Report on V2Mag Drone Magnetic UXO and Landmine Test

Danish Army Engineer Regiment EOD Test & Training Facility, Denmark

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Approved:

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Amendment record

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List of abbreviations

CORS	Continuously Operating Reference Station
GNSS	Global Navigation Satellite System
MTW	Maximum Take-off Weight
QA	Quality Assurance
QC	Quality Control
RTK	Real Time Kinematics
SoW	Scope of Work
SBAS	Satellite Based Augmentation System
UAV	Uncrewed Aerial Vehicle (”drone”)
UMag	UMag Solutions ApS
MVG	Measured Vertical Gradient (*Residual*)

List of multiplication prefixes

Factor	**name**	**prefix**
$\times 10^{-9}$	Nano	n
$\times 10^{-12}$	Pico	p

The cover images depict various targets used for the test. Image courtesy: Arne Døssing Andreasen

Contents

1. Executive Summary

This report documents the results of a V2Mag test campaign in relation to modern warfare UXO and landmines. The test was carried out on May 12th 2021 at a closed military EOD test and training facility belonging to Danish Army Engineer Regiment (Denmark) in collaboration with EOD personnel of DanChurchAid (DCA) and Danish Demining Group (DDG).

The purpose of the test campaign was to test the detection capabilities of UMag's patented drone-based V2Mag magnetic gradiometer system in relation to small UXO and landmines found in modern and recent war zones.

A selection of 36 different UXO and landmines ("targets") was placed out in an area covering 120 x 20m. The test area consisted of an overall flat field with a subsurface geology composed of glacial river and ice-marginal deposits.

All targets had total weights below 5kg and ferrous contents of ~0-2.5kg. Some of the items were composed almost entirely of plastic, composite materials or aluminum.

Magnetic data was collected with a line spacing of 0.8m and at both 1m and 2m gradiometer altitude. A background field measurement was collected at 1m altitude after removing all targets from the test area. In addition, a drone photogrammetry survey was conducted for visual overview of all targets, and supplemented by independent GNSS measurements of all 36 targets.

Complete processing of the magnetic data was done using UMag's in-house *UMAGPROC* software. The results of the processing show that data was collected with an overall system noise level of ±0.015nT, which correlates well with the expected noise level of the V2Mag system.

In this report, we provide grids of the *3rd order discrete vertical residual* and the *analytic signal gradient*. The 3rd order vertical residual is calculated as the 2nd order discrete vertical gradient of the *Measured Vertical Gradient* field, and is powerful for isolating high-frequency point sources like small UXO and landmines.

Of the 36 targets, 35 targets were overflown while one by mistake was placed just outside the survey area. Of the 35 overflown targets, 33 targets are well-defined at 1m altitude, while two (entirely plastic mines) are not detectable. At 2m altitude, 31 targets are well-defined, while two additional targets are not clearly detected. These two targets belong to the smallest munitions tested in the campaign with dimensions 10 x 2.5cm and overall weights of a few hundred grams.

In summary, the test campaign in Skive documents the strong capability of the V2Mag system for detecting various kinds of small UXO and landmines despite a small ferrous content. The ability of the V2Mag to fly close to ground level (<0.5m terrain following if needed) further enhances its potential use in pre-clearance scanning and post-clearance scanning of former war zones, even in complex terrain.

2. Introduction

This report documents the test results of UMag's **V2Mag** UAV magnetic gradiometer system, with specific focus on its detection capabilities on small modern warfare UXO and landmines.

The UAV magnetic test survey was carried out on May 12th 2021 at an EOD military test and training facility belonging to Danish Army Engineer Regiment, Denmark (Figure 2.1). The test area consisted of an overall flat field with a subsurface geology composed of glacial river and ice-marginal deposits.

Three surveys were conducted as part of the test: (i) A target field test at 1m gradiometer altitude; (i) A target field test at 2m gradiometer altitude; and (iii) A magnetic background field test at 1m gradiometer altitude. This report documents results from all three test surveys.

Figure 2.1: *Location of the test campaign (yellow marker).*

2.1. Targets

In total, 36 different UXO and landmines were selected for the test (Figure 2.2; Figure 2.3). The targets were specifically selected with relevance to EOD projects of the DanChurchAid (DCA) and Danish Demining Group (DDG) and include various landmines, cluster munitions, grenades, mortar ammunition, etc. All targets had total weights below 5kg and ferrous contents of ∼0-2.5kg. Three of the targets were composed almost entirely of plastic, composite materials or aluminum (targets 2, 5 and 26), while others (7, 9) only had small parts of ferrous metal inside.

The 36 target objects were kindly provided by the 2 EOD Battalion of the Danish Army Engineer Regiment, and the test was facilitated by Lasse Marinus Jørgensen, Chief Technical Advisor of DCA and Søren Adser Sørensen, Programme Specialist of DDG.

Figure 2.2: *Modern warfare UXO and landmines used for the V2Mag test, including landmines, cluster munitions, grenades, mortar ammunitions, etc. The yellow bar in each picture is for scale and equals about 10cm. The numbers provided in each picture will be used for target ID throughout the report.*

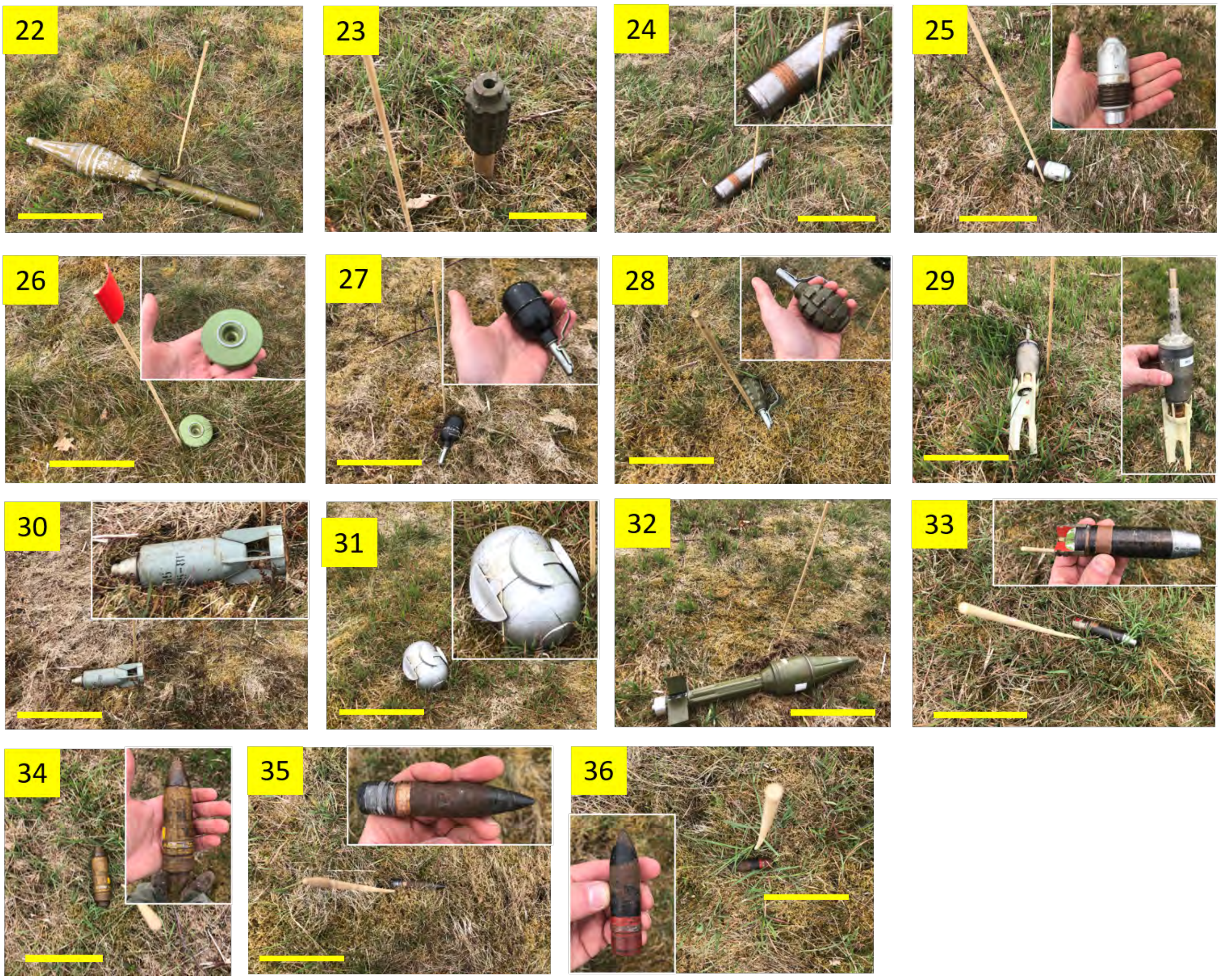


Figure 2.3: *Figure 2.2 continued.*

3. Equipment Summary

3.1. UAV Specifications

A *DJI Wind 4* heavy lifter UAV (MTW 21.0 kg) was deployed for the UAV magnetic survey. All data was collected using the same UAV, which at all times was equipped with a Differential Real Time Kinematic (D-RTK) system. The D-RTK system allowed precise 3D-positional control of the UAV (<15 cm error in XYZ) in real-time. A full explanation of the employed positioning systems and methods is described in subsection 3.3.

