ITINERIS Geophysical Technologies @CNR-IREA: Drone-Based Tests at Altopiano di Verteglia, Avellino (Southern Italy)

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Abstract. Unmanned Aerial Vehicles have become widely adopted platforms for geophysical investigations. In recent years, several geophysical sensors, including magnetometers, ground penetrating radars, hyperspectral cameras and thermal cameras, have been developed for drone-based deployment, thus enhancing the effectiveness of geophysical surveys. This work presents a multi-geophysical survey conducted to test two drone-based geophysical systems, namely, the Mag-Nimbus magnetometer system and the Zond Aereo LF GPR system. The survey was carried out at the Altopiano di Verteglia (Montella, AV - Italy) in the Southern Apennines for investigating near-surface buried metallic pipes. The knowledge of the area makes it an ideal location for our tests, allowing us to compare the results associated with different physical parameters of the target, operating with different drone-based geophysical technologies and configurations, and understand how the collected data can be used to address environmental challenges.

Keywords: UAV · drone geophysics · drone-based GPR · drone-magnetometry

1 Introduction

In the last decade, the rise of Unmanned Aerial Vehicles (UAVs) has revolutionized geophysics. The development of UAV-based geophysics has facilitated data collection expanding it even in inaccessible areas, thereby enhancing spatial coverage and significantly reducing both the physical effort of operators and survey time, compared to ground-based surveys. Consequently, geophysical instruments and sensors have been optimized to be enough compact and light-weight to be mounted as payloads under these vehicles, while still ensuring the acquisition of good-quality datasets.

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O. Gervasi et al. (Eds.): ICCSA 2025 Workshops, LNCS 15899, pp. 373–383, 2026.
https://doi.org/10.1007/978-3-031-97663-6_33

Among geophysical methods, Ground Penetrating Radar (GPR) and magnetic surveys are the most widely used for different applications, including geo-environmental, archaeological, geotechnical, and engineering purposes [1]. Their success is attributed to several factors, such as cost-efficiency, versatility, data collection capabilities, and non-invasiveness. Additionally, both methods facilitate the detection of buried targets thanks to their magnetic and electromagnetic sensing capabilities. The application of these methods with UAVs has motivated the design and commercialization of several lightweight and compact sensors. Although an exhaustive list is out the aim of this paper, examples of on the market available magnetometers are the MagArrow by Geometrics (https://geometrics.com/product/magarrow/), the MagDrone by Sensys (https://sensysmagnetometer.com/products/) and MagNimbus by SPH Engineering (shop.sphengineering.com/products/magnimbus-magnetometer). As for GPR, some examples are the Zond Aereo LF, the Zond 500 and 1000 by SPH Engineering and Radar Systems (https://shop.sphengineering.com/collections/gpr-systems), the Cobra CBD and the Cobra-PlugIn by Radar Team (http://www.radarteam.se/index.html). In addition, several GPR prototype systems and ad hoc designed data processing approaches have been proposed in the recent literature (e.g. see [2]).

Aim of this paper is to present a survey conducted to test drone-based GPR and magnetometric technologies, namely the Zond Aereo LF and the MagNimbus, and validate the results obtained from these different instruments operating under various configurations. The testing activity was performed at the Altopiano di Verteglia (Montella, AV – Southern Italy) by the Institute for Electromagnetic Sensing of the Environment of the National Research Council of Italy (IREA-CNR). The instrumentation purchases and the test activity have been financed by the project IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System (D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR- Mission 4 “Education and Research” - Component 2: “From research to business” - Investment 3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures” in the framework of the WP7 and Activities 7.5, led by IREA-CNR.

2 Materials and Methods

This section describes the drone-based geophysical systems, namely the MagNimbus magnetometer and the Zond Aereo LF GPR system, the investigated area and how the surveys were organized, outlining the data collection strategies and configurations adopted for both the systems. Furthermore, this Section provides some insights into the data processing techniques implemented for each methodology.

