
Unmanned Aerial Systems for Magnetic Survey

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<http://dx.doi.org/10.5772/intechopen.73003>

Abstract

Placing a magnetometer on unmanned aerial vehicle (UAV) seems to be an easy task as the sensor is rather lightweight in comparison with other geophysical sensors. But, the realization of an unmanned aeromagnetic system (UAMS) faces multiple technical complications, and, as a result, very few of many attempts to build a UAMS have succeeded. Even less projects have produced results of real magnetic survey. Different platforms (helicopters, multicopter, and fixed wing UAVs) and different kinds of magnetometers for UAMS have different pros and cons for the purpose. For the quality of magnetic survey, the most important is the issue of a platform's (UAV) magnetic noise and its influence on a magnetic sensor. Workbench experimental studies as well as results of magnetic surveys with multicopter UAMS in Leningrad region, Republic Sakha-Yakutia, and Kazakhstan demonstrate solutions facilitating state-of-the-art high-quality measurements of magnetic anomalies for geological, archeological, and other purposes.

Keywords: geophysics, magnetic survey, magnetometer, unmanned aeromagnetic system (UAMS), unmanned aerial vehicle (UAV)

1. Introduction

Magnetic survey represents one of the most effective geophysical methods for mapping the anomalies related with geological features and objects characterized by different magnetic properties. First evaluation of magnetic anomalies has been carried out in Sweden in 1640 using a compass for detecting iron ore deposits, but systematic magnetic surveys have started at the end of nineteenth—beginning of twentieth century with invention of magnetometers [1]. Both ground and aeromagnetic surveys are usually carried out in a regular pattern with fixed distances between parallel lines and points of measurements [2]. Aeromagnetic survey is usually being executed at 250–300 m height depending on aircraft characteristics and flight regulations. Unmanned aeromagnetic system (UAMS) can operate lower, starting from few meters.

This is important for geological interpretation of magnetic anomalies as the magnetic signal weakens at a distance from the source. Another advantage of UAMS is a pure economic one. A piloted aircraft is ineffective for surveys of areas, which are less than 200–300 km² due to high expenses on services requesting airport infrastructure and on approach from the airport to the area of survey. Unmanned aerial vehicle (UAV), especially a small one (lighter than 10 kg [3]), does not need an infrastructure and can be easily transported by car or even by operator.

The major issue of UAMS design is elimination of UAV's magnetic noise. With piloted aircraft, the problem gets resolved by one of two ways: (1) placing the magnetometer at a gondola attached to aircraft either by rope or by special bar or (2) using quite complicated systems of the aircraft's noise compensation. In traditional aeromagnetic survey, such systems contain additional magnetometers and use special algorithms facilitating results characterized by error well below 2 nT. In UAMS, such system adds sufficient weight to the load and, practically, rejects use of lightweight UAVs, which eliminates UAMS advantages over using a piloted aircraft. Thus, for UAMS, the first way is the most effective way to fight the carrier's magnetic noise. Miniaturization of equipment theoretically allows the use of compensation in UAMS using existing technologies, but it makes the system much more complex and expensive.

Each measurement in the magnetic survey, besides of the magnetic field components, should contain time and exact positioning of the magnetometer. State-of-the-art professional UAVs are usually equipped with global navigation satellite system (GNSS) and navigation system facilitating programmed flight route.

Choice of magnetometer for UAMS is also important. It should be lightweight, tolerant to the sensor's orientation, and, preferably, characterized by high frequency of measurements.

Further, we will consider solutions of these issues for fixed-wing and multirotor UAMS and will demonstrate results of magnetic surveys executed with UAMS designed on the basis of a quadcopter drone "Geoscan-401".

