Case Study

Airborne Magnetometry to Identify Metallic Debris to Support Dredging and Search Activities at the Brumadinho Disaster Site – A Case Study

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Abstract: This paper describes the procedures and results of an airborne magnetic survey using Unmanned Aerial Vehicle (UAV) conducted to support Search and Rescue (S&R) teams after the failure of a mining tailing dam at the Corrego do Feijão Mine, in the state of Minas Gerais, Southeast Brazil. The accident claimed 270 lives, practically destroying all the mine's infrastructure. After the accident, the use of a fast, efficient, and cost-effective method to locate preferential sites for the rescue team to work was critical. Due to the difficulty of direct access to the impacted area, and since most of the affected infrastructure consisted of metallic materials, an airborne magnetometer was the logical choice. First, some performance tests were conducted in order to define the survey configurations, such as flight altitude, transect spacing and anomaly's detectability threshold. After that, task priorities were set, and the survey area divided in small blocks according to their morphological characteristics using aerial photos of the impacted area. The results showed that the system was able to detect all relevant anomalies. The correlation of the anomalies with aerial photogrammetry helped to discard false anomalies, making the whole operation much more efficient. This increased the effectiveness of the S&R teams as well as the planning of the dredging operations by defining the preferential locations for the interventions.

Keywords: UAV, magnetometry, mining tailing dam, Brumadinho

1. Introduction

At lunchtime on January 25th, 2019, an unprecedented environmental disaster took place in the town of Brumadinho, Minas Gerais, Southeast Brazil. One of the local iron mining tailings dams suffered a catastrophic failure and discharged over 12 million cubic meters of mud (Figure 1). The accident was classified as the second major industrial disaster of the century and the major work accident in Brazilian history.

In a matter of seconds, the mudflow advanced over the mine's infrastructure and 270 lives were lost. Several pieces of equipment were immediately buried. The social and economic consequences for the city of Brumadinho were immense. The environmental consequences were even bigger. It is estimated that the chemical contaminants present in the material will probably be incorporated into the soil, causing a long-term environmental impact on the fauna and

agricultural activity.

Figure 1. (a) Accident area and (b) mudflow seconds after the mining tailing dams failure [1]

Considering the nature and size of the event, the localization of objects, as well as defining their type, mass, or other information to support the rescue of victims, could certainly be considered optimally at the very least. Therefore, the use of a fast, efficient, and cost-effective method to locate preferential sites for the rescue team to work is critical. Since most of the affected infrastructure consisted of metallic materials, magnetometry was the logical choice. This method measures the disturbance in the local magnetic field caused by the presence of metallic materials. Two main tasks were to be performed in the affected area: (a) Dredging Clearance Survey (DCS), which consisted of the removal of objects along the Paraopeba river valley that was totally filled with mud, before the commencement of dredging activities to restore the natural water flux; and (b) Dam Break Search (DBS), which involved the detection of pieces of equipment to feed a broader intelligence database managed by the fire department responsible for the search and rescue (S&R) of the victims.

Magnetometry measures perturbations in the ambient magnetic field caused by contrasts in magnetic susceptibility, which characterises the magnetic response of a material with ferromagnetic properties, such as iron and steel alloys, when immersed in the Earth's magnetic field [2]. Since the magnetic susceptibility of man-made metallic material is several orders of magnitude higher than that of rocks and soils [3], they are easily detected by magnetometers. On land, magnetometry is widely used for geological characterisation for mining, with little application in infrastructure projects for mapping assets such as pipelines [4] or verifying assets prior to the construction of an industrial plant. One application in the latter case is the mapping of metal barrels with hazardous waste [5].

However, given the nature of the disaster, the magnetic field anomalies could be masked and/or deformed by the presence of several objects put together during the mudflow. The result would be a complex anomaly resulting from the combination of several anomalies related to different objects. With that in mind, performing inversions and making assumptions on the kinds of objects causing the anomalies was not within the scope of the work. On the other hand, the location and size of the anomaly can be of great value for both activities, dredging and S&R. For dredging, when the dredge gets close to a magnetic anomaly, extra care is taken, and the object can be removed before damaging the equipment. In the case of the S&R in the DBS area, the magnetic hits were used to make correlations with other information, like areas marked by sniffer dogs, or to identify the whereabouts of equipment before and after the

avalanche, indicating the possible location of victims that were supposed to be close to this particular equipment.

In recent years, the Unmanned Aerial Vehicle (UAV) with various on-board sensors has been considered to be a cost-effective tool for large scale aerial mapping [6,7]. Sensors, such as optically pumped potassium or cesium, proton, overhauser and fluxgate magnetometers, are used to measure the Earth's total magnetic field from an UAV [4]. The sensor can be dragged by a cable or rod at a suitable distance from the aircraft to avoid magnetic noise from the engines, or it can be attached to the aircraft and deliver what can be called a compensated magnetic field, which are the readings of the magnetic field with the aircraft magnetic noise in the background. The magnetometer setup and sensor type should be chosen based on the job in hand. Each sensor has its specification and capabilities and there are reasons to choose between an attached or dragged solution such as sensitivity and noise level [4]. In the present work, the main objective is to identify objects that may represent an obstacle to the dredging services to be performed and, subsequently, any large metallic objects in the dam's area of influence. At the same time, UAV mobility is a key factor in the choice of equipment, since there were trees piled on the banks of the river and on the newly formed islands along the course, causing a risk of collision and therefore requiring good aircraft manoeuvrability [8]. Even with recent and accurate previous photogrammetry, there is a high risk of entanglement by a possible towed system. After all the factors considered, a vector magnetometer with two 3D fluxgate sensors mounted to the aircraft was used.

There are not many references on the use of geophysical systems to support this kind of activity. Magnetometry has been traditionally used to locate metallic debris, but most often in land surveys. Other systems, such as Ground Penetrating Radar (GPR), are also used for that purpose [9,10]. But, in this case, all kinds of relatively large debris (such as boulders and tree trunks) would be counted as anomalies. A large number of anomalies would result in more time spent on unnecessary intervention. Moreover, in order to be effective, airborne GPR would have to fly very close to the ground, increasing the risk of a crash. The present work shows the first application of airborne magnetometry, using UAV to support dredging and S&R activities, since the difficult access to the affected area imposed the adoption of aerial survey to previously map the numerous local targets. It also presents a dynamic methodology in which scientists work side-by-side with the rescue team, providing efficient, reliable, and systematic information to support search activity. The current study also supports United Nations (UN) Sustainable Development Goal No. 9, fostering innovation in the infrastructure industry.

