Automated Drone-Based Magnetic Mapping for Efficient Long-Distance Pipeline Georeferencing

M. Laichoubi[1], H. Kella Bennani[1], M. Marceau[1], S. Takillah[1], V. Benet[1]

L. Caetano[1], S. Klein[2], F. Alex[2], M. Tchantcho[2]

[1] *Skipper NDT*
[2] *GASCADE Gastransport GmbH, Kölnische Straße 108-112, 34119 Kassel, Germany*

Abstract

According to EGIG statistics third-party damage is ranked as one of the most frequent causes of damage to buried onshore high-pressure gas pipelines. Accurate knowledge of the pipeline geolocation and its depth of cover is recognized as protection from accidental damage. Encroachment on pipeline corridors potentially compromises buried infrastructure integrity and emphasizes the need for stringent georeferenced pipeline position data. Conventional handheld detection methods, including electromagnetic and ground-penetrating radar systems, face significant limitations in remote rural areas and when applied on a large scale. Factors such as complex terrain, high humidity, safety risks for field personnel, human error~~,~~ and logistical challenges related to accessibility and authorization contribute to their reduced effectiveness.

In response, Skipper NDT has developed a fully automated, drone-mounted solution that efficiently collects magnetic maps above buried pipelines, delivering centimetric geospatial coordinates (XYZ) and depth-of-cover data. The automation of this process allows for the rapid mapping of pipelines, significantly reducing deployment time and enhancing operational safety. The system overcomes the limitations of traditional handheld tools, offering fast and accurate results over significant distances while minimizing human intervention and error. In a joint effort, Skipper NDT and GASCADE carried out a geospatial survey of a more than 20-kilometer long buried pipeline section of nominal pipe size 36" in Germany. Data acquisition lasted two weeks and demonstrated the technology's capability to cover large distances efficiently. Subsequent data analysis and in-field verification of the pipe location allowed the assessment of the Skipper NDT system performance.

The fully automated procedure enabled rapid data capture with minimal human interaction, providing highly accurate results and the development of a digital twin integrating other layers of information such as bathymetry and photogrammetry. This case study project highlights the potential of the Skipper NDT drone-based magnetic mapping for pipeline georeferencing. By process automation, the applied technology offers safe, reproducible and accurate results in less time than alternative conventional methods.

Introduction

Buried high-pressure pipelines are used to efficiently transport large amounts of energy over long distances to local consumers. Since decades ensuring the integrity of buried pipelines has become increasingly challenging due to an increase of parallel and crossing infrastructure and the associated increased risk of accidental third-party damage to existing underground assets. According to EGIG statistics, a frequent cause of mechanical damage of buried onshore high-pressure natural gas transport pipelines made of steel remains the impact of third parties (0.125 per 1000 km and year, period 1970 to 2022) [1]. Directory enquiry services such as BIL [2] nowadays effectively manage the needs of third parties and asset operators. Such organizational measures led to a significant reduction of incidents resulting in a reduced frequency of 0.02 cases per 1000 km and year in the period from 2018 to 2022 (moving average). Documented accurate position of the pipe location and its depth-of-cover (DOC) is of utmost importance to safely manage activities in the pipeline right-of-way (ROW) at minimal risk to the integrity of the pipe. Several countries have introduced stringent requirements for pipeline mapping. In France, a government decree mandates operators to achieve a precision level of at least 40 cm in planimetry (X,Y) and altimetry (Z) for 90% of measured points, as outlined in the NF S70-003 AFNOR standard’s class A precision criteria [3]. In Germany, DVGW rule GW 120 [4] requires the pipe position measurement accuracy to allow the pipe network to be restored with a maximum deviation of 0.2 meters. For new pipelines, the DOC is required to be greater than 1 meter and must, without cause, not exceed 2 meters as stated in G 463-1 [5]. In addition G 456 provides guidance in case of insufficient DOC of modern but also vintage pipe [6].

Among different technologies applied to capture the geolocation of pipelines electromagnetic field (EMF) receivers and ground-penetrating radar (GPR) are the most prominent. These methods require operators to physically carry or push measurement devices along the pipeline ROW, a process often hindered in remote or rural areas by difficult terrain, safety risks and accessibility challenges. Furthermore, the data acquisition and data analysis process is often integrated leading to an inability to revisit acquired data for verification and quality assurance without repeating the measurement itself.

Recent advancements in remote sensing and unmanned aerial systems (UAS) enabled innovative solutions to overcome existing limitations. Skipper NDT has developed a fully automated, drone-mounted technology that collects magnetic field data to create precise magnetic maps above buried pipelines. This non-intrusive technology enables the determination of pipeline geospatial coordinates (XYZ) and DOC at a precision level that meets regulatory and operator requirements. By automating the data acquisition process, this approach significantly reduces field time, minimizes human error and enhances operational safety. It also allows to compare datasets in time with a high degree of confidence given the high repeatability and reproducibility of the technology.