2. UAV as a platform for unmanned aeromagnetic system

The advisability of using UAVs to carry out aeromagnetic surveys is based on the fact that UAV-based surveys are more cost effective, and their results are comparable with those of conventional aeromagnetic surveying with the use of manned aircraft. The greater the takeoff weight of a UAV is, the more difficult and expensive its development is, and the lower its reliability and operational safety are [4]. Lightweight UAVs need no airfield; they are characterized by low energy consumption. The main problems to be solved are (1) the development of a magnetic sensor to meet a number of requirements and (2) deviation minimization [5]. The requirements for magnetic-field sensors are related to the speed of a UAV (the measurement rate should be more than 10 Hz at a speed of 60 km/h, which corresponds to a 2-m spacing between measurements) and to payload restrictions. For short-range (from 10 to 120 km) lightweight UAVs [4], the payload weight must not exceed 2 kg, which means additional requirements for aeromagnetometers.

Choice of UAV type (fixed-wing, helicopter, and multirotor) for UAMS should be made on the basis of tasks to be resolved. For magnetic survey of large areas (over 150–200 km²) with

relatively flat surface, fixed-wing UAV would be the best option because of higher flight speed. For mountains, maneuverability of the UAV is more important, so helicopter and multirotor UAVs will be the favorites for mountain territories. Further, we will consider fixed-wing and multirotor UAVs as possible platforms for UAMS. The helicopters are excluded from consideration, as they are more expensive in operation and, at the same time, do not have clear advantages in comparison with multirotor UAVs.

2.1. Fixed-wing UAV

Typical magnetic signature of a fixed-wing lightweight UAV can be seen in **Figure 1** [5].

The magnetic noise induced by UAV “Geoscan-201” components has been measured using special non-magnetic stand 120 × 270 cm (**Figure 2**) and atomic scalar magnetometers MMPOS-1 (Russia) and Geometrics G-858 (Canada). To remove the background magnetic field, the measurements on the upper level of the stand have been initially executed without UAV by grid 10 × 10 cm. The amplitude of background magnetic anomalies of the stand is below 1 nT/m.

As far as use of gondola for distancing magnetic sensor from the UAV is rather impossible for such a lightweight aircraft as “Geoscan-201”, the best option for the sensor placement is the end of wing, where magnetic influence of the aircraft ranges from -4 to +4 nT. Difference between ΔT_a measured at the ends of left and right wings varies for different regimes of the engine and servo operation from 7 to 19 nT, which is much more than acceptable for the high-quality magnetic survey [5].

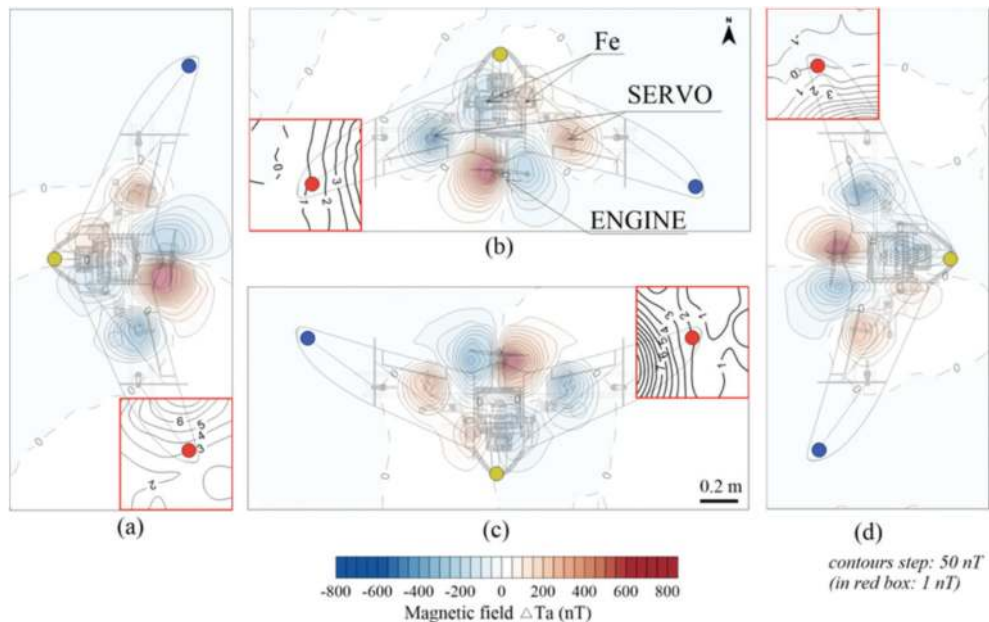


Figure 1. Magnetic signature ΔT_a of “Geoscan-201” for its different orientation at the Earth’s magnetic field: (a) west; (b) north; (c) south; and (d) east.

