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Exploratory study of potential applications of UAV magnetic surveys for unexploded ordnance detection in coastline zone

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The problem of landmine and unexploded ordnance (UXO) contamination in Ukraine, affecting up to 30 % of the territory, is staggering. Current de-mining methodologies without modern technological advancements are estimated to take tens to hundreds of years to complete. The intensive development of unmanned aerial vehicles, sensors, and detection strategies offers an opportunity to use them for remote sensing and the detection of UXOs.

We have already demonstrated that combining a UAV-based magnetometer system with proper scientific methodology can help find and classify landmines. This paper uses the same system to detect various types of ammunition in shallow water (up to several meters deep). We detected 100 % of the tested ferrous mines and ordnance in the coastal zone. All targets (duds of different types) were quickly identified using a simple data-processing method inthree water sites as part of a magnetic survey conducted in a controlled setting. Several technological and instrumental issues negatively affected data quality. Although our study confirmed the locations of magnetic targets, we did not consider a method for analysing their depths. The relationship between burial depth and magnetic anomalies should be explored, as different types of mines and UXO have unique properties. Establishing a database for their identification is also necessary. The effectiveness of the UAV-based magnetometer system has the potential to reduce the risk of mine hazards in coastal zones and shorten the landmine-detection period by providing accurate information about the surveyed area.

Key words: magnetic survey, UAV-based magnetometer system, UXO detection, mines in coastal zone.

Introduction. Since the beginning of the Russian aggression against Ukraine, the threat posed by explosive remnants of war in the area of hostilities has remained significant, with devastating consequences for civilians and military personnel. The detection and removal of mines, explosive devices, and unexploded ordnance (UXO), such as light weapons ammunition, artillery projectiles, mortar shells, cluster munitions, grenades, fuses, and missiles require advanced technologies for identification and georeferencing.

In recent years, promising results have been achieved in integrating different remote sensing methods using unmanned aerial vehicles (UAVs) and drones [Yoo et al., 2020, 2021; Kolster et al., 2022; Lee et al., 2023]. Identification and location of these hidden

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hazards by remote sensing techniques save a lot of civilian people and military personnel.

There are various strategies of mine detection using magnetometers (MAGs), ground-penetrating radars and ground-penetrating synthetic aperture radars, metal detectors, thermal imaging cameras mounted on UAVs for landmine detection (e.g., Lee et al. [2023] and references therein). However, some of these methods are ineffective if the UXOs are underwater, even at a shallow depth of tens of centimetres.

The technical survey phase of underwater detection and UXO clearance operations is often the least understood due to the technical nature of the work accomplished using manual procedures (divers). The focus is more commonly on depths of several meters.

Typical sensors used in underwater technical surveys include the following: magnetometer (MAG), side-scan sonar, multi-beam sonar, sub-bottom profiler, inductive sensor, etc. [A Guide ..., 2016]. Each of these sensors has certain limitations, and the magnetometer (in varying configurations) is considered the most effective sensor for detecting underwater UXO. It is based on the proximity to the ferrous metal in the ordnance.

However, traditional methods of de-mining and UXO detection (landmines by metal detectors and probes, «sea» — with the help of ship hydroacoustic devices, marine magnetometers, or autonomous overall underwater devices), especially immersed in a turbid water environment at shallow depths practically does not ensure the achievement of the necessary results and obtaining accurate and reliable data.

Mines settling down in shoal water area significant concern around the world. According to preliminary estimates of the State Emergency Service of Ukraine, about 14,000 km^2 of inland and marine Ukrainian water areas are currently contaminated by UXO. The mines in the coastal shallow water (a depth of several meters) area particular threat anywhere.

In this paper, we present the results of the various types of ammunition detection in shallow water using a UAV-based magnetometry system. Our preliminary findings show the potential effectiveness of the UAV-MAG system for landmines and other land-based UXO detection [Poliachenko et al., 2023], and we are expanding this technique for shallow water areas — the coastline zone.

Materials and methods. ***Basic Principles.*** Magnetic anomalies indicating UXO arise mainly from induced magnetization in the present-day geomagnetic field, in a process related to magnetic susceptibility. This is the same basic principle as when subsurface geology is investigated by measuring anomalies in the geomagnetic field caused by variations in the magnetic properties of rocks. The tool is widely used in mineral exploration to identify deposits such as iron ore, magnetite, and sulphide minerals (e.g. [Walter et al., 2020]). The magnetometer sensors are located in a horizontal plane orthogonal to the direction of movement of the drone (magnetometric survey).