In a joint effort, Skipper NDT and GASCADE carried out a geospatial survey of a more than 20-kilometer long buried pipeline section of nominal pipe size 36" in Germany. Data acquisition lasted two weeks and demonstrated the technology’s capability to cover large distances efficiently.

Subsequent data analysis and in-field verification of the reported pipe location allowed the assessment of the Skipper NDT system performance.

Section 2 of this paper will introduce the tool (payload) utilized for data acquisition and briefly outlines the workflows involved. Further details of the technology have previously been published and are only briefly introduced here [7-9]. Section 3 discusses the motivation and background of the case study, while its results are presented in section 4. In section 5 a summary and outlook conclude this paper.

Drone-based magnetometry

Skipper NDT's Argos payload is a multi-sensor payload comprising of the following elements:

- Four fluxgate-type triaxial magnetometers to capture and record magnetic data in three spatial directions.
- Centimeter-precision GNSS.
- An IMU (accelerometer and gyroscope) which is used by our algorithms to compensate formovements of the payload and their impact on the signal.
- A RADAR-based altimeter which is used to measure the distance to the ground.
- A proprietary data logger to interpolate the various information recorded.

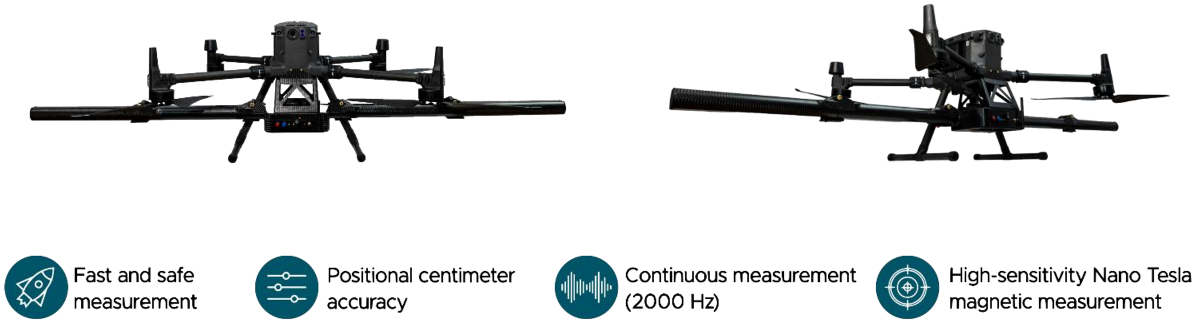

Figure 1: Drone-based technology mounted with the payload.

The system relies on two primary sensors: magnetometers and GNSS for the acquisition of magnetic data and its geospatial positioning. Of these, the fluxgate magnetometers are particularly crucial, as they can measure the three components of the magnetic field at a sample frequency of 2000 Hz with a mass of 112 g/3.9 oz per sensor. Skipper NDT utilizes a systematic multi-step process that has been designed to determine the 3D positioning of buried pipelines using magnetic-based data **(Figure 2**).

The Argos payload is integrated into a commercially available Unmanned Autonomous Vehicle (UAV), also known as drone. The drone flies a pre-programmed and automated flight path taking multiple passes over the pipeline to fully record the magnetic signal.

After data is acquired, Skipper NDT utilizes proprietary software to process the raw data and confirm its integrity. Skipper NDT patented algorithms will then perform a series of operations [10] to clean the data and perform the magnetic inversion allowing to retrieve a precise geospatial positioning of the asset. The 3D positional data enables advanced strain-based calculations for pipelines situated in areas affected by geohazards. This information is used to conduct out-of-straightness analyses, generate pitch and azimuth profiles, and calculate bending strain in both vertical and horizontal directions [11], as well as the total resulting bending strain. This complementary analysis has not been considered in the present article. Further details about the inspection and data processing methods are available in a paper presented at PPIM 2024 [11].

