Bathymetry reconstruction using UAV-mounted Echo-sounder and Lidar sensors: a case study

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ABSTRACT

This study investigates a UAV-mounted sonar approach for bathymetric mapping in complex inland water bodies, addressing challenges that hinder traditional methods like satellite-based remote sensing and USVs. Optical satellite imagery, while valuable in clear shallow waters, is limited in turbid environments. Likewise, inland waters often feature obstacles—boulders, vegetation, and anthropogenic debris—that impede USV navigation. This study introduces a UAV-tethered sonar device to overcome these constraints, leveraging UAV mobility to access remote areas and sonar precision to capture accurate depth data in deep and murky conditions. Tests in Conza della Campania reservoir, Italy, compared this method to LiDAR, showing that UAV-based sonar provides reliable bathymetric models and can detect submerged objects. Dual-frequency sonar (50 kHz, 200 kHz) captured detailed profiles, with low frequencies effectively penetrating debris-heavy water. This approach proves valuable for bathymetric reconstruction in complex environments, offering an accessible, scalable solution for inland water studies.

KEYWORDS: UAS, Lidar, bathymetry, echo-sounder, UAV.

INTRODUCTION

In recent decades, extensive research has been conducted into leveraging advanced technologies for the study of underwater morphology in permanent water bodies. This area of research has gained momentum with the availability of high-resolution optical imagery from satellites, such as Landsat, QuickBird, IKONOS, and WorldView-2. These satellites have been instrumental in capturing bathymetric data for inland water bodies by using multispectral imagery to estimate depth variations based on light penetration and reflection patterns in water (Stumpf et al., 2003; Lyons et al., 2011; Hamylton et al., 2015; Olayinka & Knudby, 2019).

Studies have emphasized that reconstructing accurate bathymetric profiles from satellite images is feasible under specific conditions: particularly when the water is extremely clear, the substrate is relatively homogeneous, and atmospheric factors—such as cloud cover and atmospheric haze—are minimal (Overstreet and Legleiter, 2017; Ilori & Knudby, 2020). However, despite their potential, passive remote sensing methods are inherently limited to clear and shallow areas where light penetration is sufficient. Consequently, these techniques tend to perform best in environments with shallow gravel beds and consistent substrate characteristics.

Inland water bodies, including rivers, lakes, and reservoirs, present additional complexities for bathymetric surveys. These environments often contain obstructions, such as submerged boulders, tree trunks, dense vegetation, or anthropogenic structures, which create hazardous conditions for Unmanned Surface Vehicles (USVs) and limit the scope of traditional field surveys. In such scenarios, USVs may be unable to navigate effectively, thus necessitating alternative survey methods to overcome these limitations (Manley, 2008; Liu et al., 2016; Tanakitkorn, 2019).

Building upon previous findings and methodologies (Bandini et al., 2018; Rossi et al., 2020; Trendafilova, 2021; Lubczonek, 2022), the present study introduces an innovative approach to estimate bathymetry in deep and turbid waters. This method employs an off-the-shelf, floating sonar device, which is tethered to and operated via an Unmanned Aerial Vehicle (UAV). This novel combination allows researchers to bypass the challenges posed by impassable or hazardous terrain, leveraging the UAV's to reach remote areas that are otherwise inaccessible for ground or water-based vehicles.

Furthermore, the use of bathymetric sonar enables accurate depth measurements in deep and turbid water conditions, thereby expanding the range of environments that can be effectively surveyed. This integrated Unmanned Aerial System (UAS) solution presents a promising avenue for conducting bathymetric surveys in inland water bodies where conventional methods face significant constraints.

MATERIALS AND METHODS

This study aimed to test a detailed surveying procedure within a specific area of the Conza della Campania dam basin in Southern Italy. This area is submerged during the reservoir's filling period and becomes exposed when the water level drops. To accurately reconstruct the morphology of this terrain in both its submerged and exposed states, two distinct acquisition methods were employed, according to the area's different water levels.

For the submerged state, a dual-frequency echo-sounder (ECT D052S) was mounted on a DJI Matrice 600 Pro UAV. This equipment was utilized to collect bathymetric data with a flight strategy known as "grasshopper mode" (UgCS-CMP 3.18). This mode was specifically chosen to account for potential obstacles (e.g., submerged branches) close to the water surface, ensuring that the UAV maintained a safe and controlled altitude, a LiDAR survey was conducted using the same UAV, equipped with the Geosun GS100C+ payload. Such specifications make the GS100C+ a reliable and cost-effective UAV-based LiDAR system, suitable for high-resolution topographic surveys across a range of applications (Li et al., 2021; Ye et al., 2022; Kovanič et al., 2023; Bartmiński et al., 2023). By flying over the exposed terrain, the LiDAR system captured a high-density point cloud, which was later processed to create a detailed digital surface model of the area in its emerged state.