2. Materials and methods

To achieve the objectives of this work, two main factors were considered. The first factor was the shape and amplitude of the detectable anomalies relative to the obstacle's size. Large anomalies (> 10 nT) were set as a priority. Objects that did not have the capacity to markedly distort the magnetic field could be associated with objects buried deeper than expected or with small objects simply not relevant to the dredging and S&R operations. Given the fact that the readings described a compensated magnetic field, and data correction for diurnal variations of the regional magnetic field were not applied, the uncertainty of the readings ranged between 2 to 4 nT. This uncertainty level normally lies within realistic single magnetometer survey specifications [11] and was considered acceptable for the present project, once the system was thought to detect larger anomalies.

The second factor relates to the definition of the equipment. Factors such as the ability of the UAV to carry up to 1 kg payload and autonomy, its lightness, and manoeuvrability were considered. The Inspire UAV, loaded with a 900 g magnetometer, was allowed for 12 to 15-minute flights, resulting in less than 1 km of real production per flight due to the low speed applied in each mission considering the risk of collision. To increase the number of flights performed in a day, several battery replacements were needed during a mission.

The weight of the system and the capability of being easily packed were critical to the success of the operations. The ability to transit through the DBS polygons was key to the synergy with the S&R team by quickly surveying different areas of interest. Likewise, for the DCS, the aircraft had to take off and land on a boat at the end of the river sections. Several trees were dangling from the river's banks or piling up on the newly formed islands along the river's talweg. Even with the help of recent and accurate previous photogrammetry, there was a high risk of entanglement for a dragged system, and the crash of the UAV would be imminent.

Considering all these factors, a 3D dual fluxgate magnetometer directly attached to the UAV was chosen (Table 1). The equipment choice was the MagDrone R3, manufactured by Sensys, and has two FGM3D/75 tri-axial fluxgate

sensors separated by a one-meter tube. An internal GPS provides 2 m positioning accuracy. The whole system weights less than 1 kg and could be operated by DJI's Inspire 1 and 2 aircrafts (Figure 2). It is worth mentioning that these two sensors do not necessarily build a gradiometer system but are two independent sensors used to improve coverage.

Table 1. Main specifications of MagDrone R3

MarDrone R3 main specifications	
Name	FGM3D/75 Fluxgate
Number and orientation of sensors	2 sensors (horizontal and parallel)
Distance between sensor centre points	1 m
Specified measurement range	± 75,000 nT
Number of sensor axis	3
Sampling rate	200 Hz
Internal GPS	U Blox PAM-7Q
GPS precision	2 m

Figure 2. Picture of the UAV with the magnetometer

Total field geophysical techniques such as magnetometry are passive and the detection and location of the desired targets depends on a series of variables, such as metallic mass, volume, shape, direction of the survey lines, strength and orientation of the local magnetic field, and distance between the sensor and the target.

For the DCS, the concept of obstructions means any material that could, once hit by the dredge, result in downtime. This is, however, a very subjective definition. For practical purposes, an obstruction was considered any object larger than 1 m and heavier than 50 kg. In situations where it was unrealistic to previously know the material which the target was made, the size of a detectable anomaly (ΔM) was estimated by Hall's equation:

$$\Delta M = 10 \frac{W}{d^2} \tag{1}$$

Hall's equation takes into account the shape of the object through its aspect ratio (*a/b*), where *a* is equivalent to length and *b* refers to width. Both values are considered in the determination of the object mass, *W*. Meanwhile, *d* is the target-sensor distance and the coefficient of 10 is a generalisation of the local field induction. When the composition of the target is known, the dipole approximation can be used [12]. This model uses the magnetic susceptibility of the object, which substitutes the "10" coefficient in Hall's equation [12].

However, estimating only the induced magnetic field typically underestimates the size of the magnetic anomalies when amplifying factors such as remnant magnetization, volume of the object, and aspect ratio are not taken into account. These are factors that are very hard to define in a catastrophic situation such as the Brumadinho accident. According to Breiner [12], remnant magnetization can be 3 to 5 times that of the induced magnetization; object volume can amplify the distortion up to 3 times; and aspect ratio can double the inducing field. When all of these amplifying factors work over each other, estimating the magnetic anomaly's real amplitude becomes a difficult and complex task. For the DCS, the aircraft was configured to fly not higher than 4 m above the water level along transects spaced every 4 m (resulting in a 3 m sensor spacing). So, in the worst-case scenario, the magnetometers should be able to detect a 2 nT anomaly caused by a 100 kg object that lies 7.5 m below the sensor. This seems low, but situations where at least one amplifying factor is not applied are very rare, since most objects present some level of remanent magnetism, have a high volume of empty space (cars, metal cabinets, etc.), and have a high aspect ratio. A photogrammetric survey was conducted prior to the geophysical operations, so the flight plans could be drawn considering the several trees hanging from the margins and islands of accumulated mud and debris along the survey site. Flights should be conducted with extreme care as any crash could result in equipment damage or loss. The UAV had to stay within the line of sight (approximately 100 m radius), so the survey area was divided into 20 blocks with survey lines running parallel to the stream (Figure 3). The waterline showed no significant height variations within a 100 m radius and the flight height was set in the navigation application DJI GS Pro. The testing of the navigation setup prior to the commencement of the survey work showed that manual flights introduced too much noise into the data, so the flights were always flown in autopilot mode. Pilot intervention occurred only in a potential crash situation. The first area to be surveyed was the region that received the first impact from the mud avalanche (named "Ground Zero"). It covers a 400 m section consisting of four 100 m blocks along the stream with debris accumulations as high as 5 m. Because the survey was carried out three months after the event, many of these mounds already had dense vegetation cover, which imposed another level of difficulty. The data acquisition frequency of the system is high (200 Hz), and the survey speed was kept at 3 to 4 knots for safety reasons.

The results were presented in a report pointing out the main targets, and 2D technical drawings summarising their most relevant information (estimation of the size of the target, its location and topography). The anomalies were split into primaries and secondaries based on their amplitude and shape. Primary anomalies were the most relevant, characteristically showing short wavelength and high amplitude, indicating that the associated object is likely to be large and/or close to the surface. With this information in hand, the dredge operator was able to take a more cautious approach to the areas where these relevant targets, or a group of targets, were spotted, avoiding damage to the equipment, reducing downtime, and making the dredging service more efficient in general.