2.1 Magnetometric Instrumentation: MagNimbus

The MagNimbus is a magnetometer system for the measurement of the total magnetic field and its vertical variations, produced by SPH Engineering (Riga, Latvia https://www.sphengineering.com/). The system consists of two QuSpin Total-Field Magnetometer (QTFM) Gen-2 atomic sensors, based on rubidium vapor technology, which are assembled into two different split arms (as shown in Fig. 1). The first one is a 1 m long foldable mast, positioned below the UAV approximately 1 m from its base and connected to the onboard computer through a serial port. The second one is instead a fixed mast, mounted above the UAV at a distance of approximately 0.5 m from its top and connected to the onboard computer through a USB port. Considering an approximately 0.2 m vertical length of the UAV body, the distance between the two MaNimbus sensors is fixed to 1.7 m. The total weight of the system is approximately 1.5 kg, making it suitable as a payload for medium sized UAVs such as the Matrice 300 RTK and Matrice 350 RTK quadcopters produced by SZ DJI Technology Co. (Shezen, China store.dji.com/). This allows for easier maneuverability and less battery consumption during the survey flights. The main technical features of the sensors are the very low sensitivity equal to 0.003 nT and the sampling rate up to 500 Hz. Data collection takes place through the use of UgCS SkyHub, and the related software, which also allows power supply for the instrumentation via the UAV batteries. Main features of this instrumentation and further information can be found in the company website [https://shop.sphengineering.com/en-en/products/magnimbus-magnetometer].

2.2 GPR Instrumentation: Zond Aero LF

The radar system Zond Aereo LF (Low Frequency) is a single-channel GPR system, developed by SPH Engineering (Riga, Latvia https://www.sphengineering.com/) and Radar Systems Inc. (Riga, Latvia https://radsys.lv/en), equipped with unshielded dipole antennas. By default, it comes with three center-frequency antennas, 100 MHz, 150 MHz, and 300 MHz (as shown in Fig. 2), operating within bandwidths of 50–150 MHz, 75–300 MHz, and 150–600 MHz, respectively. Being an extra-lightweight GPR system, with a total weight ranging from approximately 0.9 to 1.2 kg, based on the chosen antenna, it is suitable to be mounted as a payload under medium-sized UAVs such as the Matrice 300 RTK and Matrice 350 RTK quadcopters produced by SZ DJI Technology Co. (Shenzen, China store.dji.com/). Power and charging of the Zond Aereo LF GPR system is provided by the connection of the power cable directly to the UAV (or external) batteries. Data collection takes place through the use of UgCS SkyHub (SPH Engineering, Riga, Latvia) on-board computer, which is connected to the radar system by an Ethernet cable. Additional technical specifications and information can be found in [https://shop.sphengineering.com/en-en/products/zond-aero-lf].



Fig. 1. MagNimbus magnetometer in vertical gradiometer configuration mounted on a DJI Matrice 300 RTK drone.

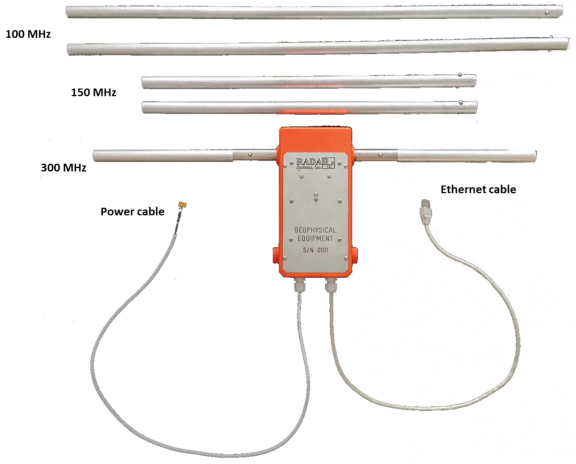

Fig. 2. Photo of the Zond Aereo LF GPR system and its components.

2.3 Test Site: Altopiano di Verteglia (Montella, AV - Southern Italy)

The Altopiano di Verteglia is a small tectonic-karst basin situated in the Northen-Western sector of the Picentini Mountains group (Southern Italy, Fig. 3b). The main massif,

the Terminio-Tauro, is characterized by a typical carbonate succession in platform facies, consisting of Jurassic and Cretaceous fissured limestones covered by Quaternary deposits, which are mainly represented by discordant accumulations of pyroclastic products of the Somma-Vesuvius activity and lacustrine sediments [3, 4]. The area has already been partially studied through ground-based geophysical investigations, such as electrical resistivity and seismic methods [5]. Additionally, magnetic measurements have been performed in both ground- and drone-based configurations [6], confirming the presence of three steel pipes systems at variable depth, ranging from approximately 1 to 2 m. These pipe systems (Fig. 3c) and the knowledge of the site made it an ideal location for the testing of the magnetometric and GPR instrumentations, as well as assessing the performance of these different systems in detecting the targets, even when placed at a close distance from each other.