3.2. Magnetic Acquisition System - the V2Mag

UAV magnetic data was collected using UMag's patented V2Mag vertical gradiometer system. The V2Mag houses two high-precision and high-sensitivity GSMP-35U optically pumped Potassium magnetometer systems from GEMSystems, sampling at 20 Hz. Based on a typical surveying flight speed of 4.5m/s, about 4-5 data points were collected per meter.

Specifications of the GSMP-35U is listed in Table 3.1.

Table 3.1: *Sensor specifications of the* V^2*Mag GSMP-35U magnetometer.*

Name	Type	Sensitiv.	Res.	Abs. Acc.	Head. Err.	Dyn. Range	Grad. Tol.	Sampling
GSMP-35u	Potassium	0.0002nT@1Hz	0.0001nT	±0.1nT	±0.05nT	15,000-120,000nT	50,000nT/m	20Hz

3.3. Positioning Systems

Three independent positioning systems were employed:

1. UAV positioning system (Differential Real Time Kinematics)
2. V2Mag payload positioning system (*TerraStar*-enabled *NovAtel* GNSS receiver with *VectorNav* IMU)
3. Ground Survey GNSS receiver (CORS enabled *North Surveying SmaRTK* Rover)

The three positioning systems together provided a versatile positioning solution, with added robustness to partial satellite signal outages (the data can still be accurately positioned in the unlikely event of, for example, TerraStar or RTK Base Station outages).

3.3.1. UAV positioning system

The UAV Differential Real Time Kinematics (D-RTK) system comprises three GPS/GLONASS L1/L2 antennas in a base-rover pair (two on the rover and one in the base). This provides the UAV with an accurate horizontal position and precise altitude relative to the take-off point. The UAV follows the charted flight path with high precision, while either retaining an overall constant altitude level with respect to a local vertical datum (measured relative to the take-off location altitude) or retaining a constant altitude level with respect to the ground (measured relative to a predefined Digital Surface Model).

3.3.2. V2Mag payload positioning system

The V2Mag payload positioning system records the attitude (by IMU) and position (by GNSS) of the magnetometer payload using state-of-the-art real-time corrections. Apart from GPS/GLONASS L1/L2 data, the system also receives real-time corrections from the state-of-the-art TerraStar positioning service. We use the measured GNSS-IMU information, combined with the rigid geometry of the V2Mag payload system, to calculate the true positions of the lower and upper V2Mag sensors. The mean value of the sensor positions is used as the position of the Measured Vertical Gradient (MVG), i.e. the first order vertical residual field.

3.3.3. Ground Survey positioning system

A ground-based positioning system was used to measure targets and Ground Control Points positions on the ground for construction of a precise orthophoto from UAV photogrammetry and for an independent target positioning.

UMag employs two SmaRTK ground-based systems from *North Surveying*. The SmaRTK is a multi-constellation, multi-frequency GNSS RTK system, able to receive almost all commercially available signals, including GPS L1/L2/L5, GLONASS G1/G2, COMPASS B1/B2, and GALILEO. The systems are also able to receive CORS correctional or other reference station data, and both units may be used in conjunction as a base station/rover pair. Further information regarding the hardware can be found at *https://gnssrtk.com/index.php*.

3.4. Flight Planning and Operation Software

UgCS PC Mission Planner software was used for UAV survey planning and real-time monitoring during the operation. The UgCS software is suited for autonomous (supervised) UAV flights as well as detailed planning of custom operations with specific line spacing, survey line orientations, and altitude above any given vertical reference.

All survey lines operations were carried out by autonomous flights controlled by UgCS, while take-off, landing and transit line manoeuvres were carried out manually.

4. Operational Summary

4.1. Skive Operational Overview

UAV magnetic data was collected at Solgårdsvej 50 (Skive Kaserne EOD test and training facility) on May 12th 2021 together with Lasse Marinus Sørensen of DCA and personnel of the Skive Kaserne EOD group.

The UMag operational team was composed of two certified UMag UAV pilots of which one acted as Chief Remote Pilot and one as Payload Operator/Observer.

4.1.1. Weather and Geomagnetic conditions

Weather conditions during the test survey were well and within the operational limits of the drone system with no rain and light wind. The Planetary K-index was at KP3 during all parts of the test, suggesting a nominal natural magnetic variation during surveying.

4.2. Operational Details

Upon the arrival to the site, the team selected inspected the selected test site as proposed by Lasse Marinus Sørensen. Next, all 36 target were placed out in an area covering 120 x 20m. Some targets were placed out close to each other in order to test the ability of the V2Mag to distinguish the magnetic signal of closely-spaced objects. Two target field surveys were then conducted at 1m and 2m gradiometer altitude, respectively. No surveys were conducted at lower altitude despite the ability of the V2Mag to closely follow the terrain to less than 0.5m separation as the purpose of the survey was to test the UXO and landmine detection capabilities of the V2Mag at increasingly higher altitudes. This was done in order to mimic some realistic scenarios in the field where high grass or small bushes may prevent a very close-to-the ground survey setup.

Next, the position of all targets were determined using the SmaRTK ground-based systems from *North Surveying*, supplemented by pictures of each target for identification. A low-altitude drone photogrammetry survey was then conducted for visual overview identification of the targets in the area.

Finally, a magnetic background field test was conducted with the V2Mag at 1m gradiometer altitude after removing all targets from the test area. All magnetic surveys of the test were conducted with a designated line spacing of 0.8m.

4.3. Legal, safety, and quality considerations during the operation

4.3.1. Legal requirements

UMag's operated within its existing flight permissions, no special additional permission were required for the operation. All legal requirements were adequately handled prior to the operation, and all legal requirements were conformed to for the entire duration of the operation.

4.3.2. General QA and QC Procedures during the Operation

UMag is committed to deliver high quality data. Therefore, UMag has employed a three step strategy to achieve or exceed the predefined requirements.

During the operation, the on-site Operational Team (OT) ensures that the operation is performed safely, and that the collected data is consistent and of high-quality. UMag has a number of standard operational procedures in place to ensure a consistently high data quality, including:

- Planetary K-index: The Planetary K-index is evaluated prior to each operation day. If the index is high (>5), surveying is halted (weather downtime) until the index decreases;
- Magnetic background noise: The potential magnetic noise sources in the survey area are always evaluated prior to the first flight and documented (e.g. nearby roads with traffic, power lines, visible ferrous metal in the ground etc.). If possible, steps will be taken to reduce the impact of the noise;
- Sensor orientation: The two GSMP-35u sensors of the V2Mag system are adjusted prior to a survey in order to optimize the field recording and minimize unlocks while surveying; the optimal orientation depends on survey line direction and wind speed/orientation;
- Real-time UAV attitude: The attitude (heading) of the UAV while surveying is continuously monitored and kept fixed in order to minimize the (already very small) inherent heading error of the V2Mag system and to maintain the pre-set sensor orientation;
- Real-time survey altitude: The altitude of the V2Mag survey system is frequently monitored by the OT to ensure that the UAV D-RTK positional control system is continuously active (D-RTK data link quality is monitored through information LEDs on both the RTK ground station, the UAV data receiver and on the control station);
- Day-to-day altitude: The D-RTK basestation is (if possible) always placed at the same location on operations that require multiple days to complete;
- Survey line spacing: Line spacing criteria are evaluated prior to the operational and are adjusted according to target threshold and wind conditions;
- Line turns: An overshoot buffer is always (if conditions allow) added to the survey area boundaries in order to maximize coverage and minimize the effect of turns on the survey data quality;
- Real-time data collection; GNSS and magnetic data of the V2Mag system are being monitored and checked between UAV take-offs during a campaign in order minimize gaps in the data.

Following an operational day, all data is extracted and backed up on both an external hard drive and an online UMag server. QC is performed by a team member off site, who provides feedback on the QC results to the OT. Data are rejected if noise levels exceed 0.03-0.04nT peak-to-peak.

5. Data Processing

5.1. UAV magnetic data

UAV magnetic data processing is performed using a combination of UMag's state-of-the-art, in-house produced *UMAGPROC* magnetic processing software, and *Geosoft Oasis Montaj*. The general processing steps are described here, while a flowchart outlining the entire processing workflow is shown in Figure 5.1.

1. **Pre-processing (I):**
   - Cleaning and de-spiking of raw GSM-19W basestation data
   - Moving mean filtering over 60s.
2. **Pre-processing (II):**
   - Cleaning of raw V2Mag data files
   - Adding date column
   - 3D true positioning of upper and lower sensors using the V2Mag payload-integrated GNSS-IMU
   - De-spiking, including removal of erroneous GNSS values and sensor unlocks
   - Correction of diurnal (via mobile basestation placed near the SoW), main, and super-regional fields (via CHAOS-X6-8) to obtain the pre-processed total-field of the lower sensor (TFL) and upper sensor (TFU)
   - Calculation of the pre-processed vertical residual field (hereafter Measured Vertical Gradient; MVG) from the upper sensor reading (nT2) and lower sensor reading (nT1) and the sensor distance (0.5m).
3. **Pre-processing (III):**
   - Survey trimming (removal of transit lines etc.) and survey sorting
   - Survey trimming
4. **Mid-level processing:**
   - Line levelling over 6 iterations;
   - Reduction-to-the-pole (RTP) using local Geomagnetic inclination and declination values;
   - Micro-levelling;
   - Gridding;
   - Calculation of various Fast-Fourier Transform (FFT) derivatives of the TFU, TFL and MVG.
5. **High-level processing:**
   - Target identification and positioning through source inversion, using a combination of pre-processed data and derived data products;
6. **Geosoft Oasis Montaj projects:**
   - Import of processed UAV magnetic data and target identification lists into *Geosoft OASIS Montaj*;
   - Compilation of final grids, plots, databases and maps.