The DBS is intended to detect any metallic object or debris agglomeration that could be related to previously known objects. As for the DCS, a photogrammetric survey was conducted to support survey planning and operations. Commonly, a survey block had to be split into more than one flight plan if the topographic relief exceeded 10 to 15 m.

The topography of the DBS areas was frequently very irregular, especially closer to the dam, so that a flight altitude between 5 and 10 m was defined.

There is no preferential transect orientation in geophysical surveys. However, by planning the transects in the North-South direction, it ensures that the magnetic anomaly is mostly the result of the induced magnetization of the object [2]. In areas with steeper topographic features, a special survey plan had to be designed to avoid accidents with the UAV. Similar to the DCS, all of the flights were done without pilot intervention. However, whenever a remarkable anomaly in terms of size and/or shape was discovered, two or three extra low altitude (approximately 2 m) manual flights were made to validate the anomaly, helping to improve the target's location and serving as a quick validation procedure.

Figure 3. Example of the flight plans in the area known as "Ground Zero"

The final survey plan was designed with transects every 5 m apart, resulting in a 4 m sensor spacing. Based on Hall's equation, with this configuration, a 500 kg object buried 4 m into the ground would produce a 2 nT anomaly. This magnetic survey was conducted to support the rescuers from the fire department in their task of recovering the victims of the disaster. The survey consisted of gathering as much data and as fast as possible, to include new targets in their database. The chosen excavation locations were ranked after crossing the magnetic information (expected debris location) with several other pieces of information gathered and organised by the rescue team, such as sites of interest as detected by sniffing dogs, mudflow models, previous information about equipment and people's locations before the collapse, video footage, and so on. For instance, the location of relevant magnetic anomalies could be cross-referenced with flow models and the known location of a piece of machinery or physical installation could aid in determining whether there are people nearby before the dam breaks. To quickly respond to the dynamics of the rescue team, a clear data acquisition, quality control and processing workflow was organised. Data was processed and interpreted on a daily basis and if any remarkable anomaly was identified, it was immediately reported. Some caution was required to avoid

triggering a false alarm in areas where the anomalies were unrelated to the job's purpose, such as geological features or known or exposed objects. The precise photogrammetric mosaic is a great tool to identify exposed materials, which are likely to represent known and irrelevant debris moved by the trucks during the opening of roads for the machinery before the accident. Magnetic targets located at the side of the roads were only reported if the related anomalies were wide enough to indicate that the object was buried in the ground. This procedure for eliminating non-relevant anomalies based on the photogrammetry and previous satellite images was applied to the DCS as well, but was more relevant for the DBS, thereby avoiding rescue efforts in non-relevant spots and saving a lot of time and resources for the rescue crew.

Reporting timing for the DBS was key to the efficiency of the operation. The most important survey results arrive a day after data was collected. Moreover, a weekly compilation of all the results was delivered to feed the fire department database. Results were presented in two formats: (i) a single-page PDF document with all of the information about each detected magnetic anomaly, and (ii) a KMZ file with the precise location and size (standardised to the whole project) of the anomalies, flight navigation lines, and the compensated magnetic field as a raster background. The reports could span different defined polygons once the design of the flight lines was made based on areas with similar topography gradients and the extents were limited to battery duration and keeping the aircraft within the line of sight.

The MagDrone R3 stores compensated magnetic field values in binary format along with positioning and heading information for each sensor using the native Data Tool software. As the data was relatively noisy, some data processing was needed. The data was filtered with a moving average filter of 15 points to obtain the compensated magnetic fields for each magnetic output.

Further pre-processing steps were carried out by the design of Python scripts [13]. The processing steps accomplished with Python scripts were: organisation of the data according to each transect; conversion to local project coordinate (Projection: UTM, Datum: SIRGAS2000, and Zone: 23 S); removal of samples from the first and last 5 to 15 m of the transect (an important step of the data processing workflow because the aircraft instability during manoeuvring between transects introduces a lot of noise to the data); and generation of an image profile for each transect for quality control purposes.

The output from the scripts was loaded into MagPick for interpretation. The location of the target was defined by picking the central point between the highest and lowest magnetic value of the dipole in question [14]. The influence area of the magnetic anomalies was determined from the anomaly size, allowing the dredge and bulldozer to afford a little shift in the actual location of the object. Figure 4 shows the workflow sequence for the DCS and the DBS.