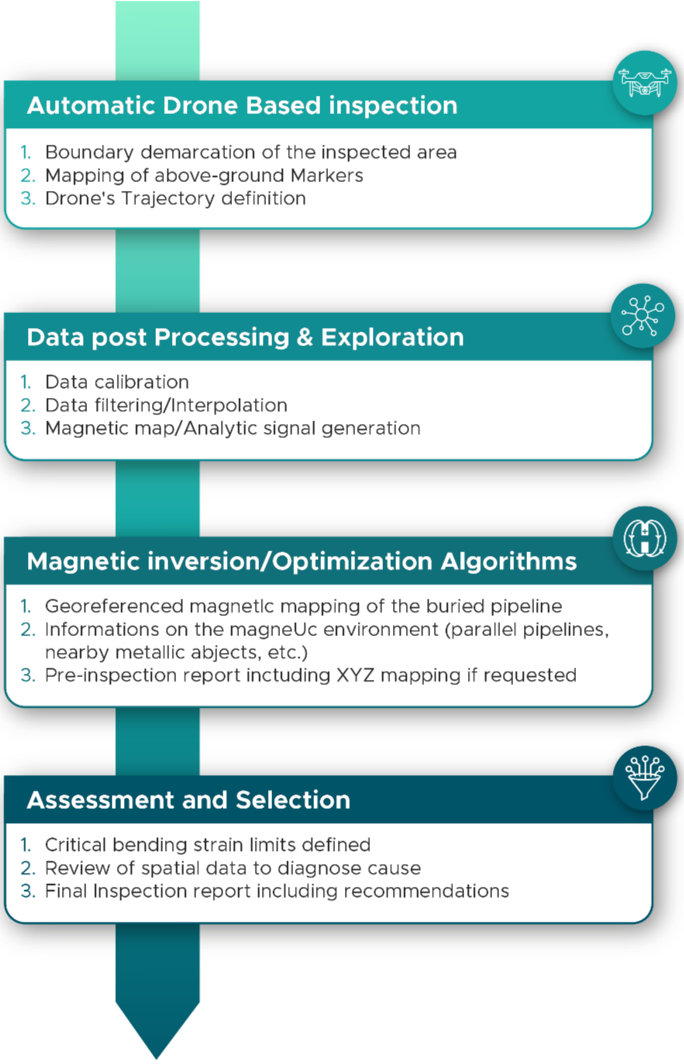

Figure 2: Multi-step procedure from magnetic data collection to assessment and selection.

Case study and operating procedure

Site background

Skipper NDT conducted a geospatial positioning and DOC survey of a 22 km buried 36" pipeline section in Germany (Fig. 3). The project was carried out over a period of two-weeks. At the start of the project five random GNSS reference points were selected for calibration and comparison of the GNSS system. At the end of the project GASCADE assessed the Skipper NDT system performance by exposing the pipeline's top dead center and verifying the reported pipe location and coverage by comparing the reported GNSS coordinates and DOC with the actual data at the same location.

This section provides an overview of the general measurement protocol and summarizes the results. Skipper NDT delivered pipeline positioning data, including the top dead center coordinates (X, Y, and depth of cover), in agreed formats (CSV files, GPKG, shapefiles). Horizontal and vertical positioning data were supplied in the predefined coordinate systems.

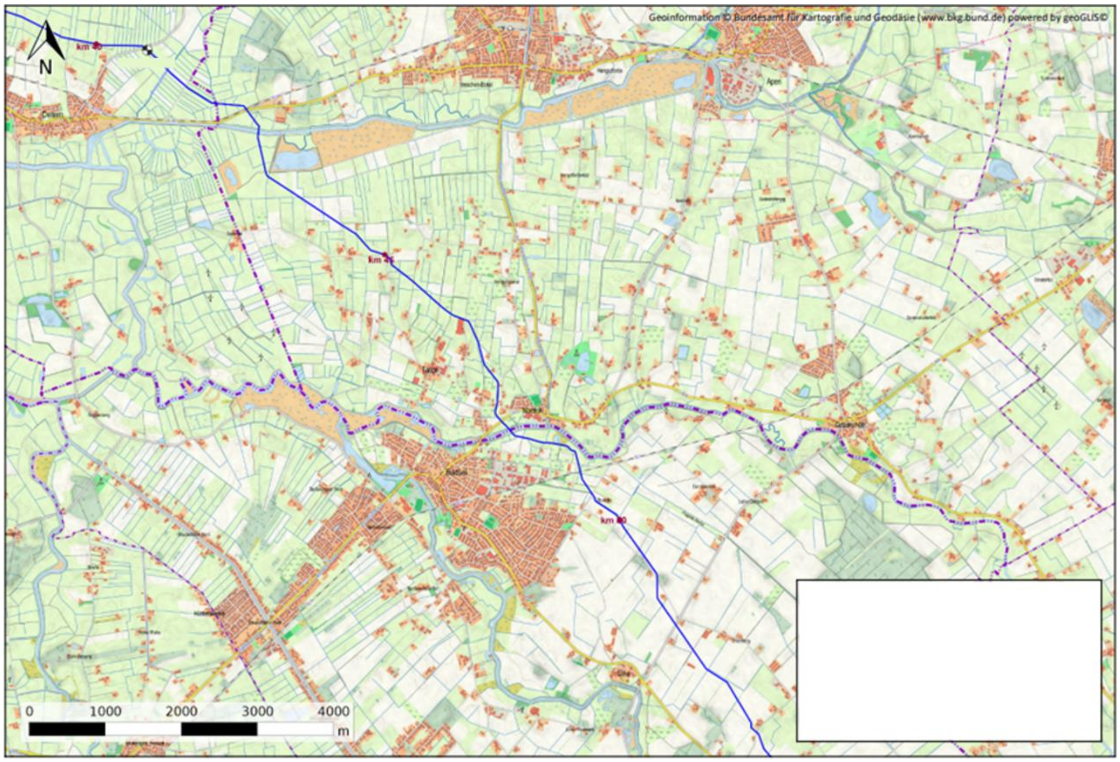

Figure 3: Location of the 22km inspected pipe section

Fig. 4 illustrates the pace and progress throughout the in-field period of two weeks. Notably, on the 7th day, the team achieved a peak pace of 3.3 km (Fig. 4), showcasing field operator capabilities to adapt and optimize resources. The estimated acquisition pace for the field magnetic measurements, set at 2 km per day, was effectively maintained throughout the period of deployment despite adverse weather conditions (Fig. 5).