Geodetic orthorectification was applied to both the bathymetric and LiDAR datasets using the Post-Processing Kinematic (PPK) method (Famiglietti et al., 2021, 2024; Memmolo et al., 2023). This process relied on GNSS data from the nearby RING network station AV04, located approximately 10 km from the survey area, providing a highly accurate reference for positioning. After collecting data from the echo-sounder, it was essential to correct the recorded

Fig. 1 - Aerial photo of the Conza della Campania dam. The red box indicates the test site location.

depth values based on the UAV-sensor configuration (illustrated in Fig. 2). This correction was crucial to transform raw depth measurements from the bathymetric probe into elevations relative to sea level. The radar altimeter integrated into the UAS provided a constant altitude reference throughout the mission, allowing for precise depth-to-elevation conversion.

For this purpose, the following formula is applied to ensure an accurate transformation of depth measurements into elevation data above sea level:

$$H_{TOPO} = H_{UAV} - H_{ECHO} - H_{DEPTH}$$

Where:

- **H_{TOPO}** is the elevation above the sea level
- **H_{UAV}** is the drone flight height, set during flight mission planning
- **H_{ECHO}** is the probe cable length equal to 2 meters
- **H_{DEPTH}** is the measure acquired in a certain point corresponding to the depth of the bottom.

This comprehensive approach enabled a precise representation of the area's morphology, addressing the challenges associated with surveying terrain that alternates between submerged and exposed states in the dam reservoir.

RESULTS

The processing of data from the LiDAR survey enabled the extraction of a high-precision Digital Terrain Model (DTM) from the Digital Surface Model (DSM), leveraging the sensor's capability to capture three echo returns. This methodology allows for an accurate separation of terrain data from vegetation and other surface features. The DTM derived from LiDAR was compared with data obtained from 50 kHz measurements, as both are suitable for assessing the morphology of bare soil. On the other hand, the DSM was compared to the data gathered at 200 kHz, as both reflect details of vegetation, sediment deposits, and rock formations within the surveyed test area.

High-resolution LiDAR products (0.1 m) are used as the benchmark "ground truth" to evaluate the accuracy of echo-sounder measurements. Elevation differences were assessed at 30 specific echo-sounder acquisition points (checkpoints) spaced at intervals of 3 meters and covering an approximate area of 270 m^2 (see Fig. 3).

The findings from this comparative analysis are summarized in Table 1, with the altimetric profiles along sections X-X', Y-Y', and Z-Z' presented in figure 4.

The results demonstrate that echo-sounder measurements vary depending on the operating frequency. The 200 kHz dataset provides a high-resolution representation of the underwater environment, effectively capturing detailed features of the bathymetric profile. However, this frequency shows higher sensitivity to interference from obstacles such as vegetation, sediment accumulation, and submerged debris. In contrast, measurements at 50 kHz produce a more stable representation of the bottom profile, mitigating the impact of obstructions such as rocks and typical barriers encountered in inland water bodies.

This frequency-dependent behavior is clearly illustrated in figure 4, which shows the elevation profiles along the three sections (X-X', Y-Y', Z-Z'). The blue and red curves represent the reference "ground truth" models obtained from LiDAR data, while the green and pink lines correspond to the 50 kHz and 200 kHz datasets collected during the UAS survey, respectively. Although both echo-sounder datasets effectively capture the general