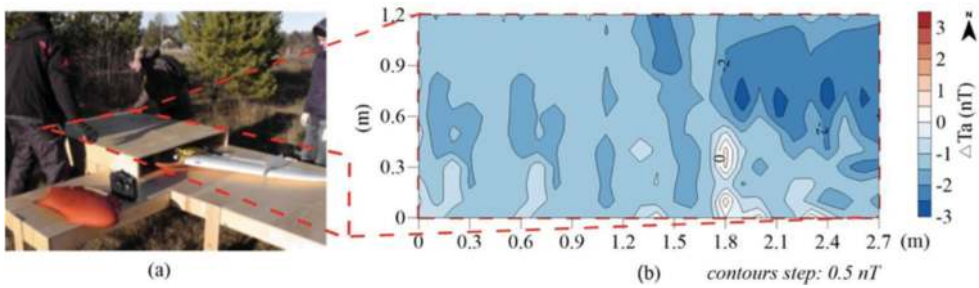


Figure 2. “Geoscan-201” magnetic noise measurement (a) and background magnetic field (b).

From **Figure 1**, it is absolutely clear that, for a lightweight UAV:

- major sources of magnetic noise are electric engine and servos producing anomalies with amplitude of 600–700 nT;
- the most appropriate location of magnetic sensors is at the ends of wings, and, in that case, the servos should be placed in the UAV’s main body instead of wings.

Another obvious conclusion relates with the UAV’s engine type. Replacement of an electric engine with combustion one in accordance with the results of mathematical modeling makes a horizontal gradient of the magnetic field at the end of a wing three to four times lower. However, the combustion engine fitting the task weighs about 700 g versus 284 g of electro engine. This, along with the additional weight of a magnetic sensor (up to 200 g) at the end of a wing, has made UAV “Geoscan-201” unstable in the air because of displacing center of mass.

To comply with the results of the experiment, a new UAV “Geoscan-301” has been designed (**Figure 3a**) and built (**Figure 3b**).

Aerodynamic modeling and measured magnetic effect (**Figure 4**) demonstrate compliance of the new UAV with all the requests of high-quality magnetic survey. Nevertheless, the new problem appeared during the flight tests: complicate control of the combustion engine makes flight control extremely difficult, and it requests fundamental changes in the software facilitating UAV operation.

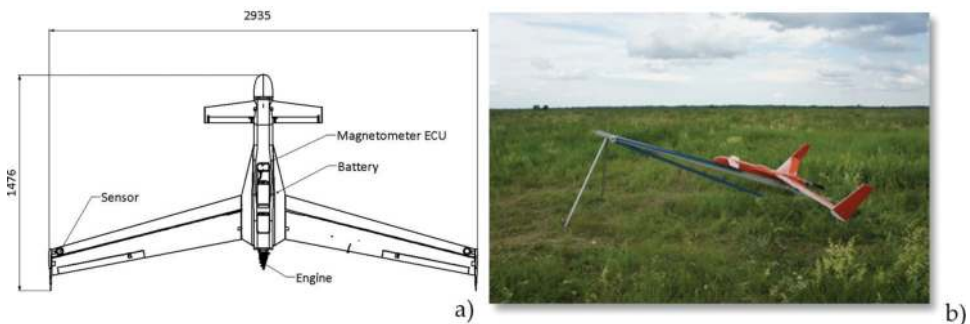


Figure 3. Design of “Geoscan-301” (a) and its launch (b).