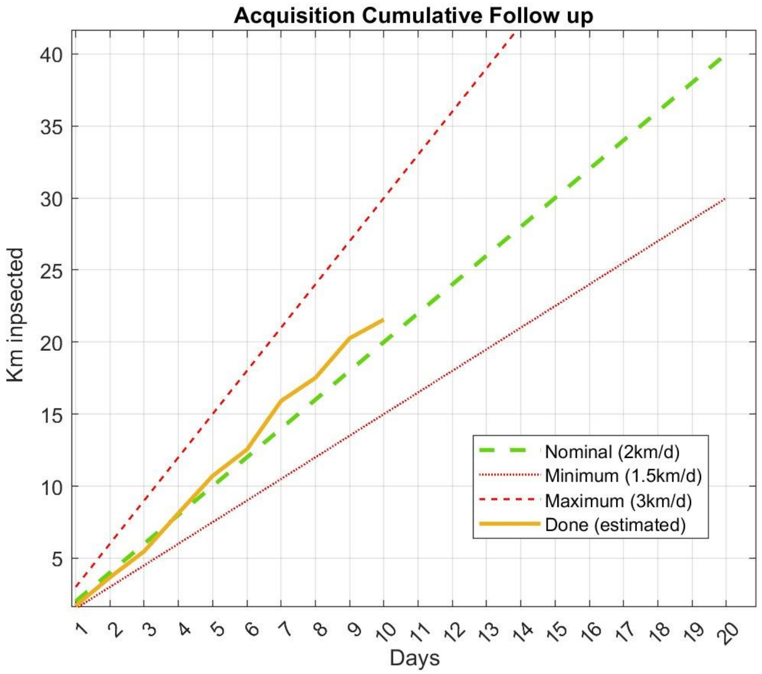

Figure 4: Overview of cumulated acquisition pace

It should be noted that several points on the ROW were not safely accessible to ground-based operators due to harsh weather conditions (Fig. 5). This highlights the added value of the drone vector deployed.

Figure 5: Difficult-to-access areas where the drone was optimally utilized

In total, 21,561.427 meters were inspected, with a total coverage of 97%. 502 meters were not covered due to inaccessible areas along the ROW.

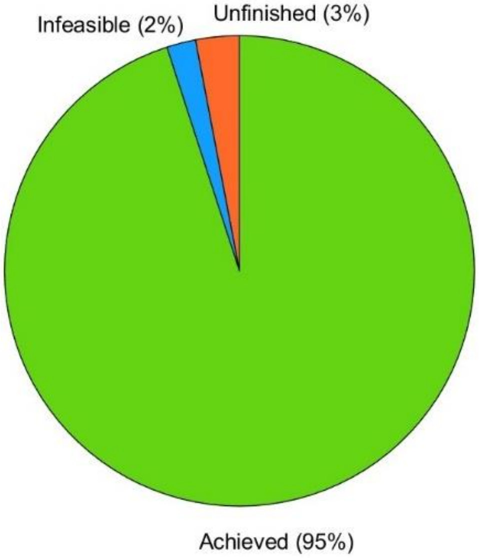

Figure 6: Coverage Rate Partition

Pipeline geolocation and depth of cover

Skipper NDT derived from its data acquisition two types of magnetic maps providing different information about the buried structure [7-9]. The data for these two maps were acquired in the same dataset, and then separated through frequency filters:

- A **high-frequency** magnetic map (provided in units of 10^{-9} (nano) Tesla) in **Erreur ! Source du renvoi introuvable.** depicts the pipeline's response to a current injection at a given frequency. Skipper NDT proprietary inversion algorithms are then applied to this

data to obtain the 3D position of the pipeline centerline. Several current injection frequencies can be tested on the field to determine the most appropriate one.
- A low-frequency magnetic map (below 5 Hz, measured by 10^{-6} (µ) Tesla), which can be seen in Fig. 8 illustrates the passive signature of the pipeline as well as the position of any ferromagnetic objects within the inspected area. It can be read as follows: magnetic dipoles, alternating cold (blue) and warm (red) colors, indicate the presence of magnetic anomalies due to the presence of a pipeline or any ferromagnetic objects.

The 3D geolocation generated by Skipper NDT, coupled with an orthophoto, provides an accurate 3D representation (Fig. 10), making data visualization more intuitive and helping operators to identify significant features on their structures. To facilitate visualization, the interactive 3D model is supported by the following applications:

- A simple Web browser by opening the .html file
- It can also be managed, in a more comprehensive way, on dedicated GIS software (QGIS, ArcGIS, ...) with the Threejs extension.

All GIS data can be included into a 3D model to represent how the data has been acquired.

