The potential of rotary-wing UAV-based magnetic surveys for mineral exploration: A case study from central Sweden

Alireza Malehmir[1], Lars Dynesius[1], Kent Paulusson[2], Alex Paulusson[2], Henrik Johansson[3], Mehrdad Bastani[3], Mats Wedmark[3], and Paul Marsden[4]

Abstract

Unmanned aerial vehicle (UAV)-based geophysical surveys are attractive for land mineral exploration and are gradually opening extraordinary opportunities in providing high-resolution definition of geologic structures and for direct targeting of mineral deposits. There are, however, challenges such as electromagnetic noise from the UAV, limited load capacity, and short flight times. If these are overcome, there will be a new era in using UAV-based geophysical systems for mineral exploration and for a number of mining-related purposes. In this study, we have tested the potential of rotary-wing UAV systems, given their flight flexibility and robustness for direct targeting of iron-oxide deposits in central Sweden. A walking-mode high-precision Overhauser magnetometer was reassembled so that it could be lifted by the rotary-wing system. Successful backyard tests were performed, but during the real experiment several issues related to high UAV noise level and extreme magnetic field from the mineralization delayed data acquisition. At the end, within nearly three hours and 10 sorties, approximately 20 km-line total-field magnetic data were collected covering an area of about 2 km^2. Flight lines were designed perpendicular to the strike of the mineralization to maximize data sampling. Two distinct mineralized zones, magnetite- and hematite-rich and only 50–100 m apart, are notable in the magnetic data due to the fine sampling spacing provided by the UAV survey. Historical low-altitude (30 m above the ground) fixed-wing aeromagnetic data are available from the study area and are compared with the UAV data. Both data sets are consistent in delineating the mineralization, therefore demonstrating the potential of UAV-based surveys for mineral exploration in geologically and logistically challenging areas.

Introduction

Geophysical methods for mineral exploration require rapid evolution to provide cost-effective ways of tackling not only a number of challenges related to high-resolution delineation of host-rock structures and mineralization but also for their deeper targeting (Malehmir et al., 2012, and references therein). Unmanned aerial vehicle (UAV)-based surveys can be superior to fixed-wing airplane or helicopter-based surveys for shallow-target exploration particularly because of their cheaper accessibility and better performance over challenging terrain (e.g., valleys, waste and ore dumps, and tailing dams). While there are still challenges for electromagnetic-based surveys, UAV-based magnetic methods are rapidly finding their position in the market for mineral exploration and a number of other applications (e.g., Partner, 2006; Barnard, 2008; Gavazzi et al., 2016; Wood et al., 2016). Case studies illustrating this potential are limited however, and most published accounts do not directly target mineralization; hence the possible impact is not fully illustrated.

In a pilot test within an ongoing exploration project in Sweden and Finland (Malehmir et al., 2017a), we examined the potential of UAV-based magnetic surveys for direct targeting of iron-oxide apatite-bearing deposits of an area in central Sweden given a great control on their physical properties and 3D geometries from several boreholes (Maries et al., 2016; Malehmir et al., 2017b). Due to budget restrictions, no dedicated light magnetic sensor and acquisition were employed. Instead, a walking-mode magnetometer was used. The main objectives of the experiment were (1) to study the noise level of the UAV systems for both magnetic- and electromagnetic (EM)-based methods, (2) to experience practicalities involved while using UAV systems for mineral exploration, and (3) to check the potential of UAV systems for mineral exploration. For example, we demonstrate that the UAV-based magnetic survey was capable of providing comparable data to existing low-altitude (30 m) fixed-wing aeromagnetic data and distinguishing two zones of magnetite- and hematite-rich mineralization that are 50–100 m apart.

UAV magnetic setup and data acquisition

Prior to the real experiment, we first studied noise-related issues from rotary-wing systems. This was done for a total-field magnetometer and a radio-magnetotelluric (RMT) system that operates using a 3C induction-coil magnetometer and two sets of east-west and north-south current electrodes (Ex and Ey, respectively; for details see Bastani et al., 2015). The intention was to use the RMT induction-coil magnetometer for this noise test, which was not being used in its current setup by UAVs. In a backyard experiment, the rotary-wing UAV system was turned on while stationary on the ground and then the total-field magnetometer (Figure 1a) and the 3C magnetometer (Figure 1b) brought close to it from a distance of approximately 20 m to 0.5 m. The total-field magnetometer showed stable data up to 1 m distance, after which it became unstable and even saturated (beyond its dynamic range). However, the RMT system that uses distant transmitters (10–250 kHz) as the plane-wave EM sources was not able to find any reasonable transmitter at 15 m distance because of the large electromagnetic noise around the 3C magnetometer. Unfortunately, no data time series was recorded to detail the noise level and its characteristics. Nevertheless, these tests were a motivation to carry out the real experiment nearly 300 km away from Uppsala in the Ludvika mining area of central Sweden using the total-field magnetometer.