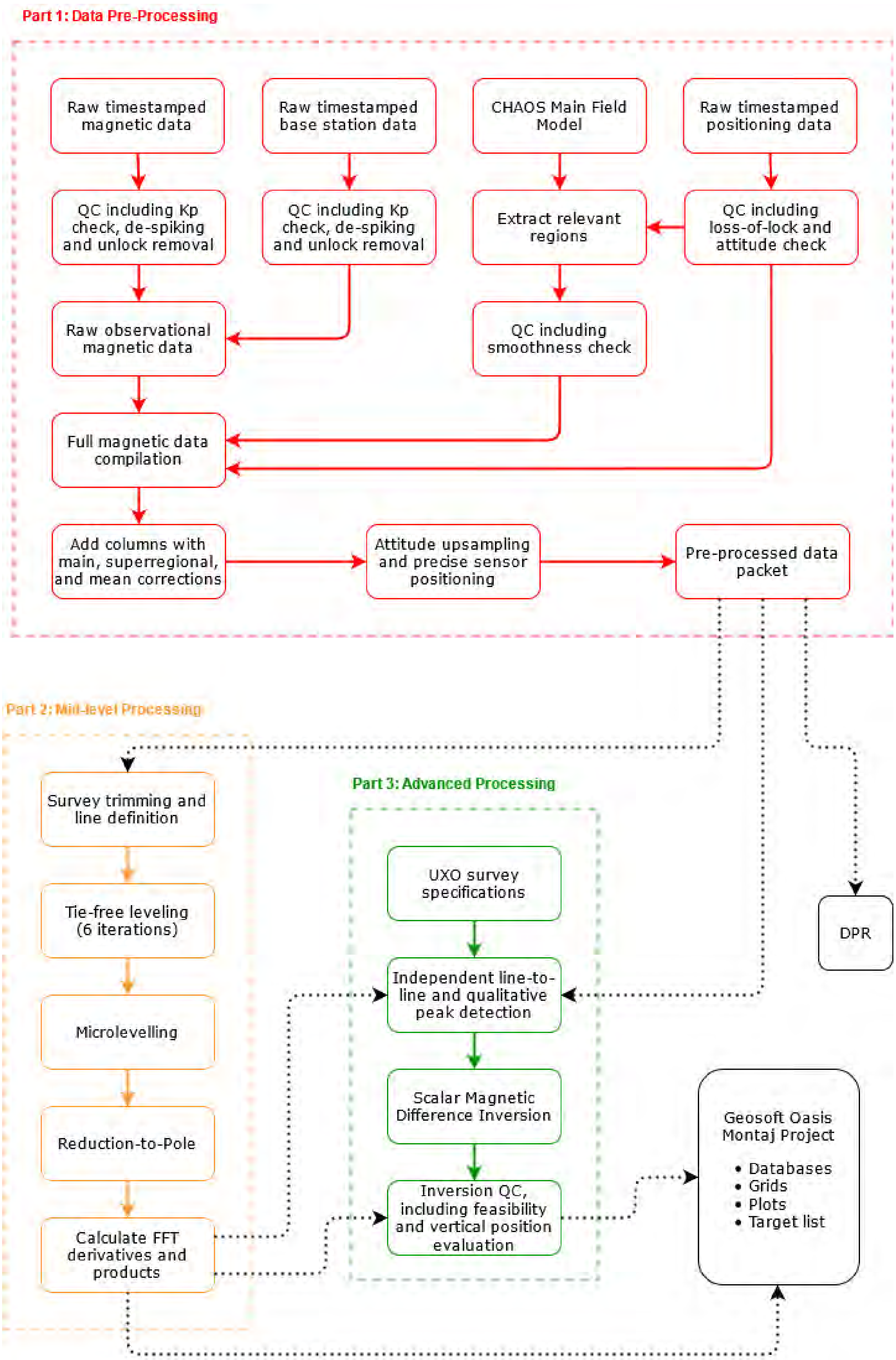


Figure 5.1: *General processing flowchart for magnetic data collected with the V2Mag system. Note: A DPR was not produced for this test campaign.*

6. Results

6.1. Data collected and Coverage

An example of the trimmed survey lines from the 1m gradiometer altitude target field survey is displayed in Figure 6.1 together with the position of all 36 targets. The 36 targets were spread out in the test area, with some being only 1m apart. Unfortunately, the target labelled 26 (see Figure 2.3 was by mistake placed just outside the survey boundaries.

Note: Four flag poles were used to outline the survey area to help design the drone survey. The tip of these flag poles was made of metal and the poles therefore turn out as small magnetic anomalies in the data to be shown.

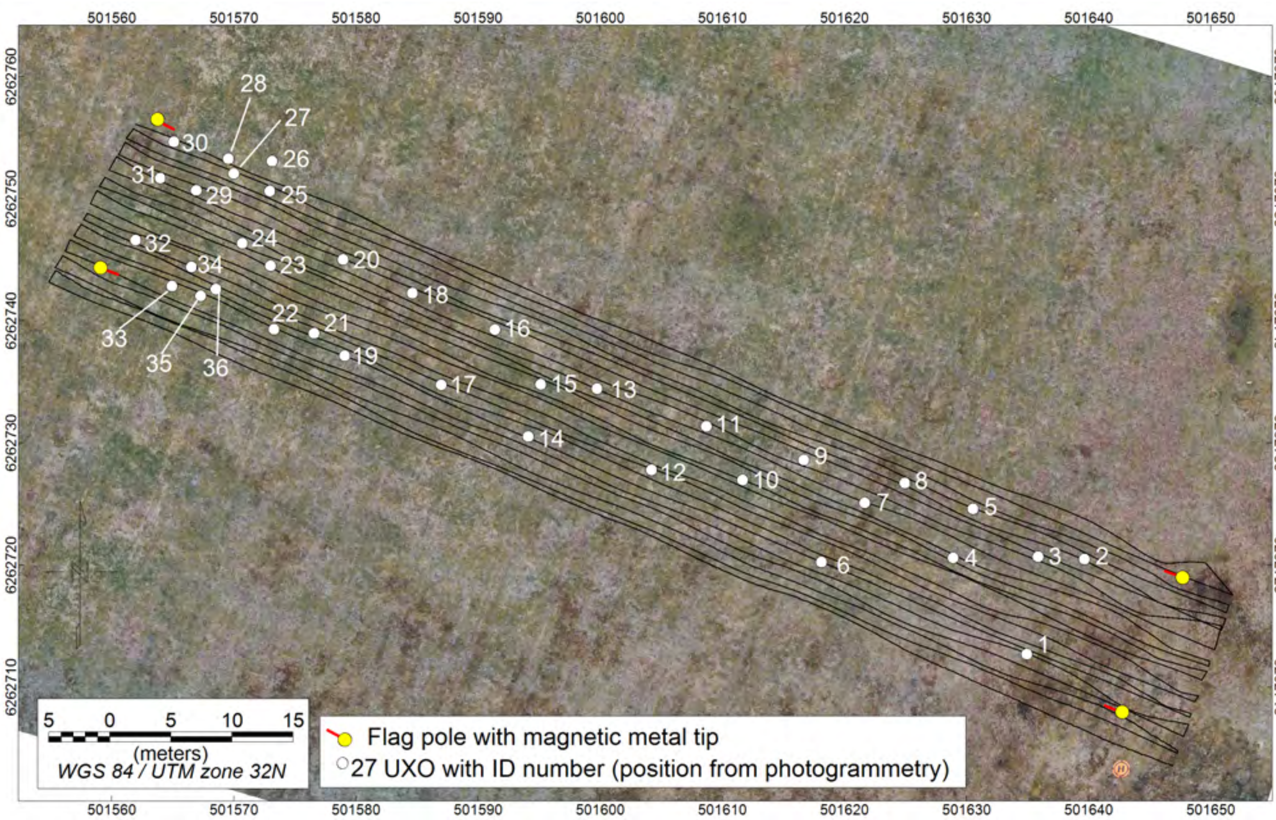


Figure 6.1: *Overview of the trimmed survey lines and true target locations as constrained by a combination of drone-based photogrammetry and SmaRTK measurements.*

In order to verify the low noise level of the V2Mag survey system, we have calculated the 4th order difference noise of the surveys conducted. An exmaple of the noise level for the 1m gradiometer altitude target field survey is shown in Figure 6.2. A noise level of ±0.015nT is found, which complies with UMag's previous survey results.