Due to the emergency of the situation, no data reduction from the reference station was made, since only anomalies high above the background were considered. This procedure, however, should be applied for future related projects.
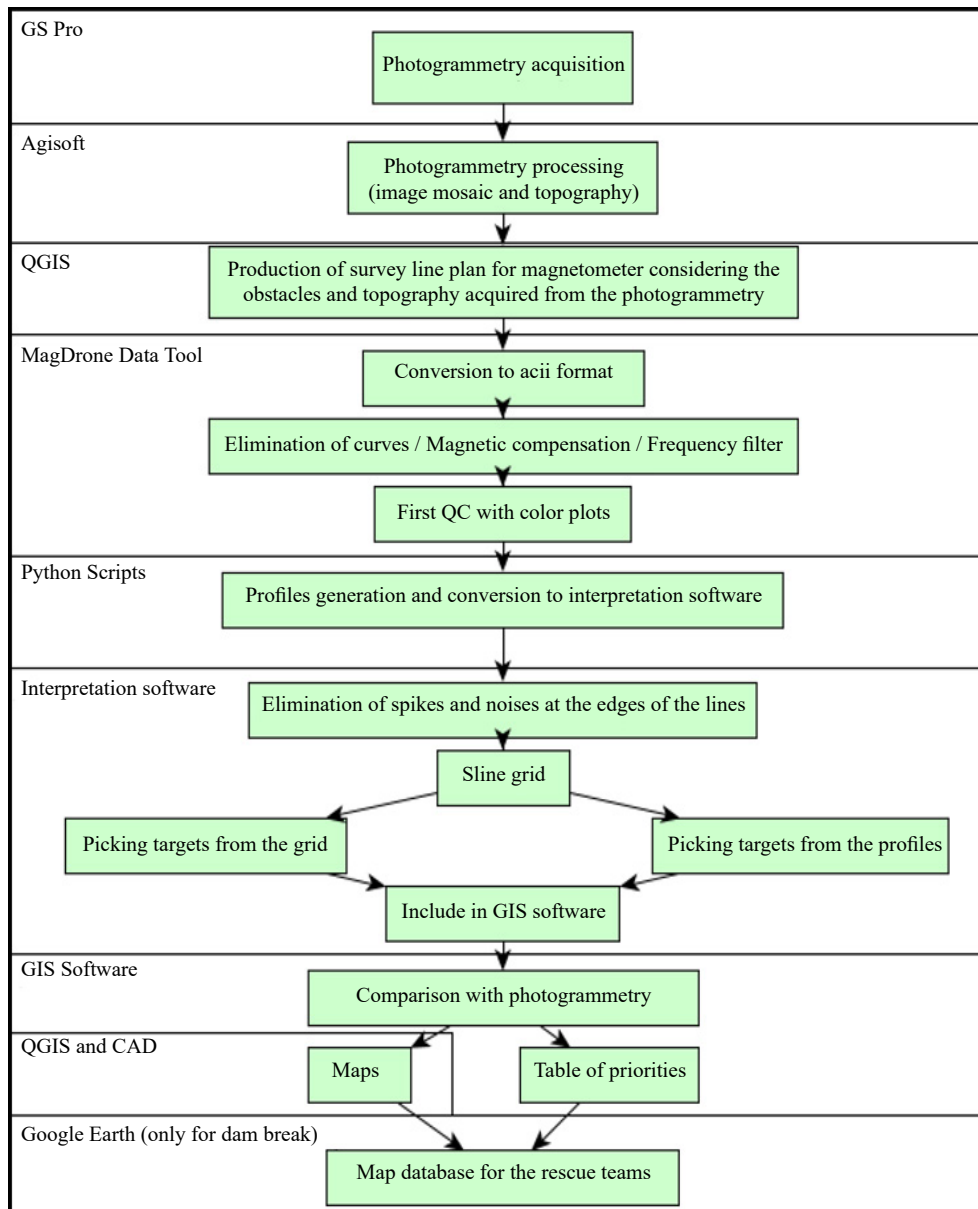
Figure 4. Workflow sequence from data collection to reporting stages

3. Results

As in any survey with a focus on metallic object detection, it is necessary to verify or prove the detection capacity of the equipment and thus provide data for the preparation of survey procedures. For that purpose, a performance test was conducted. It consisted of flying over an object of known dimensions and mass, with different distances between lines and flight altitudes, keeping in mind the various factors that influence a magnetic survey.

The test also checked the pilot's ability to hold altitude variations during flight and verify what was the minimum number of received satellites needed to keep a steady flight. This is in case the Real Time Kinematics (RTK) connections are not used.

Two particular sets of performance tests were carried out prior to the commencement of each of the operations. The DCS was the first task, so the interface between magnetometers and the aircraft was also assessed at this stage, in addition to each of the task's inherent tests.

Two main tests were conducted to evaluate some key points: noise level caused by the drone's engines to the data; detection capacity related to the size of the anomalies over known objects; and positioning of anomalies. Other subjective, but also very relevant tests were related to the flight behaviour of the drone, choice of the best form of equipment assembly, and acquisition parameters, including speed and stability.

The detection of an object that expressively distorts the magnetic field was evaluated, mainly to analyse its radius of influence. So, a flight over a compact car and a small cast iron wheel was made (Table 2). This test took a practical approach because machinery of similar size was expected to be found in the area, potentially masking other anomalies caused by smaller objects. It is also interesting to check how far away from the object the magnetometer can detect a reliable anomaly.

Table 2. Survey parameters of the tests

Object	Mass	Diameter	Line Spacing	Height of flight
Cast iron wheel	50 kg	0.5	4 m	5.8 and 12 m
Compact car	990 kg	-	4 m	4.7 and 12 m

Obstruction for dredging could be defined as any debris or object that is capable of causing damage when hit by the dredge, which results in downtime and delays for the project. Thus, the detection of a finite and small object was evaluated, in this case, a 50 kg cast iron wheel (Table 2).

The choice of the object was made based on the fact that its dimensions are measurable and it is a good example of debris that would likely lie on the site in a worst-case scenario, despite the fact that it is not very magnetic permeable due to its high content of carbon and other components [15].

The test was positive since, in addition to demonstrating detection capacity, the captured anomaly was relatively large (~40 nT) and undisputed in the 5 m altitude flight. However, the cast iron wheel detection did not yield good consistency in the repetition of the lowest flight. As a result, such objects may be overlooked in the real survey.

For the DBS task, detection tests were carried out to try to assess the shape of the magnetic field distortion caused by a large object (like a car or machinery), and its detection dependence on the distance to the sensors. The test consisted of positioning a pickup in a magnetically silent location (in this case, the parking lot at Brumadinho College), and performing the same flight plan at different altitudes, namely 5, 10, 15 and 30 m. The flights were performed twice, with the vehicle aligned parallel and perpendicular to the field flow vector magnetic location (declination of -22°). The results showed no change in the form of distortion of the magnetic field between the two positions, nor in the magnitude of the anomaly (Figure 5).

As expected, the detection of the magnetic field distortion becomes larger and clearer as one gets closer to the object. However, it was discovered that the higher the distance from the object, the more pronounced the drop in the values of the anomalies as predicted by Hall's equations (with adaptations for the minimum detectable anomaly). This may be due to the fact that the MagDrone R3 uses a compensated magnetic field, and weak signals could be lost as background magnetic noise increases. However, this conclusion is only speculative and should be validated through additional studies.

Other tests were carried out over a lighting tower and a pickup truck chassis (the pickup truck was destroyed by the avalanche), which showed a strong decay of magnetic anomalies as a function of the distance in the same order as found in the controlled tests. The fact is that at 5 m away from the object, a very strong magnetic anomaly of 1040 nT was obtained; at 10 m, this value dropped to 19 nT; at 15 m, there was a very small distortion of 4 nT, with great difficulty in precisely locating the object; and above 30 m altitude, the car was not detected. On flights between 5 and 10 m high, there was a clear distortion of the field.

After the tests were considered satisfactory and all survey procedures defined, survey priorities were set, and operations commenced.

