Lightweight TEM and VLF systems for low-altitude UAV-based geophysical prospecting

Introduction

Currently, UAV-based geophysics technologies, individually or in combination, are widely used in geological prospecting and mapping (Park and Choi 2020; Parshin et al 2016-2021; Jackish et al 2019; Cunningham et al 2018 and many others). In Russian practice, the technologies of magnetic and gamma-ray surveys have become widespread and have actually completely replaced the ground versions of the same methods (Parshin 2018-2021). In addition to these two methods, classical airborne geophysics necessarily includes one of the electromagnetic (EM) prospecting methods, which makes it possible to better solve inverse problems and carry out geometrization of the subsoil (Macnae 2007; Orta et al 2013; et al). Until recently, the UAV-based electromagnetic prospecting that actually existed in geological practice were apparently limited to the very low frequency technology (VLF) (GEM Systems, 2020 and the like), where the source of the EM field in the geological environment is the fields of radio stations in the range of the first tens of kilohertz. The depth of such a variant of electromagnetic prospecting is limited to the first tens of meters even with a high resistance of the rocks, the possibilities of inversion are very limited or even impossible at all - if the available radio stations do not have significant differences in broadcasting frequencies. There is no doubt that in order to further increase the efficiency of integrated UAV-aerogeophysics, it is necessary to develop new methods of UAV-EM prospecting, which provide greater depth and the possibility of full-fledged 3D-inversion. In classical airborne geophysics, time-domain electromagnetic (TDEM, TEM) methods are widely used, in which a helicopter tows a transmitter and measuring system. But the mass and dimensions of the towed system (and the generator itself) are large. The legislation of the Russian Federation allows a simplified procedure for the operation of unmanned aerial systems with a total mass of up to 30 kg, in connection with which we wanted to create a lightweight EM prospecting system, or several complementary technologies, that would allow us both to carry out electrical prospecting on relatively large areas and to obtain data suitable for high-quality inversion in class 1D and 3D models in the future. Moreover, since the authors had previously created a set of technologies for magnetic, gamma, lidar and multispectral surveys (Parshin et al 2016-2021), we wanted to implement the possibility of simultaneous surveys with all these methods, including electrical prospecting, without going beyond 30 kg of the weight of the unmanned system.

Two technologies of UAV-based EM prospecting

Two technologies of UAV electrical prospecting were developed and applied in practice:

1) 1) For integration with magnetic and gamma-ray surveys in the early stages of geological prospecting, the VLF technology is used. In our version, the measuring system is located on a remote cable a few meters below the UAV and includes two or three magnetic antennas. The antennas are oriented for measuring the horizontal and vertical field components, and at each new survey site, the horizontal antenna is directed to the maximum signal from the radio station by rotating the gimbal. Accordingly, the measuring system simultaneously records two or three audio tracks with recording the time and coordinates of the GNSS measurements. Using fast Fourier transforms, the values of the spectral amplitudes of the signal at the selected frequency (or several frequencies) are extracted from the parts of audio recordings, i.e. Hy and Hz values. In the last years, we often come across the presence of one, maximum of two available radio frequencies, in connection with which the inversion is not performed, but maps of individual parameters are built - the horizontal or vertical magnetic component of the electromagnetic field, their ratios, the full vector, which, in our opinion, sufficient to solve the problems of mapping of resistance anomalies. The registration system includes an inertial system (IMU) that allows to monitor the possible tilt of the antennas. The measurements are accompanied by observations of daily variations in the level of VLF radio waves from a fixed antenna, since these changes can be significant. The mass of the measuring system with two antennas does not exceed 2 kg, which makes it possible to combine this option with other types of geophysical survey.