The underlying principle for UXO detection is the ferrous magnetization by the direction of the Earth's magnetic field according to the inclination and declination of the studied area. The induced magnetic field disturbs the distribution of the Earth's magnetic field around the UXO, thus producing a magnetic anomaly. The latter is identified from the variations in the parameters of the horizontal and vertical derivatives of the magnetic field, which delineate the boundaries of magnetization contrasts and allow outlining of their sources onto the surface or subsurface layers.

Although the magnetometers are very sensitive to iron, certain drawbacks of UAV-borne magnetometers (UAV-MAG systems) need to be considered in UXO detection applications [Yoo et al., 2020, 2021]. A decrease in magnetic field strength is inversely related to the third power of the distance from the magnet isocenter, resulting in reduced detection capabilities for small metallic objects at depths. Magnetometers are susceptible to environmental magnetic interference, e.g., geomagnetic field variations caused by geological structures, nearby ferrous garbage, electromagnetic interference noise from UAVs, etc. These interferences can distort the measurements and compromise the accuracy of mine detection. Also, UAVs are influenced by electromagnetic warfare stations near combat zones.

Despite these limitations, magnetometers in varying configurations are widely considered the most effective sensors for detecting underwater UXOs [A Guide ..., 2016].

Equipment and data processing. Even if we use only a UAV-MAG system without any other detection strategies, it should be a valuable tool in a UXO search. For the detection of underwater UXO, we applied the same «MinesEye» system as we tested for landmine detection [Poliachenko et al., 2023].

A two-sensor magnetometer Mag Drone R3 (Germany, SENSYS company, three-axis fluxgate sensors) was connected through the proprietary extender and placed 2.5 meters below a DJI Agras T30 heavy agricultural UAV platform (Fig. 1, *a*).This system was tested in the lab and in the field and showed repeatable results with low background noise. The extender was designed to reduce background magnetic noise from the UAV (<2.5 nT) and keep a minimal safe distance from the water surface.

Accurate geolocation referencing is extremely important for plotting magnetic anomalies and their interpretation. Geolocation data is especially critical in surveys with dense observation grids. Conventional GPS receivers do not allow sufficient accuracy and usually have an error of at least 2—5 m. Therefore, it is necessary that both the drone and the data collection devices be tied to a reliable RTK (Real Time Kinematic) geolocation system. In our case, we used a DJI D-RTK 2 base station to position the drone and build flight missions and an Emlid RTK system (Emlid RS3 base station and Emlid Reach M2 rover) for georeferencing the magnetic survey data. Both base stations and the rover were referenced to the Emlid RS3 coordinate system, with a relative reference error of less than 0.1 m. The deviation of the geolocation of the magnetic data relative to the Emlid RS3 base station does not exceed 0.05—0.1 m. It should be noted that the Emlid RS3 base station itself was georeferenced using only the GPS. Therefore, all geolocation data may have a systematic deviation of up to 1.5 m (according to our evaluation) relative to their true position.

The distance between UAV flight profiles was the same as we used in a magnetic survey on land [Poliachenko et al., 2023]. Because the minimum programmable distance between the flight profiles of the DJI Agras T30 drone is 1.6 m and the distance between the magnetometer sensors is 1.0 m, magnetic data was collected along parallel magnetic profiles located alternately at 1.0 and 0.6 m. The distance between the sensors and the water surface was 0.5—0.8 m, and the velocity of the UAV was 15 km/h. The sampling rate of fluxgate sensors was 200 Hz.

The magnetic survey data was processed using MagDrone DataTool (primary processing) and Oasis Montaj (main processing) software. The processing included: referencing RTK geopositioning data to magnetic data; splitting the magnetic record into separate magnetic profiles; sensor offset and lag correction; setting appropriate filters and applying them to amplify/extract the useful signal; calculating the anomalies of the geomagnetic field T_a; visualising the result as magnetic maps of the T_a. Anomalies of the geomagnetic field T_a for each profile were obtained by extracting the background calculated using the moving median method with a window of 15 m. The array of T_a anomaly profile data was gridded using the minimum curvature method with a 0.5×0.5 m cell, based on which magnetic maps of the T_a anomaly were created. The results are presented as maps of magnetic anomalies T_a in UTM (WGS84 datum) projection.