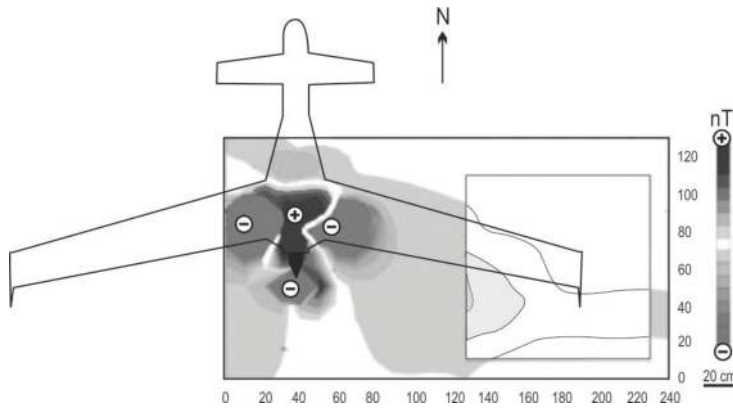


Figure 4. Measured magnetic effect of “Geoscan-301”. Contour interval—25 nT; contour interval in the sidebar—1 nT.

2.2. Multirotor UAV

Multirotor UAV can be characterized as easiest-to-control type of unmanned aircrafts. At the same time, its magnetic noise is much more complicated in comparison with a fixed-wing UAV because of minimum four electric engines. And, there is no room for a magnetic sensor in the main UAV body, so we have to consider use of non-magnetic gondola attached to the UAV by rope (cable).

Magnetic noise of “Geoscan-401” quadcopter (Figure 5) measured at different distances from the UAV is given in Table 1.

It is obvious that at 3 m from the UAV, the magnetic noise is already negligible. Nevertheless, in UAMS built on the basis of “Geoscan-401”, the length of the rope is 20 m, which is reasoned by aerodynamic specifics of this UAV. The lesser distance between gondola and UAV affects stability of the flight. It is necessary to note that for another UAVs, these figures can differ.

At the first tests, the gondola itself was a ring-shaped non-magnetic frame with rubidium vapor magnetometer (RVM) and additional differential GNSS receivers with external antennas [6]. Later, in order to improve UAMS aerodynamic characteristics, a crossbar-shape gondola had



Figure 5. Quadcopter “Geoscan-401”.

Distance from the UAV, m	Max amplitude of magnetic noise, nT
1	≈5
2	≈1
3	≈0.1

Table 1. Measured magnetic noise of “Geoscan-401” quadcopter.

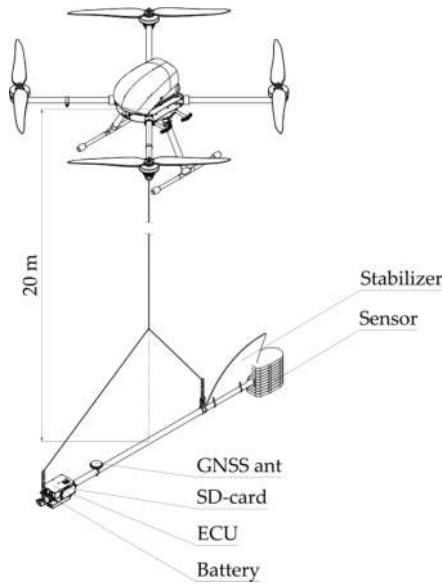


Figure 6. Unmanned aeromagnetic system (UAMS) on the basis of “Geoscan-401”.

been designed (Figure 6). During the flight, the autopilot uses copter’s GNSS for navigation, and GNSS on the outer frame registers the magnetometer’s allocation using time synchronization method. The GNSS horizontal accuracy is about ±2.5 m, and vertical accuracy is about ±3 m.

Thus, both fixed-wing and multirotor UAVs can be used as a transport platform for UAMS. For the fixed-wing ones, optimal location of magnetic sensor(s) is at the ends of wings, and for the multirotor UAVs—at a gondola attached to UAV by a rope (cable) not less than 3 m in length, depending on magnetic and aerodynamic characteristics of the aircraft.

3. Magnetometer

Different models of magnetometers have been considered for UAMS. The magnetic sensor for unmanned aeromagnetic survey should be: (a) lightweight, not over 300 g; (b) quite fast, not

less than 10 measurements per second; and (c) insensitive to orientation. As far as no one from the magnetometers in the market responded to these requests without a sufficient adaptation, a new rubidium vapor magnetometer (RVM) has been designed and built for the purpose.