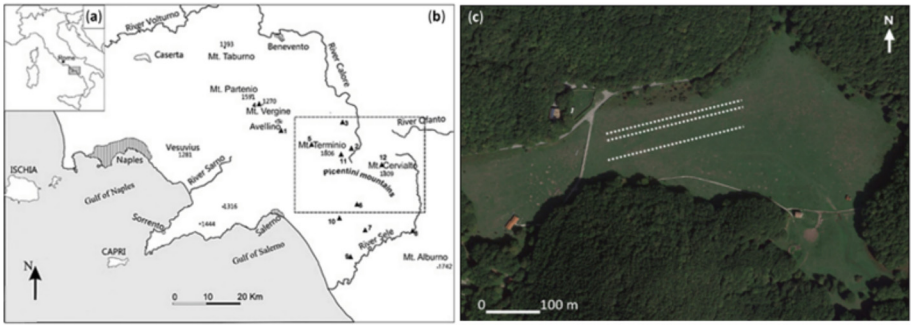

Fig. 3. (**a**) Map of the Italian Country (**b**) Map of the western Campania The dashed box indicates the Picentini mountains system region [modified from [4]) (**c**) Google Earth view (google.it/earth/) of the Altopiano di Verteglia. White dashed lines represent the surface projection of the pipe systems (modified from [6]).

2.4 Magnetometric Survey

The magnetometric survey using the MagNimbus system was performed in the Eastern zone of the proposed test site. In particular, the survey covered an area of approximately $30 \times 120\ m^2$ (magenta purple in Fig. 4a) with flight lines oriented along a N/NW – S/SE direction and with 2 m spacing (black continuous lines in Fig. 4b). The drone system flew in True Terrain Following (TTF) mode automatically keeping constant the elevation over the surface using real-time data collected by the NRA24 K-band radar altimeter developed by Hunan Nanoradar Science and Technology Co. (Changsha, China http://en.nanoradar.cn/). Specifically, the system was kept at a distance from the ground surface equal to 5 m. Therefore, the two sensors have an elevation of 4 and 5.7 m with respect to the ground surface. The flight speed was set to 2 m/s, while the MagNimbus sampling rate was fixed to 500 Hz.

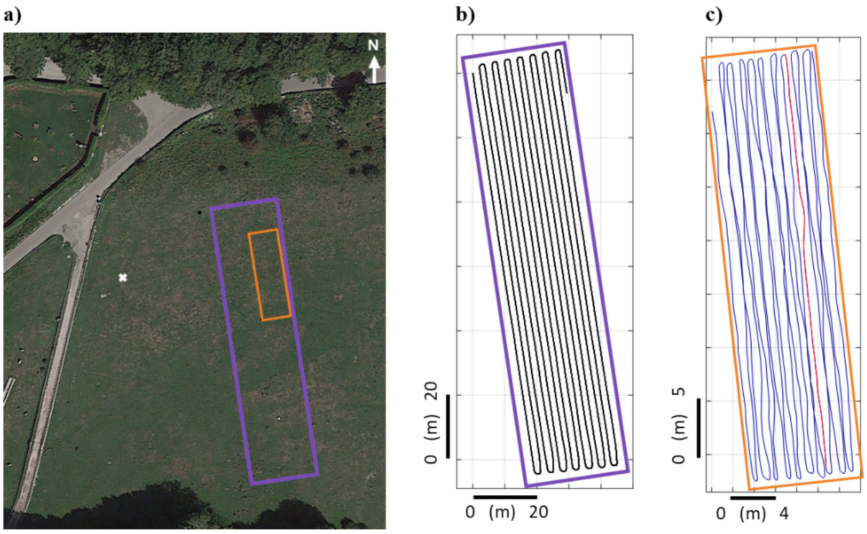

Fig. 4. (**a**) Google Earth view (google.it/earth/) of a zoomed area of the Eastern zone of Altopiano di Verteglia. The purple rectangle represents the area interested by the magnetometric survey, the orange one represents the area interested by the GPR survey, while the white cross is the drone take-off point. (**b**) Distribution of the performed magnetometric flight lines (black continuous lines). (**c**) Distribution of the performed flight lines (blue continuous lines); the red one represents the flight line considered for the processing. (Color figure online)

