailed in-field quality control in conjunction with review of flight videos, followed by cultural noise editing and filtering (Peirce *et al.*, 1998). Microlevelling of HRAM data may also be applied to reduce residual flight-line related corrugation, which might otherwise hinder successful application of digital enhancement, transformation and filtering techniques (Ferraccioli *et al.*, 1998).

Prime current applications of HRAM include volcano and earthquake hazard assessment, ground water exploration and mitigation problems, waste site characterization and location of buried man-made ferrous objects, as briefly described hereafter. High-resolution aerogeophysics may provide for example unprecedented views of the 3D internal structure of active volcanoes with hazardous collapse-prone alteration zones, such as verified over Mt. Rainier in the U.S. (Finn *et al.*, 2001). HRAM investigations also improve and extend fault delineation and structural characterization in seismically active regions, in particular in areas concealed by alluvial deposits, vegetation and urban development and therefore mostly inaccessible to other geophysical methods (Blakely *et al.*, 1995; Liberty *et al.*, 1999). Furthermore, the extent and character of ground water hydrogeological systems, whether profitable or hazardous, may be imaged and interpreted using integrated aeromagnetic and airborne electromagnetic approaches (Grauch *et al.*, 2000; Wightman *et al.*, 2000; Siemon *et al.*, 2000a). Waste site characterization from airborne geophysical surveying is a valuable tool for rapid screening of hazardous disposal areas, minimizing personnel risk and directing subsequent ground follow-up (Lerssi *et al.*, 1997; Doll *et al.*, 2000; Siemon *et al.*, 2000b). Detection of hazardous Unexploded Ordnance (UXO) has also recently been achieved by very high-resolution low level helicopter-borne surveys (Lahti *et al.*, 2001).

Many of these diverse natural and man-made environmental problems also pose well recognized hazards for the Italian territory. Nevertheless the utility of high resolution airborne geophysics to assess such hazards appears to have been severely underestimated over the national territory which is largely devoid of such studies compared to other countries world-wide. Existing aeromagnetic data acquired for the national Italian oil company in the late 70's (AGIP, 1981) and a newly compiled ground magnetic anomaly map (Chiappini *et al.*, 2000) are much too regional in character to contribute towards assessment of environmental hazards. An attempt to perform higher resolution aeromagnetic surveying in the area of Roccamonfina volcano was made with an Italian helicopter-borne platform in 1994 and was mainly targeted to regional structural mapping rather than to volcanic hazard (Chiappini *et al.*, 1998). In 1999 some active Italian volcanic regions were covered with flight specifications broadly similar to HRAM type surveys by using the Geological Survey of Austria airborne geophysical platform (Supper *et al.*, 2000).

Adaptation of airborne geophysics to detailed environmental research over Italy is not straight forward but requires testing, experimentation and experience as verified for example in the U.S. (Doll *et al.*, 2000). Hence, in July 2000 we performed the first HRAM field test in Italy over Friuli to test the capabilities and limitations of the currently available aeromagnetic system for environmental characterization, in particular for location of buried ferro-metallic bodies. The magnetic signatures we identified and enhanced over a major buried pipeline and over a small domestic waste site are described in comparison with similar but more extensive HRAM patterns detected by others outside the Italian territory.

2. Aeromagnetic system and survey layout

In July 2000 an HRAM field test was performed near Trieste, northeast Italy, in Friuli (inset in fig. 1a). The EliFriulia company provided an Ecureil 350 helicopter, fuel and logistic support for the test. The aeromagnetic system we adopted was used in the last decade to perform reconnaissance, 4-km line spacing field work over the Antarctic targeted to crustal exploration (Bozzo *et al.*, 1999; Ferraccioli and Bozzo, 1999). The system has also been employed on a single 500-m line spacing, low-altitude (125 m above sea level) campaign for an Antarctic drill site survey (Bozzo *et al.*, 1997).

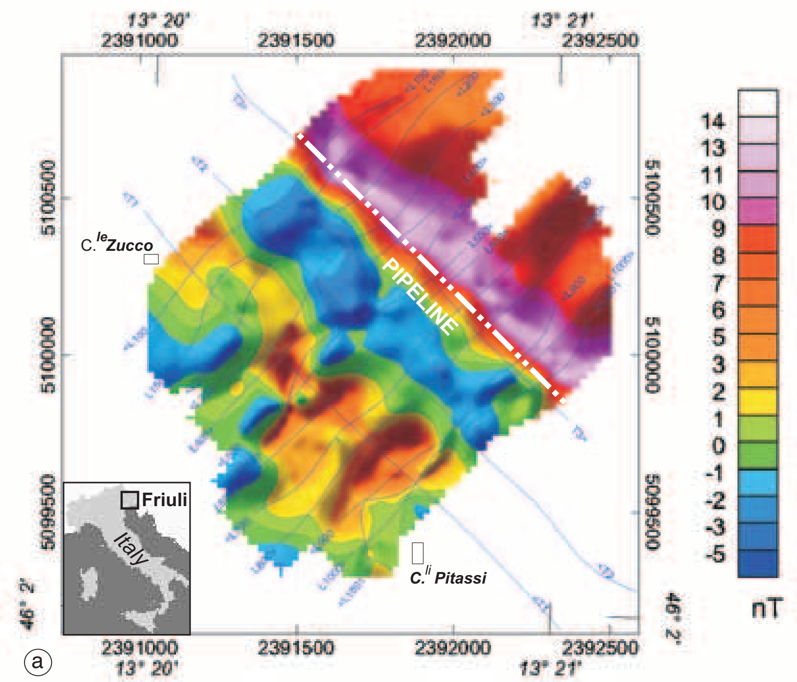
A Scintrex Cesium magnetometer (CS2) measuring the total magnetic field to an accuracy of 0.001 nT was installed in towed bird configuration. The magnetometer was set to cycle at 10 Hz to achieve an approximately 2-3 m ground sampling rate. The bird was towed on a 25 m long cable also serving for data transmission to the acquisition system placed inside the helicopter. The position of the helicopter was recorded by means of a Magnavox GPS rover. For later differential GPS correction a Magnavox GPS base station was installed at a small airfield in the Premariacco area where the Scintrex magnetic base station was also deployed. In-flight data control was accomplished by the operator through an electro-luminiscent screen. The navigator assisted the pilot over the flight grid using a Picodas navigation system interface. No video is included in this aeromagnetic system.