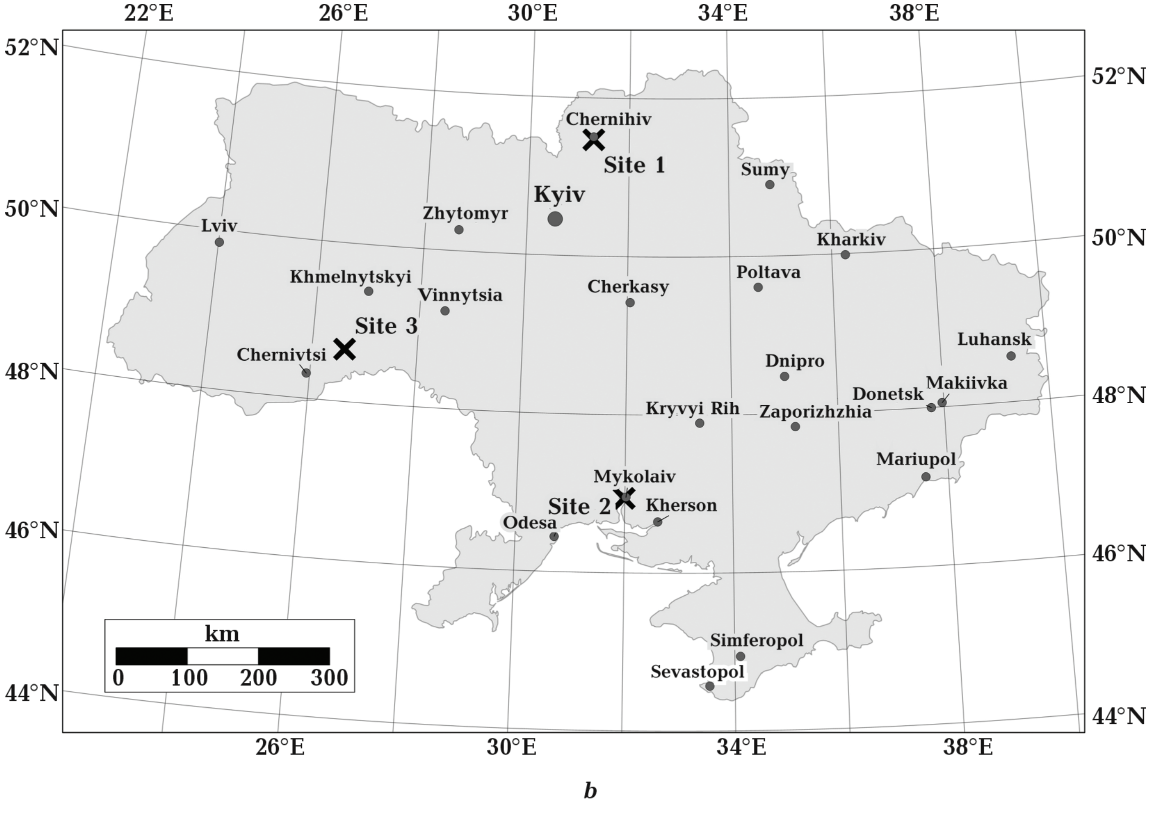
Results and discussion. To conduct controlled experiments (with known target objects and their locations), our team was given access to three water areas indifferent regions of Ukraine (Fig. 1, *b*). The tests were performed to detect targets, knowing what they were and where they were located under the water. Key criteria for planning the experiment included the parameters of the target (volume, size, iron content) and its depth below the water. The anomalies of the geomag-

a

netic field T_a are given as magnetic anomaly maps, the objects are listed in the Table.

In *site 1* (an unnamed lake at the training ground for sapper divers near Kamyanets-Podilsky city), the dud PDM-1M amphibious mine was installed at the 2 m depth. Magnetic profiles and primary magnetic survey data are present in Fig. 2, *a*. The results after processing with emphases for the target object(s) are presented on the Figю 2, *b*. The T_a anomaly from PDM-1M is bipolar with amplitudes from –30 to 20 nT and traced witha maximum diameter of ~10 m. Other magnetic anomalies that appear within the study area are caused by unknown ferrous objects.