The specification of the rubidium vapor magnetometer (RVM; **Figure 7**) is listed in **Table 2**. The RVM includes: (i) magnetic sensor with a bulb containing vapor Rb^{87} ; (ii) the Electronic Control Unit (ECU) including the optical pumping lamp; and (iii) the power source (not shown in **Figure 7**). All the parts are designed as separate modules connected by fiber-optic and electric cables, which facilitate distribution of the weight in the UAMS.

The RVM's noise has been checked at the magnetic field stabilizer, and it is about $10 \text{ pT}/\sqrt{\text{Hz}}$. The transition process (speed of reaction to a jump field) takes 30 ms.

To evaluate an absolute error of the RVM, a series of comparative tests has been conducted using the commercially available cesium vapor Geometrics G-858 and Overhauser MMPOS magnetometers. The field tests were organized in the area free of industrial noise and anomalous magnetic field gradients (Leningrad region, Russia).

Range of tests has been conducted in order to evaluate an influence of temperature on the measurements. The results demonstrate independence of measurements as well as of the measurement's error estimation of the temperature of both magnetic sensor and electronic unit of RVM [6].

Another standard test was conducted inside the calibration test station UPTM-4 in order to define the metrological characteristics of the magnetometer. The test had taken place at the



Figure 7. Rubidium vapor magnetometer (RVM).

Sensitivity	10 pT/√Hz
Field range	20,000–100,000 nT
Frequency response	200 Hz
Sampling rate	1000 Hz
The range sensor angles	±45°
Power	8–35 V, 10 W
Environment temperature	–20 ... + 60°C
Weight of the sensor/ECU	120 g/300 g

Table 2. Specification of the rubidium vapor magnetometer (RVM).

B, nT	$\Delta_{se}(B)$, nT	S(B), nT
20,000	0.86	0.02
30,000	0.19	0.02
40,000	–0.19	0.02
50,000	–0.60	0.02
60,000	–1.28	0.01
70,000	–2.07	0.01
80,000	–3.05	0.03
90,000	–4.51	0.04
1000 000	–6.31	0.03

Table 3. RVM systematic errors $\Delta_{se}(B)$ and standard deviation S(B) depending on the magnetic induction (B).

facilities of FGUNPP “Geologorazvedka” in Leningrad region, Vsevolozhsk district. Results of the RVM systematic errors $\Delta_{se}(B)$ and standard deviation S(B) with a measurement range of magnetic induction module (B) are shown in **Table 3**.

All the experiments demonstrate conformity of all RVM characteristics with requests of high precision aeromagnetic survey.

4. Experiments and surveys

A number of magnetic surveys measuring total magnetic intensity (TMI) have been carried out using UAMS during the fall of 2016 and 2017 in different regions of Russia and Kazakhstan (**Table 4**). In all cases, the preprogrammed flights were executed along the parallel lines. Example of a flight layout is demonstrated in **Figure 8**.

Location	Size of area	Height of the survey (position of the sensor)	Distance between the flight lines	Type of the survey
Leningrad region, Agalatovo village	0.8 × 1 km	150 m from the highest point	50 m	Test survey
Republic Sakha-Yakutia	1 × 1 km	100 m from the highest point	100 m	Demonstration survey
Republic Kazakhstan, Eastern Kazakhstan, southwestern part of Kazakhstan Altay	7.5 × 4 km	50 m from the surface	50 m	Commercial survey
	1 × 1 km detalization	30 m from the surface	50 m	Commercial survey
		70 m from the surface	100 m	Commercial survey
Republic Kazakhstan, Central Kazakhstan	3.5 × 12 km	30 m from the surface	100 m	Commercial survey

Table 4. Magnetic surveys executed by Geoscan, Ltd. between September 2016 and November 2017 using UAMS on the basis of “Geoscan-401” quadcopter with RVM.