6.2. Magnetic Data Compilations

In the following, we display maps of the MVG_DVG2 magnetic field and the *Analytic Signal Gradient* field. The MVG_DVG2 field is the *3rd order vertical magnetic residual field* of the total field and is produced as the 2nd order Discrete Vertical Gradient (DVG2) of the Measured Vertical Gradient (MVG) field. Hence, the name MVG_DVG2. Such calculations are only possible due to the very low

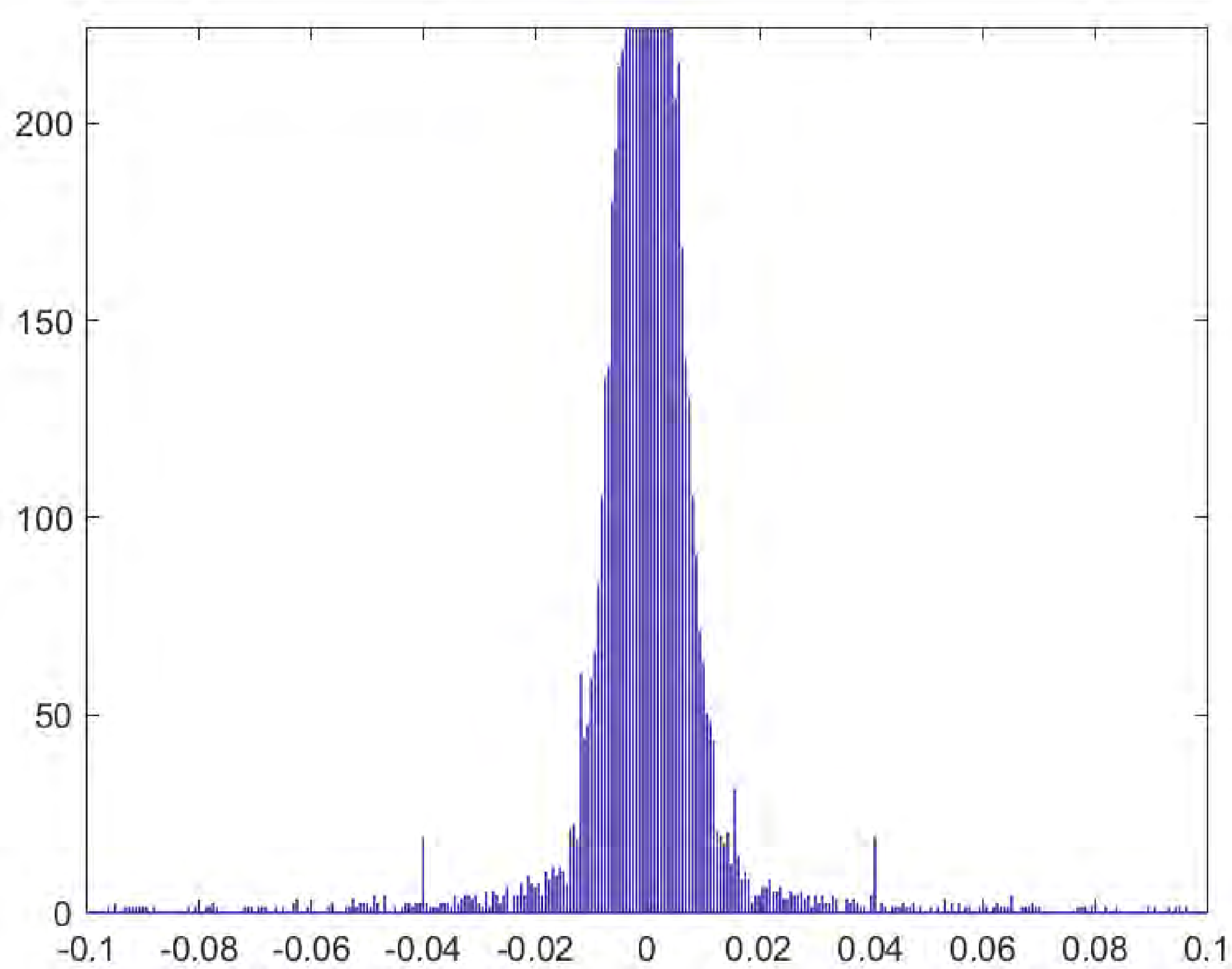


Figure 6.2: *4th order noise estimate of the data collected during the 1m gradiometer altitude target field survey. X-axis is in nT.*

noise level and high-positional precision of the V2Mag. The advantage, however, is the almost complete elimination of background noise and enhancement of short wavelength signals from UXO and landmines.

6.3. Background field at 1m altitude

A map of the background field is shown in Figure 6.3. As shown, the test area is characterized by overall weak magnetic gradients except for two significant short wavelength pUXO-type anomalies observed in the southeastern part of the survey area. The origin of these anomalies is unknown as no targets were found on the surface prior to the test.

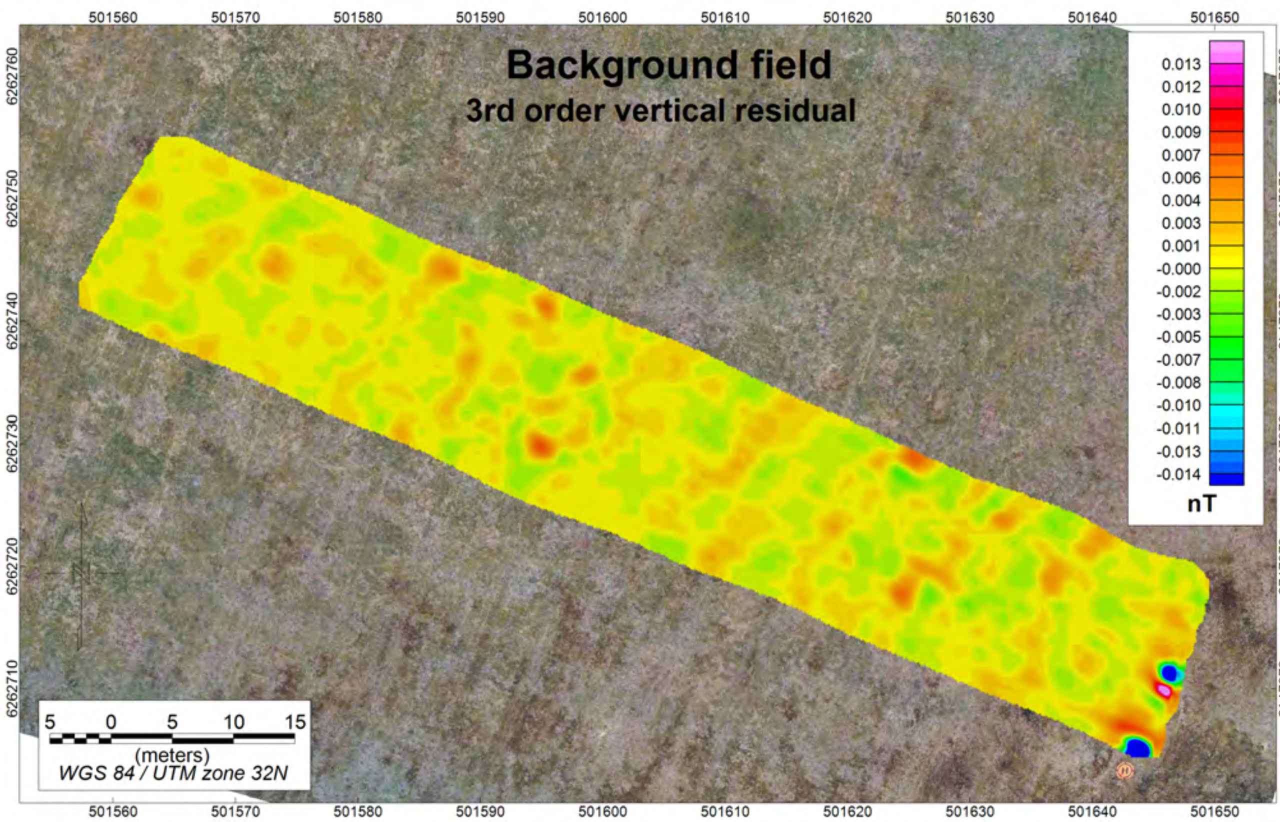


Figure 6.3: *Background MVG_DVG2 field data at 1m altitude. Data are displayed with same color scale as target field data at 1m altitude in Figure 6.4*

6.4. Results at 1m altitude

In Figure 6.4-Figure 6.6, we show the results of the 1m gradiometer altitude target field survey. Note that the Analytic Signal Gradient is displayed in two figures with two different color scales in order to highlight both strong and weak anomalies.