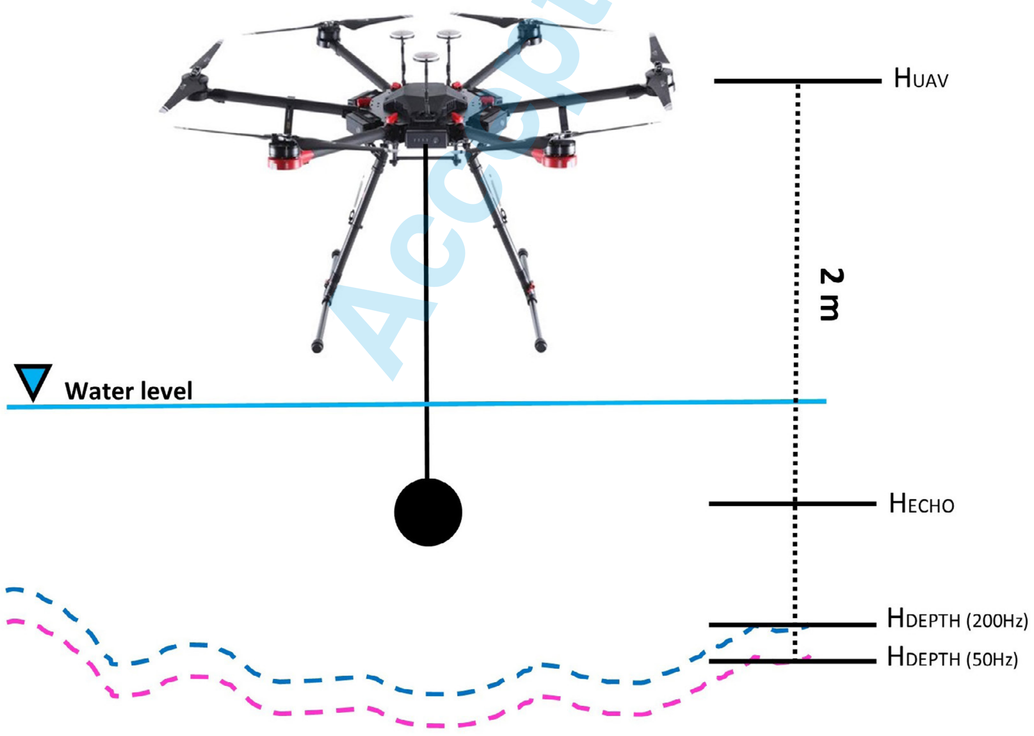

Fig. 2 - Scheme of the echo-sounder survey configuration. The blue line represents the water level; the dotted blue and pink lines correspond to the 200Hz and 50Hz measurement respectively.