The section of the Paraopeba river to be dredged was a little more than 2 km long, in which 31.10 km of usable magnetic data was collected. The area called "Ground Zero" showed the highest concentration of magnetic anomalies that could represent obstructions to dredging activity. This was expected since this is where the avalanche first hit the

Paraopeba River. In this way, primary and secondary targets were determined. A total of 216 magnetic anomalies were mapped and classified as "priorities" and "secondary". An example of a clear validated anomaly is presented in Figure 6.
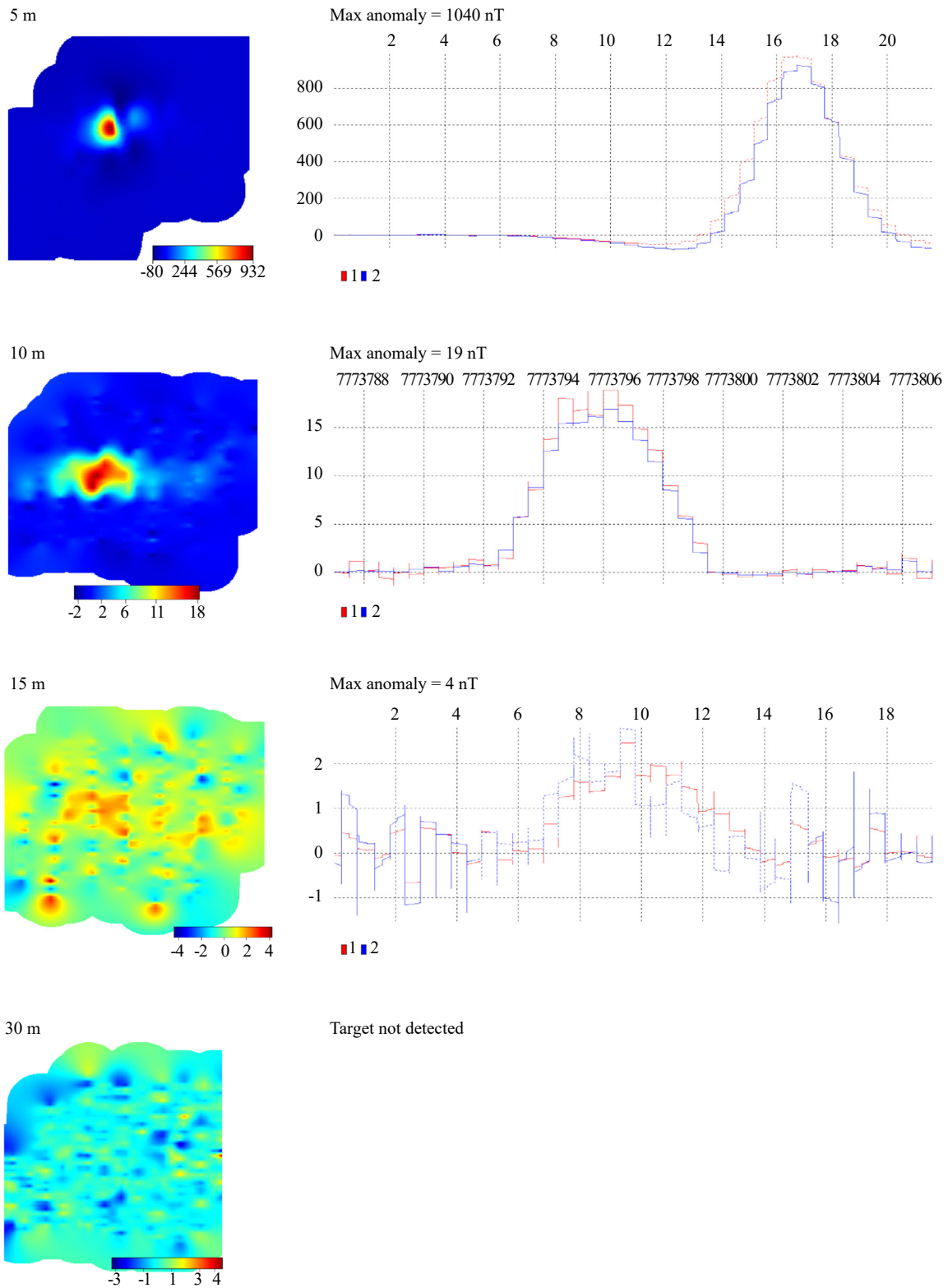

Figure 5. Results from the test on destroyed truck. From top to bottom, flights flew 5, 10, 15, and 30 m above the target
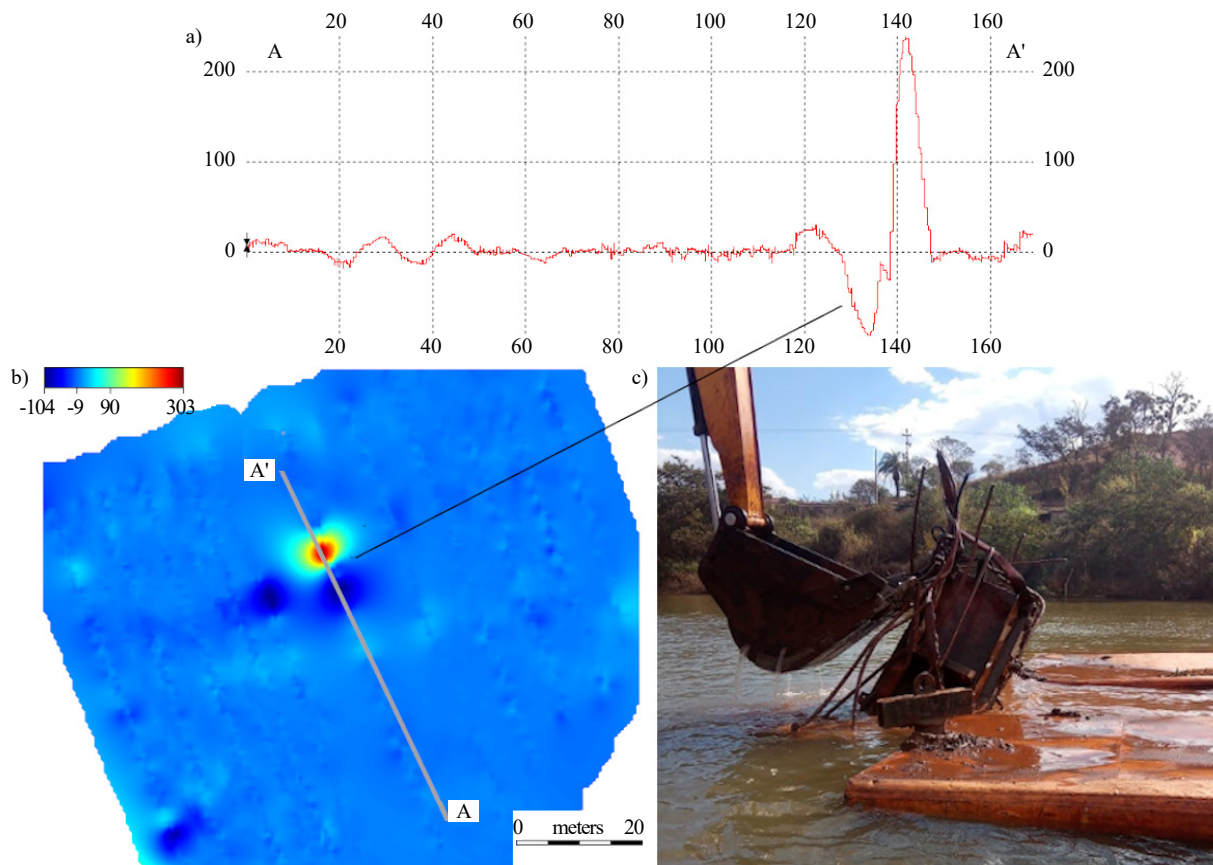
Figure 6. Example of a clear magnetic anomaly validated by investigations during dredging activities. (a) Magnetic profile showing the anomaly; (b) anomaly showed as a compensated and interpolated (spline) grid surface; and (c) object causing the magnetic anomaly