Therefore an extra operator spotted and noted the main cultural features which were positioned in-flight by placing digital event marks using the acquisition system. No laser altimeter is included either, limiting altitude measurement accuracy.

The HRAM test flight included two grids. Area 1 flight grid was located to the southwest of Premariacco (see IGM sheet Premariacco) and spans 1.5 km^2 (figs. 1 to 4). Area 2 flight grid was placed just south of Premariacco; its extent is equal to 3 km^2 (figs. 6 to 8). Line spacing was selected to be 100 m over a buried pipeline known to occur within Area 1. A more detailed 50 m section was flown over a small exposed and active domestic waste site in Area 2 (figs. 7 and 8). The whole survey area is a flat, low-lying alluvial plain with mean elevation of 100 m above sea level. Safety regulations impede flying lower than 50 m terrain clearance under standard conditions. Since the bird is placed about 20-25 m beneath the helicopter during survey operations 175 m was the nominal altitude selected for barometric mode surveying. The aeromagnetic system had never been tested before on such a tight line spacing and low altitude survey. The fairly low level of urban development and the weakly magnetic alluvial plain were favourable local conditions for improved ferro-metallic target delineation in both areas. Conversely the small size of the selected targets was a challenging test for assessing the capabilities and limitations of the reconnaissance magnetic exploration instrumentation to much higher resolution environmental research.

3. Data processing

The baseline of magnetic data processing was adapted from standard procedures extensively used for regional magnetic anomaly exploration programmes (Bozzo *et al.*, 1999). These included repositioning of flight lines by means of differential GPS corrections, removal of external field magnetic time variations using base station magnetic data, removal of the IGRF reference field using the provisional IGRF2000 model, statistical levelling and microlevelling (Ferraccioli *et al.*, 1998). No additional filtering of anomalies linked to cultural features was attempted so as not to affect the rest of the data. More careful levelling and microlevelling compared to standard processing was however required. Root mean square residual errors are estimated to be less than 0.5 nT outside areas of cultural noise.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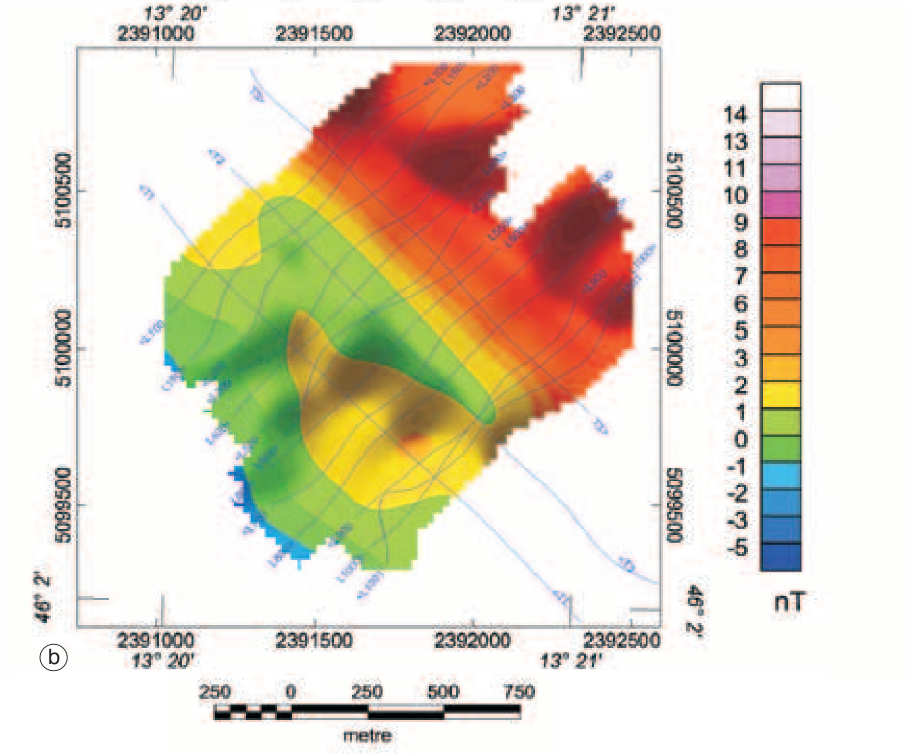
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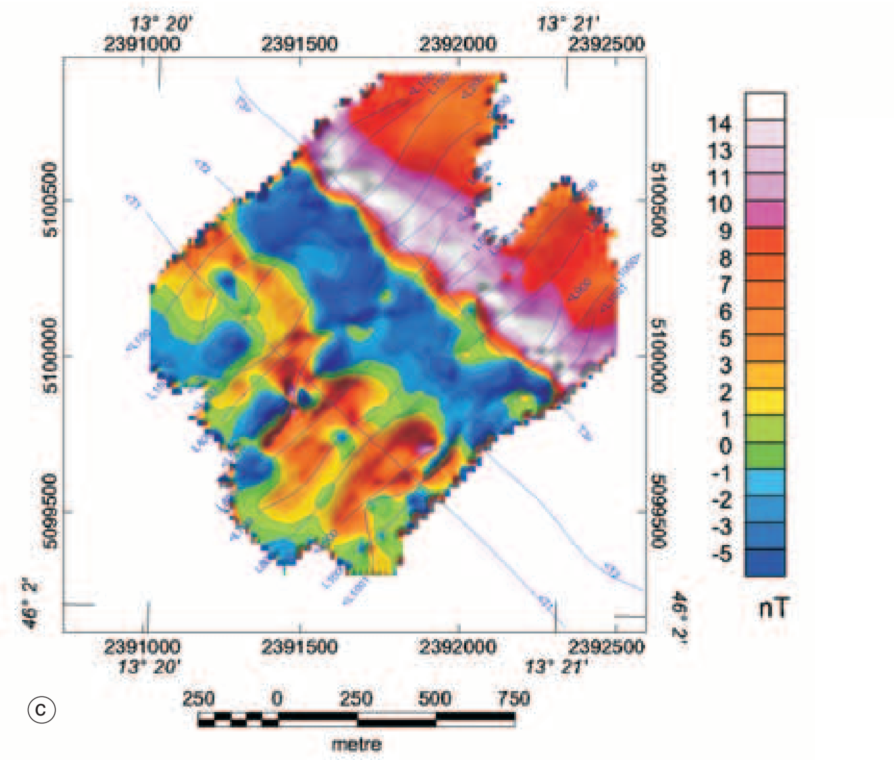

