The results of experimental and methodological work with the new UAV-TEM technology on Lake Baikal

Introduction

Experimental and methodological work on the new technology of electromagnetic soundings of the UAV-TEM was carried out on Lake Baikal in March 2021 (Parshin *et al*., 2021b). Transient processes are recorded by an inductive sensor attached to an unmanned aerial vehicle (UAV), which moves along lines over the survey area at a given height with terrain envelope (Parshin et al., 2021a). The source of a non-stationary electromagnetic field is a horizontal electric line, into which a sequence of bipolar current pulses is fed, alternating with current pauses. The work was carried out in order to determine the optimal registration parameters of the measuring system, as well as to assess the depth and resolution.

To test this measuring system, Lake Baikal was chosen, which is a unique geological test site, where huge volumes of fresh water make it possible to carry out measurements both in half-space conditions and in conditions of one-dimensional and three-dimensional models.

Information about the structure of the upper part of the sedimentary sequence was obtained from the results of drilling and seismic surveys (Khlystov *et al*., 2014). Most gas hydrate formations are found near of the bottom surface at depths of 360-400 m – below their stability is hindered by heat flow, above - insufficient pressure (Golmshtok *et al*., 1997). According to the MTS and EMS-IP measurements carried out on ice, at a depth of 600-1000 m, a high-resistivity granite base is located under the sedimentary layer (Shkiria *et al*., 2018). The heterogeneity of the sedimentary stratum is reflected in the resistivity sections according to the EMS-IP data (Davidenko *et al*., 2021) and the mTEM – shallow near-field time-domain electromagnetic sounding (Sharlov *et al*., 2017): the upper layer, probably corresponding to the layer of diataceous sludge, is significantly heterogeneous; layers with a resistivity of 10-40 Ω·m, the lower, denser and isotropic layer (probably clay sediments) has a resistivity of about 50-60 Ω·m. Interestingly, according to VES data, the Baikal water near the mouth of the river Goloustnoye is divided into 2 layers: the upper layer is 28-35 m thick and has a resistivity of 170-185 Ω·m, and the lower one is with a resistivity of 200-235 Ω·m.

Method

The UAV-TEM technology was first successfully applied in the search for uranium deposits in the Eastern Sayan Mountains, where it was used to map the “unconformity” boundary between sandstones and granites and map fault zones (Parshin *et al*., 2021a).

The hexacopter tows a measuring system consisting of a microcomputer with a GNSS-reference system, a 2-channel Mars recorder with a sampling rate of 100 kHz, recording transients, and an induction sensor - a multi-turn loop. Cruising flight speed of UAV – 8-9 m/s. In this case, the sensor was located at a height of 16 m from the ice surface. For two days, including extremely bad weather 15 lines were recorded with a total length of 14.5 km (**Figure 2a**). Current – 4 A. Length of the cable between the UAV and the receiving loop – 4 m.

After the surveying, in the post-processing mode, the transients were averaged in the amount of 25 realizations per second (thus, the step along the line was about 8 m). At the same time, the same approaches were used to process UAV-TEM data as for the marine towed electromagnetic sounding system (Davydenko *et al*., 2019, Veeken *et al*., 2009). This processing graph includes the following steps: accumulation and averaging of records of transient processes over specified spatial or temporal intervals; suppression of industrial interference; elimination of the trend caused by the movement of the receiving loop in space; robust smoothing in a sliding window, where the length of the window is the ADC counts along the transient, and the width of the window is the records; integration into the sounding curve; binding sounding curves to coordinates (Parshin *et al*., 2021a).

Part of the flights was carried out in the area of the transmitter line’s grounding to assess areas where the inductive sensor allows or does not allow obtaining adequate data.

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Results and its discussion

At the first stage of the work, the issue of choosing an induction sensor was decided: PDI-20 (equivalent to a 20x20 m loop) or PDI-50 (equivalent to a 50x50 m loop). Test measurements on several flights showed that the PDI-20 has an extremely low signal-to-noise ratio. As a result, the conditional survey was performed by the PDI-50 sensor, which in this configuration ensured the registration of transient processes from 30–40 μs to 600–800 μs. (Parshin *et al*., 2021b).
The flight task was designed in a way that some line passed through the transmitter line and in close proximity to the ground point. This position of the lines allows to estimate the effect of the source-receiver position on the inversion results. In addition, the analysis of transient processes by secant lines made it possible to evaluate the effect of the real shape of the current pulse front.
Figure 1 clearly demonstrates the effect of the complex shape of the current pulse on the recorded transients. As an example, the transient curves of the line 11 are taken, which crosses the transmitter line AB (**Figure 1a**). The shape of the current pulse switching off has an alternating form – the transient curves from observations 1, 5, 9 are in the negative part along the ordinate axis (the EMF is negative), and 26, 33 are in the positive part; at the same time, the transient curve from observation 9, which is closest to line AB, constantly changes sign (**Figure 1b**). The model curves without taking into account the current pulse switching-off front (calculated for a rectangular current pulse) (**Figure 1c**) do not have sign-changing peaks of values characteristic of the observed curves and will introduce systematic errors when solving the inverse problem. The current pulse switching-off front in the line AB was modelled by minimizing functional of the residual of the transient curves' early times on the lines crossing the transmitter line. **Figure 1d** shows graphs of the model curves calculated taking into account the selected current pulse switching-off edge. The difference is observed not only in the amplitude, but also in the shape of the curves.