The study area, Blötberget, which hosts iron-oxide apatite-bearing ore bodies, was chosen because of a vast number of activities currently ongoing, including knowledge of the

[1]Uppsala University.
[2]Amkvo AB.
[3]Geological Survey of Sweden.
[4]Nordic Iron Ore.

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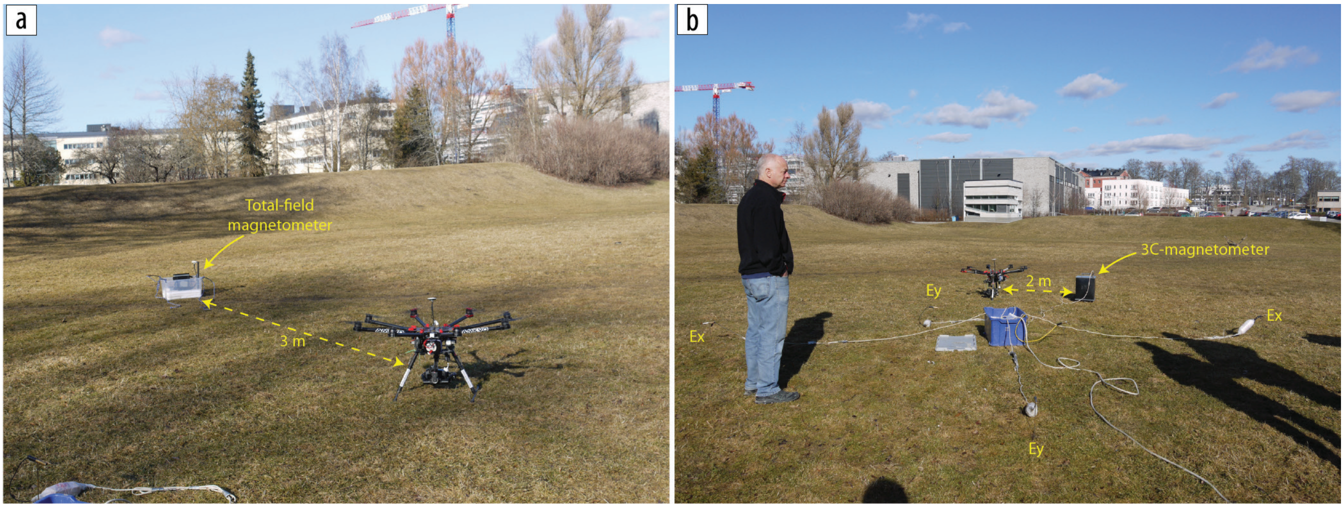

Figure 1. Backyard tests examining the noise level for (a) total-field magnetic and (b) RMT surveying. In these tests, the rotary-wing UAV system was kept fixed on the ground while in operation (not full power) and the total-field and 3C induction-coil magnetometers brought close to the UAV system. The RMT system equipped with the 3C induction-coil magnetometer did not function due to the high noise level; however, the total-field magnetometer worked reasonably well up to 1.5–2 m distance from the UAV system.