The primary targets are those captured in a magnetic profile with amplitudes equal to or greater than 40 nT or determined from the compensated grid. The latter indicates a very clear dipole caused by the object. Anomalies subjected to inversion processes are also listed as primary.

The anomaly determination process is laborious and time-consuming because it is also necessary to determine whether or not several anomalies detected in other survey lines are caused by the same object. This is not always possible, and in some areas, the magnetic field becomes extremely noisy due to the presence of surrounding objects. As a result, locating anomalies with simple magnetometers becomes impractical [11]. These areas were marked as "polygons anomalies". Since the area marked as PV04pol4 has a chaotic magnetic signal, it is difficult to discern anomalies from different sources. Caution was suggested when investigating this area. However, there is no evidence of very heavy materials.

Some of these polygons could also represent the area of influence of a large magnetic anomaly, which could mask smaller objects nearby. As a drastic example, the train waggon shown in Figure 7, which is approximately 10 m long and 2.8 m wide, caused an anomaly of 1905 nT and has a radius of influence of approximately 50 m. In this case, the anomaly was so high that even the process of defining the polygon of influence was complicated.

Secondary anomalies were those with an amplitude smaller than 40 nT and usually related to smaller objects. However, it doesn't mean that all secondary anomalies should be ruled out. Some of them can be associated with objects that can cause significant obstruction to the dredge. As an example, in area PV02, one secondary anomaly (20 nT) could be correlated to the aerial image of a refrigerator (Figure 8), which is a clear obstruction for the dredge.
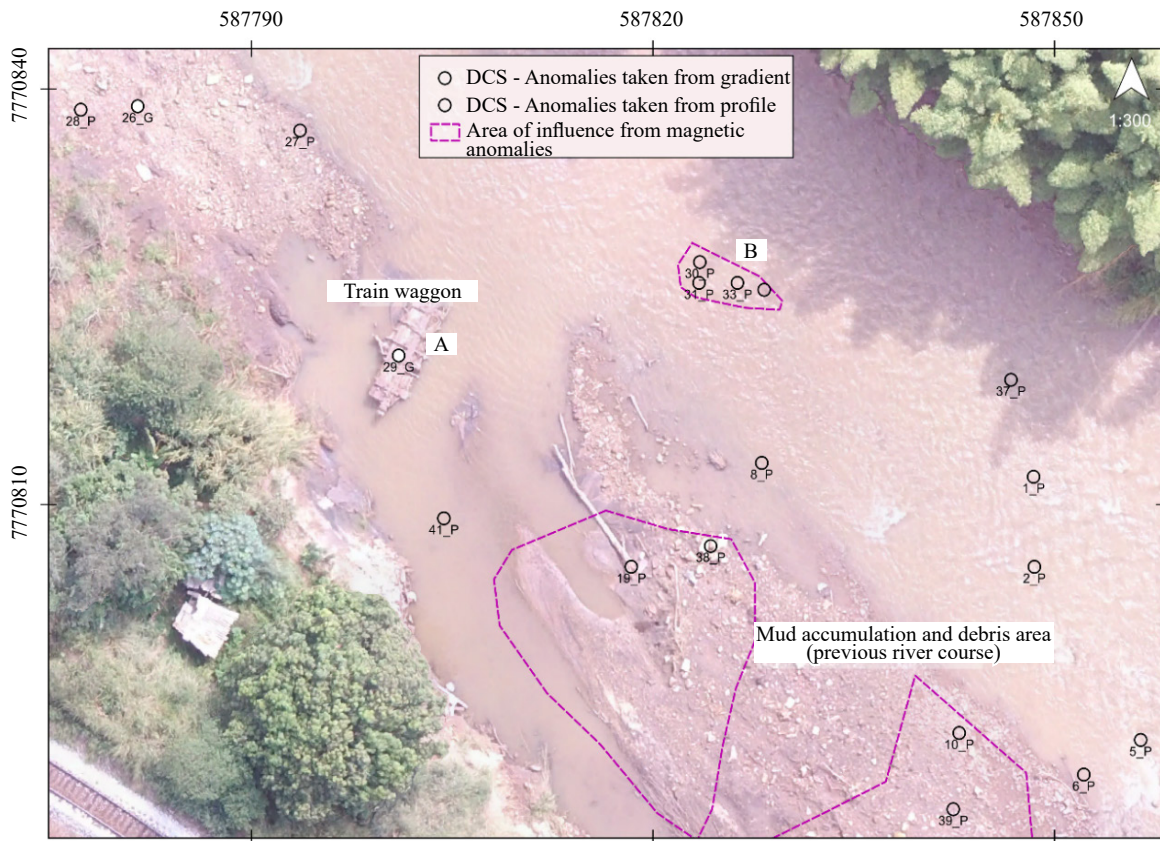
Figure 7. Magnetic hit interpretation on top of photogrammetric imagery. The train waggon (A) gives an idea of the dimension of the avalanche and a group of hits (B) that could be caused by the same object or several smaller objects
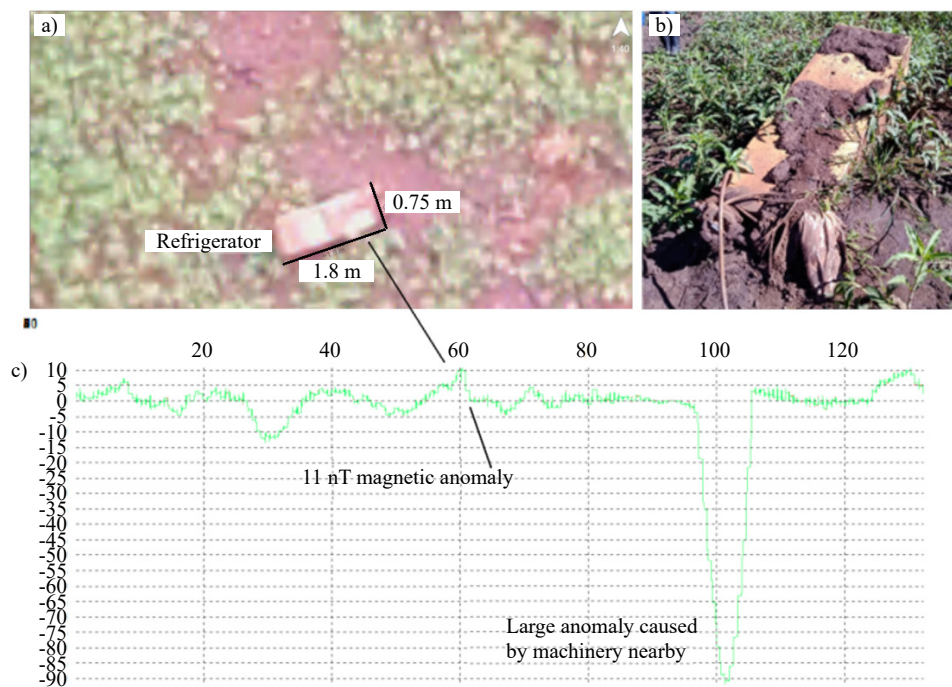