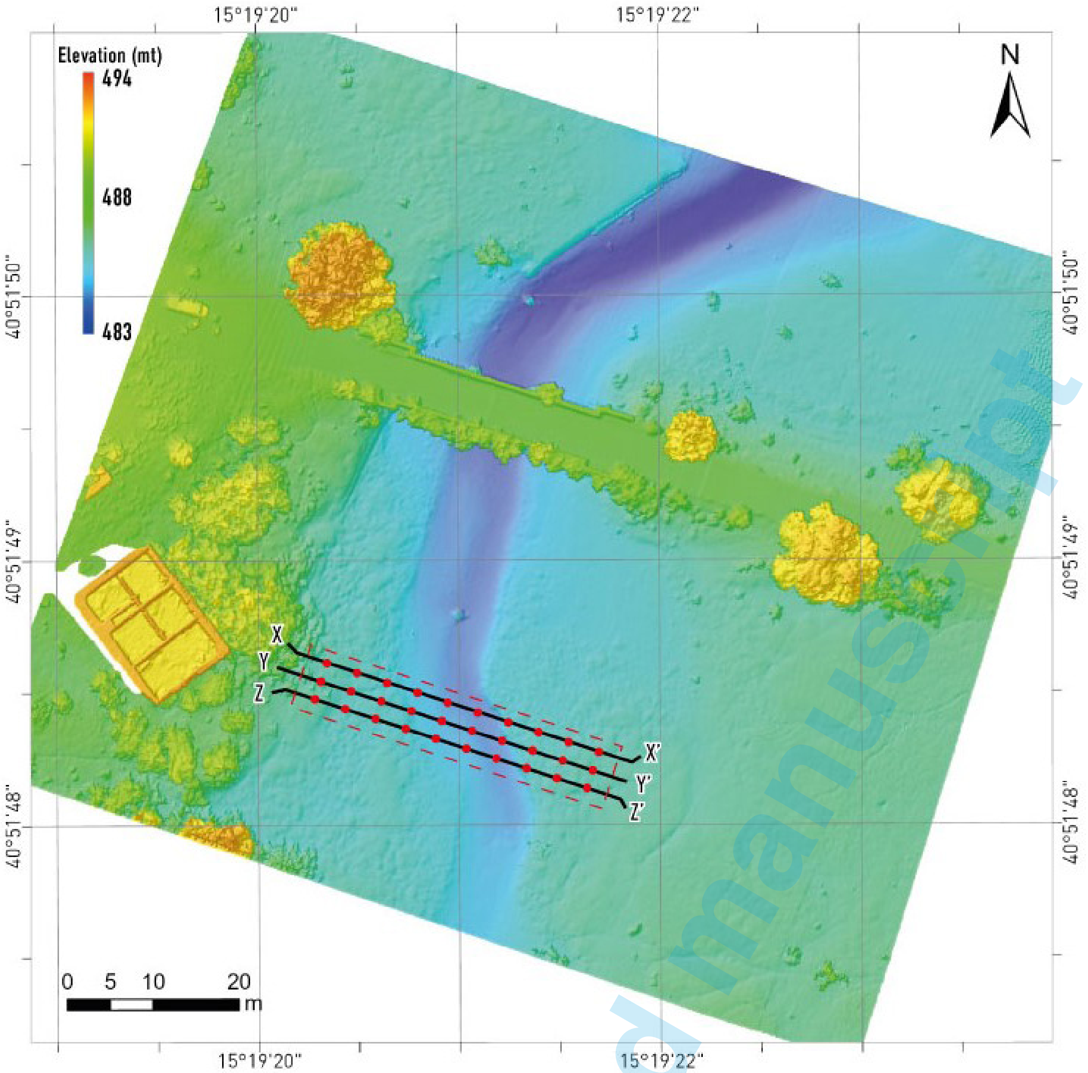

Fig. 3 - Acquired echo sounder profiles within the Conza della Campania dam area. Lidar DSM is used as basemap.

terrain morphology, the high-frequency (200 kHz) data shows greater variability, especially in areas with presence of significant obstructions.

The 50 kHz data provide less detailed but more robust profiles in the presence of obstructions, whereas the 200 kHz data offer higher resolution at the cost of stability in complex areas. The LiDAR models act as an accurate reference, confirming that both survey methods, despite differences in performance, are effective for morphological characterization of the terrain and adjacent surfaces. In particular:

- *Section X-X' (Checkpoints 1-10):* this section shows a fair degree of consistency among the models. Noticeable deviations occur at checkpoints 3, 7 and 8, where the 200 kHz profile deviates more significantly (about 10 cm), suggesting potential interference from vegetation or rocks.
- *Section Y-Y' (Checkpoints 11-20):* in this section, the 50 kHz and 200 kHz data diverge more clearly between checkpoints 14 and 16, where dense vegetation or sediment might influence the readings. At checkpoint 15, located on the tributary canal bed with minimal obstructions, all profiles align closely, indicating uniform terrain conditions.
- *Section Z-Z' (Checkpoints 21-30):* variations between the two frequencies are also observed here, with the 200 kHz profile showing more pronounced peaks and dips, particularly between checkpoints 24 and 27. The LiDAR DSM and DTM lines remain in an intermediate position, indicating the general terrain trend.

Results highlight the significant potential of using a dual-frequency echo sounder in shallow, turbid waters (depths of less than 4-5 meters). Both high- and low-frequency echo sounder surveys demonstrated their ability to accurately map bathymetry and successfully identify key features, such as tributary channels. The low-frequency measurements are especially useful in situations where other survey methods are impractical, providing an effective solution for submerged or otherwise inaccessible areas. Conversely, the high-frequency acquisitions offer distinct advantages in detecting underwater features, delivering greater detail that can be crucial for identifying submerged objects.

This study also showcased the effectiveness of deploying the sonar via an UAV in "grasshopper mode," which allows access to areas that would be difficult or impossible to reach by conventional means, such as narrow, shallow, or obstructed streams. This

Table 1 - Echo-sounder and LiDAR elevation measurements along the 30 checkpoints.

Section	Checkpoint	Echo 200kHz Elev. (m.)	LIDAR DSM Elev. (m.)	Echo 50kHz Elev. (m.)	LIDAR DTM Elev. (m.)
X-X'	1	486,086	486,066	485,950	485,910
	2	484,606	484,570	484,470	484,480
	3	485,038	485,036	484,902	484,870
	4	484,846	484,780	484,710	484,690
	5	484,500	484,540	484,470	484,450
	6	485,526	485,440	485,390	485,376
	7	485,953	485,940	485,795	485,820
	8	486,085	486,087	485,890	485,902
	9	485,812	485,834	485,780	485,805
	10	486,200	486,145	486,120	486,134
Y-Y'	11	486,220	486,210	486,120	486,110
	12	486,026	486,006	485,890	485,870
	13	485,426	485,396	485,290	485,260
	14	485,189	485,210	484,930	484,990
	15	484,530	484,500	484,440	484,410
	16	485,478	485,589	485,214	485,169
	17	485,940	485,960	485,880	485,880
	18	486,020	486,030	485,970	485,970
	19	486,020	486,000	485,960	485,960
	20	485,990	485,972	485,940	485,940
Z-Z'	21	486,278	486,258	486,258	486,200
	22	486,070	486,120	485,934	485,902
	23	485,423	485,380	485,287	485,227
	24	485,280	485,318	485,060	485,150
	25	484,666	484,630	484,530	484,580
	26	484,549	484,639	484,390	484,430
	27	485,975	486,125	485,785	485,855
	28	486,040	486,070	485,950	485,900
	29	486,040	486,065	485,940	485,970
	30	485,980	486,040	485,930	485,910