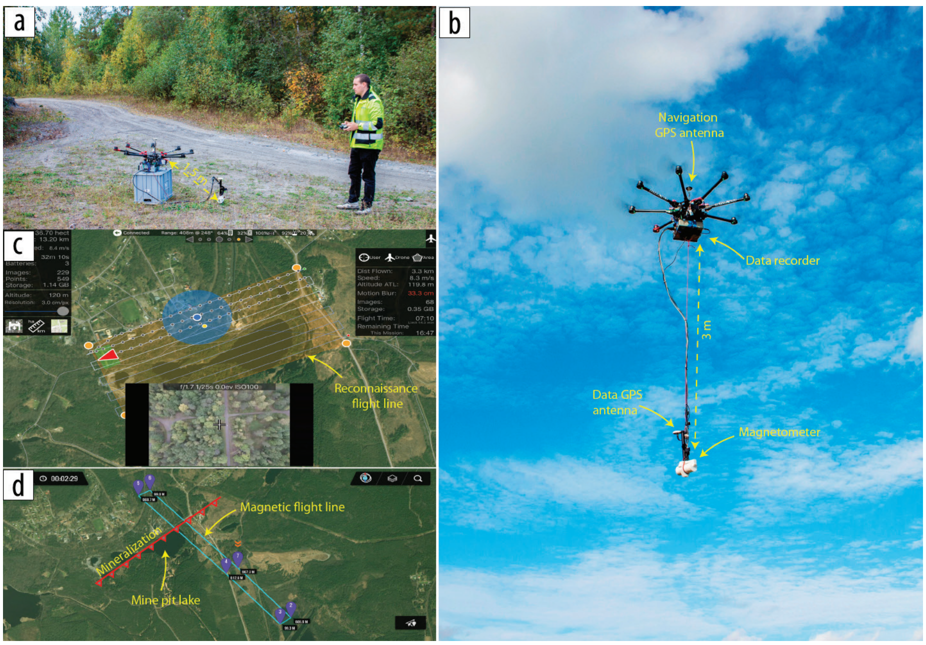

Figure 2. (a) The rotary-wing UAV magnetic setup before taking off and (b) during the flight. (c) Reconnaissance survey using smaller rotary-wing UAV equipped with high-resolution camera to check for the highest elevation in the study area, and (d) example of designing magnetic flight lines for auto-navigation during the experiment.

mineralization and their 3D geometry and the wealth of geophysical and downhole logging data available (e.g., Maries et al., 2016). Important for this study were the facts that (1) there is currently no mining operation, although there are plans to reopen the mine; (2) the mineralization is dominantly magnetite, but there are horizons where hematite is rich or notably present; and (3) the estimated intact ore is about 45 Mt and is known to extend to at least 850 m depth. The earth's magnetic field at the time of the experiment (October 2016) was estimated to be approximately 51,520 nT with 5° declination and 73° inclination. We will compare our data with another data set acquired during 1972 for which the earth's magnetic field at the time was estimated to be approximately 51,280 nT with 0° declination and 72° inclination.

The walking-mode magnetometer of the GEM 19 GW system equipped with a GPS antenna and data recorder was reassembled in such a manner that it could be lifted by the rotary-wing UAV with one magnetometer having about 3 m distance from it. To avoid complications from the swinging of the magnetometer during flight, for this test a further decision was made to only employ a total-field magnetometer that is less sensitive to tilting and noise. The magnetometer, cables, and its recorders (in total approximately 5 kg) were tied carefully to the UAV so that the main load was on the UAV and not on the data and power cables (Figures 2a and 2b). No dedicated platform was built for takeoff or landing. Instead, a plastic box was used to place the rotary wing, and the magnetometer and data GPS antenna were left on the ground (Figure 2a). While the UAV was landing, we manually held the magnetometer thanks to the control provided by the rotary-wing system and the 3 m cable. Here we realized that a well-prepared nonmagnetic platform for both takeoff and landing would have been more practical and safer.

The rotary-wing UAV system used in the experiment was a 5 kg DJI S1000 Premium Folding Octocopter powered by a 20,000 mAh lithium-polymer battery. The UAV is capable of flying for approximately 20 minutes with a 2 kg load and 15 minutes with a 4 kg load. It can fly with a maximum speed of 18 m/s. In our experiment and based on a 5 kg load, the flight times were estimated at eight to 10 minutes, but we limited the time to a maximum of five minutes to avoid risk.