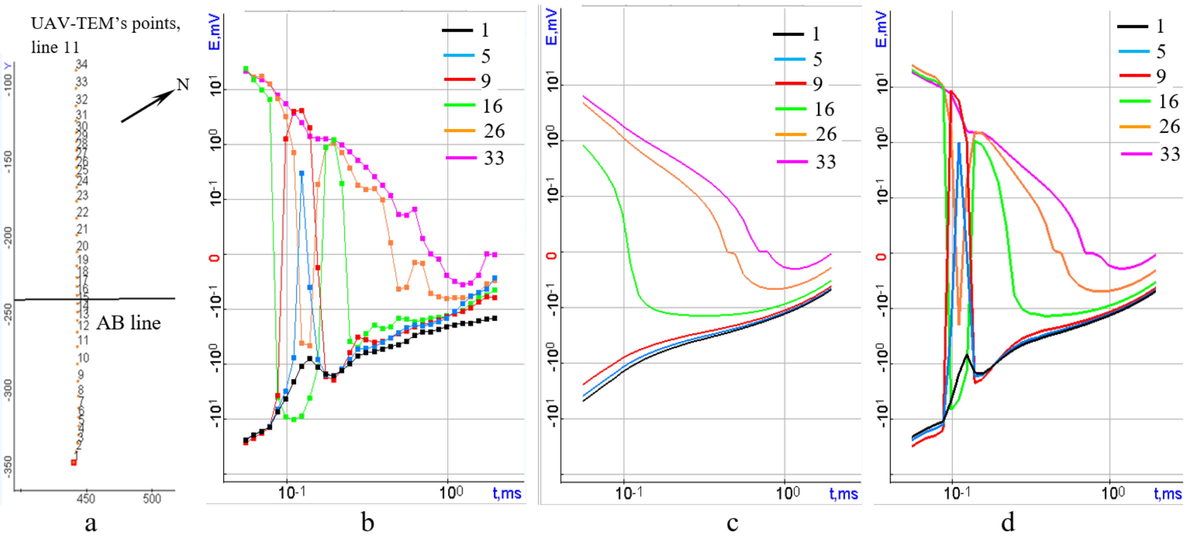
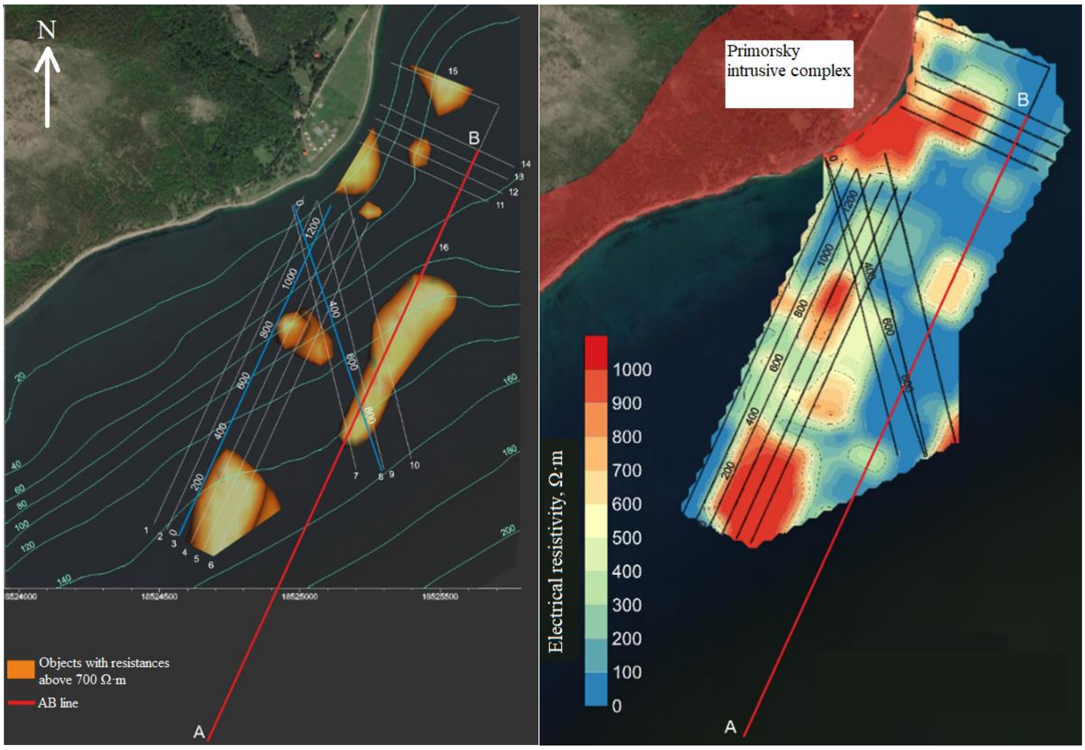


