Interpretation of Integrated Aerial Geophysical Surveys by Unmanned Aerial Vehicles in Mining: a Case of Additional Flank Exploration

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Abstract. Low-altitude remote Earth sensing (RES) performed by unmanned aerial vehicles (UAV) helps run geological surveys more efficiently; aeromagnetic surveys have been on rise recently. UAV surveying can be made significantly more informative and cost-effective by switching from monomethod surveying to integrated efforts that combine multiple complementary methods. However, how to run such surveys efficiently is a question barely covered in special literature. This paper uses evidence from a site in Bodaybinsky District (Eastern Siberia, Russia), a promising black-shale gold mineralization site, to analyze a typical geological exploration case, namely additional exploration of underexplored areas near a known deposit. It considers a method for integrated UAV geophysical surveying and its interpretation; this multi-method approach comprises aeromagnetic surveys, gamma radiometry, and multispectral photography. Emphasis is made on how important correct interpretation of geophysical data is for the latter. The paper shows that such photography is necessary for identifying man-affected segments in the area and for assessing the distribution of vegetation in it; this helps adjust the gamma background charts. Use of integrated low-altitude surveys taken from UAVs helps quickly and cheaply identify potential gold-bearing sites by a set of indirect features. Exploratory drilling has proven the approach effective.

1. Introduction

Today, geological exploration is mainly intended to find latent sites located far from the existing infrastructure, where the terrain is (nearly) impassable. Given this and the total global economic crisis coupled with the objectively existing trend towards robotization and digitalization in all aspects of economy, it is not surprising that low-altitude remote Earth sensing, a technology that appeared several years ago and uses geophysical surveying methods, is in demand and on the rise. Robotic aerial geophysical systems can be used for low-altitude drape surveying features high performance, low costs, and high data quality; where the terrain and surface morphology are complicated, such
systems outperform ground surveys [1]–[3]. Low-altitude aeromagnetic surveys by means of multirotor UAVs have recently become popular worldwide ([4],[5],[6],[2]) and completely ousted the more conventional ground surveying in some areas. Far less prominent is UAV gamma surveying ([6], [7], [8], [9]), although the technology has been a success in radioecology ([10], [11], [12]).

It should be noted that the cited papers describe single-method (or monomethod) UAV systems. Similarly to conventional ground and aerial geology (aerogeology), the performance of such systems can be boosted further by integrating multiple complementary methods. This is due to the very role of UAV aerogeology as a tool that is specifically necessary in early geological surveying, as the single most important advantage of UAV low-altitude surveying is that it can quickly and cheaply produce highly informative data on underexplored sites with unknown reserves, which are not clearly investment-worthy. Detailed objective geodata obtained early geological surveying, which is the riskiest stage of any exploration effort, provide invaluable decision support, while the multi-aspect nature of such data helps make more sound decisions. While UAV surveying can be highly efficient by sequentially running multiple UAV systems carrying a single type of payload, a single UAV must be able to perform multiple survey types if its performance and cost-effectiveness are to improve. This is a far more complex endeavor, as different geophysical methods work at different rates and in different modes while some of the instrumentation may cause interference with other; another hindrance is that such UAV must be designed to carry far heavier payload.

Guidelines for effective use of UAVs can be created by analyzing typical use cases. One case where a UAV can shine is to analyze the underexplored areas adjacent to the known concessions. This paper dwells upon running and interpreting integrated UAV surveys to assess the reserves in areas adjacent to a a developed gold mine. The authors hereof believe this case is interesting methodologically, as geophysical works related to the transition from a developed site to unexplored areas are associated with man-caused anomalies that have to be considered in data interpretation. The case also demonstrates the advantages of integrated UAV surveying and the technology that backs it.