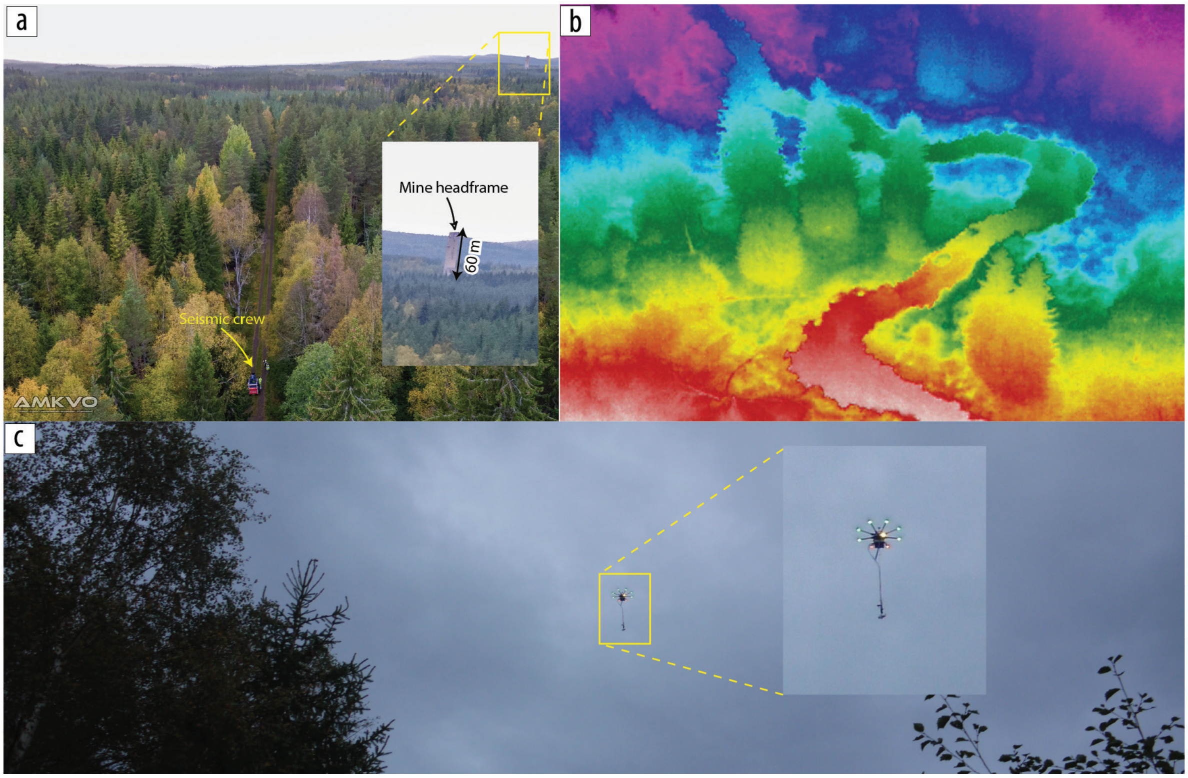

Figure 3. A number of photos taken during the late afternoon with (a) showing the general topography of the study area, visible mine headframe, and seismic reflection crew operating at the same time this study was being conducted. (b) A thermal picture clearly showing a river and dense trees in the study area (logistical challenge for ground magnetic surveying). (c) The rotary-wing UAV system while magnetic surveying around 6 p.m. with a good visibility provided by the system's lights.

Due to regulations for drones in Sweden, we first had to check for the highest elevation in the study area and ensure that the pilot had good visibility of the flight path. A smaller rotary-wing UAV system equipped with a camera and GPS antenna was used to quickly scan the area of investigation (Figure 2c) and check the flight altitude that should be used. The highest elevation in the study area was found to be 60 m above the ground and from the mine headframe (Figure 3a). Flight lines (Figure 2d) were designed to give the pilot a good vision to the UAV system and also to ensure the surveying team could reach the UAV quickly in case of accident. A 1 km flight range was used in this study. Given this restriction, we had to change the landing position three times during the survey. We realized later that a late or evening flight time would have been more practical for the pilot's vision because the UAV was equipped with several lights (Figure 3c), making it visible from far distances. If doing evening surveys, other safety factors obviously should be considered.

We used a diesel-driven generator to charge the batteries powering the UAV. To save time, four additional batteries were used. At the end of every flight, charged batteries replaced the empty ones. Given the weight of the magnetometer and the pilot vision required, this was equivalent to three to five minutes of flight and about 2 km flight line for 8 m/s flight speed, including takeoff and landing. Flight lines were flown perpendicular to the strike of the geologic structures and mineralization, 10 m above the mine headframe and on average 70 m above the ground. A base station placed in a magnetically quiet area was used to correct for the diurnal effect. The magnetometer was set up so that it recorded the total field and geodetic position at every 1 s time interval. No control was available to remotely check the performance of the magnetometer during the flights, which is another issue requiring specific attention for future developments.