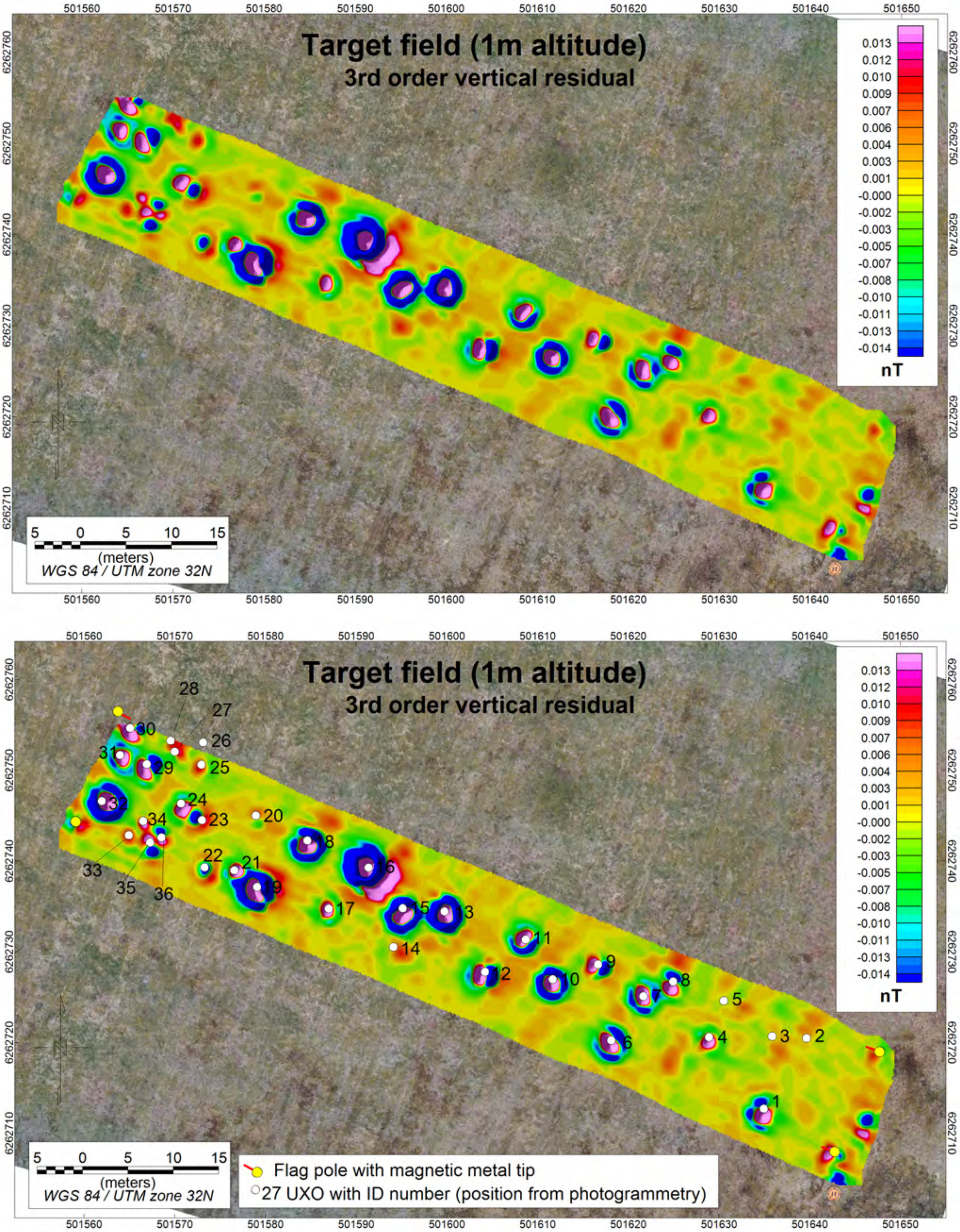


Figure 6.4: *MVG_DVG2 target field data at 1m gradiometer altitude. (Upper) Data without target locations. (Lower) Data with target locations overlain. See Figure 2.2 and Figure 2.3 for target ID pictures.*

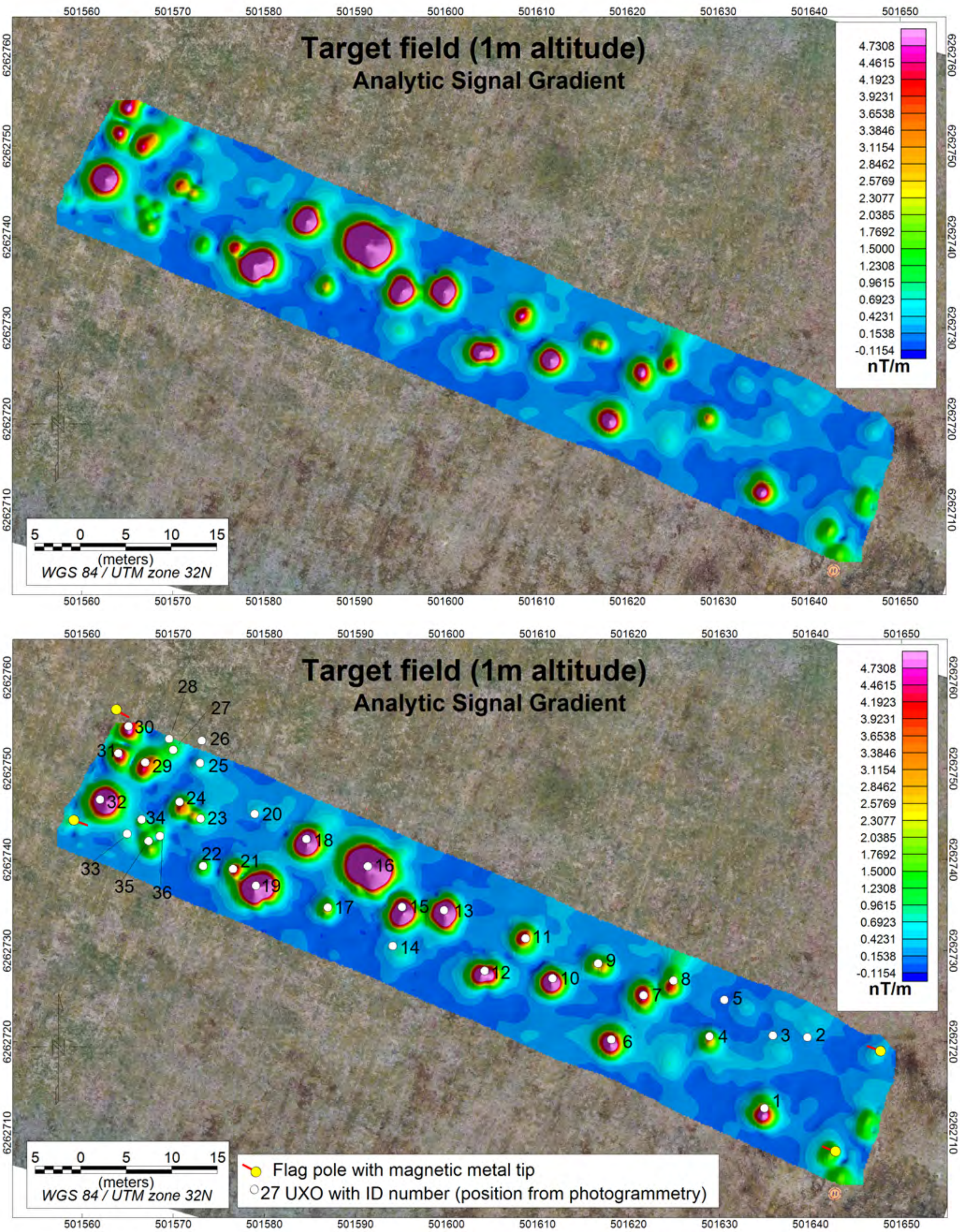


Figure 6.5: *Analytic Signal Gradient of the MVG target field data at 1m gradiometer altitude (linear color scale: 0-5nT/m). (Upper) Data without target locations. (Lower) Data with target locations overlain. Data are displayed with a linear color scale of 0-5nT/m in order to separate strong and closely spaced anomalies. See Figure 2.2 and Figure 2.3 for target ID pictures.*