Fig. 1a-c. a) Microlevelled total field HRAM map over a buried pipeline in Friuli (see inset) located in test site area 1. The pipeline anomaly signature is evident despite high-frequency noise corresponding to a low voltage electric line between Colli Pitassi and Colle Zucco. b) Upward continued version at 100 m above original observation level. c) Downward continued version at 25 m below original observation level.

4. Advanced HRAM mapping to locate buried ferro-metallic bodies over the test site areas

4.1. *Aeromagnetic anomaly maps over the test pipeline*

The total field aeromagnetic anomaly map over survey Area 1 was gridded at a 25 m cell size, equal to 1/4 of line spacing (fig. 1a). It was compiled to verify if the buried pipeline exhibited a magnetic signature in the area and, if so, if it could be used to relocate the pipeline itself. This is a segment of the Transalpine oil pipeline, a major 465 km long feature built in 1967. The oil pipeline connects Trieste industrial harbour in Northeastern Italy with Ingolstadt in Southeastern Germany. The presently functioning pipeline has an outer diameter of 1016 mm, a thickness of 8.74 mm and has an annual oil capacity of up to 54 million tons. It is estimated to be buried at about 1.5-2 m below the ground. A 1.2 V negative DC current is applied to the pipeline for cathodic protection.

The buried pipeline clearly shows up in the HRAM image as a linear NW trending high-low magnetic pair with mean peak to peak amplitudes of 14 nT. The aeromagnetic anomaly amplitudes and shapes we detected over the test site are comparable to those mapped with high resolution magnetic data over buried natural-gas pipelines with cathodic protection over the Albuquerque

Basin, New Mexico (Grauch and Millegan, 1998; Grauch, 2001). The typical anomaly we observed over the pipeline is asymmetric with a negative peak of −2 nT on the south western flank and a positive peak of +12 nT on the north eastern flank (see also fig. 3). The shape of the observed anomaly deviates from the one expected for a linear NW trending 2D body with induced magnetization only. This suggests that remanent magnetization or the effect of the DC cathodic protection current is responsible for the Transalpine pipeline magnetic anomaly signature. Indeed Grauch and Millegan (1998) showed that the polarity of the typical high-low magnetic pair reversed where there was a change in current direction along the Albuquerque basin pipelines. However Bozzo *et al.* (1994) used vertical gradient ground magnetic measurements over Liguria in Northwestern Italy to argue that remanent magnetization was likely to determine the leading magnetic anomaly signature of oil pipelines, but that current effects were less significant. Smaller amplitude, short wavelength, 1.5 to 5 nT mostly positive anomalies, forming a NW trending magnetic chain parallel to the pipeline correlate with a low voltage DC powerline. This feature does not appear to severely hinder recognition of the pipeline itself.