Several problems occurred and delayed the survey to 2 p.m. from the initially planned time of 10 a.m. First, we realized after a couple of flights that the magnetic field at the landing station was already too high, possibly due to magnetite mineralization. Therefore, we had to move the first landing position and check for this carefully before takeoff. Second, when the UAV was taking off, it was extremely important that it was not approaching the magnetometer too closely sideways to avoid saturation (Figure 2a). Since we had no direct access to the instrument while data were being recorded, we lost a couple of pieces of flight-line data because of oversaturation of the magnetic field. In this circumstance, the magnetometer had to be rebooted and the operation halted for a period of approximately 10 minutes. To overcome this issue, we took care to ensure that follow-up flights took off only when the magnetic field was not saturated and readings were stable or did not change more than 5–10 nT at the station. Obviously most of the data near the landing and takeoff stations were influenced by the UAV noise. Here, we also realized the value of long flight times and a landing station outside the area of interest.

On some occasions during landing, we also experienced saturation of the magnetic field data, but we were unsure whether this was due to UAV noise or magnetite mineralization in the study area. From earlier ground-magnetic surveys, we knew that when

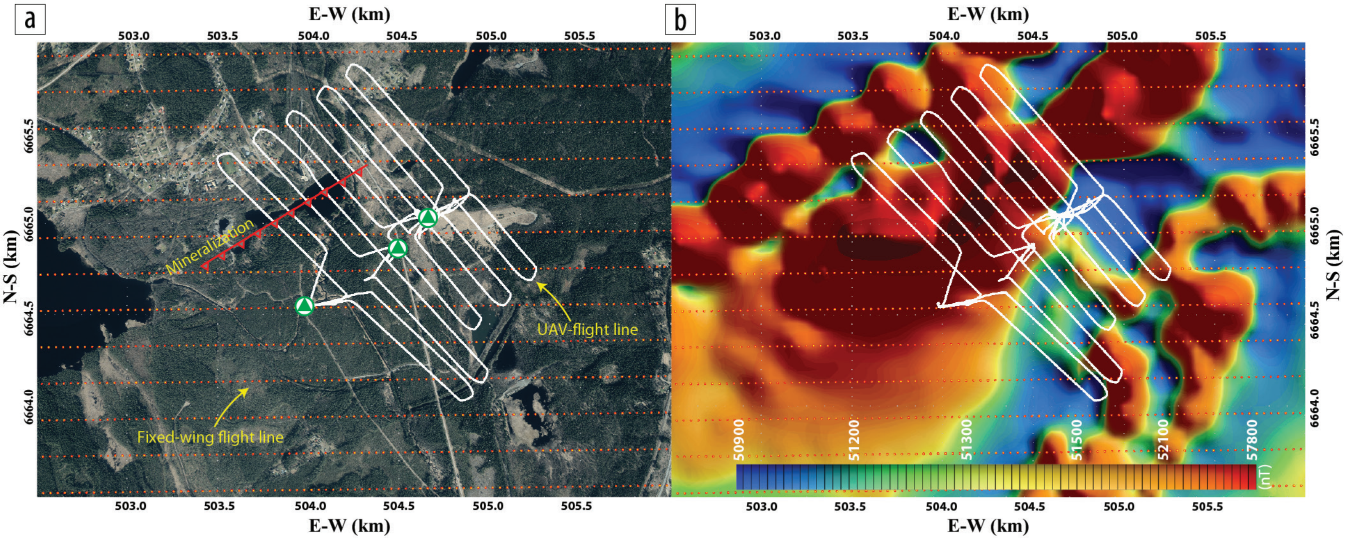

Figure 4. (a) Aerial photo of the study area and the flight magnetic lines (white points) as surveyed by the UAV system. The three triangles represent the locations of landings and takeoffs. (b) Total-field aeromagnetic map of the study area (surveying was done in 1972 in east-west direction [red circles filled with orange], 30 m above the ground) was used to design the flight lines. The existing aeromagnetic survey (provided by SGU) was flown using approximately 40 m station spacing and 200 m line spacing. The UAV magnetic survey has approximately 8 m station spacing and 100 m line spacing.

approaching too closely to the magnetite mineralization in the study area, the magnetic field becomes so high that the magnetometer does not function (likely beyond its dynamic range). Moreover, UAV navigation systems (e.g., heading compass) also may malfunction over locations where highly magnetized formations are present, which is an issue requiring detailed investigation in the near future. Nonetheless, we believed if this experiment was not capable of detecting mineralization with more than 50% volume magnetite, then the potential of UAV systems would be quite limited with this setup and sensor type. UAVs have an advantage over ground magnetic surveys in that they can fly at an altitude where saturation of the magnetic instrument is less of an issue.