2.5 GPR Survey

The GPR survey, carried out by means of the Zond Aereo LF GPR system, was also performed in the Eastern zone of the proposed test site. The survey covered a smaller area than the magnetometric survey one and was approximately 10×40 m^2 (orange rectangle in Fig. 4a) with flight lines orientated along an approximately N/NW – S/SE direction and about 40 m long with 0.5 m spacing (blue continuous line in Fig. 4c). The drone system flew in TTF mode, which makes possible to automatically keep constant the elevation over the surface by using real-time data collected by the NRA24 K-band radar altimeter. The drone flew a distance of 1.5 above ground surface. The flight speed was set to 1 m/s, while the Zond Aereo LF, equipped with its 300 MHz center-frequency antenna, operated with a 128 ns time range and 512 samples per scan.

2.6 Data Processing

A first process for magnetic data regards the need to correct the collected data by considering the Earth's magnetic field and its temporal variations; it is done by taking into account the International Geomagnetic Reference Field (IGRF) and by subtracting its values from the measured dataset. However, in the case of vertical gradient configuration this correction is not necessary. Then, heading error correction is performed when the survey is performed by changing the direction of the sensor axis with respect to the direction of the measurement line [i.e., 7]. Among the different strategies to mitigate the

heading error effects, we subtract the own median value at each measurement profile. In addition, a low-pass filter is applied to these datasets to suppress both spikes and high-frequency noise from the recorded signal. These operations are performed in the wavenumber-domain based on the properties of the Fast Fourier Transform (FFT) [8].

The first processing step in UAV-based GPR imaging involves standard time-domain procedures [2]. Among them, zero-timing adjusts the time-axis reference. For the system at hand, this task is carried out to ensure that the signal reflection due to air-soil interface occurs at the time instant corresponding to the round trip time that the signal takes to cover the distance of the UAV from the soil surface, as estimated by the radar altimeter [9]. Moreover, when processing UAV-based GPR data, it is crucial to distinguish the signal reflected from the targets of interest from other undesired signal components or environmental clutter. At this regard, the common time gating and background removal procedures are employed to mitigate clutter and reduce noise [10–12]. Time gating consists in selecting a time window containing signals coming from the targets of interest and setting all the signals outside this window to zero. It is worth pointing out that time gating must be carefully used when targets are close to the air-soil interface, as parts of the useful signal may be erased. Background removal is a filtering procedure that consists in replacing the current A-scan with the difference between it and the average of all A-scans composing the radargram. As the time gating, also the background removal must be used with care because it can alter the data. Indeed, if the UAV distance from the soil surface does not change significantly during the flight, the background removal is useful to remove undesired constant signals, i.e. data components occurring at the same time instant for all the measurement points. Examples of these signals are multiple reflections related to the antenna direct coupling and the air-soil interfaces. On the other hand, the background removal also erases information about buried flat interfaces or, in the case of extended (along the measurement direction) targets, it may introduce data artefacts, i.e. signal components that can be erroneously interpreted as localized target reflections.

3 Results

This section presents both the data as collected from the two drone-based geophysical systems (raw data) and the results obtained by after applying the aforementioned processing methods (processed data).

3.1 Vertical Gradient of the Total Magnetic Field

Figure 5 shows the maps of the vertical gradient of the total magnetic field before (Fig. 5a) and after (Fig. 5b) the application of the processing procedures. These maps were computed using a natural neighbors interpolator and a 0.5 m sampling step along both directions. Anomalies of the vertical gradient display the typical alternating magnetic high and low peaks that can be measured over a metallic pipe [13], which generally acquires a permanent magnetization during the manufacturing process.