2. Site features

The site is one of Russia’s gold-richest provinces, Bodaybinsky District in Irkutsk Oblast, Eastern Siberia, some 30 kilometers from the famous major Sukhoi Log deposit and 20 kilometers off the major Golets Vysochayshy deposit. The exact coordinates of the site are subject to no disclosure; however, the site itself and the problem stated herein are typical for this gold-mining province, while the geological features and gold-bearing data of the Bodaybinsky synclinorium can be found in ([13]; [14; 15]). This is a mid-mountain site with a few hundred meters of difference in altitude between watercourses and watersheds; on-foot geophysical surveying is difficult due to wetlands, rubble slopes, and ubiquitous dwarf cedar thickets [2].

The most important search criteria applicable to gold mines in Bodaybinsky district are their structural positions and confinedness in specific strata. The most promising stratigraphic units are Riphean deposits of Buzhuikhta, Khomolkhin, and Aunakit formations (specifically their black-shale benches); the fundamental condition of industrial-scale gold mining is that the deposit must be confined to the third-order anticlines (core or near-core) [16]. These folds may be associated with sulfide mineralization (pyrite, halmopyrite, arsenopyrite, pyrotine), which is mostly paragenetically linked to gold. Such placement of zones with increased sulfide mineralization can be explained by the fact that the near-core positions of an anticline are prone to brittle strain due to metamorphosis of the rock at the stage of syn-orogeny, which is why they also have the highest fluid permeability. In comparison to the higher Mariinsky formation and the lower Ukhagan formation, the promising stratigraphic units (the interface of black-shale and carbonate benches in Buzhuikhta formation) are more radioactive due to the local redistribution of potassium- and uranium-enriched fluid during the formation of ore body. These positions effectively give rise to the gold search criteria detectible by aeromagnetic and gamma surveying:

(1) higher radioactivity,
higher-radioactivity areas feature such anomalies as a high-gradient magnetic field (may be as high as to cause sign reversal) or negative anomalies. These magnetic anomalies are caused by monoclinal pyrrhotite and map the bodies of sulfide mineralization.

3. Integrated UAV survey: technology and method
For geophysical surveying, the researchers used a multirotor version of the SibGIS UAS complex they had been making over past five years [2]. As of writing this paper, the latest implementation, unlike the former monomethod versions of 2014-2017, was designed for simultaneous aeromagnetic and gamma surveying. Thus, the baseline sensors the unit was equipped with were an Overhauser magnetometer that provided accurate absolute values of the full magnetic field vector; and a lightweight small-size radiometer that used a CsI(Tl) scintillator, which is a more efficient and thermally stable option compared to conventional sodium iodide, and a silicon photomultiplier tube (PMT) resistant to temperature drops and electromagnetic interference. The set of payloads also contained gamma spectrometers with different crystal types, multispectral cameras, a VLF electric surveying system, and an experimental solid-state lidar scanner. Table 1 shows the specifications of payloads; the figure below shows the basic implementation of the unit.

Figure 1. SibGIS UAS designed for simultaneous aeromagnetic and gamma surveying (A) with additional payloads (B): multispectral cameras, (C) a gamma spectrometer with a CsI 63x63 crystal, (D) experimental solid-state lidar scanner.
Table 1. Payload specifications.

| Payload                        | Specifications                                                                 | Weight, kg | Sampling rate, Hz |
|-------------------------------|-------------------------------------------------------------------------------|------------|------------------|
| **Magnetometer**              | Overhauser proton device, max. absolute error: 1 nT                           | 1.60       | 1 to 4           |
| **Gamma-radiometer**          | 2 CsI(Tl) 8x100mm detection units with silicon photodetectors, Integral stream error, no more: 15% | 0.3        | 0.5              |
| **Gamma-spectrometers**       | CsI (Tl) 40x80, 63x63 crystals; CsI (Na) 30x150, vacuum PMT                    | 0.8 to 2.1 | 0.5 (radiometry), 0.1 to 0.02 (full spectrum) |
| **Multispectral cameras**     | A dual-camera unit, Resolution: 12 Mpix, Five spectral channels: Visible Light RGB + Yellow 615nm and NIR 820nm | 0.2 with no GPS module | 0.2 to 0.5 |
| **LiDAR (experimental prototype)** | Based on one or two 16-segments solid-state M16-LSR modules (Ground Sampling Distance ~1.8 meters/pixel at flight height 80 m) | 0.7        | 10 to 20         |