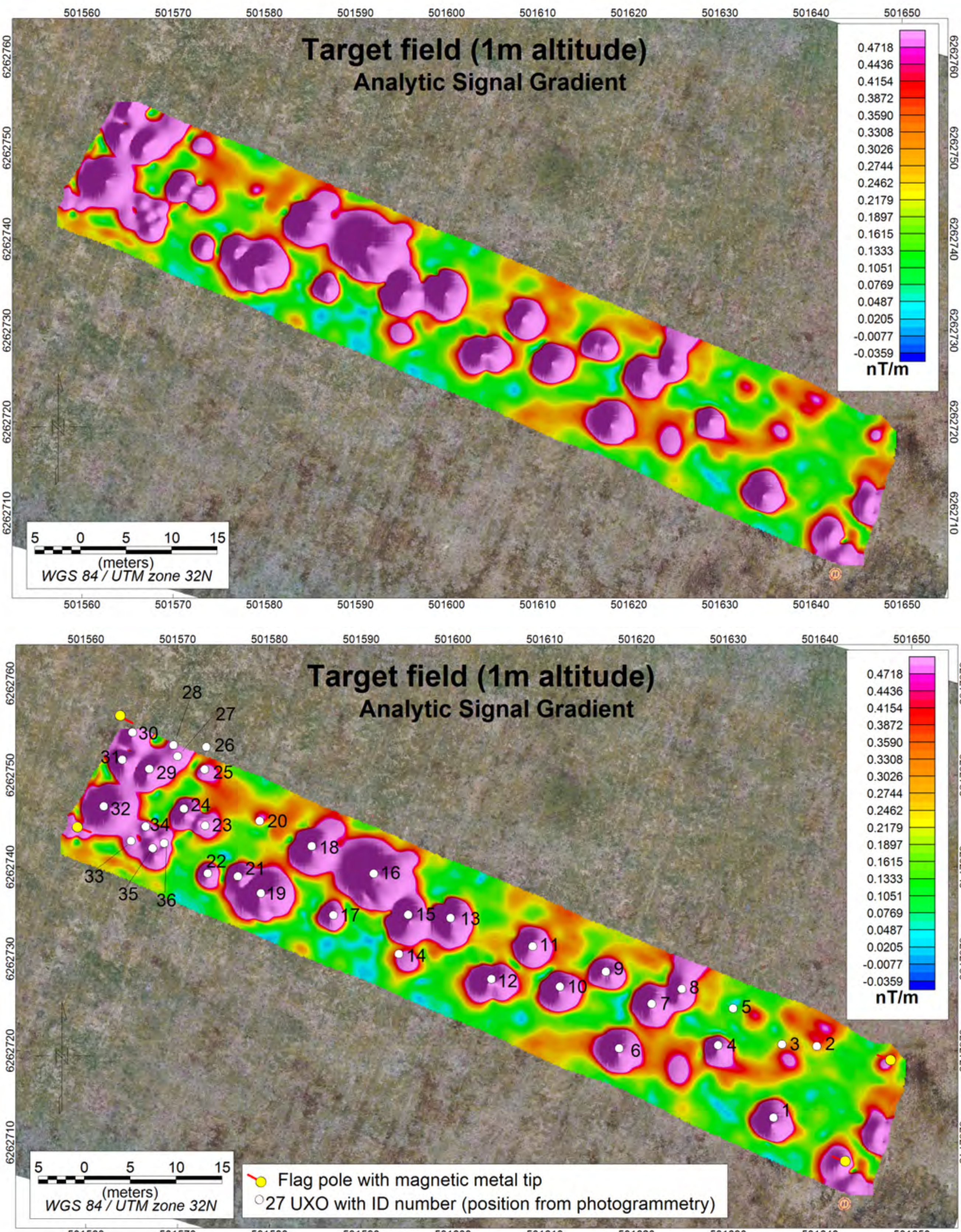
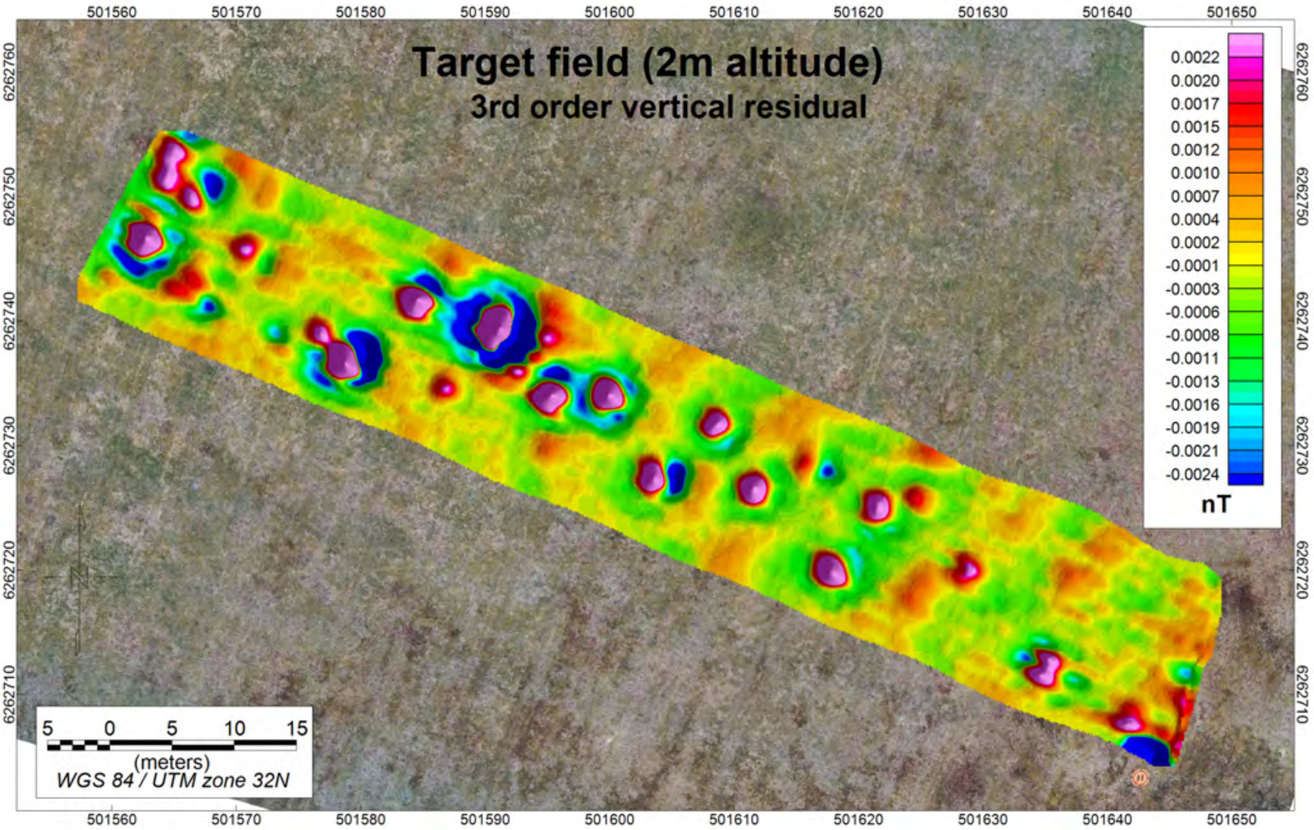


Figure 6.6: *Analytic Signal Gradient of the MVG target field data at 1m gradiometer altitude (linear color scale: 0-0.5nT/m). (Upper) Data without target locations. (Lower) Data with target locations overlain. Data are displayed with a linear color scale of 0-0.5nT/m in order to high-light weak anomalies. See Figure 2.2 and Figure 2.3 for target ID pictures.*

6.5. Results at 2m altitude

In Figure 6.7-Figure 6.9, we show the results of the 2m gradiometer altitude target field survey. Note that the Analytic Signal Gradient is displayed in two figures with two different color scales in order to highlight both strong and weak anomalies.



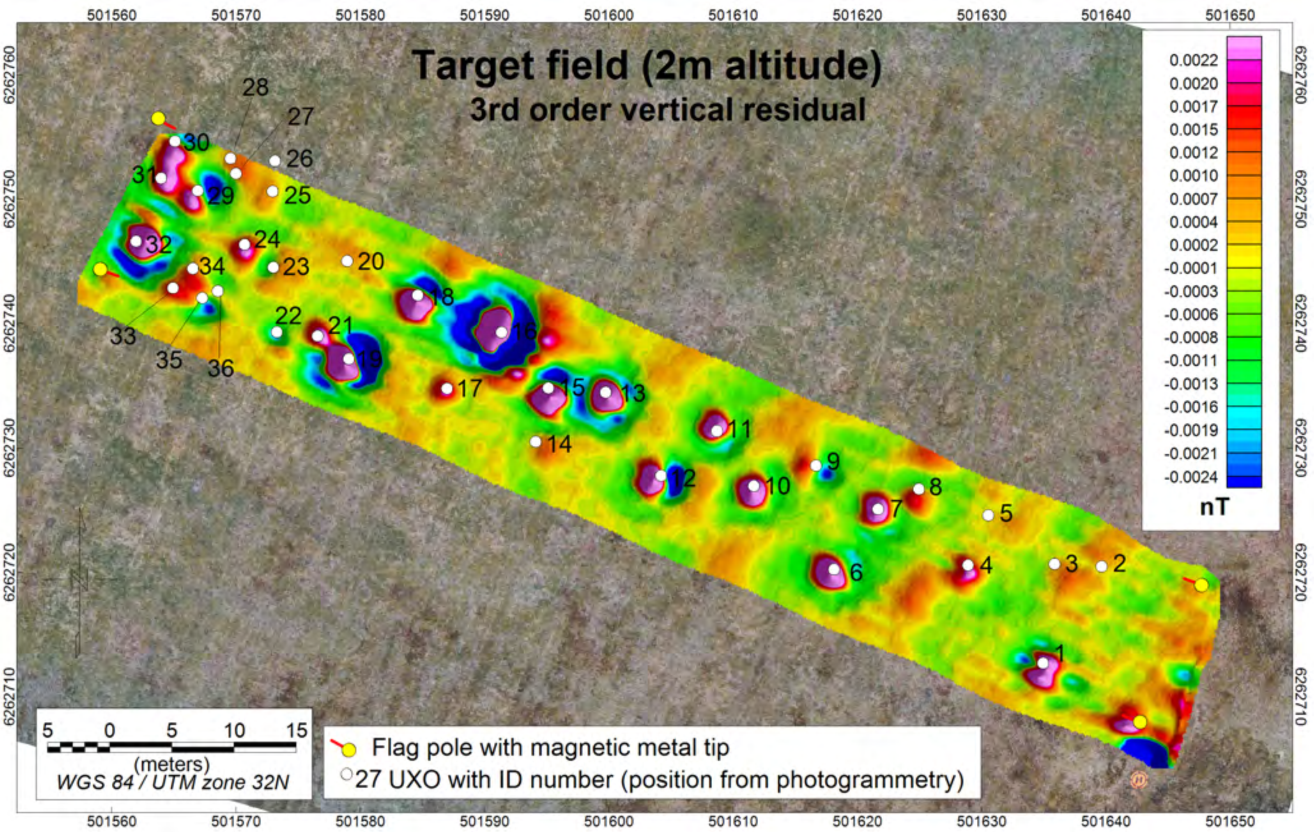


Figure 6.7: *MVG_DVG2 target field data at 2m gradiometer altitude. (Upper) Data without target locations. (Lower) Data with target locations overlain. See Figure 2.2 and Figure 2.3 for target ID pictures.*