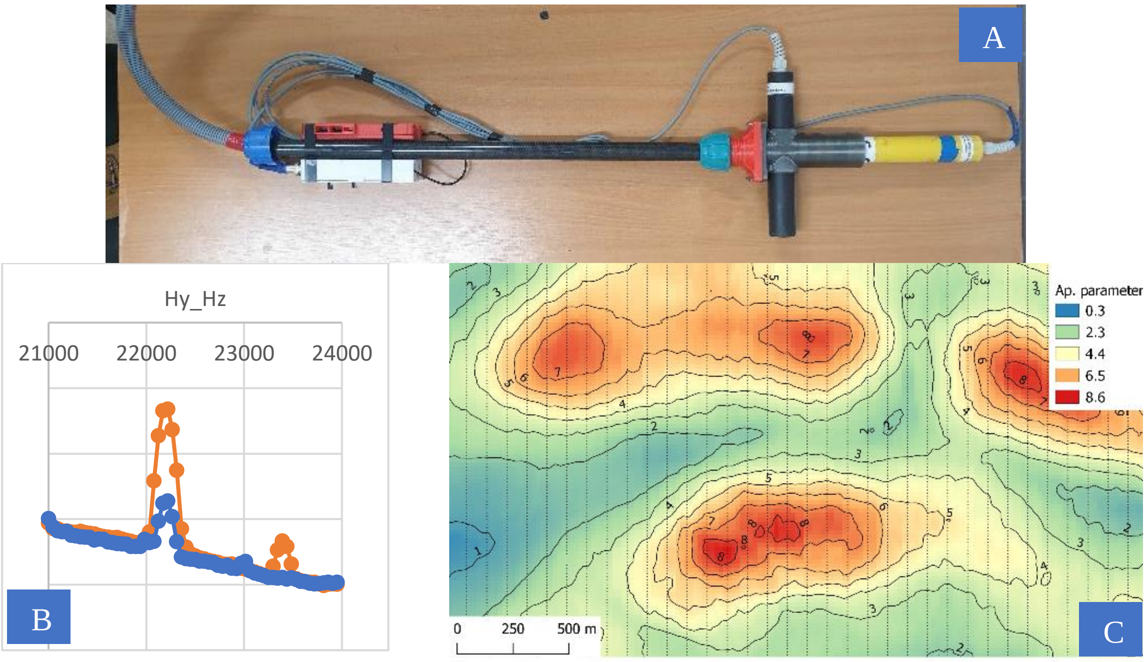

***Figure 1** SibGIS UAS VLF system (a); sample of FFT result: amplitudes of horizontal (Hy) and vertical (Hz) components of EM field at 22.2 kHz frequency (b); sample of map of apparent parameter (c)*

2) After the most interesting areas have been identified within the entire site using a set of methods, the second developed technology is applied - full-fledged UAV-TEM soundings. However, since a lightweight UAV cannot carry a power station and a large transmitter loop, measurements are made over a network of parallel routes near a galvanically grounded line several kilometers long (Fig.2a) (Parshin et al 2021). The maximum distance of the UAV from the transmitter line is usually half of its length, that is, with the line length, for example, 3 km, it is possible to make a survey over an area of 9 square kilometers. The MARS-1D environment we use for processing electromagnetic sounding data allows us to simulate and take into account the effects of the influence of the line ends and of the geometry of transmitter line as a whole. The UAV tows a measuring system with an inductive sensor - the equivalent of a fifty-meter receiver loop. The weight of the towed part in the existing version reaches almost 8 kg, but in the future it will be significantly reduced. The suspension design provides a sufficiently high-quality stabilization of the measuring system along the horizon in conditions of a mid-mountainous relief at a cruising flight speed of 7-8 m / s to obtain conditional data. The registration unit uses a 100 kHz/18-bit ADC, which is similar in hardware to that used in the MARS system for ground-based soundings using EMS-IP technology (Shkirya et al. 2020), but with different registration parameters: in the UAV-TEM version, recording is carried out at two amplification factors with frequency of 50 sounding curves per second, the sounding curves are recorded up to a time of 1 ms. The duration of the current and the pause are the same and amount to 5 ms. The UAV-TEM data processing includes: accumulation and averaging of transient records at specified spatial or time intervals of the survey to eliminate "noise" in the data; suppression of industrial noise (50 Hz) from the used electric power station; highlighting recessions; elimination of the trend caused by the movement of the receiving loop in air; robust smoothing in a sliding window, where the window length is the ADC decay counts, and the window width is the accumulation; integration into the sounding curve; binding of sounding curves to coordinates. Until recently, inversion was carried out in the class of 1D models, but now it is already possible to perform 3D data inversion using the ITEM-IP software package (Persova et al 2019).

Example

Figure 2 shows the results of tests for the sensitivity of the SibGIS UAS-TEM, carried out on a reference site (Sharlov et al 2017) in the shelf zone of Lake Baikal. Based on the results of the survey, which was carried out both in the direction from the coast to the depth, and along the coast, as a result of the 1D-inversion, we received a three-layer model. The upper layer (water) has a resistivity of about 160-170 Ohm*m, the next layer is low-resistivity terrigenous sediments with a resistivity of about 60 Ohm* m, and the bottom layer is also sediments with an even lower resistivity (less than 20 Ohm* m). The results obtained are in good agreement with the depth map of Lake Baikal, and with the data of electromagnetic sounding of the predecessors, obtained by the methods of terrestrial (on ice) TEM (Sharlov et al 2017). The reached depth of UAV-TEM sounding is more than 300 meters. From Figure 2c, it is noticeable that, compared to earlier versions of the SibGIS UAS-TEM (Parshin et al, 2021), the data quality has been significantly improved by optimizing the transmitter and measuring system.