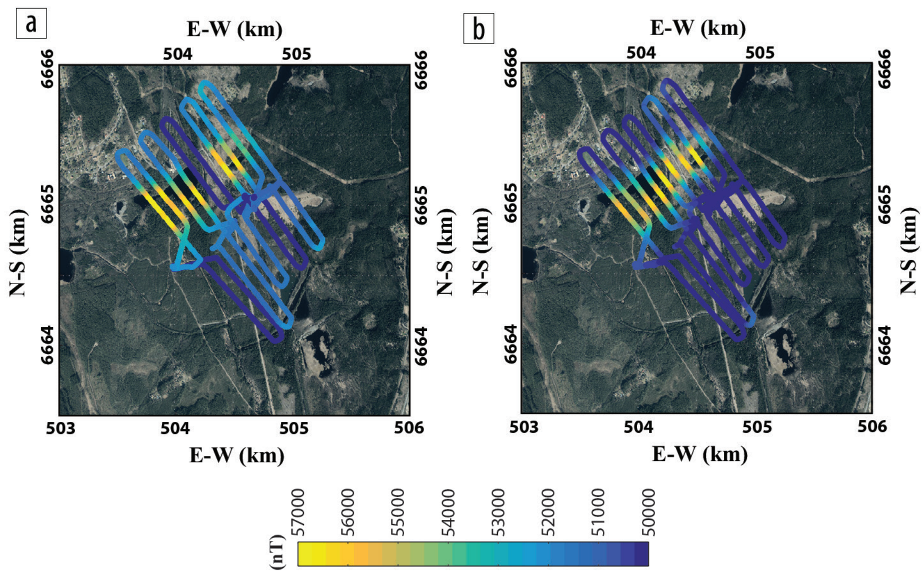

Figure 5. (a) Total-field magnetic data as acquired by the rotary-wing UAV system and (b) those from 1972 acquired by a fixed-wing airplane approximately 30 m above the surface. The UAV-magnetic data clearly delineate the iron-oxide mineralization as magnetic highs trending in the southwest-northeast direction. They are consistent overall with those from SGU.

Suitable magnetic field data eventually started to be collected around 2 p.m., and the survey continued until 7 p.m. (October 2016). In total, 10 flight sorties were carried out, and more than 20 km-line data were recorded covering an area of approximately 2 km^2. Data were then extracted from the recorder containing geodetic positions (easting, northing, and altitude) of the measuring points, GPS times, and total-field magnetic. Figure 4a shows the aerial photo of the study area and the flight lines projected onto it as surveyed by the UAV system. Figure 4b shows the surveyed lines projected on the existing, from 1972, total-field magnetic map of the study area. It also clearly shows the magnetic response of the mineralization and a number of magnetic high lineaments associated with iron-oxide mineralization in the study area. The three landing stations are evident on the flight-line patterns (Figure 4a).

Results

Figure 5a shows the total-field magnetic data acquired in this study after being corrected for the diurnal effect. Diurnal was not so significant and only varied up to 50 nT during the survey period. Three flights had data with severe noise issues (Figure 5a) and hence were excluded. Spiky points were filtered using a 1D median filter operating using 10 data samples. No correction for the heading or lag was done (not possible). For comparison, equivalent data from the 1972 fixed-wing aeromagnetic survey are shown in Figure 5b. A careful inspection of these figures suggests a noticeable magnetic high trending in a southwest-to-northeast direction at the same location where the mineralization occurs. Therefore, with a high degree of confidence, we argue the survey was able to clearly delineate the mineralization. However, the UAV magnetic data have finer sampling (8 m against 40 m) and hence resolution compared to the Geological Survey of Sweden (SGU) data from 1972.

Comparison with fixed-wing aeromagnetic data

Figure 6 shows a location-by-location comparison between the total-field magnetic data as obtained in this study and those from the fixed-wing airplane obtained from SGU. Where no data were available from the airplane survey, the nearest points are used. Overall, except for noisy points, the two data sets resemble each other in all their major highs and lows.