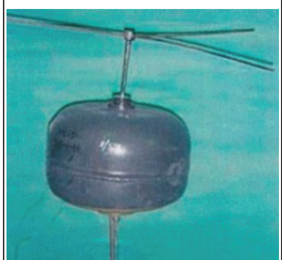
Site 2 (Dnieper estuary bay near Mykolaiv city) was located in an industrial area where a large amount of iron was expected at the bottom. In an area of 60´20 m with a bottom depth of 6—7 m, two amphibious YaRM anti-landing mine models were anchored at a depth of 0.5 m. The mine models appeared as positive



b

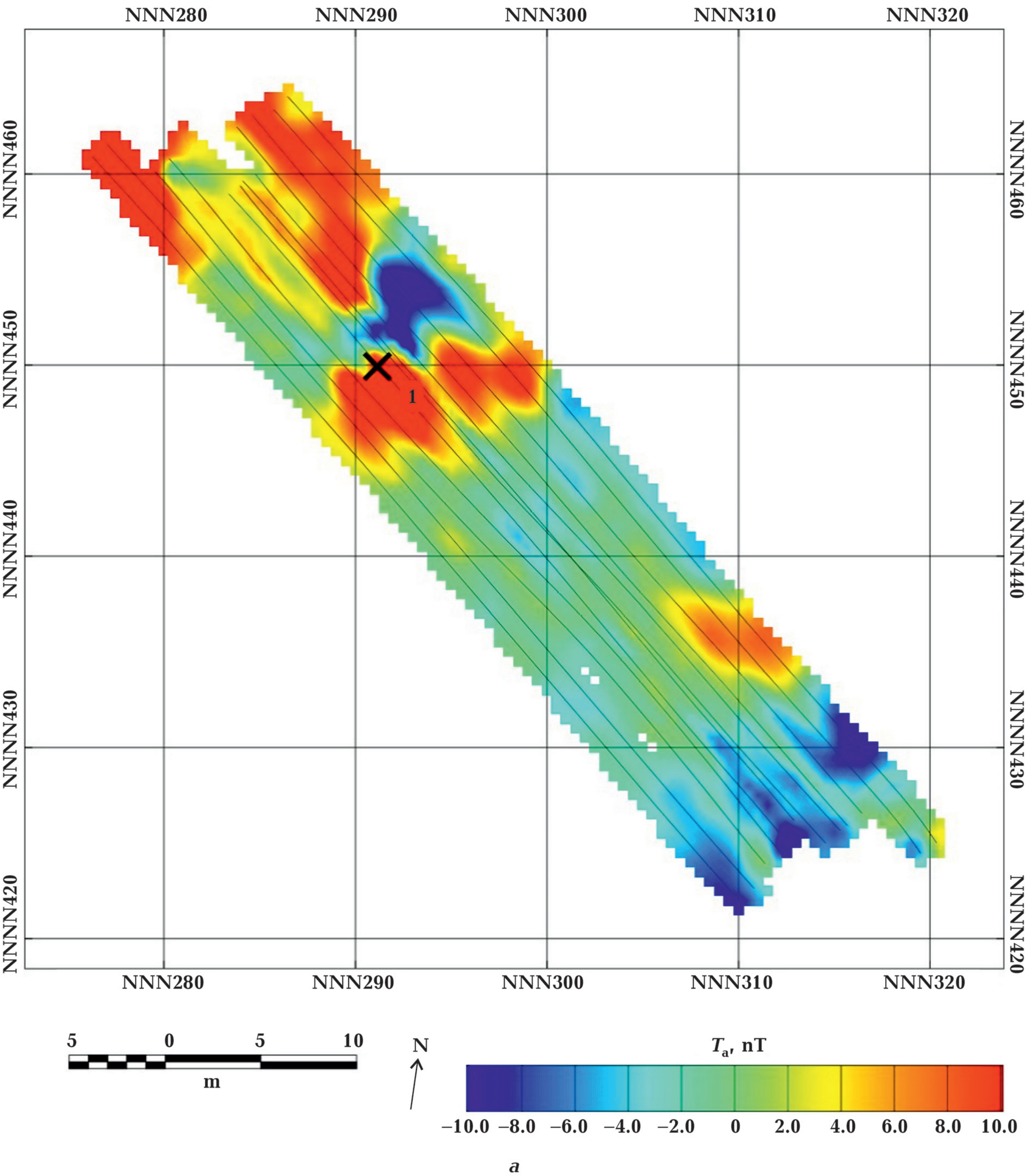
Fig. 1. Integrated system of Mag Drone R3 magnetometer set up under UAV (*a*); map of Ukraine with the position of study sites (*b*).