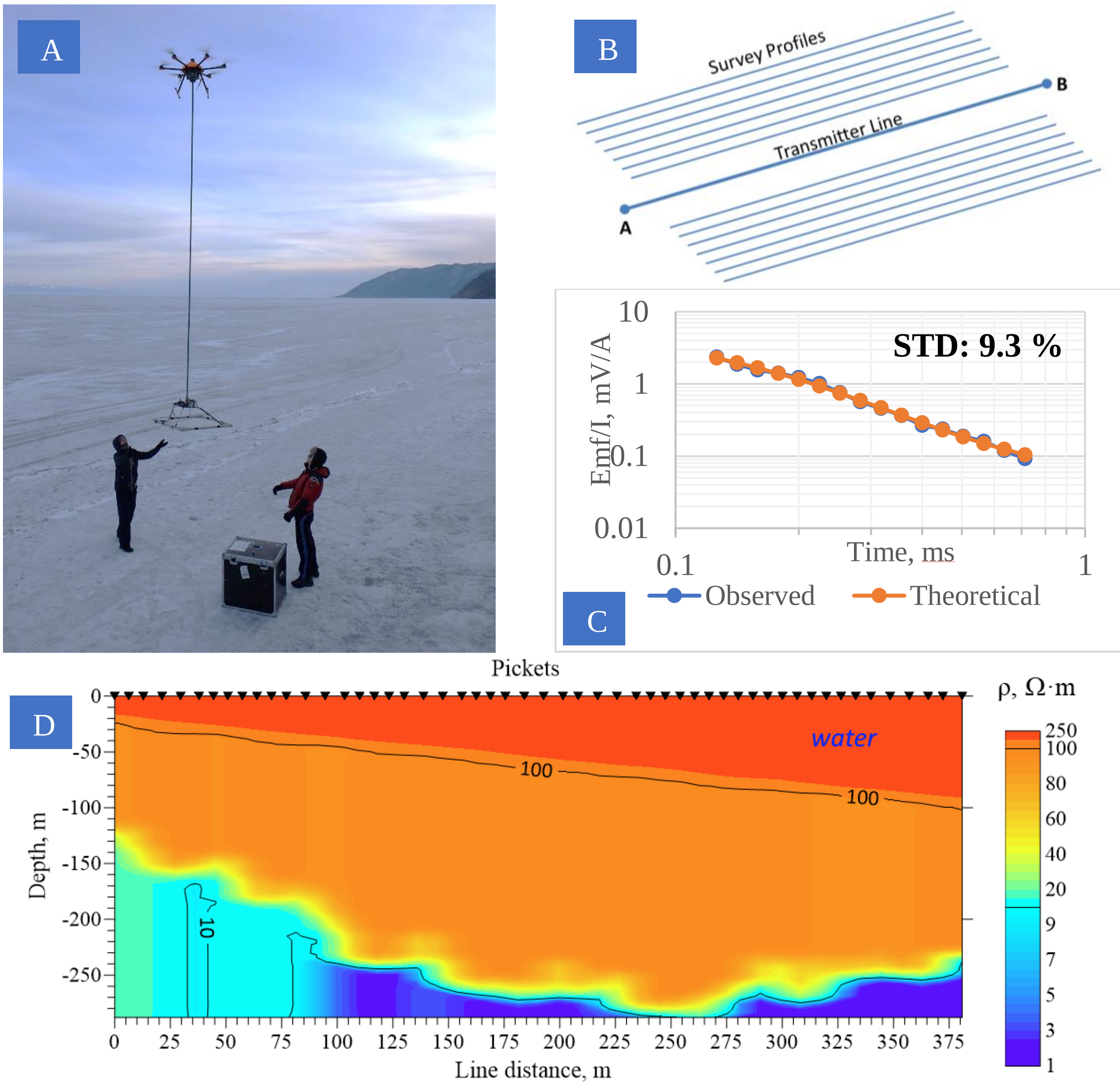

Figure 2. *SibGIS UAS-TEM system: at flight (a), geometry of measurements (b); samples of obtained and model sounding curves(c); and example of 1D inversion (d).*

Conclusion

In modern conditions, on heavily forested areas with a complex relief, terrestrial EM prospecting is very laborious to set up, and with the help of the developed technologies, we can obtain tens of square kilometers of VLF and tens of linear kilometers of TEM soundings per day. However, in the second case, the rearrangement of the transmitter line takes at least two to three hours, and therefore the developed version of the UAV-TEM is primarily focused on a detailed study of areas of several square kilometers, characterized by difficult cross-country ability. At the first stage of geological prospecting of "green sites", a set of magnetic, gamma-radiometry, and VLF surveys is effective, and after identifying promising areas, UAV-TEM can be used, which can be performed simultaneously with gamma-spectrometry with light detectors, since both of these surveys are best performed with a step between profiles of 50 meters or less (Parshin et al 2021). Further development of both electrical prospecting systems lies in the technical plane and does not present any scientific problems.

