Objective 2: Testing a new method for measuring topographic details on the field that are not visible in images, using a system that integrates a pole, Sony A6000 digital camera, Reach RS2 receiver, and a stabilizer.

- Mounting the integrated system
- Acquiring images on the ground for different areas not visible in the images
- Processing the images
- Evaluating the accuracy of the information extracted from the georeferenced images

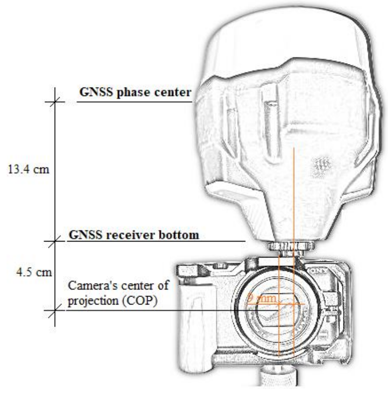
A.2.1 Mounting the integrated system

For measuring topographic details that are not visible in UAS images, have been proposed and tested two different systems for GNSS-aided close-range photogrammetry ***(Figure 1)***. Both systems are based on the Sony ZV1 digital camera (13.2 x 8.8 mm sensor, image resolution of 5472 x 3648 pixels, pixel size of 2.41µm and a nominal focal length of 9 mm). The first system (S1) integrates a RTK GNSS Emlid Reach RS2 receiver mounted on a geodetic pole whereas the second (S2) features a PPK GNSS hand-crafted device consisting of an Emlid Reach M2 module, the Emlid Reach M2 camera hotshoe adaptor, a cable for power bank supply, a camera flash adapter and a multi-band helical GNSS antenna).***The second device was developed additionally to the activities within the project.***

The S1 system features the following components: a Sony ZV1 digital camera, a smallrig cage, an Emlid Reach RS2 GNSS receiver connected with the cage with a Reach RS2 thread adapter. The geodetic pole is connected to the cage with a screw thread adapter of 5/8″-1/4″. The integrated system is very easy to transport, weighing around 1.9 kg including the GNSS receiver and the system autonomy is ca 22 hours. Once mounted ***(Figure 1)***, the pole and the COP are on the same axis, but between the GNSS antenna phase center and the COP there is a small offset. The vertical and horizontal offset between the antenna phase center and the COP was determined with millimeter precision using a caliper.

The principle of the S2 system ***(Figure 2)*** is the same as for S1, but the lever-arm between the COP and the phase center of the GNSS antenna is calculated by calibration. Every time an image is taken with the Soy camera, a pulse is produced on the flash hot-shoe connector, which is synchronized with the shutter opening. The Reach M2 module records flash sync pulses with sub-microsecond precision, saving them in a raw data RINEX log stored in its internal memory.

<table>
<tr><th colspan="3">Sistem RTK (S1)</th><th>Sistem PPK (S2)</th></tr>
<tr><td>

</td><td>
</td><td>


</td><td>


</td></tr>
<tr><td colspan="3">Figure 1. The RTK system integrated with the Sony ZV-1 camera. The components of the S1 RTK system: the Emlid Reach RS2 receiver, a smallrig cage, geodetic pole and thread for attaching the camera, as well as the GNSS device on the pole.</td><td>Figure 2. The PPK system integrated with the Sony ZV-1 camera. The components of the S2 PPK system: the Emlid Reach M2 module, with the adapter for the flash, and a multiband GNSS antenna.</td></tr>
</table>