Figure 8. (a, b) Images and (c) magnetic anomaly of a refrigerator

After passing through the Ground Zero area, the stream becomes very narrow. In addition to this, the flights in this sector were difficult due to the occurrence of superior vegetation in the tailings banks and vegetation that projects to the river thalweg. It was necessary to avoid such areas to preserve the integrity of the equipment, including the fact that this vegetation inevitably hindered the pilot's ability to visually follow the aircraft and to navigate at a constant altitude and course. Several possible obstacles were identified that may have the same object as the source of the respective magnetic anomalies or have been mistakenly marked due to curves in the flight plan. Nevertheless, as a precautionary measure, these points were maintained and grouped as a "polygon anomaly".

For the DBS, the fire department divided the entire area into 469 square polygons of 125 m sides with a total area of 7.4 km². Magnetometer surveys were carried out per demand from the rescuers in areas where prior information could indicate the occurrence of victims. These could be associated with large magnetic anomalies, including machinery and cars, among others. A total of 276.71 km of magnetic data was acquired, mostly using the automatic flight mode and predefined survey lines. Meanwhile, extra manual flights and land acquisitions to assist the rescue team in narrowing down the search area were making approximately 300 km of data.

The reporting was made according to the polygon's code and data acquisition date. All information was used to weekly feed a Google Earth compatible database. This database was interactive and when clicking on one of the targets, information such as geographic coordinates, anomaly amplitude (nT) and flight path could be retrieved. The targets were separated into 4 classes of anomalies: A (0 to 10 nT); B (10 to 100 nT); C (100 to 250 nT); and D (greater than 250 nT). A one-page PDF summary was also sent along with the KMZ file database (Figure 9). In this example, ID 18 shows a point that was not recommended, thus not excavated. It was verified in the photogrammetry image (upper right corner of Figure 9) that it is an exposed pipe. On the other hand, ID 6 shows a heap of metal alloys (lower right corner of Figure 9) found after excavating ~5 m into the mud.
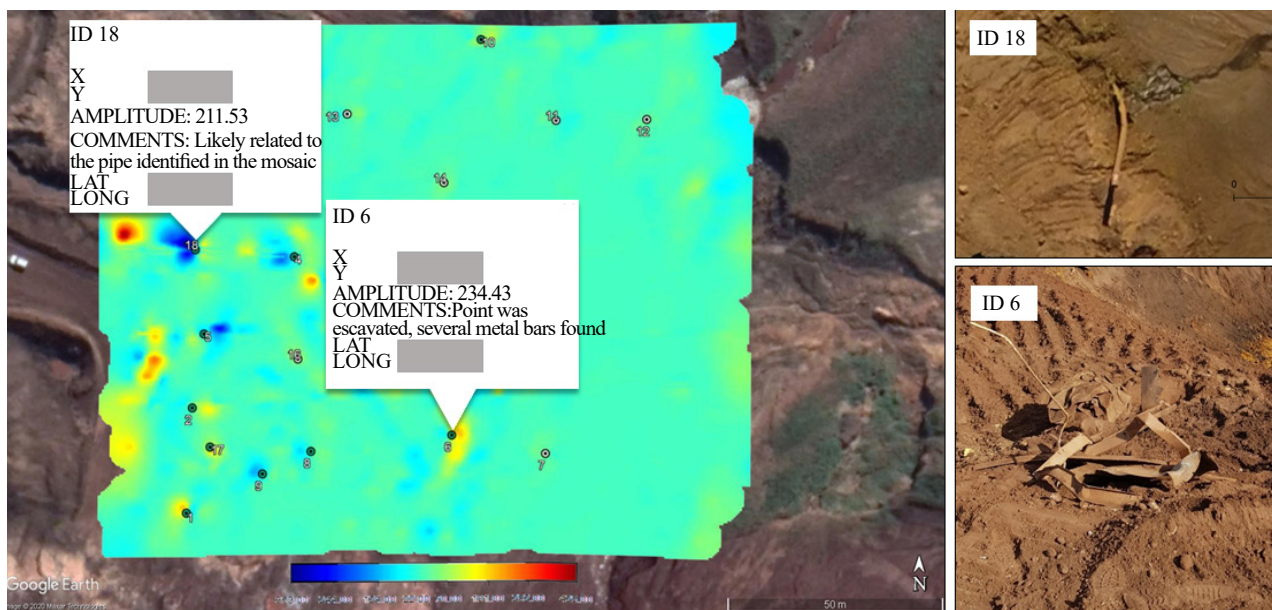