Figure 7: High-Frequency Magnetic Map, with intensities in nano Tesla

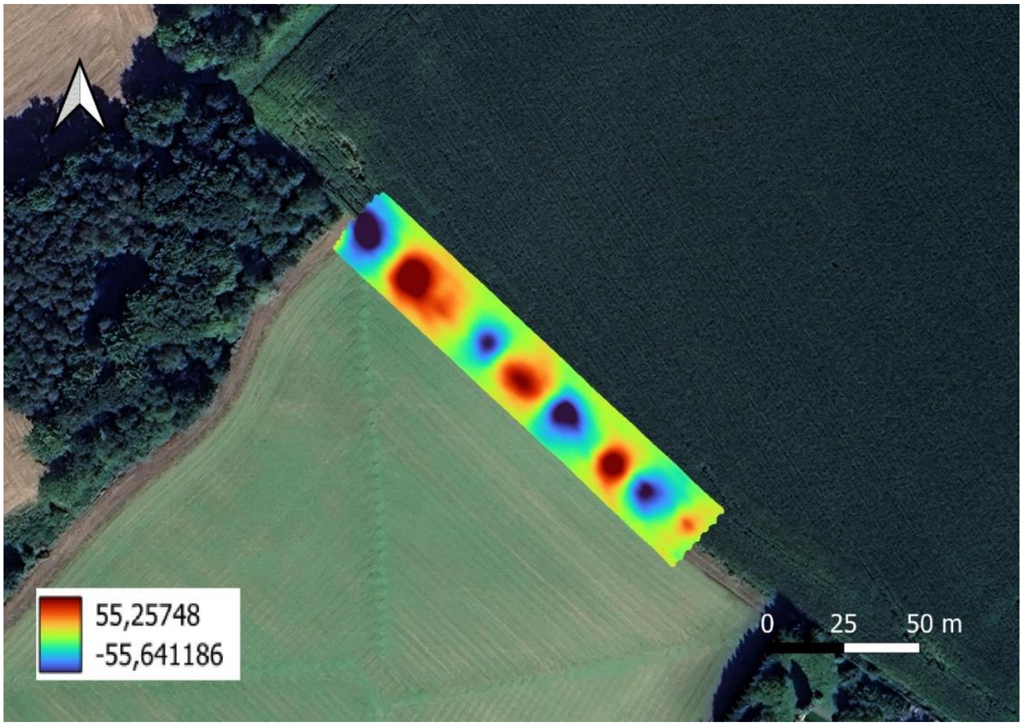

Figure 8: Low-Frequency Magnetic Map, with intensities in µTesla

Both magnetic maps are used during the data interpretation process to gain more insights about the inspected area and derive the 3D position of the pipeline. Fig. 9 depicts the XY position of a surveyed area and the corresponding DOC along the pipeline. The point density in axial direction of the pipe is 1 point per 50 cm, demonstrating a high-resolution dataset that can also be utilized for strain-based calculations.

Figure 9 : XY position and DOC as measured along a section of the entire pipeline length