***Figure 1** The behaviour of the transient curves with and without taking into account the current front in comparison with the observed curves at different distances from the transmitter line AB: a) the position of the receiver relative to the transmitter line; b) observed curves; c) model curves without taking into account the current switching-off front; d) model curves taking into account the current switching-off front;*

Thus, the fundamental influence of the current front on the recorded signals is shown. If the front of the current pulse is not taken into account in solving the direct problem, then systemic distortions will inevitably be obtained in the simulation results, namely: in the resistivity of the enclosing medium, in the resistivity of anomalous objects and in the depth of these objects.
Let's move on to the results of 3D inversion of UAV-TEM data, performed in the IFGEM 3D software package (Persova *et al*., 2021). During the inversion, the resistivity of water was fixed at a value of 200 Ω·m, and the depth value was fixed according to the bathymetry. As a result, several high-resistivity objects were identified in low-resistivity lacustrine sediments, extending to a depth of several hundred

meters (**Figure 2**). They may represent blocks of bedrock displaced as a result of catastrophic tectonic events that took place about 150,000 years ago in the area. An elongated lenticular body in the east of the survey area may be a lens of gas-saturated rocks. **Figure 2a** shows the position of these objects relative to the survey lines in plan view. The depth of constructions according to the results of 3D inversion is estimated at 400-500 m, including the water layer.
Based on the standard map at a scale of 1:200,000, the coastline is composed of Early Proterozoic intrusions of the Primorsky intrusive complex, porphyritic alasquitoid granites, leucokarst and biotite granites, and plagiogranites. In **Figure 2b**, which shows a map of averaged resistivities, the northern anomaly with high resistivities corresponds to the coastal outcrop of the granite layer.



a) b)

Figure 2 *Results of 3D inversion of UAV-TEM data. a) A map with objects with a resistivity of more than 700 Ω·m, b) A map with averaged resistivities in a 500 m thick layer.*

The overthrust in the cape area is clearly visible at the beginning of line 8, approximately from 700 m to 1000 m along the line to a depth of 100 m to 150 m (above the gas hydrate stability region), a high-resistivity reservoir body is identified, which probably corresponds to a gas-saturated reservoir. In favor of the collapse is the fact that low-resistivity lake deposits are observed under high-resistivity blocks.

Conclusions

For a correct solution of the inverse problem, it is necessary to take into account the alternating shape of the current pulse switching-off front, which significantly affects the transient process in the recorded time range. The front is selected in this way by minimizing functional of the residual of the transient curves' early times on the lines crossing the transmitter line.
As a result of 3D modelling, performed taking into account bathymetry, it was shown that under the water column of 200-300 m, high-resistivity objects are distinguished in conductive sediments to a depth of at least 200 m, some of them are continuations of coastal structures. As a result, the depth of the UAV-TEM technology in these geoelectric conditions is estimated at no less than 500 m.
Experimental and methodological work made it possible to identify a number of directions in improving the equipment for transmitting and registration. Since the reliably recorded time range does not exceed 2-3 ms, it is advisable to reduce the pulse/pause duration to 2-5 ms, which will increase the density of shooting and the signal-to-noise ratio due to a larger number of transients. In order to increase the

current, a compact and more powerful source of bipolar pulses of 20 kW is being developed. An attempt to register with an induction sensor with a lower torque – PDI-20 was recognized as unsuccessful due to the low signal-to-noise ratio, as a result, PDI-50 was taken as the optimal sensor. In order to increase the dynamic range, registration is carried out by a lightweight two-channel Mars 2.0 2 module with two different gains.
In 2022, due to the increase in the length of the cable between the UAV and the receiving loop (PDI-50) from 4 to 10 m and the Current from 4 to 6 A, it was possible to increase the signal-to-noise ratio, compared to the data of 2021.

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