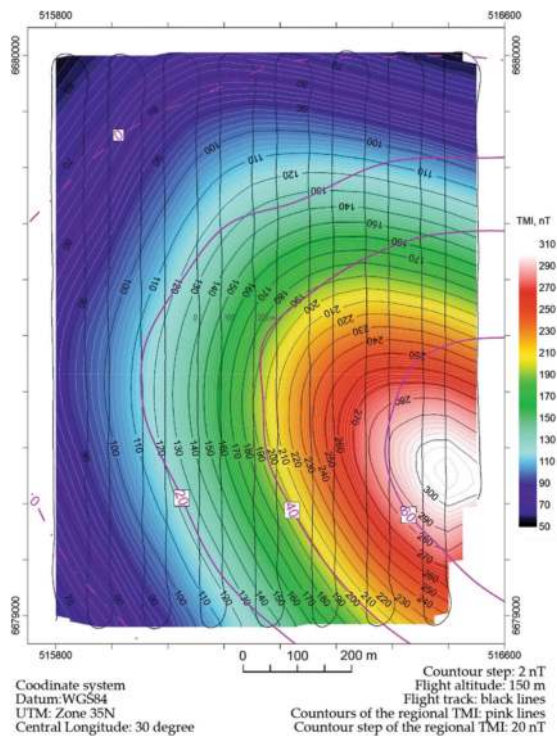


Figure 8. TMI map of the first test survey in Leningrad region.

The first survey has been carried out in Leningrad region just as a test of UAMS in the area with relatively quiet natural magnetic field with a local TMI anomaly of over 60 nT amplitude measured during regional aeromagnetic survey. The test survey has revealed an anomaly of concordant shape with higher (above 300 nT) intensity, which is due to lower height of the flight.

The results of the survey confirm workability of UAMS. Also, the comparison of task lines and real survey lines shows the difference of about 10 m for all flights of southward direction and approximately 1 m when the UAS moved northward (Figure 8). The latest demonstrates an influence of west wind (10 m/s) on a ring-shaped gondola. After this survey, the new gondola design (crossbar) has been implemented and used in all the subsequent surveys. The rope length has been cut from 50 to 20 m.

The second test was conducted in Republic Sakha-Yakutia in the area determined by potential UAMS buyer (Figure 9). The area is located at the flank of iron ore deposit and is characterized by more intensive TMI anomalies.

The survey has demonstrated stable measurements under conditions of high-gradient (up to 30 nT/m) magnetic field and, by conclusion of the buyer, good compliance with results of ground survey. Two UAMSs have been acquired, and, by now, about 100 km² of 1:10,000 magnetic survey has been carried out.

In 2017, 465 line km of 1:10,000 UAMS magnetic survey has been carried out in Central Kazakhstan [7]. The task of the survey is geological mapping, in particular—tracing of zones prospective for lead-zinc and iron-manganese ores of stratiform type in carbonite rocks buried under sand and clay deposits. What is important, a comparison was made between UAMS and ground survey (Figure 10) as well as between UAMS and traditional aeromagnetic survey (Figure 11).

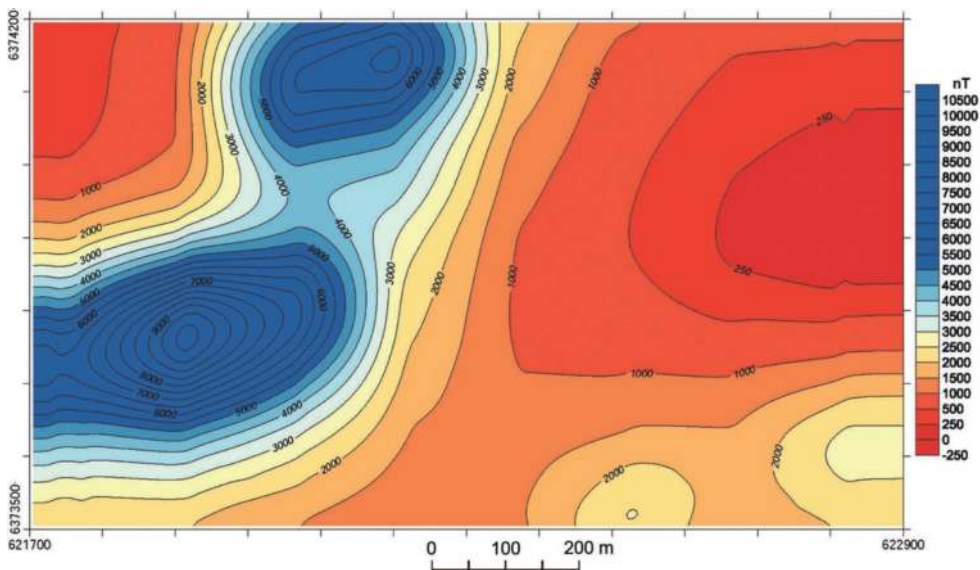


Figure 9. TMI map of the demonstration survey in Republic Sakha-Yakutia.