To better scrutinize the data, we plotted the magnetic data in 3D as a function of their location (easting and northing) and the total-field magnetic data. Figure 7a shows this for the fixed-wing airplane data from 1972 and Figure 7b for the data obtained in this study. Although there is obviously a shift in values between the two data sets (change in the magnetic field but also different altitude and possible instrument static shift), the UAV data show two peaks, one having larger magnitude than the other. There are some indications of these two peaks in the fixed-wing airplane data but not as pronounced as in the UAV magnetic data. The mining operation stopped in 1979 with most of the mining taking place at approximately 240 m depth. We do not know if the approximately 10 years of mining contributes to this difference. However, from several boreholes in the study area we know today that there are two distinct mineralized horizons nearly 50–100 m apart (Figure 7c) at the same locations where these two different magnitude magnetic highs are observed. One horizon, the southernmost one(s), is magnetite-rich; another, the northernmost one, also contains hematite. The two peaks observed in the UAV data depict these two zones. This may not be surprising given the coarser station and flight spacing and the flight lines being surveyed in an east-west direction, contrary to the fine sampling spacing and better-suited flight-line direction (northwest-southeast) provided by the UAV system.

To summarize, this pilot rotary-wing UAV magnetic survey proved to be challenging in the beginning; however, it also demonstrated that with careful planning and instrumentation, it could be used successfully for mineral-exploration purposes. We clearly see the mineralization in the data and are even able to distinguish different zones within it. Ground or helicopter-based systems would not likely achieve this result in such a cost-effective manner, although more surveys and tests are required to properly justify this claim.

Future works

UAV-based magnetic instruments should be developed to allow data streaming to the pilot or operators to save time and cost of collecting poor-quality or even nonuseful data. In ideal situations, they need to be modular so that many types of sensors can be connected and data can be live streamed. EM-based methods remain the ultimate dream, and this could be achieved if the UAV-noise issue is overcome. We will develop a dedicated nonmagnetic platform from which taking off and landing can be done successfully. More studies on the noise level and how to shield noise generated by the UAV's electromotors, UAV-battery types, and lighter sensors will be conducted given the great potential of the UAV-based systems for mineral exploration, particularly in remote areas where renting a helicopter or airplane is either impossible or too expensive to be embraced by exploration companies. In addition, UAV-based systems are more environmentally friendly with minimum contribution to CO_2 emissions because of their requirement for less power, on the order of 200 times.

SGU also acquired new magnetic data in 2016 using a more up-to-date system in the study area and using similar flight-line direction (130° heading). These data should become available to provide a better comparison (time wise) with the UAV data and to show whether the new data with better sampling frequency and optimum flight-line direction can support the two peaks observed in the UAV magnetic data.

Conclusions

We have successfully tested the potential of rotary-wing UAV magnetic systems for mineral exploration using an off-the-shelf solution in central Sweden. Within three hours, approximately 20 km-line total-field magnetic data were acquired showing the potential cost effectiveness of the method over geologically and logistically challenging terrains. For safety reasons, we were limited to flying above the highest elevation in the area and to having pilot's vision to the UAV system while surveying. Despite a number of challenges, some of which require detailed investigation, the acquired data show good quality and are comparable to the high-resolution low-altitude airplane data available from the site. Not only do the data delineate iron-oxide mineralization, two distinct zones — one magnetite- and another hematite-rich — also can be inferred. This is encouraging and opens up opportunities for developing modular-based UAV systems for mineral exploration, particularly when the noise issue is overcome and flight times are increased. Future studies should tackle sensor saturation over highly magnetized formations, improve accuracy of UAV-based magnetic survey over conventional airborne survey using either different types of sensors or longer cables, and provide more experiments for geologic structural identifications and live data streaming to operators. TLE

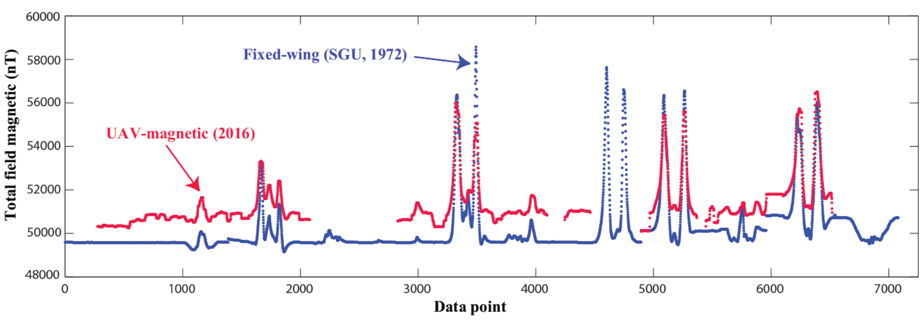

Figure 6. Comparison between point-by-point total-field magnetic data from the UAV system (red points and this study) and those from the 1972 fixed-wing airplane survey.