An upward continued map (fig. 1b) was produced to verify the fall-off rate of the pipeline anomaly at a distance of 100 m above observation level, *i.e.* equal to a 150 m sensor-ground distance. This map shows that the broadened positive component of the anomaly decays in amplitude to about 6 nT while the negative peak is now close to 0. The signature of the low-voltage line is also considerably broader and tends therefore to merge with the one of the pipeline at grid edges making recognition of the pipeline much less confident. Indeed in-flight experimentation on a single profile flown at a 200 m bird ground clearance suggests no clear pipeline signature. Conversely a map downward continued to 25 m enhances the pipeline magnetic signature, which is marked by an almost 20 nT peak-to-peak linear anomaly (fig. 1c). Despite Hanning convolution filtering, noise is clearly discerned especially along grid edges. In flight experimentation at this lower level was not possible owing to safety regulations.

The exact plan location of the pipeline is not obvious from the total field aeromagnetic anomaly maps because of the asymmetric dipolar character of the associated anomaly. We therefore compiled a 3D analytic signal map (fig. 2a) which is computed from the square root of the squared sum of the horizontal derivative and vertical derivative of the total field aeromagnetic anomaly data (Roest *et al.*, 1992). The analytic signal might be appealing for pipeline location because it is considered to exhibit maxima over magnetization contrasts, independent of the ambient magnetic field and of source magnetization directions (Roest *et al.*, 1992). Some authors pointed out however that the magnetization direction may influence analytic signal results (*e.g.*, Linping and Zhining, 1998). Notwithstanding this, the pipeline is better located by using the maxima of the 3D analytic signal than by total field data. Analytic signal peaks were picked by applying the Blakely and Simpson (1986) automated detection approach, conventionally used for pseudo gravity anomalies. The width of the analytic signal is however fairly broad (about 200 m) and some individual peaks are de-focussed and apparently located along the flight lines. This may relate to the vertical derivative needed to calculate the analytic signal which appears to enhance residual flight line-related noise.

We then tested the maximum horizontal gradient of the pseudo-gravity method (Cordell and Grauch, 1985) for aeromagnetic pipeline location because this approach does not require vertical derivatives. On the other hand pseudo-gravity involves reduction to the pole which may be critical when the assumption of magnetic anomalies related to induced magnetic effects does not hold and when magnetization direction parameters cannot be well estimated (MacLeod *et al.*, 1993). Regardless of this probable limitation, we found an improved plan location of the pipeline using this method (fig. 2b). Figure 3 compares the typical total field, 3D analytic signal and pseudo-gravity signature over the pipeline and electric power line.

Aiming at refining the horizontal location of the pipeline and estimating its depth we then applied 3D Euler deconvolution to the total field data (Reid *et al.*, 1990). This method might be

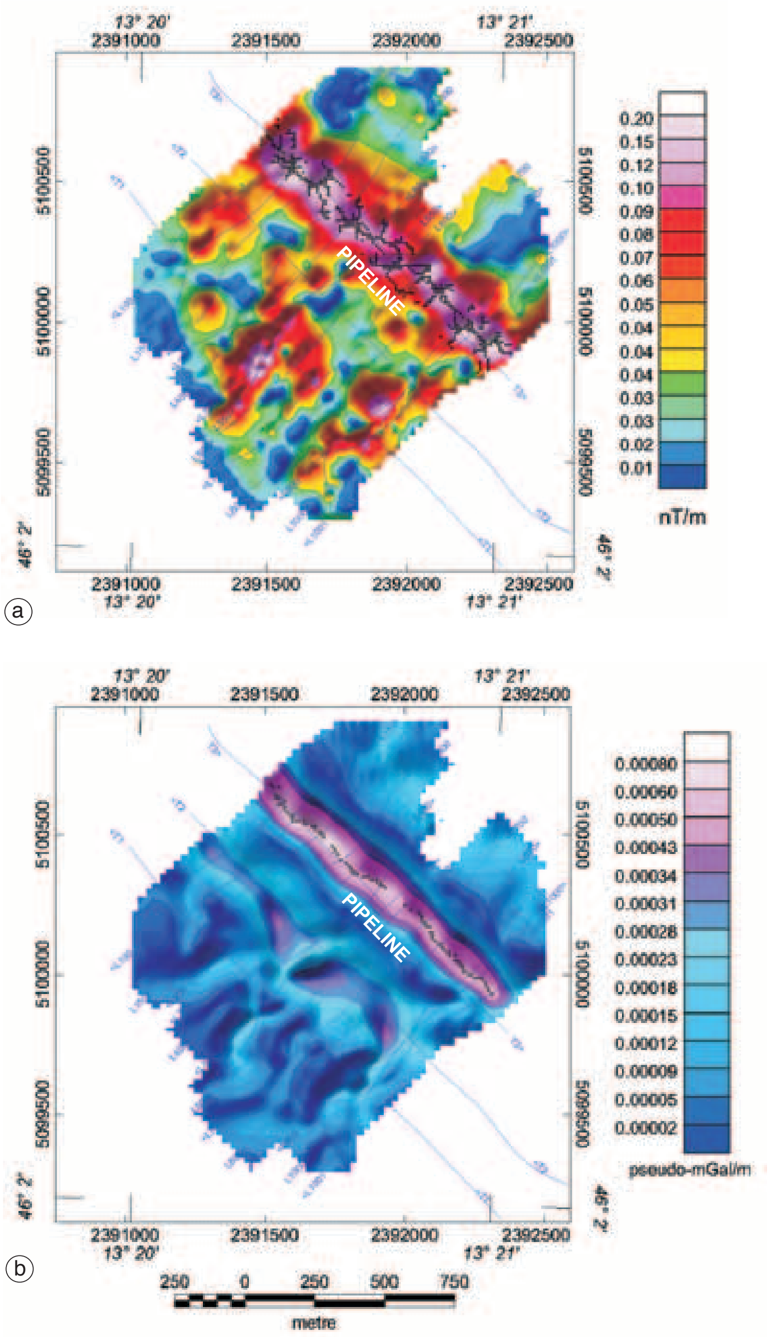

Fig. 2a,b. a) Three-dimensional analytic signal map in the pipeline area. Local peaks over the buried pipeline are displayed as black triangles. b) Maximum horizontal gradient of pseudo gravity with local peaks indicated with black crosses.