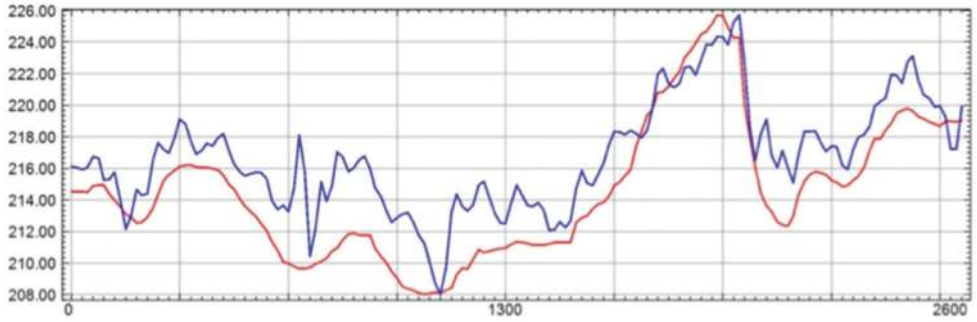


Figure 10. Comparison of ground (blue) and UAMS (red) measurements along the same line. X-axis—distance, m; Y-axis—TMI, nT.

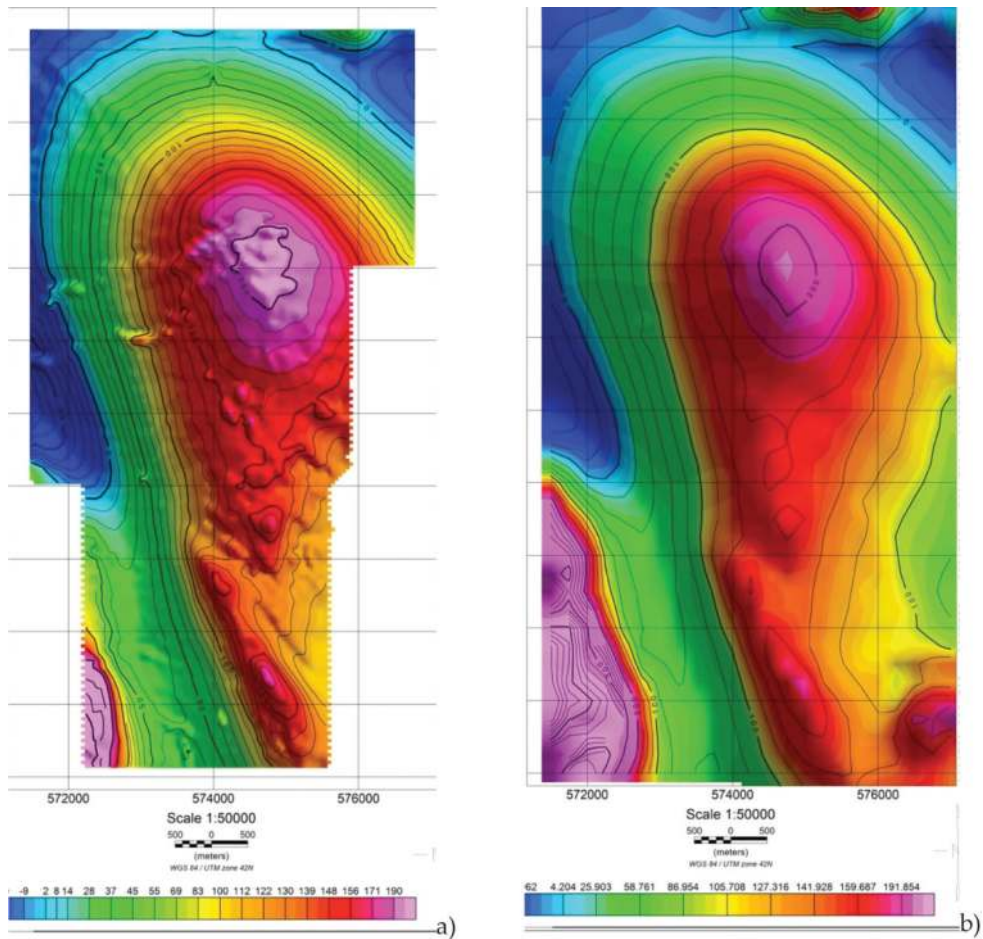


Figure 11. TMI map of the commercial survey in Central Kazakhstan: (a) UAMS 1:10,000 survey, 2017 and (b) 1:25,000 aeromagnetic survey, 1988.

The survey was carried out at as low as 30 m height (sensor position). Control measurements demonstrate TMI standard deviation at ± 0.35 nT, which is a very good characteristic in comparison with both traditional aeromagnetic and ground surveys.

The more detailed (1:5000) UAMS survey was executed in the Eastern Kazakhstan over an area of 30 sq. km in the frames of gold ore deposits prospecting.

5. Conclusions

At the moment, the use of UAV in geology, including UAMS magnetic survey, experiences a fast grow. In 2016, special session named “Unmanned aerial vehicles (UAV)-based technologies for geology and Earth sciences” had been organized in the frames of 35th International Geological Congress. In 2018, similar session is supposed to take place at 15th Quadrennial Symposium of International Association for Genesis of Ore Deposits (IAGOD). These events indicate an interest of geological community to the new opportunities and, vice versa, growing readiness of the technologies for implementation.

In the frames of this study, few technical conclusions can be made, including the following:

- fixed-wing and multicopter UAVs can be used as a transport platform for UAMS;
- for UAMS based on the fixed-wing UAVs, optimal location of magnetic sensor(s) is at the ends of wings, and for the multicopter UAVs—at a gondola, it is attached to UAV by a rope or cable;
- design of UAMS includes deep adaptation of both UAV and magnetometer, targeting minimization of magnetic influence of UAV and its components on the magnetic measurements;