Names and parameters of test search objects

Number	Name	Type	Pictures	Size, mm	Weight, kg	Material
1	PDM-1M	Seamine		11.9×6.4×2	21+40 down platform	Iron
2	YaRM anti-landing mine	Seamine (anchor mine)		Ø 320 *H*: 510	13	Iron
3	TM-62M	Anti-tank blast mine		Ø 320 *H*:128	7.5	Many variants+ iron elements
4	220 mm, Uragan (9M27) rocket	Submunitions		Ø 220 *H*: 5178	270	Many variants+ iron elements
5	120 mm, mine	—		*H*: 675	16	Iron

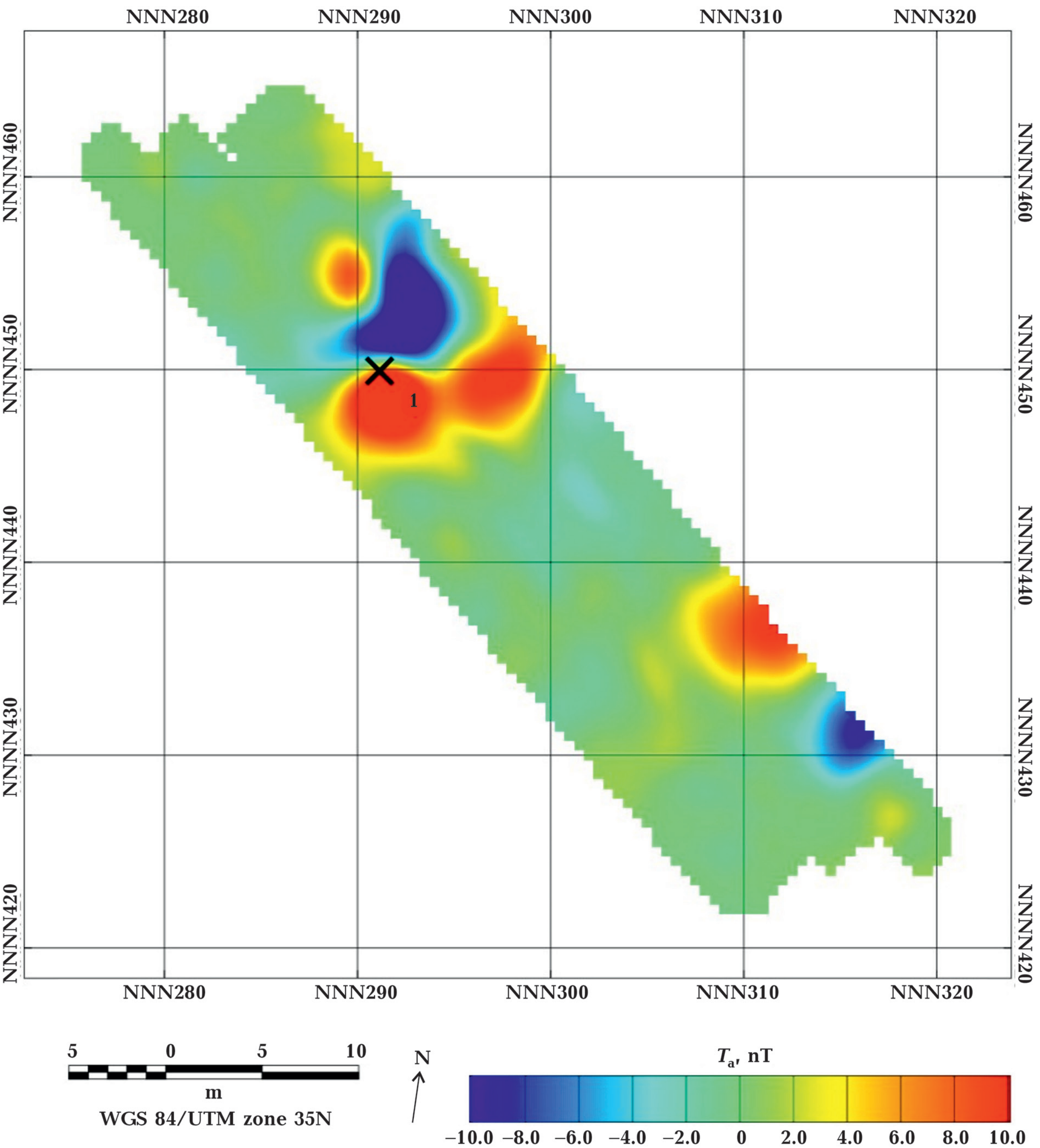
magnetic anomalies close to a round shape with maximum T_a values of up to 8—10 nT and a diameter of ~5 m (Fig. 3). Alternation of positive and negative anomalies along the southern part of the map is due to the proximity of the dock with ferroconcrete stilts. Much ferrous garbage on the bottom is manifested by a number of other chaotic anomalies. However, the target mines were well detected and had similar magnetic signals (shape and amplitude) on the map.