The magnetometer and the radiometer weighted 2 kg in total or 2.3 kg if suspended on an extension rig, which enabled long continuous flight at up to 10 km. This means a UAV can survey about 10 to 15 square kilometers from each take-off point in a two-way flight. Monomethods were covered in previously published papers (); it should also be noted that the cruising speed has risen to 10 m/s in recent years, while preliminary flights for checking the mission routes as noted in [2016] have not been run since 2016, as experience has proven them unnecessary thanks to the flight controllers getting more points, more accurate satellite DEMs [17; 18], and more advanced photogrammetry.

Consider the main points of integrated geophysical surveying:

1. Preliminary digital elevation modeling of required accuracy by multispectral photogrammetry, lidar surveying, topographic precursor maps, or satellite elevation models. The accuracy and detailedness of DEMs should meet the requirements of Low-Altitude Aeromagnetic Survey Guidelines 2018 [19] for a specific geophysical surveying accuracy class and scale; for instance, SRTM and Alos DEM can be used for 1:10,000 surveying with a 100-meter inter-profile distance, while high-accuracy surveying on a 1:5,000 scale require conditional topographic data on a scale of no less than 1:10,000.

2. As the task force arrives at the surveying location, they use the SibGIS Flight Planner to generate mission route point arrays so that the draping accuracy would match the requirements cited above; these guidelines set forth thresholds for plane and vertical UAV positioning accuracy with respect to Earth depending on the survey accuracy class and scale.

3. Mission route is loaded to the flight controller. UAV takeoff and landing are usually done manually with the autopilot being engaged in flight. Geophysical instrumentation readings are sampled at rates specified in Table 1 and written in the recorder memory with precision satellite time-stamping. Magnetometry is accompanied by variational observations. After the mission is complete, replace UAV batteries and repeat Step 3.

4. Export and process data: analyze the variations, align the measurements with the coordinates recorded by the flight controller (can be equipped with an RTK system and a laser altitude...
meter). To that end, use specialized modules that, similarly to SibGIS Flight Planner, as implemented as QuantumGIS plugins. Data collected by SibGIS UAS does not require any extra software or filtering; the very first studies showed [2] that thanks to high measurement accuracy and zero electromagnetic interference from the medium, the data were suitable for mapping and analysis right away. The field charts presented there were generated by simple kriging interpolation on a 120-meter radius for aeromagnetic survey and by local polynomial interpolation with a fifth-order polynomial on a 300-meter radius for gamma survey.

Multispectral aerial photography is usually performed by the same UAV that is used for further geophysical surveying; however, thanks to a lighter payload, the UAV is able to fly at up to 12 m/s and cover two to three times greater distance. A real time kinematics (RTK) system based on UBlox Neo-M8P modules is used to obtain highly accurate coordinates of photography centers, which are necessary for generating accurate DEMs. A base station should be installed at each takeoff point, as the UA should be within the reach of the radio telemetry system to receive augmentation data, although primary data can be recorded in the memory and augmented by RTKlib later. Photographs are taken while draping at 150 to 250 meters; as the difference in altitudes in the surveyed area can be as great as hundreds of meters, photography has a sample rate of 0.2 to 0.5 Hz to attain 80% overlap. Multispectral aerial photography is subject to further photogrammetry, which (and the digital elevation modeling) is performed by OpenDroneMap, while the multispectral indices for analysis of geology, terrain, and morphology, e.g. Iron Oxide Index, WorldView Soil Index, etc., are calculated by QuantimGIS, a raster calculator.

4. Results and discussion
Geophysical surveying of the site was performed over two days in mid-September 2018. Flight altitude was 70 meters (65 to the magnetometer sensor); the flight covered 26 square kilometers on a 1:10,000 scale. To assess the quality of generated data, Figure 2 shows primary measurements; some data is missing, as the site had a slag heap several dozens of meters in height, and the UAV skipped that point. Table 2 assesses the accuracy of surveying several points by comparing them against control profiles located in different parts of the site. The survey was performed in difficult climate, as fall winds and blizzards had already taken on the region, although the snow cover was not continuous yet; the standard error of aeromagnetic survey was below 1.5 nT while that of gamma surveying was below 8%.