- UAMS based on “Geoscan-401” quadcopter is efficient for high-precision magnetic survey in the areas from first to $n \times 100$ km². One UAMS facilitates from 120 to 160 line km of magnetic survey per day;
- UAMS magnetic survey is more informative in comparison with traditional aerial survey at the count of lower flight and technical ability to circumvent the terrain;
- use of fixed-wing UAV can be more effective than of multicopter one, especially for large (over 100 km²) areas, but fixed-wing UAMS still has issues to be resolved before entering the market.

One of the promising directions of the further development of UAMS magnetic survey is multilevel magnetic survey. Theoretical basis for such survey has been developed in the middle of twentieth century, but it would be extremely expensive to fly few times the same area by piloted aircraft. UAMS survey makes it effective when 3D magnetic field measurements are useful for geological purposes.

In comparison with traditional magnetic survey, advantages of UAMS are:

- the possibility of conducting a night flight;
- the simplified obtaining of resolving documentation for the flight;
- simultaneous survey by several UAMSs;
- independence from the location of the airports;
- reducing the cost of flight hours;
- the increase profitability of detailed survey compared to aeromagnetic and ground surveys.

Altogether, UAMS magnetic survey represents the future of magnetic prospecting, especially—in the ore geology, and provides geologists with new effective tool for field work.

Acknowledgements

Sufficient part of this research was funded by the Ministry of Education and Science of Russian Federation, under Agreement no. 14.607.21.0081 (ID no. RFMEFI60714X0081). The authors would like to thank FGUNPP “Geologorazvedka” and, personally, Vadim Tsirel for assistance in the testing of RVM. TOO “NPTs Geoken” and TOO “Kazzinc” have kindly allowed authors to demonstrate results of the first commercial survey executed with UAMS.

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