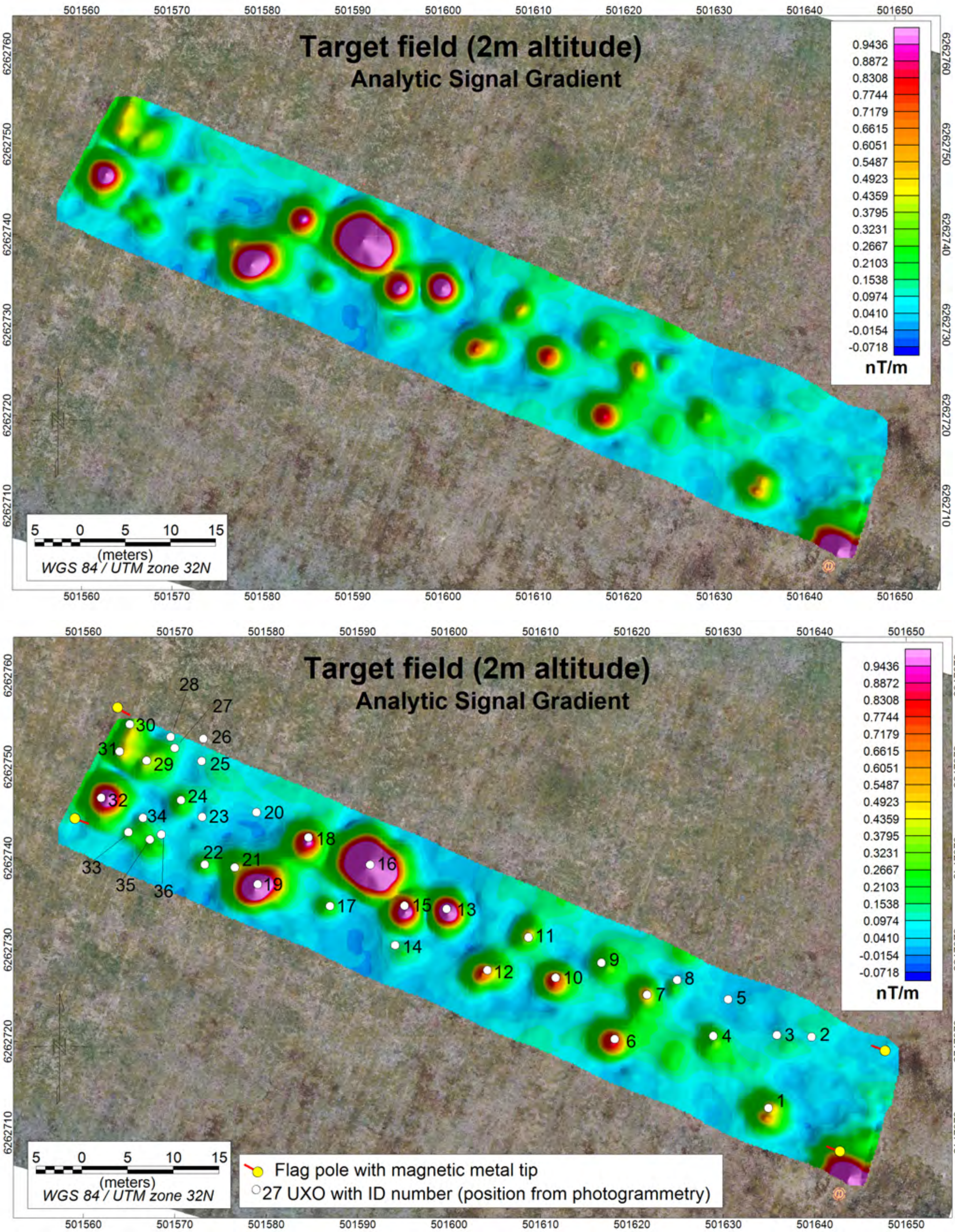
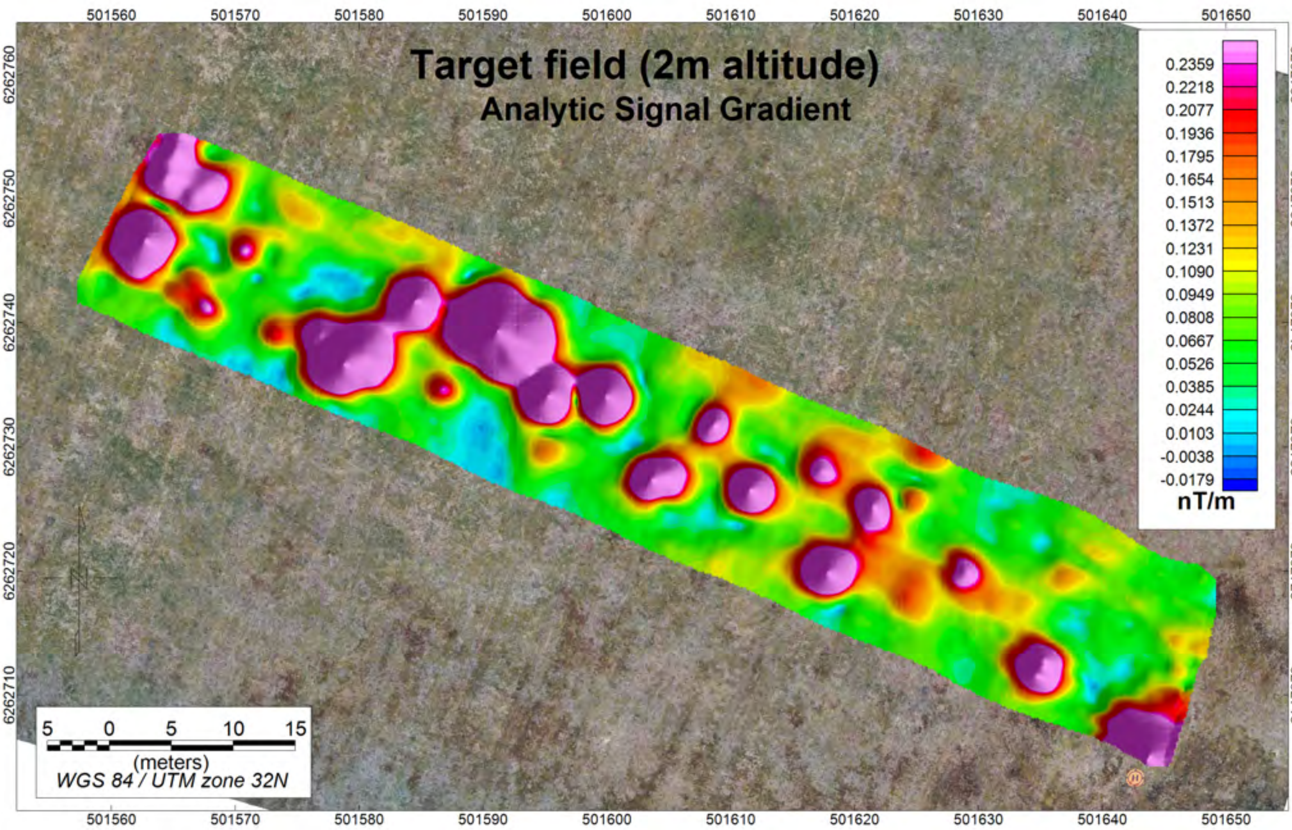


Figure 6.8: *Analytic Signal Gradient of the MVG target field data at 2m gradiometer altitude (linear color scale: 0-1nT/m). (Upper) Data without target locations. (Lower) Data with target locations overlain. Data are displayed with a linear color scale of 0-1nT/m in order to separate strong and closely spaced anomalies. See Figure 2.2 and Figure 2.3 for target ID pictures.*