In *site 3* (Mlynovishche lake in Chernihivska oblast) along the north coastal zone, target 3 (a dud of TM-62M anti-tank mine),



a

target 4 (the frame of shell from the Uragan MLRS) and target 5 (a discharged 120 mm mine) were set up on the depths up to 3 m. The magnetic survey was performed above the lake surface and coastal zone on an area of 100×50 m. All three objects were well detected (Fig. 4). Target 4 is characterized by a bipolar T_a anomaly with maximum amplitudes from –50 to 35 nT with a diameter of anomalous zone of about 10 m. The anomaly from target 5, with a diameter of ~6 m, is close to a near-round shape with a maximum T_a up to 15 nT. Target 3 is reflected by T_a anomalies of a near-round shape and diameters of ~3 m with a maximum up to 10 nT. Other magnetic anomalies in the NE part of the study area are caused by unknown underwater objects. At the same time, the calm background of mag-



b

Fig. 2. Magnetic profiles (black lines) and primary magnetic survey data (*a*); map of magnetic anomalies of T_a of site 1 after processing the data using Oasis Montaj software (*b*). The PDM-1M target is indicated by the cross, the corresponding numbers are given in the Table. Geoposition is presented in the hidden UTM projection.

netization in the deeper central and southern parts of the lake indicates the absence of ferrous garbage on the bottom.

According to the survey, all objects were clearly detected. The objects appear as either unipolar or bipolar anomalies depending on the type of ammunition, its iron mass, and the depth from the water surface.

Targets 1 and 4 are characterized by the maximum weight of metal and, consequently,

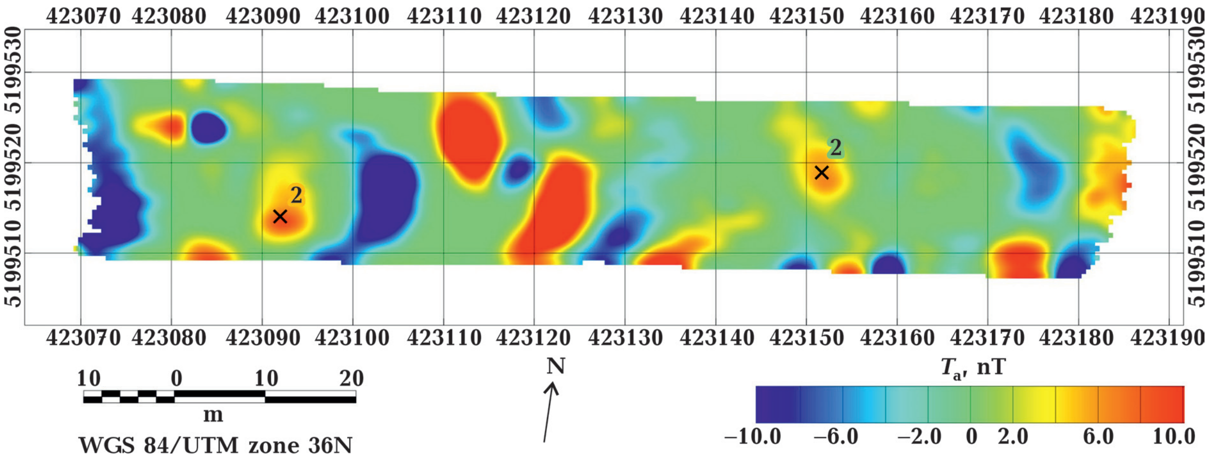


Fig. 3. Map of magnetic anomalies of T_a of site 2. Coordinate reference system WGS 84/UTM zone 36N. Other signs as in Fig. 2.