Figure 9. Example of report on the DBS area with validated points

The main goal of the project was to identify and map large anomalies that could be related to machinery or any other large metal object that could guide the rescue efforts. Nevertheless, a pick-up truck with three victims remained missing, and whenever an anomaly was found, it was immediately reported to the rescuers who were in charge of deciding whether or not to excavate in that location. As the procedure for acquiring magnetometry data is much less laborious than the excavation, polygons were defined in some areas and detailing flights were conducted with the aircraft flying less spaced at a controlled height and closer to the ground (between 2 to 3 m relative to the normal 6 to

10 m of the regular flights), while the survey lines were kept in different directions over the anomaly in question. This allowed better conditions for specifying the coordinates and, in some cases, validating the anomaly and even estimating the order of magnitude of the object(s).

The terrain was often very irregular, so the sensor's altitude relative to the ground varied drastically in some areas. Manual test flights performed for this study show that it is not advisable to change flight altitude during data collection due to the dynamic induction noise that can be input to the data, and that using laser sensors in the aircraft to maintain a constant height from the ground is also not recommended. To overcome this limitation, the flight was always made over an area with less than 10 m terrain gradient.

After four weeks of surveying, 41 reports were sent with 297 anomaly spots, and 52 were tagged as priorities, where chances of finding large machinery or vehicles were higher.

4. Discussion

The Brumadinho disaster was a non-precedent event in Brazil's history. This work presents a methodology based on an airborne magnetometer survey with an UAV as a tool in the search for metallic debris to support uncommon dredging and rescue activities in very obstructed areas.

This work also shows that airborne magnetometry operated from an UAV is an effective tool for post-disaster applications. Fast data acquisition process, combined with the possibility to detect man-made objects in areas with very difficult access, makes it a handy tool to help decision makers and rescuers regarding asset location and its association with victims.

An extensive data acquisition effort was made to accomplish the job in hand. Hence, much could be learnt from the constant equipment interface, and such experience from the basic application of good practises to the empirical knowledge acquired can be useful for operators in this growing line of geophysics acquisition. The most important considerations to be made are:

1. For both the DCS and DBS tasks, good photogrammetric data was key to the survey planning and data interpretation (by helping to identify known sources of magnetic anomalies). It is not imaginable to perform aerial surveys within a restricted area with irregular terrain without a good terrain model and a high-resolution image.
2. Manual flights are way too noisy and should be avoided, unless for detailing areas with plenty of obstacles and risks to the aircraft. In this case, despite the relative low quality of the data, it is still usable and can surely contribute to the objectives of the survey.

5. Conclusions

Magnetometry data proved to be an excellent tool for locating debris that can obstruct dredging activities and victims of avalanches by association with anomalies related to man-made metallic objects after a major disaster event when combined with precise photometry and an airborne solution. Great effort was made to select relevant targets, which were defined by anomalies caused by large objects that could provide an idea of the behaviour of the mudflow. In other words, knowing the position of an equipment prior to the accident can shed light on the behaviour of the avalanche's energy, and victims who may have been working in the vicinity of this particular equipment can be more easily located. To do that, a map with the previous location of all fixed structures in the area should be available. A previous magnetic survey that located all anomalies associated with natural or man-made structures, would also be useful for comparison with a post-event survey, allowing the interpreter to focus on the differences between the two maps.

The procedure adopted for this project was based on the idea that the size and shape of magnetic anomalies are good indicators of their relevance for detailed search operations. Caution must be taken during the interpretation of noise generated by variations in flight altitude and direction, as well as composite anomalies due to the presence of closely spaced objects. Taking this into account, the rescuers defined the excavation sites after crossing magnetic

anomalies and a variety of other information based on fluid flow models, sniffing dogs, victim job locations, and many others. It is recommended that the managing parties of such facilities keep an updated database regarding characteristics of the soil, detailed aerial photographic mosaics, topography and magnetic maps.

- This work demonstrates, with relative success, a very practical approach to the problem at hand. However, the following improvements should be considered for future projects: Improve data processing by considering the detailed topography of the area;
- Consider more variables in the performance tests (object size, type of material, flight altitude and course, object orientation), as well as building a reference data bank with all kinds of anomalies;
- Install a magnetic reference station to allow the filtering of the diurnal component, making it possible to analyse all the surveys together in the same database;
- More than one drone is carrying out data collection to speed up the mapping process, saving precious time for the rescue and search teams.

Even after analysing previous satellite imagery and the precise photogrammetry, some secondary anomalies may have been suggested for verification due to the complexity of such an extreme event. This could be minimised if a previous magnetometer survey had been performed. In other words, the ideal situation is obviously to take all necessary safety and investigation measures in order to avoid drastic and tragic events like this. However, airborne magnetometer surveys are relatively cheap, and producing a magnetic model of the area under normal circumstances would aid in the use of the magnetic approach to locate machinery following incidents such as mudslides, floods, and so on. Another important aspect of improving the search is reporting the results after investigating each site. However, this is not always possible due to the immediacy of the operations.

Other geophysical equipment could be used to locate debris. Yet, the airborne magnetic approach is the most cost effective and provides a very quick assessment of large areas. For instance, electric resistivity and GPR can be considered potential tools for locating debris and even non-ferromagnetic material. However, the data acquisition rate of these methods is very low, and the time required to cover such large areas would make the cost and reporting delay prohibitive. In addition, the rough terrain would impose more difficulties on electric surveys. GPR can also be acquired using an airborne solution, but only in 2D, whereas the magnetometer can detect objects in 3D as long as it provides relative intense distortions of the local magnetic field. 3D GPR could be an interesting tool to add as another validity layer prior to excavations due to its fast data acquisition rate when compared to the digging process, but the rough terrain and budget could be limiting factors.

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