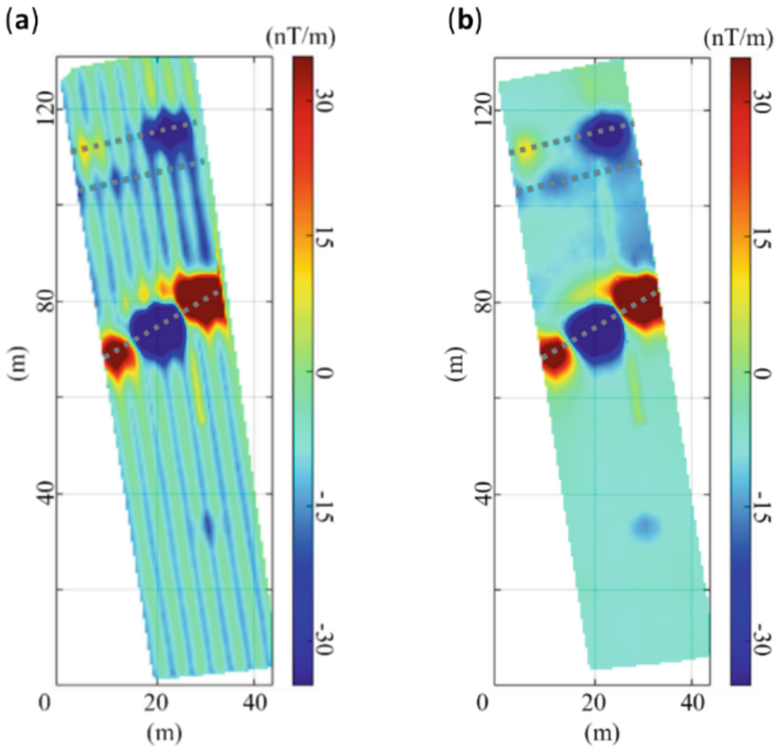

Fig. 5. Maps of the computed vertical gradient before (**a**) and after (**b**) the applied processing procedures. Grey dashed lines represent the surface projection of the pipes.

3.2 Radargrams

The raw radargram acquired during the whole flight of the Zond Aereo LF GPR system is shown in Fig. 6a. From it, the radargram corresponding to a single survey line (depicted by the red continuous line in Fig. 4b) is selected (Fig. 6b) and considered to illustrate the results of the GPR data processing. In the raw radargram, signals coming from the targets of interest are masked due to the strong ringing characteristic of the Zond Aereo LF system and the unshielded nature of the antennas. This represents the first issue encountered, which implies a notable difficulty in determining the zero time. Indeed, the standard procedure for setting the zero time properly requires finding the time instant corresponding to the first positive (or negative) peak of the average A-scan [10–12]. After that, the background removal is applied to reduce the clutter, which represents a not negligible source of disturbance. Finally, the processed radargram (Fig. 7) clearly shows the diffraction hyperbolas associated to the buried targets. Specifically, two close hyperbolas are at the x ranging from about 5 m to 15 m and another one is visible at x ranging from about 30 m to 35 m (see the blue boxes in Fig. 7).

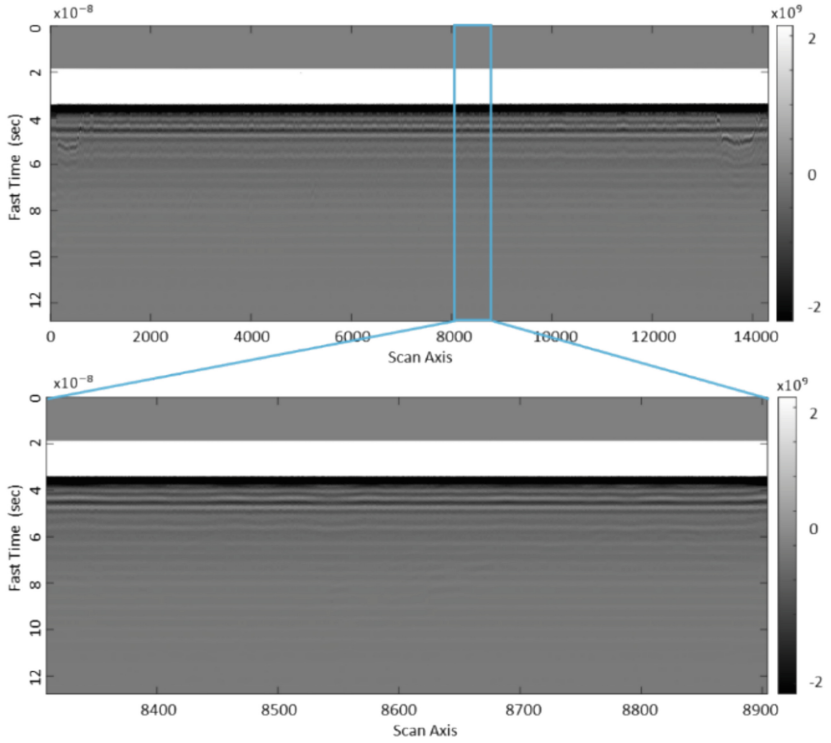

Fig. 6. (**a**) Raw radargram acquired during the whole flight of the Zond Aereo LF GPR system and (**b**) raw radargram corresponding to a single survey line (red continuous line in Fig. 4b).