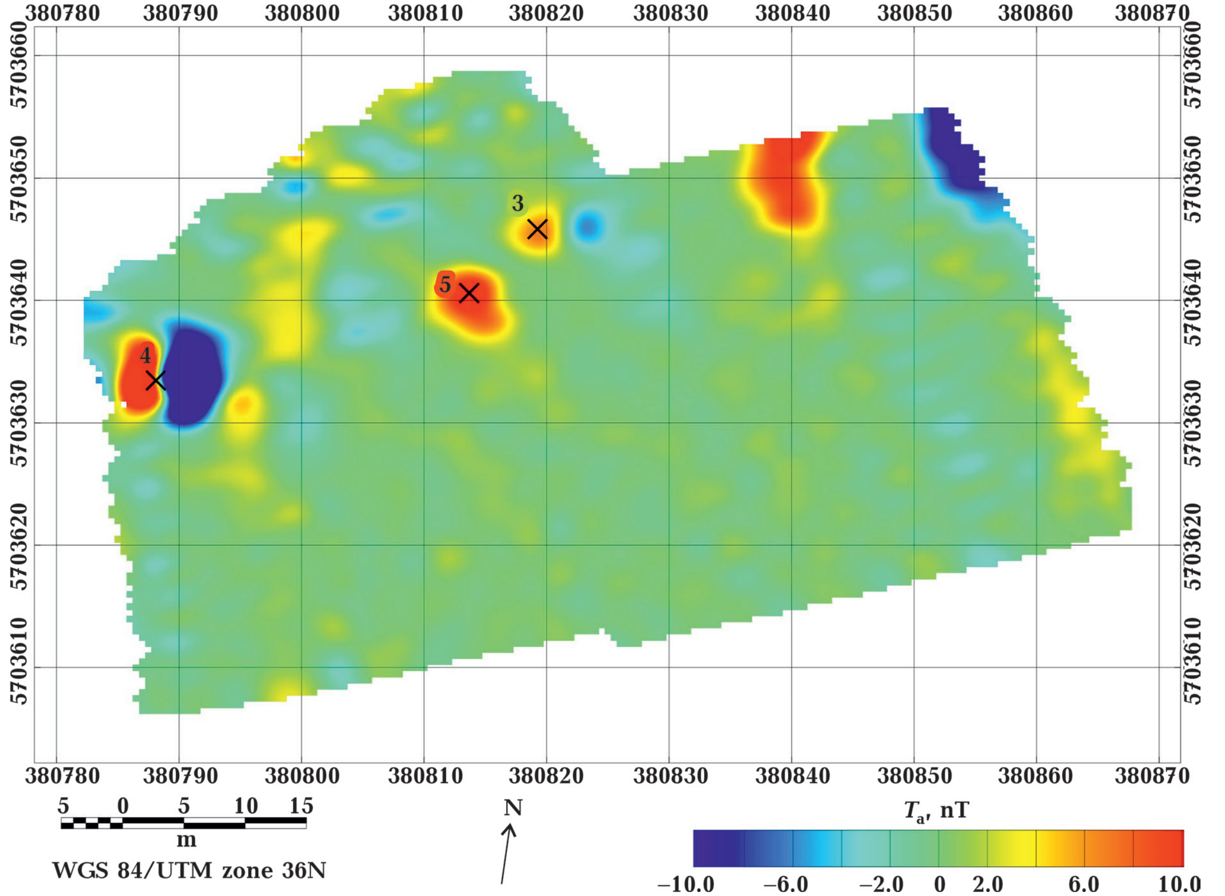


Fig. 4. Map of magnetic anomalies of T_a of site 3. Coordinate reference system WGS 84/UTM zone 36N. Other signs as in Fig. 2.

the greatest amplitudes of clearly expressed bipolar magnetic anomalies with amplitudes of 50 and 85 nT, respectively. Target 3, with less ferrous content, also appears as T_a anomalies of 10 nT. Targets 2 and 5 are reflected in the T_a as unipolar near-round anomalies with amplitudes of about 10—15 nT.

The testing revealed issues that require resolution for assessing system effectiveness and obtaining reliable data. They could be divided into instrumental and environmental problems associated with the initial conditions of the survey.

Instrumental problems are due to the instability of the platform's operation. The swinging of the sensors results in false anomalies at the edges of profiles when the UAV stops to reconfigure to another flight profile for about 10 seconds until the platform is stabilised. Therefore, a more careful stabilisation of the platform is required to reduce swinging or to exclude erroneous records from interpretation.

Another instrumental problem is the geographical position of the underwater target. A precise RTK system with an accuracy of a few centimeters does not mark a target in the water for its subsequent detection. Although there is no vegetation that would obstruct scanning, visual access to the targets is difficult.

It should also be noted that a UAV-MAG system requires special protection in case of landing on water, which can lead to irretrievable loss of all equipment.

During data processing, spatial filtering techniques can be used for extracting UXO anomalies (e.g. [Yoo et al., 2021]). Direct-task modelling in magnetometry for individual objects is well-known, but when objects are close to each other, there is a risk of anomalies combining. Therefore, the magnetic method has limited applicability foran agglomeration of objects with a significant iron content. For example, when a UXO lies in the «magnetic shadow» of a more magnetic object, there is a risk of missing even a target that can be easily determined in other conditions. This applies to both land mines and underwater mines in shallow waters.