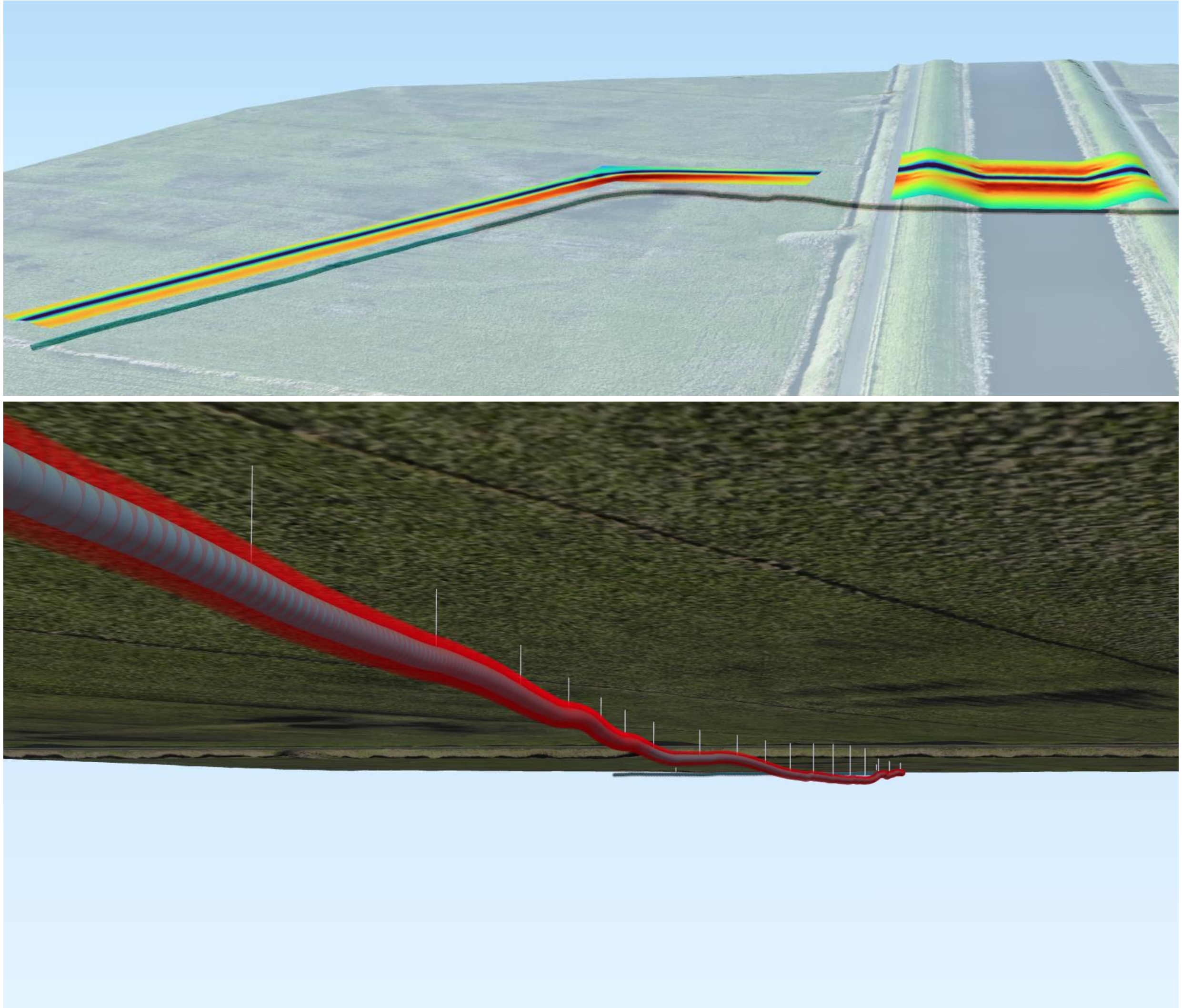

Figure 10: Digital twin of the pipeline obtained as reconstructed from magnetic data

Data evaluation and discussion

System performance assessment

Table 1 shows the deviation of the reported and actual position of the pipe and DOC for the 23 verified individual locations. For all locations the top of the pipe was exposed and its GNSS position and the DOC at the same location manually recorded. The XY difference represents the discrepancy between the verification and Skipper NDT data in the horizontal plane, while the DOC difference quantifies the variation between the two datasets in the vertical direction. Manual verification is recognized as the ground truth and inaccuracies of the GNSS pipe position measurement and the DOC measurement during verification are not taken into account.

Table 1: Comparison between reported (subscript R) and in-field verification data (subscript V) for 23 locations. The highlighted rows represent outliers discussed in detail in the text. X_diff = X_R-X_V; Y_diff = X_R-X_V

ID	X_diff (m)	Y_diff (m)	Abs. DOC_difference (m)	Abs. XY_difference (m)
1	0.017	0.094	0.191	0.095
2	0.200	0.030	0.619	0.203
3	-0.036	-0.101	1.231	0.107
4	-0.081	-0.379	0.133	0.387
5	-0.109	-0.169	0.255	0.201
6	-0.083	-0.059	0.092	0.102
7	-0.148	-0.105	0.938	0.181
8	-0.016	-0.024	0.248	0.029
9	0.012	0.018	0.130	0.022
10	0.138	0.382	0.239	0.406
11	0.163	0.208	0.057	0.264
12	0.251	0.060	0.168	0.258
13	0.289	0.229	0.277	0.369
14	-0.123	-0.124	0.013	0.174
15	-0.088	-0.084	0.124	0.122
16	-0.376	-0.069	0.437	0.382
17	-0.142	0.008	0.630	0.142
18	-0.019	-0.013	0.227	0.023
19	0.055	0.026	0.032	0.061
20	-0.336	-0.190	0.203	0.386
21	-0.134	-0.165	0.152	0.212
22	-0.069	-0.036	0.197	0.078
23	-0.077	-0.089	0.139	0.118

In the horizontal plane, the average deviation is 19 cm with a 90% confidence interval of 38 cm. 100% of the 23 locations are within the specified 40 cm locations accuracy and in agreement with published performance specifications.

In the vertical direction, the average deviation is 29 cm with a 90% confidence interval of 69 cm. The 90% confidence interval value is mainly due to five outliers (highlighted rows in Table 1) where the vertical differences exceeded 40 cm.

The data of the five outliers (ID 2, 3, 7, 16, 17) were reprocessed to investigate the root causes of the discrepancies:

ID 2 and 16 are in areas where the drone trajectory was not correctly selected. The trajectory of the equipment was perturbated during the flight, resulting in a wrong cluster of points on the top right-hand corner of the first two passes (Fig.11). This perturbation impacted the magnetic signal at that point and the issue was corrected by simply disregarding the impacted area. Consequently, the magnetic data was truncated and not considered for processing prior to analysis. Data of ID 2 and 16 were reprocessed and analyzed to 36 cm and 23 cm, respectively.