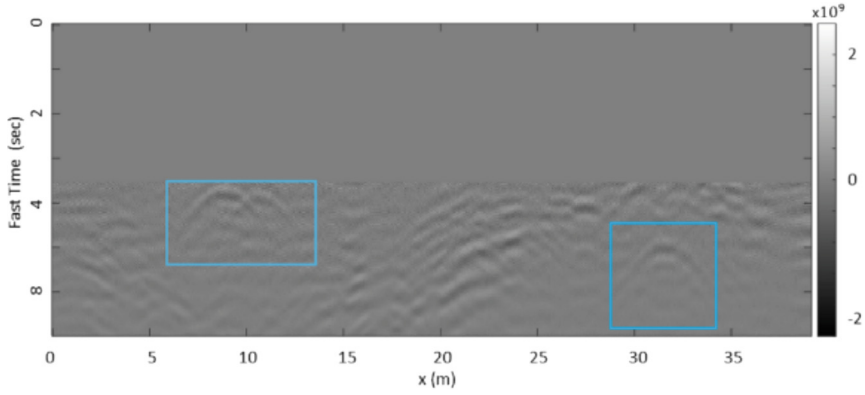

Fig. 7. Analyzed radargram after the time-domain processing procedures (i.e., time zero and background removal); the cyan rectangle highlights the position of the diffraction hyperbolas associated to the buried targets. (Color figure online)

4 Discussions and Conclusions

In our study, we conducted a comprehensive test on two UAV geophysical systems: the MagNimbus magnetometer and the Zond Aereo LF GPR. These evaluations yielded significant insights into their performance and effectiveness across various configurations and operational conditions, highlighting their potential and identifying any limitations to overcome in the future.

The MagNimbus system is a natural gradiometer, consisting of two sensors positioned at different vertical positions. These sensors simultaneously measure the total magnetic field, facilitating the evaluation of the vertical gradient. The vertical gradient is a valuable tool since it benefits from several properties. It is insensitive to temporal variations of the magnetic field, so no magnetic references are needed. Additionally, it is more sensitive to shallow sources since it is less sensitive to magnetic regional fields and deep magnetized bodies. Moreover, vertical gradient has an increased ability in distinguishing and separating signals coming from nearby sources, providing higher resolution. For instance, in the presented test-site, we showed that the vertical gradient made possible the identification of all the three targets (i.e., the three pipe systems), confirming the potential of UAV surveys for high-resolution subsurface investigations [e.g., 14]. However, the adopted flight configuration introduced a significant heading error effect in the collected data. This occurred because, the radar altimeter, necessary for the TTF mode, is mounted on the UAV front to read the correct altitude information. Consequently, as the UAV changes its direction from a flight line to another, the sensors axes also change direction, strongly enhancing the heading error effects. As shown in the filtered maps (Fig. 5b), this effect can be mitigated through a suitable processing.

The Zond Aereo LF GPR system is equipped with very lightweight dipole antennas, which allows the system to be mounted beneath medium-sized drones such as the DJI M300 RTK. This configuration enables the acquisition of data in a very fast and stable way. However, the absence of antenna shielding makes data processing more challenging, since the recorded backscattered echoes result from a broader radiation pattern, leading to increased complexity in data interpretation. Specifically, as shown in the raw radargram (Fig. 6), the antenna coupling, the air-soil interface reflection and the ringing signals mask the signal from targets of interest, whose detection was possible thanks to the data processing. However, it is worth underlining that the exploitation of altimeter data was crucial for the zero time setting. Accordingly, future studies are needed to reduce the uncertainty on the selection of the zero time of the Zond system and to investigate if the encountered uncertainty depends on the considered central frequency. The processed radargram (Fig. 7) shows three diffraction hyperbolas whose spatial location is compliant with that of the magnetic anomalies visible in Fig. 5b, confirming the ability of the Zond Aereo LF GPR system to image the three pipes.

Acknowledgments. These activities were supported by the project IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System (D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR- Mission 4 “Education and Research” - Component 2: “From research to business” - Investment 3.1: “Fund for the realisation

of an integrated system of research and innovation infrastructures" and "Geo Agro Interdisciplinary Analysis interdepartmental LABoratory (GAIA iLAB) – Interdepartmental agreement between CNR-IREA and CNR-ISAFOM".

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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