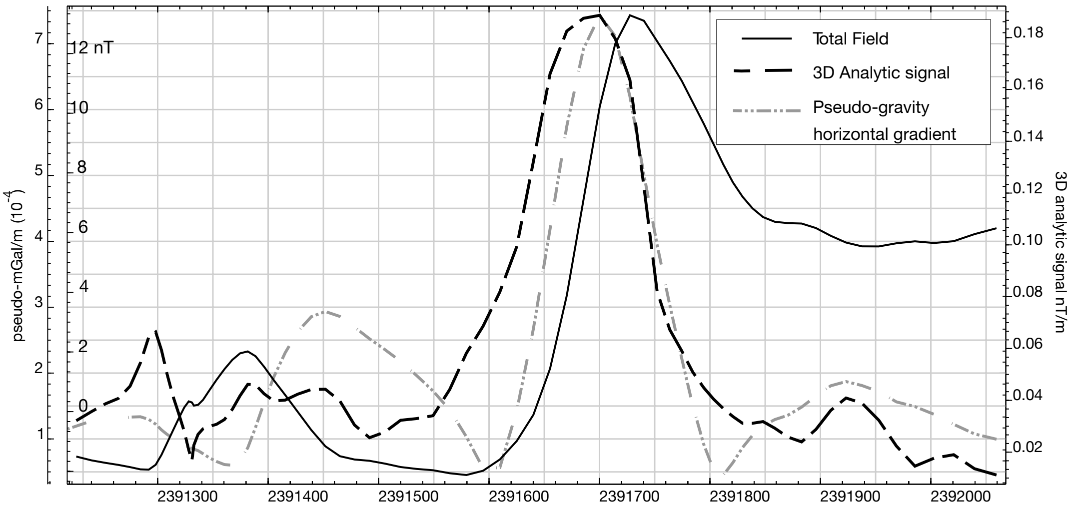

Fig. 3. Profile view comparing HRAM total field data with calculated 3D analytic signal and pseudo gravity signatures. Note the main peaks over the pipeline and over the electric line to the west.

particularly suitable for pipelines because it was thought to be insensitive to magnetic inclination, declination and remanence. More recently, the method has been claimed to exhibit a magnetization direction dependence (Ravat, 1996). An appropriate structural index for the source body must be introduced and then Euler's homogeneity relationship is solved by least-squares inversion. The structural index essentially relates to the rate of change with distance of the field (Reid *et al.*, 1990). We found that a structural index equal to 2.0 could adequately represent the pipe-like source, broadly consistent with results from a ground magnetic test site targeted to buried ferro-metallic body detection in Columbia (Yaghoobian, 1993). The plan location of the pipeline is visually well defined by spatially clustered solutions (fig. 4), with minimal de-focussing, if solutions are plotted according to a spatial window defined by previous analytic signal and pseudo-gravity mapping. Mean depth estimate is also fairly accurate, within 10% of the real mean depth level which is known in the test site area to be about 91 m, *i.e.* 1.5-2 m below ground. This Euler deconvolution result is encouraging since

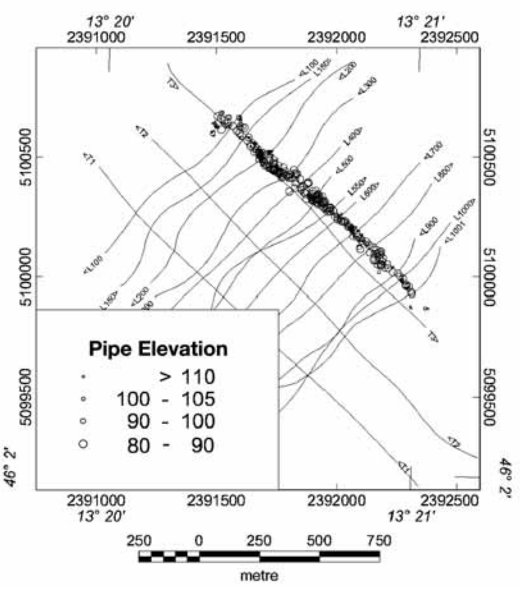

Fig. 4. Three dimensional Euler deconvolution map over the buried pipeline. Plan location of the pipeline is well defined and most depth solutions plot in 80-90 m elevation interval, *i.e.* fairly consistent with real depth.