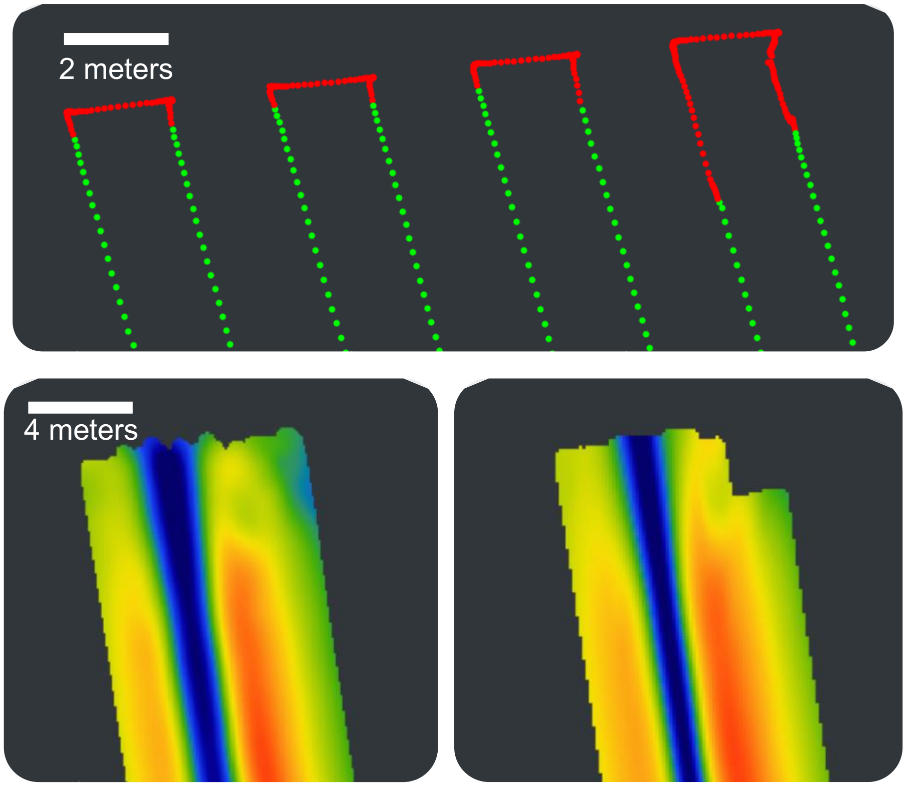

Figure 11: Top graph (trajectory) – Red dots correspond to the disregarded measurement and green dots correspond to the valid points. Bottom left – High-intensity magnetic map with all points. Bottom right – High-intensity magnetic map with only valid points.

IDs 3 and 7 coincide with a curved pipeline section, which explains the discrepancy. This issue arises in a specific pipeline configuration when a bend is convex. The inversion algorithms used to derive the pipeline's 3D position from magnetic maps are influenced by adjacent sections of the bends. To overcome this issue, sections impacted by this phenomenon are partially disregarded for inversion. This change allowed the data to be corrected to a deviation from the actual position of 4 cm and 16 cm for ID 3 and 7, respectively.

At the location of ID 17 no reasonable sensor calibration data was available at that point. To address this issue, missing data were substituted by available calibration data at the nearest neighboring location. The corrected DOC deviation at this location is 36 cm. While this approach is not entirely rigorous, it is sufficiently accurate for analysis and identification of areas of reduced coverage.

After applying correction, the statistical analysis of the data yields results, with a calculated mean deviation of 17.5 cm in the vertical direction at a 90% confidence interval of 29 cm. Future magnetic data processing and analysis will include additional algorithms for automatic checks in the processing steps to prevent or identify these issues for elevated deviations.