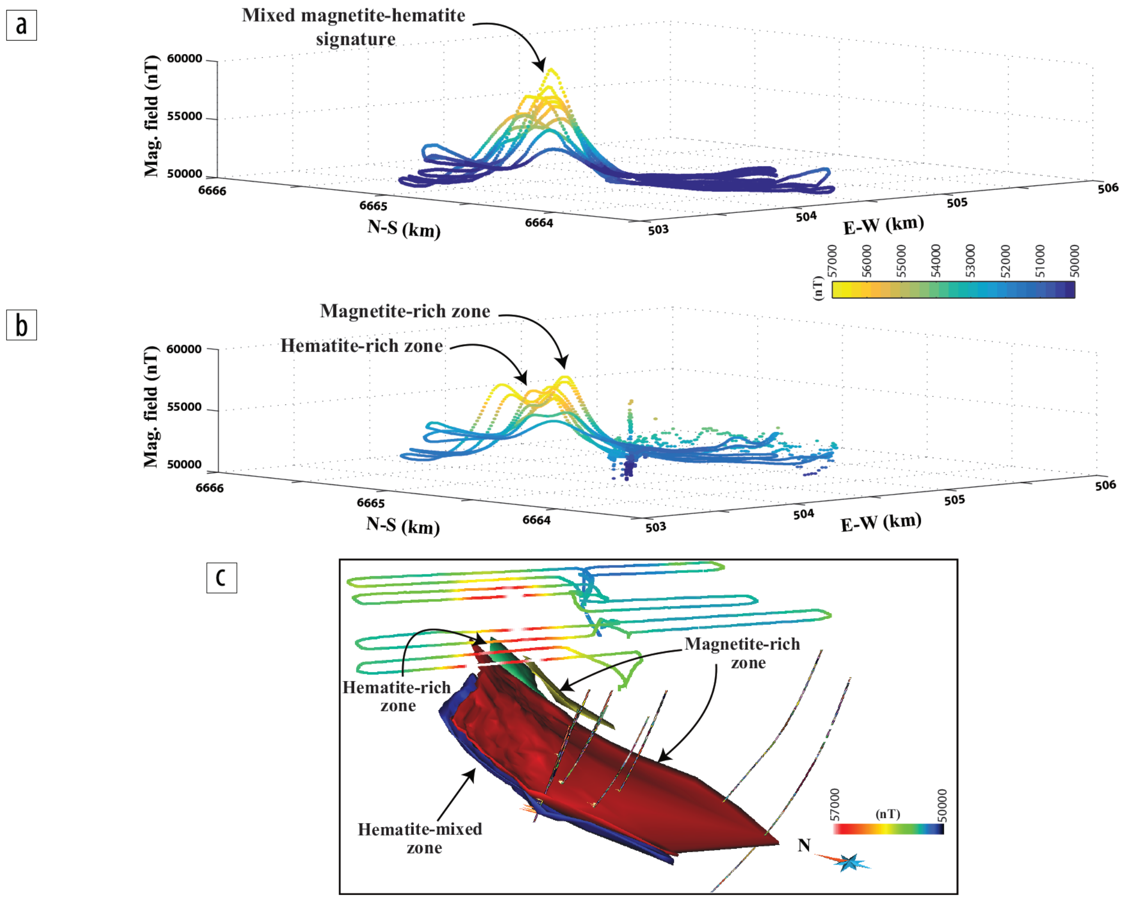

Figure 7. Comparison between location-by-location total-field magnetic data from (a) the fixed-wing airplane (SGU) and (b) the UAV system (this study). Note how the UAV data depict two magnetic highs (black arrows in [b]) associated with two known magnetite- and hematite-rich mineralized zones nearly 50–100 m apart. This is clearly illustrated using the 3D model of the ore bodies and visualization of the UAV magnetic data as shown in (c).

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Corresponding author: alireza.malehmir@geo.uu.se

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