![Figure 2A. Primary aeromagnetic survey data (variations considered). Dots show the location of expected ore benches within Buzhuikhta formation.](image1)

![Figure 2B. Primary gamma survey data.](image2)
Table 2. Error of geophysical survey on control routs.

| Magnetic Survey, nTl | Gamma Survey, mkR/h |
|----------------------|----------------------|
| **Ordinary**            | **Control**            | **Ordinary**            | **Control**            |
| measurement            | measurement            | measurement            | measurement            |
| 60,380.9 60,381.1       | 4.82 5                |
| 60,140.7 60,141.1       | 3.51 3.09             |
| 60,069.4 60,070         | 4.28 3.77             |
| 59,903.2 59,906.1      | 8 8.33                |
| 60,003.2 60,004.6      | 10.54 9.7             |
| 60,398.1 60,396.1      | 5.06 4.79             |
| 60,398.2 60,399.1      | 9.83 9.58             |
| 60,402.2 60,401.2      | 8.65 8.23             |
| 600,095.7 600,096.2    | 6.79 6.16             |
| 60,375.2 60,374.7      | 7.86 7.65             |
| **Standard error** 1.38 nTl | **Standard error** 7.68% |

However, trees still retained their foliage; given that the forest on the site was of uneven density, while the gamma field anomalies were not expected to have high contrast, a question arose whether the effects of vegetation on radiometry had to be given special consideration: live plants have >30x larger gamma radiation absorption rates of air. The need for such adjustments was mentioned in the literature when aerial gamma surveying became a thing [20]; however, no such adjustments could be made at the infancy of the technology. Aerial gamma surveying by UAVs is expected to provide more accurate data than conventional methods, making such adjustment even more critical [2; 11]. Besides, since a part of the site was prone to being man-affected, correct interpretation of gamma surveys required extra materials to map such alterations.

The authors hereof believe calculating multispectral indices from aerial photography data is the most efficient way to estimate the vegetation and to automatically detect man-affected sites. To calculate the most common normalized difference vegetation index (NDVI, calculated as (NIR−RED)/(NIR+RED), where NIR and RED are spectral brightness values for the near-infrared and infrared channels of the electromagnetic spectrum), it is enough to have an extra near-infrared channel with a wavelength of 800 to 850 nm in addition to the visible-spectrum photographs that can be taken by an ordinary digital camera. Multispectral cameras included in SibGIS UAS feature a 820-nm channel, see Table 1.

Figure 3 presents the results of aeromagnetic, gamma, and multispectral surveying as NDVI indices complete with interpretation elements as discussed further.

The resulting magnetic field chart shown in Figure 2 could be interpreted as a recumbent anticline facing south with a partially eroded core. According to the structural diagram, if an erosion has a recumbent fold while the hinge is absent (eroded), the same stratigraphic horizons must be within its recumbent wall. At the moment, the quarry operations included gold mining from the recumbent wall. In both the recumbent (lower) wall and in the upper wall, sulfide mineralization manifested itself as linear anomalies; however, the magnetization and subsequent folding seemingly resulted in the recumbent subhorizontal wall being entirely in the positive domain, while the upper nearly subvertical wall, sulfide formations manifested themselves as contrasting local negative anomalies. More
specifically, sulfide mineralization (and, possibly, the useful component) were localized in the upper wall in three nearly vertical benches shown in Figures 2 and 3 with dots. Indeed, the model described above suggested a presence of carbonate layers between ore horizons; these layers prevent the ore fluid from dissipating at the pre-mining stage, when catagenic fluid was concentrated in anticline traps. In general, aeromagnetic survey identified a closure of the third-order anticline known from geological survey data. The anomalies relating to the sign reversal in the lower-amplitude field (100 to 150 nT in the upper wall) near the core most likely corresponded to the lower bench of Buzhuikhta formation (bz$_1^3$), see Figure 2. The ore shoots in the bench bz$_2^5$ are currently being quarried. bz$_2^5$ has maximum contrast associated with the second body explored in this deposit. According to geodynamic structuring [14; 21], Buzhuikhta formation is the first stage of enrichment of the surrounding formations in the Baikal-Patom area with sidero-chalcophile elements; this enrichment occurred due to the explosive effects of the Mui island arcs. Thus, the external impact on the enrichment of rocks in the Far Taiga — Zhuya horizon can be expected to be greater towards the upper Buzhuikhta formation and further towards Khomolkhin and Aunakit formations, which the presented geophysical data confirms.