The classification of UXO based on magnetic signals from individual targets will partially help to solve the problem of detecting objects in conditions of significant contamination by ferrous metals. This takes time to perform a significant number of tests o n special training grounds with different models of the most common UXO and mines. It is necessary to collect high-quality data with minimal effect of the external factors for further processing and to set up a database identifying unique properties for the objects of interest.

To achieve optimal performance of the combined sensing and data processing technique for UXO detection and classification in the natural environment, a combined UAV-MAG system should be developed based on deep learning. Recently, deep-learning techniques have been adapted for anomaly detection using time-series or sequential data (e.g. [Fan et al., 2020; Xu et al., 2020; Ruff et al., 2021]). Data acquisition from known targets will help to speed up the training of machine learning algorithms for image recognition and magnetic anomaly classification.

Conclusion. In this study, we advanced a model of UAV-borne magnetometry system, which was previously tested on the full-scale models of disarmed landmines and other ordnance [Poliachenko et al., 2023]. This system was applied to identify underwater targets in the coastline zone and demonstrated a 100 % detection rate of mine and ordnance with a significant content of ferrometals.

To increase the likelihood of mine detection, the magnetometer was placed far 2.5 meters under the UAV to reduce the distance between the water surface and the sensors and minimize the background noise (<2.5 nT) from the UAV. All objects in the three sites were identified quickly using a simple data-processing method with Oasis Montaj software. In a controlled setting, detecting the used types of mine (PDM-1M, TM-62, YeaR) was undoubted.

We identified several issues affecting data quality. First of all, these problems are associated with technological and anthropogenic contamination. In the near future, the main emphasis will be on platform stability and optimizing the system for collecting geospatial and magnetic data under significant magnetic contamination associated with ferromagnetic debris and exploded ordnance. The relationship of burial depth with magnetic anomalies should be explored together with the unique properties of different types of mines and UXO. A database for their classification should be set up.

Although our study confirmed the locations of magnetic targets, we did not consider a method for analysing their depths. The relationship of burial depth with magnetic anomalies should be explored in future studies. Detection of mines before removal operations using a UAV may reduce the risk to personnel by identifying possible minefields and reduce the mine-detection time.

Authors' contributions. We explicitly declare that this manuscript is original, has not been published before, and is not currently being considered for publication elsewhere. We confirm that the manuscript has been read and approved by all co-authors. We further confirm that the order of authors listed in the manuscript has been approved by all authors who equally participated in data acquisition, selection, interpretation, and analysis.

Competing interests. No Competing Interest.

Conflict of Interest. No Conflict of Interests.

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Застосування магнітної зйомки з БПЛА для виявлення нерозірваних боєприпасів у прибережній зоні: попередні результати

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Проблема забруднення України мінами та боєприпасами, що не вибухнув (НВБ), коли вражено до 30 % території, приголомшує. За різними оцінками при сучасних методах розмінування, але без застосування новітніх технологій, для розмінування знадобляться від десятків до сотень років. Інтенсивний розвиток безпілотних авіаційних технологій у поєднанні із сучасними приладами ініціював розробку нових інструментів дистанційного зондування для виявлення НВБ. Наші попередні дослідження на моделях НВБ продемонстрували, як використання безпілотних літальних апаратів (БПЛА) у комплексі з магнітометричним обладнанням та відповідною науковою методикою може бути корисним при ідентифікації та класифікації наземних металевих мін. У статті наведено результати виявлення різних типів металевих боєприпасів на мілководді (на глибинах до кількох метрів) за допомогою того ж самого обладнання. Результати продемонстрували 100%-ну ефективність запропонованої методики. Усі об'єкти (моделі металевих мін різних типів, закладені у контрольованих умовах) на трьох водних ділянках були оперативно виявлені при магнітному зніманні та обробці даних. Визначено технологічні та інструментальні проблеми, які негативно впливають на якість даних. Було виявлено розташування всіх об'єктів пошуку, але не розглянуто методи аналізу особливостей їх прояву. Необхідно дослідити зв'язок між їх захороненням та магнітними аномаліями, оскільки різні типи мін та НВБ мають унікальні магнітні властивості, що потребує створення бази даних для їх ідентифікації. Ефективність магнітометричної системи на базі БПЛА може зменшити ризики у замінованих прибережних акваторіях та скорочує час для виявлення мін, надаючи військовим інформацію про потенційно небезпечні ділянки мілководдя до їх розмінування.

Ключові слова: магнітна зйомка, магнітометрична система на базі БПЛА, виявлення НВБ, міни в прибережній зоні.