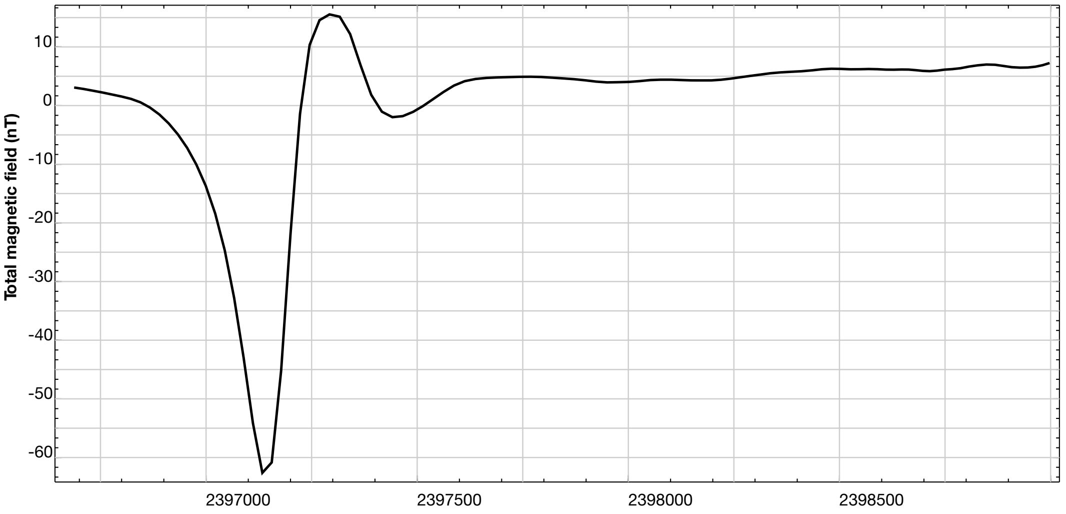

Fig. 5. Profile view displaying microlevelled total field HRAM signature over the domestic waste located in test site area 2.

previous ground magnetic modelling efforts in Liguria over a buried pipeline were claimed not to lead to reliable depth determination because of its remanent magnetization (Bozzo *et al.*, 1994).

4.2. *Aeromagnetic anomaly maps over the test waste site*

A typical total field aeromagnetic anomaly profile over the largest waste site of area 2 is displayed in fig. 5. A smooth dipolar aeromagnetic anomaly was consistently detected over the exposed domestic waste site with a mean peak to peak amplitude of 70 nT. The typical anomaly is asymmetric with a negative peak of –60 nT on the western flank and of + 10 nT on the eastern one. This may indicate the existence of ferrometallic objects or at least higher apparent susceptibility waste site infill, enriched in ferrometallic components with respect to background values. Outside the waste site area anomaly values decay to an average close to 0 nT over the alluvial plain where such infill is lacking. Relative highs (5-10 nT) superimposed upon the regionally flat anomaly field were recognized in field as being other cultural anomalies (*e.g.*, roads, pylons, small villages).

We then compiled the 3D analytic signal, the maximum horizontal gradient of pseudo-gravity and 3D Euler deconvolution maps. The NNE strike of the 3D analytic signal anomaly over the waste site is evident in fig. 6. Within the waste site, area 1, which is the saturated part of the waste site body, features a relative high with respect to relative lows over the western part of areas II and IV. An individual peak is identified just north of area 2 along the north-western margin of the waste site. Moreover, a small positive anomaly parallels the main waste site body to the east speculatively indicating a satellite disposal site.

It appears that the edges of the «regional» 3D analytic signal high over the waste site slightly underestimate the true dimensions of the waste site (fig. 6). On the contrary, the local peaks of the maximum horizontal gradient of pseudo-gravity appear to overestimate the true dimensions of the waste site, particularly on the north-western flank (fig. 7). It is unknown if this reflects some errors in apparent inclination due to non-induced magnetization components within the waste site body (Mac Leod *et al.*, 1993). It is

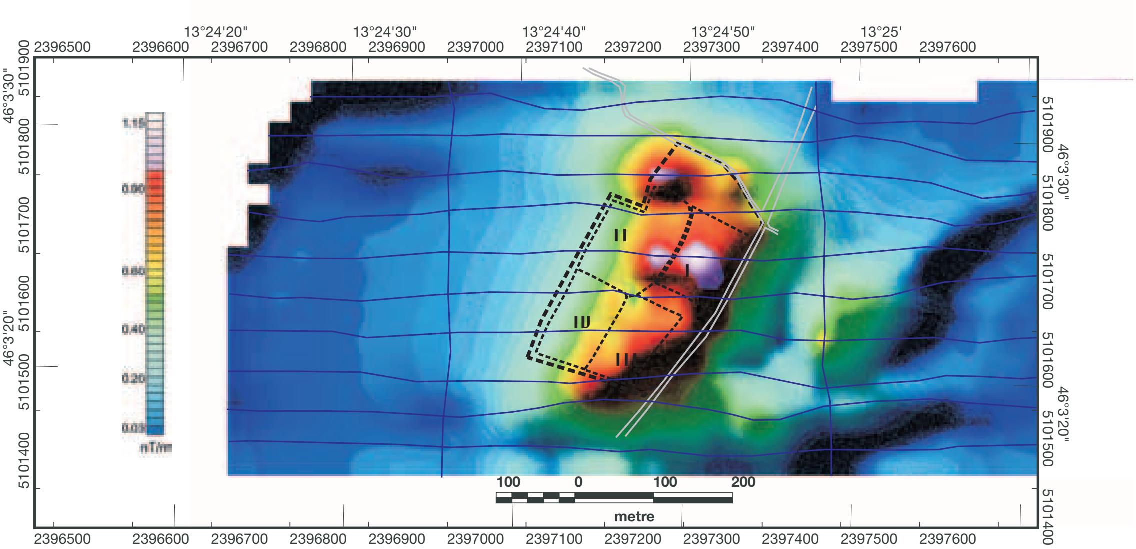

Fig. 6. Three-dimensional analytic signal map in the waste site area. Note contrasting signatures over different parts of the waste site.