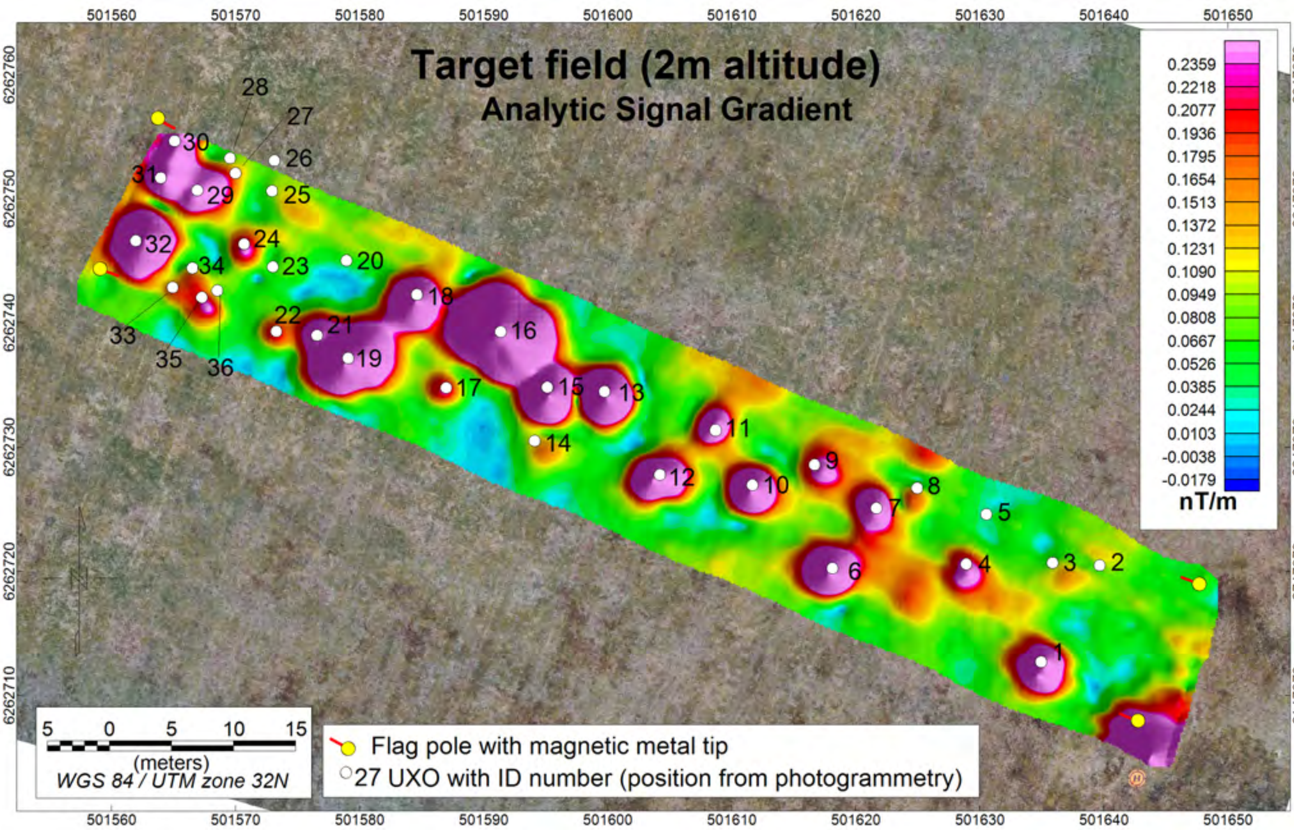


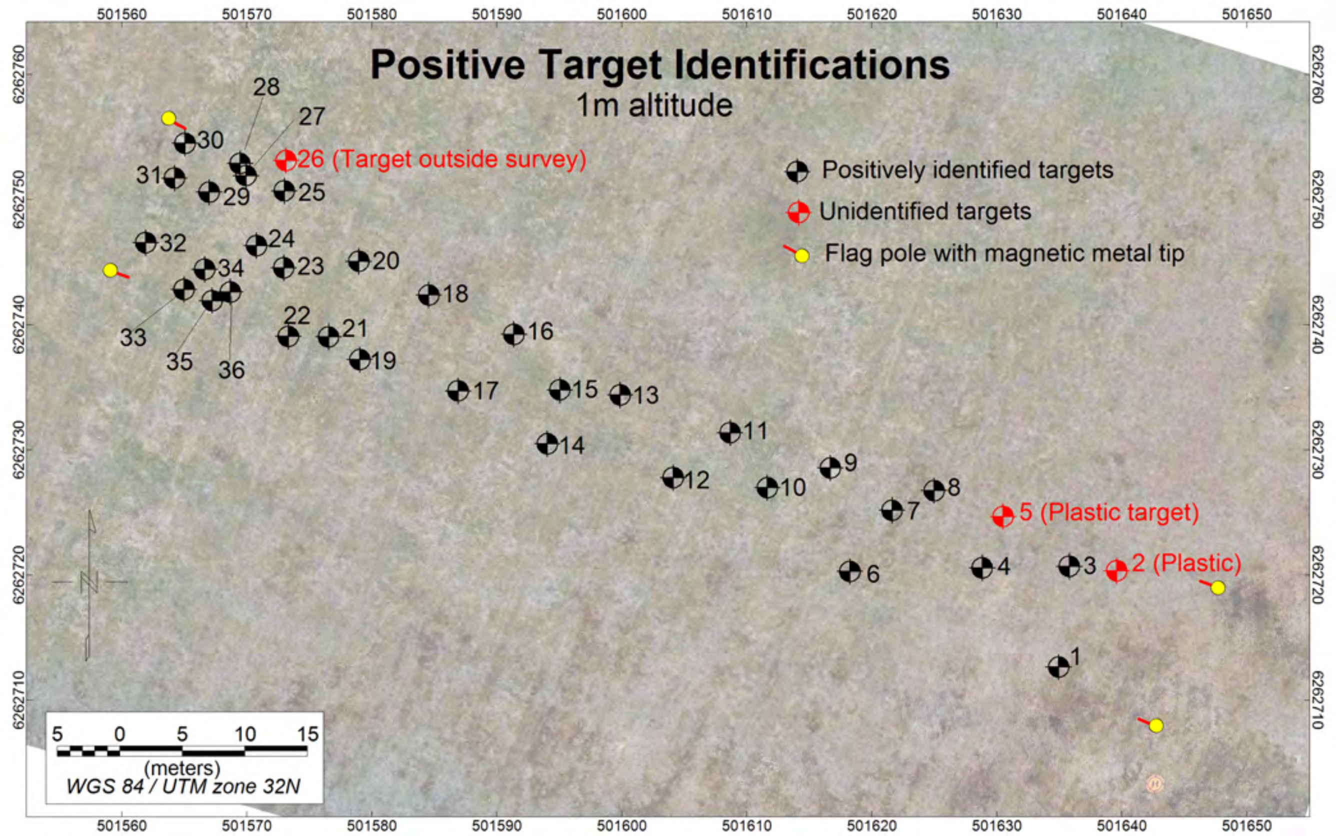
Figure 6.9: *Analytic Signal Gradient of the MVG target field data at 2m gradiometer altitude (linear color scale: 0-0.25nT/m). (Upper) Data without target locations. (Lower) Data with target locations overlain. Data are displayed with a linear color scale of 0-0.25nT/m in order to high-light weak anomalies. See Figure 2.2 and Figure 2.3 for target ID pictures.*

7. Targets identified and concluding remarks

Based on the results in Figure 6.4-Figure 6.9, we have compiled a summary of the targets that have been positively identified at the two flight altitudes (Figure 7.1). The target identification was done based on visual inspection of the gridded magnetic data as well as UMag's in-house target detection software that works solely on the raw total field line data of each of the V2Mag sensor readings.

As shown in Figure 7.1, the V2Mag appears to provide stable results for almost all targets at both altitudes, excluding the almost entirely plastic/composite-composed targets (labelled 2, 5 in Figure 2.2). At 2m gradiometer altitude, the V2Mag system proved unable to clearly detect the smallest ammunition shells (labelled 35, 36 in Figure 2.3), while the separation of anomalies also becomes increasingly difficult for the targets labelled 33 and 34 although they have a detectable signal.

In conclusion, the test campaign in Skive documents the strong capability of the V2Mag system for detecting various kinds of small UXO and landmines despite a small ferrous content. The ability of the V2Mag to fly close to ground level even in complex terrain (<0.5m) further enhances its potential use in pre-clearance scanning and post-clearance scanning of former war zones.



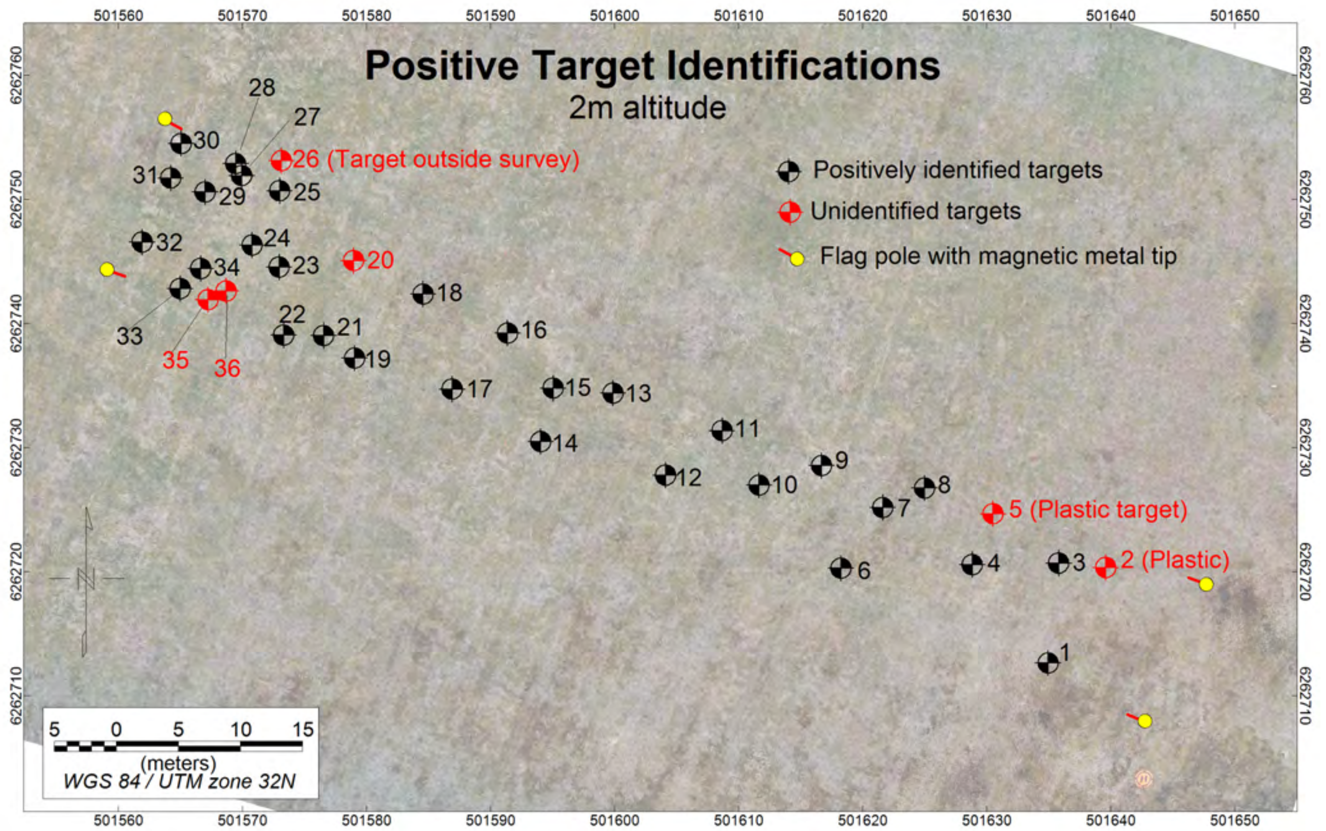


Figure 7.1: *Target identifications. (Upper) 1m altitude; (Lower) 2m altitude. Only a few targets are not detected. Two plastic mines (labelled 2 and 5 in Figure 2.2) as well as a small mine located outside the survey (labelled 26 in Figure 2.3). At 2m altitude, targets labelled 35 and 36 in Figure 2.3 are no longer clearly mapped as separate anomalies.*