It is important to note that the design of the suspension of the induction sensor is of decisive importance for obtaining high-quality electromagnetic sounding data. Due to the use of inertial systems that measure the position of the sensors in both types of electrical prospecting systems, it is possible to only partially compensate the small tilts of the sensors.

We believe that the development of UAV-TEM technologies in the near future will significantly affect the change in the geophysical prospecting market in Russia, and then in the world. So, at present, this technology is already widely used in business cases and Russian state prospecting programs for uranium (Parshin et al 2021) and a number of other ore minerals.

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References

1. Belova, A., Davydenko, Y., Gurevich, D., Bashkeev, A., Bukhalov, S. and Veeken, P. [2020] Mineral prospecting for copper-molybdene ores in northern Kazakhstan using electromagnetic sensing and induced polarization technology (EMS-IP). *EAGE Annual 82nd Conference 2020*, p.1–5.
2. Cunningham, M., Samson, C., Wood, A. *et al.* [2018] Aeromagnetic Surveying with a Rotary-Wing Unmanned Aircraft System: A Case Study from a Zinc Deposit in Nash Creek, New Brunswick, Canada. *Pure Appl. Geophys.* **175**, 3145–3158.
3. GEM Systems [2020] UAV VLF-EM SYSTEM: Resistivity Mapping Solution *https://www.gemsys.ca/uav-vlf/*
4. Jackisch, R., Madriz, Y., Zimmermann, R., Pirttijärvi, M., Saartenoja, A., Heincke, B.H., Salmirinne, H., Kujasalo, J.-P., Andreani, L., Gloaguen, R. [2019] Drone-Borne Hyperspectral and Magnetic Data Integration: Otanmäki Fe-Ti-V Deposit in Finland. *Remote Sensing*, ***11***, 2084.
5. Macnae, J. [2007] Airborne Electromagnetic Systems. *ASEG Extended Abstracts*, **1**, 1-4.
6. Park, S.; Choi, Y. [2020] Applications of Unmanned Aerial Vehicles in Mining from Exploration to Reclamation: A Review. *Minerals*, ***10***, 663.
7. Parshin, A., Budyak, A., Chebokchinov, I., Sapunov, V., Bulnayev A. and Morozov, V. [2019] Complex UAS-Geophysical Surveys at the First Stages of Geological Prospecting: Case in the Western Sayan (Russia). *First EAGE Workshop on Unmanned Aerial Vehicles*, Extended Abstracts, MoUAV02.
8. Parshin, A.; Morozov, V.; Snegirev, N.; Valkova, E.; Shikalenko, F. [2021] Advantages of Gamma-Radiometric and Spectrometric Low-Altitude Geophysical Surveys by Unmanned Aerial Systems with Small Scintillation Detectors. *Appl. Sci.* ***11***, 2247.
9. Parshin, A.; Bashkeev, A.; Davidenko, Y.; Persova, M.; Iakovlev, S.; Bukhalov, S.; Grebenkin, N.; Tokareva, M. [2021] Lightweight Unmanned Aerial System for Time-Domain Electromagnetic Prospecting—The Next Stage in Applied UAV-Geophysics. *Appl. Sci.* ***11***, 2060.
10. Persova, M., Soloveichik, Yu., Vagin, D., et al. [2019] Finite element solution to 3-D airborne time-domain electromagnetic problems in complex geological media using non-conforming hexahedral meshes. *Journal of Applied Geophysics* ***172***, 103911.
11. Sharlov, M., Kozhevnikov, N., and Sharlov, R. [2017] Lake Baikal - A Unique Site for Testing and Calibration of Near-surface TEM Systems. *23rd European Meeting of Environmental and Engineering Geophysics*, Sep 2017, Volume 2017, p.1-5.
12. Shkirya, M., Gurevich, D., Tereshkin, S., Belova, A., Davydenko, Y. [2020] Application of Pulsed Electric Prospecting for Allocation of Zones of Sulfide Mineralization of Copper-Porphyry Type in the Territory of Northern Kazakhstan. *EAGE GeoBaikal 2020 Proceedings*, Oct 2020, Volume 2020, p.1–5
13. Orta, M., Legault, J., Prikhodko, A., Plastow, G., Zhao, S., Moreton, M., and Ulansky, C. [2013] Ztem-Vtem-Aerotem Helicopter EM Comparisons Over The 501 Project Cu-Zn Vms At Mcfauld's Lake, Northern Ontario, Canada. *13th SAGA Biennial Conference & Exhibition*, cp-378-00015.