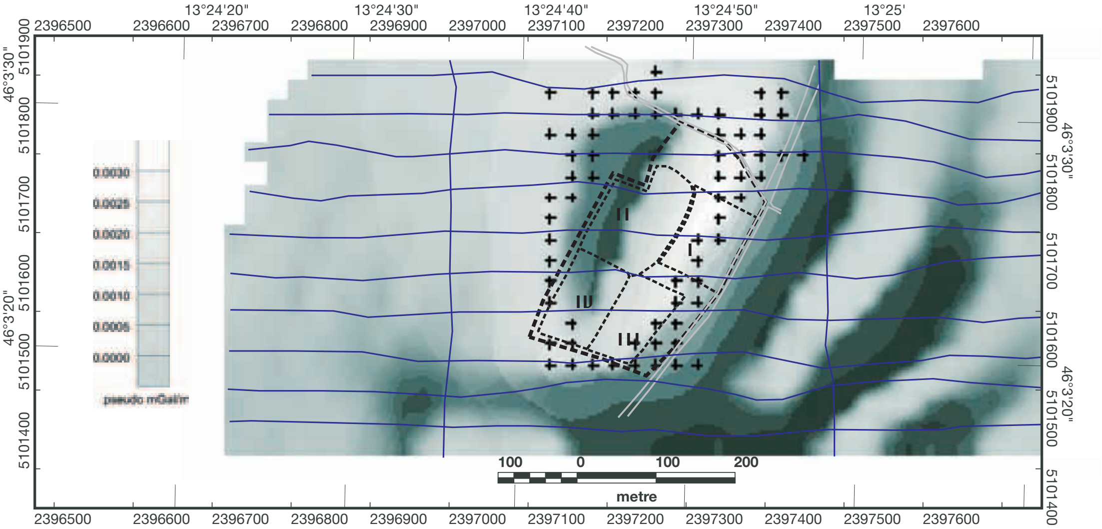

Fig. 7. Maximum horizontal gradient of pseudo gravity over the waste site area with local peaks indicated with black crosses. Note relative peak over the saturated part of the waste site (I).

noteworthy however that a relative pseudo-gravity maximum corresponds to area 1, consistent with the analytic signal results.

The 3D Euler deconvolution map for structural index 2.0 (fig. 8), is appropriate for 2D finite dimension bodies as might be encountered within a waste site (*e.g.*, drums, pipes, etc.) (Yaghoobian, 1993). This map shows preferential clustering of solutions in areas I and III with respect to areas II and IV. The advanced processing products (figs. 6 to 8) might collectively be interpreted to indicate that areas II and IV are «cleaner» areas, *i.e.* with lower apparent susceptibility infill, possibly reflecting volumetrically less significant ferro-metallic bodies.

Our aeromagnetic anomaly maps delineate the waste site quite well. Our local finding is consistent with much more extensive aeromagnetic imaging of waste sites in Tennessee, in the U.S., revealing that the boundaries of waste sites may be delineated fairly accurately using HRAM data (Doll *et al.*, 2000). In our aeromagnetic test site no higher frequency anomalies were detected and related to individual ferro-metallic waste site bodies despite ground sampling rate of about 2 m. Only areas of enhanced apparent magnetization may be delineated. It is clear that considerably lower terrain clearance and tighter line spacing would be necessary to delineate individual ferrous bodies (*e.g.*, drums, pipes, scrap material) within the waste site, if indeed present. Doll *et al.* (2000) attempted to delineate such thresholds for magnetic sensitivity over waste disposal areas in relation to system noise, acquisition parameters, geologic noise and transient noise effects. Their field test indicated that a single 55-gallon barrel could be detected under ideal circumstances at 5 m bird altitude (*i.e.* 10 times less than our test), but that generally it was not possible to distinguish fewer than 10 barrels from background heterogeneity. This low-level aeromagnetic figure is very promising and would be comparable with results from a ground magnetic test site performed in Central Italy (Marchetti *et al.*, 1998).

Siemon *et al.* (2000b) presented higher resolution waste site imaging compared to our field test over a specially prepared test area (150