capability enables bathymetric surveys in remote, hazardous, and complex environments.

However, to ensure reliable data collection and successful post-processing, this approach requires initial investment and expertise from a multidisciplinary team. Key roles include UAV pilots for precise mission planning, surveyors for GNSS data correction, technicians for payload calibration and data processing, and geologists for interpreting the results within a geospatial framework.

While this method demands coordination and resources, it offers an effective and highly detailed approach to bathymetric surveys in challenging settings, bridging the gap between traditional methods and areas that have long remained difficult to survey.

DISCUSSION AND CONCLUSIONS

The presented study highlights the potential of UAV-mounted dual-frequency echo sounders as a valuable tool for bathymetric surveying in shallow, complex inland waterbodies. While similar approaches have been explored in previous works, our study introduces a novel and distinctive methodological innovation: the validation of bathymetric measurements acquired during submerged conditions using echo sounders, against high-resolution LiDAR data collected in the same area during a dry phase of the reservoir.

This approach—leveraging the seasonal hydrological cycle to access both submerged and emerged states of the same site—has not been previously documented in the literature. It offers a unique opportunity for direct and highly reliable comparison between active sonar and LiDAR techniques. Such a configuration enables the quantification of measurement accuracy under real environmental conditions and strengthens the scientific validity of UAV-based bathymetric methods, especially in contexts where traditional validation strategies are limited or infeasible.