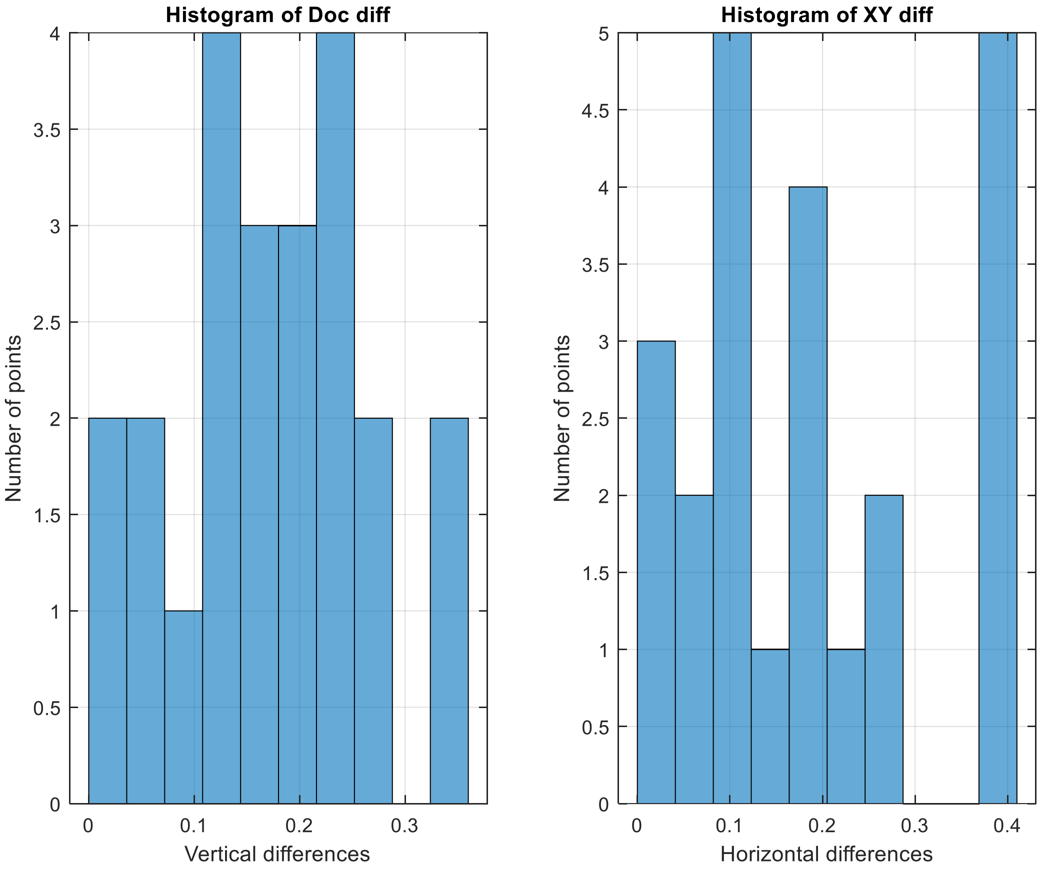

Figure 12: Histogram of absolute vertical and horizontal difference between the reported and verification datasets

Table 2: Statistical analysis of the deviation of the two datasets

Metric	Vertical	Horizontal
Mean	0.175	0.188
Median	0.168	0.174
Standard Deviation	0.094	0.126
Minimum value	0.013	0.022
Maximum value	0.360	0.406

Summary and outlook

In a joint effort, Skipper NDT and GASCADE carried out a geospatial survey of a buried 22 km long 36" pipeline section. Two weeks data acquisition time demonstrated the technology capabilities to cover large distances efficiently. In-field verification of the reported pipe location enabled an assessment of the Skipper NDT system performance.

23 verification digs showed a calculated mean deviation of the reported and actual pipe position of 18.8 cm in the horizontal direction (XY) and 17.5 cm in the vertical direction (DOC). The 90% confidence interval on the dataset after identification and reprocessing of outliers corresponds for XY and DOC to 38 cm and 29 cm, respectively. The achieved performance is meeting the published performance specification and allows to identify areas of reduced DOC with sufficient accuracy and confidence.

The applied technology and analysis process can especially be of high value in cases the pipe location and DOC requires verification due to missing, incomplete or low confidence data. This might especially be the case for pipelines for which the pipe location has been transformed to digital data from paperwork, pipelines that are difficult to inspect by free swimming inspection tools or pipe sections affected by *e.g.* landslides or subsidence.

Future projects will investigate possible effects of smaller pipe diameters on the system performance and application to river and water crossings.

Acknowledgment

We extend our gratitude to the GASCADE team for their support during data acquisition and for the insightful discussions following the project, which allowed for a thorough evaluation of the technology's performance.

References

[1] EGIG – 2024, Gas Pipeline Incidents, 12th Report of the European Gas Pipeline Incident Data Group; downloaded in January 2025 https://www.egig.eu/reports
[2] BIL Directory Enquiry Service : https://bil-leitungsauskunft.de/
[3] NF S70-003-3, December 2019, Travaux à proximité des réseau – Partie 3 : géoréférencement des ouvrages.
[4] DVGW GW 120 (2021): Network documentation in supply companies
[5] DVGW G 463 (2021): High pressure gas steel pipelines for a design pressure of more than 16 bar; design and construction
[6] DVGW G 456: Guidelines in case of insufficient coverage of pipelines
[7] M. Laichoubi et al, "Pipeline 3D-positioning at river crossing: long-range magnetic mapping via Unmanned Aerial System (UAS)", Pipeline Technology Conference 2023, Berlin
[8] M. Laichoubi et al, "3D-Localisation and Magnetic Mapping of Buried Pipelines Using Unmanned Aerial System.“ Pipeline Technology Conference 2022, Berlin.
[9] M. Laichoubi et al, "Automatic 3D-Localisation Of Buried Pipeline And Depth Of Cover: Magnetic Investigation Under Operational Conditions" Pipeline Technology Conference 2021, Berlin.
[10] Munshy M, Boulanger D, Ulrich P, Bouiflane M. "Magnetic Mapping for the Detection and Characterization of UXO: Use of Multi-Sensor Fluxgate 3-axis Magnetometers and Methods of Interpretation“. Journal of Applied Geophysics, Volume 61, Issue 3-4, p. 168-183.
[11] Kella Bennani, et al, "Novel Non-contact, Drone based technology for Pipeline Movement Assessment". Pipeline Pigging & Integrity Management Conference, Houston, 2024.