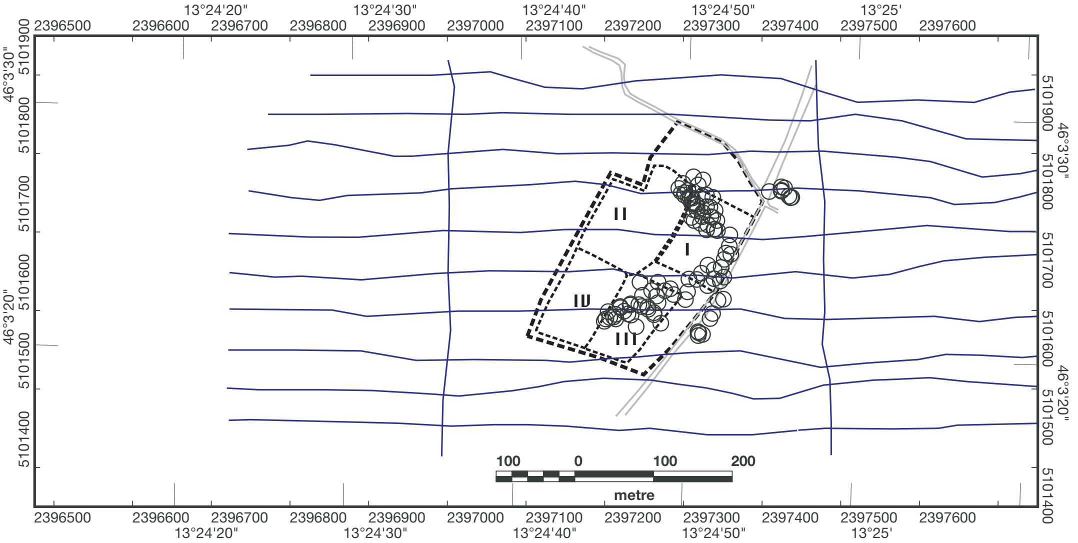

Fig. 8. Three dimensional Euler deconvolution map over the waste site area. Note clustering of Euler solutions in area I and III of the waste site. A single depth solution range of 80-90 m is plotted.

m × 300 m) containing typical waste site materials including steel drums, a tank, ordinance, scrap metal, and a pipeline. Using the test site indications, they later performed a detection survey covering an area of 86 km^2 surveyed with a nominal flight-line spacing of 50 m and achieved a high detection level over small waste occurrences.

Lerssi *et al.* (1997) described more extensive high-resolution airborne geophysical studies including HRAM over three potentially contaminated landfills over Finland. In the Helsinki region, southern Finland, results from a repeat survey were used to assess changes in the environment prior to and after installation of a large municipal landfill. Magnetic anomalies with magnitudes up to 1000 nT were detected in the repeat survey over non-magnetic granite bedrock clearly indicating the presence of metallic waste.

5. Conclusions

High-resolution aeromagnetic surveys have recently addressed environmental characterization and hazard studies. HRAM experience is lacking in Italy to date, despite the variety of environmental problems which the Italian territory and population faces. Amongst the broad range of such problems we used newly acquired HRAM data in Friuli to test airborne location of buried ferro-metallic bodies. Previously such an application was one most universal and well established targets of environmental ground magnetic field studies. Our HRAM test demonstrates that it is possible to identify well-resolved magnetic anomaly signatures over a buried pipeline and over a small domestic waste site.

Because of the vector nature of the magnetic field and of remanence, it appears necessary to apply transformations and advanced digital analysis to total field aeromagnetic data to simplify aeromagnetic location of buried ferro-metallic objects. We found that the maximum horizontal gradient of pseudo gravity was efficient in determining the plan location of the pipeline. Three dimensional analytic signal mapping was effected to a higher degree by flight-line related noise, but still leads to an enhancement in pipeline location. The most useful characteristic of three-dimensional Euler deconvolution is its relative insensitivity to the magnetization direction, which can be exploited for improved plan location and for approximate depth determination of the pipeline.

Over the second area of the test site, we found that the true dimensions of the waste site appear to be slightly underestimated by 3D analytic signal and overestimated by local peaks of the maximum horizontal gradient of pseudo-gravity. Both techniques delineate an area of enhanced magnetic signature over the saturated part of the waste site, which may reasonably contain larger volumes of magnetized ferro-metallic (?) materials. Clustering of Euler deconvolution solutions also highlights possible differences in volumes of magnetized materials between individual waste site areas.

HRAM is envisaged as a good remote approach for rapid waste site screening in terms of location of unmapped or poorly documented waste site areas. Once individual anomaly areas have been delineated within a waste site these may be more efficiently selected for very low-altitude surveying or ground-follow up, if safe, aiming at recognition of potentially hazardous materials in ferro-metallic containers or scrap materials.

Acknowledgements

The authors wish to thank the pilot, engineer and mechanics of EliFriulia for providing assistance, the helicopter, fuel and logistic support during the high-resolution aeromagnetic test site over Friulia. Dr. Marco Gambetta is acknowledged for his help in test site survey planning and execution. Giorgio Caneva of the Dipartimento per lo Studio del Territorio e delle sue Risorse performed technical installation work of the aeromagnetic rack on board and deployed base stations on the ground. The Ufficio Tecnico del Comune di Premariacco kindly sent us a 1:2000 scale map of the surveyed waste site. Dr. Giorgio Macorini of the Società Italiana per l'Oleodotto Transalpino S.p.A. provided necessary background information on the oil pipeline. This research was funded with the Finanziamenti a progetti di singoli e/o giovani ricercatori (D.R. 226 del 25.10.2000). Discussions with experts in airborne environmental geophysicists such as R. Supper of the Geological Society of Austria, D. Eberle of BGR, Hannover and C. Finn of the U.S. Geological Survey, Denver, Colorado were highly constructive. In particular, C. Finn provided access to many references during F.F's visit to the USGS. The suggestions of two anonymous reviewers and of M. Chiappini improved the clarity and focus of the manuscript.

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