![Figure 3A](image1.png)  
**Figure 3A.** Magnetic field chart (quantile classification): 1 are projected ore benches within Buzhuikhta formation; 2 are sites of the upper wall expected to be rich in resources.

![Figure 3B](image2.png)  
**Figure 3B.** Gamma field chart (quantile classification).
Gamma field (3b) had multiple anomalies of varying intensity. Comparing Figures 3a and 3b makes clear that the most intense anomalies corresponded to man-affected sites. A longer anomaly with more intense sub-meridian gamma background was detected in the southwest of the studied area. This could be considered a rock-related anomaly, as multispectral surveying did not detect any man-made structures. Interestingly, vegetation indeed prove to affect gamma background, as the gamma radiation was most intense where that anomaly had minimum vegetation. This radioactivity anomaly spread from the western edge of the site towards the slag heap; it was split into two parts by a region of less intense gamma field, which was partly due to wetland overlapping the actual gamma background of rock; however, the same segment had zero concentration of sulfide mineralization according to aeromagnetic survey.

Comparing the aeromagnetic and gamma survey data reveals a coincidence of the two search criteria: negative magnetic field anomalies due to pyrrhotite coupled with increased radioactivity of Buzhuikhta formation in the southwest of the area as well as near the slag heap (and, as it seems, under it). These sites were identified as the best candidates for drilling.

As for the northern wall of the fold currently in operation, it had likely had increased radioactivity similarly to the recumbent wall before operations began; vegetation and soil simply raised the contrast of these anomalies. However, some other anomalies, also in the form of increased radioactivity in the northeast of the area, were definitely man-caused, as they were induced by trenches, dumps, and road/site dumping of quarried wallrock from Buzhuikhta formation, a material of increased radioactivity.

5. Conclusions
Integrated geophysical and multispectral survey performed over three days proved feasible a more detailed geological exploration of the identified promising site. The site was subjected to lithochemical surveying; however, since chemical analysis would be time-consuming, some exploratory drilling was performed near the slag heap on the basis of UAV aerogeophysical surveying data in the winter and spring 2019. So far the detected geophysical anomalies yielded good results.

Therefore, an important advantage of integrated UAV surveying in this case was that it enabled faster and cheaper while also highly informative mapping based on the knowledge of gold mine genesis; this mapping helped further find gold-bearing ores, in some cases without any ground-level geological and geophysical surveying. Notably, this bi-method integrated surveying only cost $50 per square kilometer excluding the costs of transporting the equipment and the team to the site; this is only a fraction more expensive then aeromagnetic surveying alone. However, using the latter as a monomethod will not yield reliable projections, as similarly manifesting sulfide mineralization could occur in (nearly) goldless structural units, while the geological maps created by predecessors decades
ago are on scale from 1:200,000 to 1:50,000 at best, and the geological boundaries on them are not accurate enough. The conclusion is that integrated UAV geophysical surveying is always the single best approach for the Bodaysinsky synclinorium, whereby gamma surveying helps map the promising structural complexes while aeromagnetic surveying identifies concentrations of sulfide mineralization. Multispectral photography in that case helps create highly detailed elevation models for low-altitude flight as well as correctly interpret gamma survey data collected from man-affected areas.

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