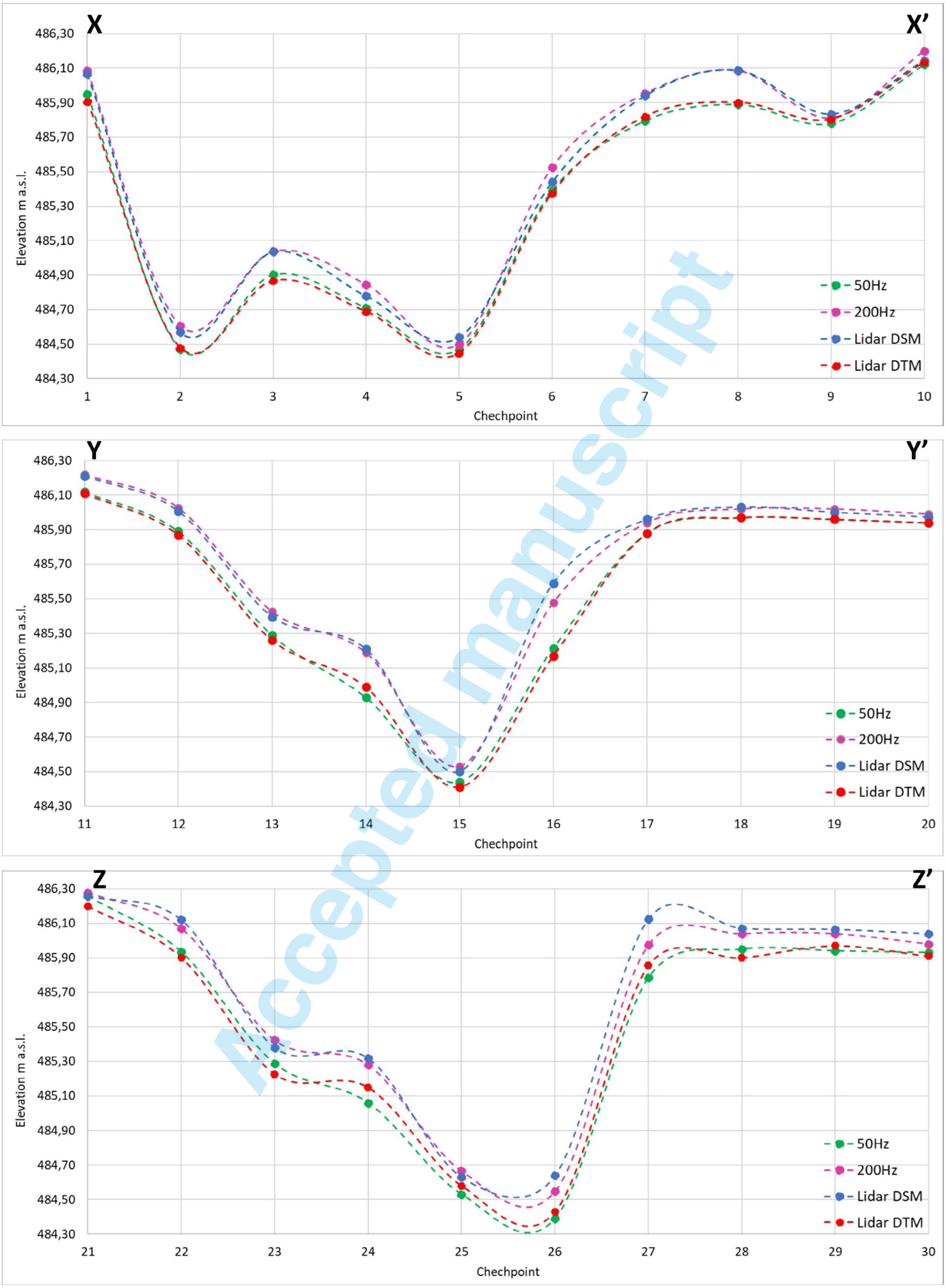

Fig. 4 - Altimetric profiles of sections X-X', Y-Y' and Z-Z'. Each marker (dot) represents a checkpoint where echo-sounder measurements were taken for accuracy assessment.

From a technical standpoint, the dual-frequency echo sounder setup (50 kHz and 200 kHz) allowed for a multi-scale reconstruction of submerged terrain. The low-frequency component demonstrated its capacity to penetrate turbid water and produce stable bathymetric profiles, while the high-frequency component proved effective in capturing finer morphological details. When compared to the LiDAR-derived model, the bathymetric reconstructions showed coherence in shape and elevation trends, validating the reliability of the UAV-sonar system in such settings.

Although the test area was limited in spatial extent and depth (generally not exceeding 2 meters), this apparent limitation enabled a rigorous and detailed validation of the sonar measurements. Such a high level of control is rarely achievable in deeper or less accessible environments. The results therefore offer a solid basis for evaluating performance parameters such as vertical accuracy, stability in the presence of obstructions, and sensitivity to different acquisition configurations.

of our experiment lies in the precise integration between acquisition planning and post-processing. The use of the UAV in "grasshopper mode" made it possible to safely operate in proximity to surface obstacles, maintaining constant altitude and measurement geometry. The combination of onboard radar altimetry and GNSS positioning—corrected via a local RING network station—allowed for an accurate transformation of depth values into absolute elevations. This methodological rigor ensured data consistency and minimized uncertainties related to sensor movement or water surface variability.

Furthermore, the modularity of the UAV platform and the portability of the echo sounder setup allowed us to easily deploy the system in a remote, unstructured environment without the need for launching ramps, pontoons, or specialized transport vehicles. This operational flexibility confirms the applicability of the system not only for controlled experiments but also for rapid-response surveys in post-flood scenarios, sedimentation monitoring in artificial basins, or geomorphological studies of semi-permanent water bodies.

Rather than proposing untested improvements, this study focused on applying and validating a complete and operational methodology. The experience gained confirms the effectiveness of the system in real environmental conditions and provides a solid benchmark for other researchers or institutions aiming to adopt UAV-based bathymetric techniques. The replicability of the workflow, the consistency of the results, and the robustness of the validation strategy make this contribution a practical and scientifically grounded reference for future applications.

In conclusion, this study confirms that UAV-mounted sonar systems represent a robust and innovative alternative for bathymetric mapping in complex inland waters. By bridging the gap between airborne and underwater surveying technologies, our approach paves the way for new applications in environmental monitoring, geospatial analysis, and hydrographic research—particularly in areas that are tipically challenging to access or survey using conventional methods. The validation strategy adopted here—comparing submerged sonar measurements with dry-phase LiDAR data—sets a precedent for future experimental designs and opens the possibility for creating reference datasets that enhance the development and calibration of remote sensing techniques for bathymetric applications.

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