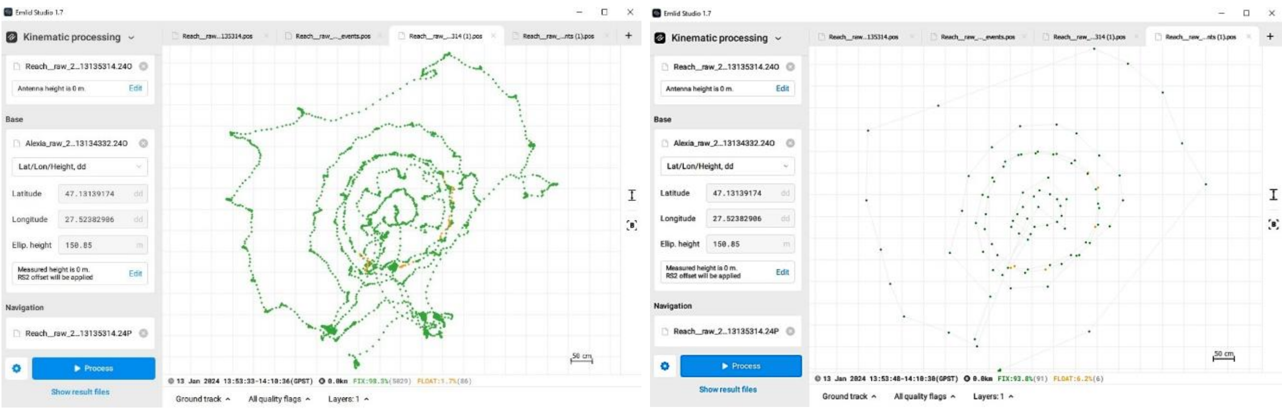
A.2.2 Acquiring images on the ground for different areas not visible in the images

Before the image acquisition stage, it was necessary to calibrate the S2 system. Thus, a total of 7 ground control points (GCPs) were placed on the ground ***(Figure 3 a)*** and measured with the Emlid Reach RS2 GNSS receiver for one minute to determine ground coordinates in the Stereo-70 coordinate system. Then, 97 images were captured with the camera oriented in nadiral and oblique positions ***(Figure 3 a,b)***, as well as rotated 90 degrees to the left and right. The trajectory of the GNSS-PPK device is calculated using the kinematic processing option of Emlid Studio 1.7 software ***(Figure 4 a)***. The base station is the Emlid Reach RS2 GNSS receiver mounted near the calibration field. Thus, using the observation and navigation files downloaded from the Reach M2 module and the RINEX file downloaded from the Emlid Reach RS2 base station, the trajectory is calculated, with each camera position being recorded as a separate event in the "events.pos" file. The solution was 93.8% fixed, so only 6 camera positions out of the total 97 were "float" (orange color in Figure 4).

The calibration process was conducted using Agisoft Metashape software, and the GCPs were manually measured in each image. The positions and orientations of the camera calculated through the bundle adjustment process, along with the positions of the GCPs, are presented in ***Figure 5***.

(a) (b)

Figure 3. *Marking GCPs for calibrating the PPK S2 system using plexiglass plates. (a) Image taken in an oblique position, (b) Image taken approximately in a nadiral position.*



(a) (b)

Figure 4. *The kinematic processing of the GNSS-PPK device trajectory with Emlid Studio 1.7 software: trajectory with positions calculated every 0.05 s (a), positions calculated for each image acquisition position (b).*

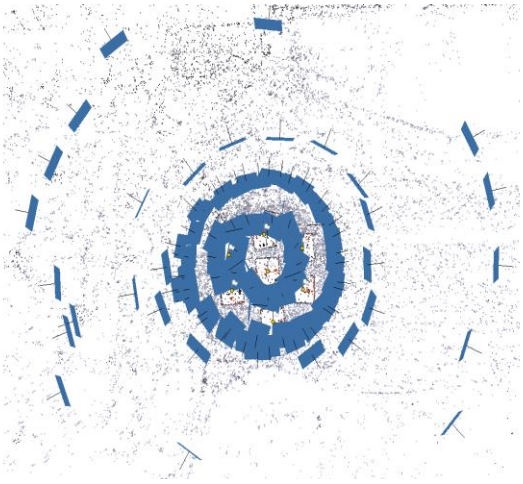


Figure 5. *The positions and orientations of the camera for estimating the calibration parameters in the kinematic approach.*

The resulting calibration parameters have the following values: (X, Y, Z) = (-0.0197, 0.1501, 0.0073) m. Systems S1 and S2 were tested to determine the georeferencing accuracy of the images captured with them, focusing on the Galata Church in Iași Municipality and a house in the rural study area.

1. Study area, Galata Church

Using the S1 GNSS-RTK system, 41 images were acquired from various positions around the church, with the pole leveled, at a distance of approximately 20 m from the facade (resulting in a spatial resolution of about 5 mm).

To evaluate the accuracy of the image block georeferencing process, 10 checkpoints (ChPs) were distributed around the church, marked by plexiglass plates ***(Figure 6 a,b)*** and measured with the Emlid Reach RS2 GNSS-RTK receiver ***(Figure 6 c)***.

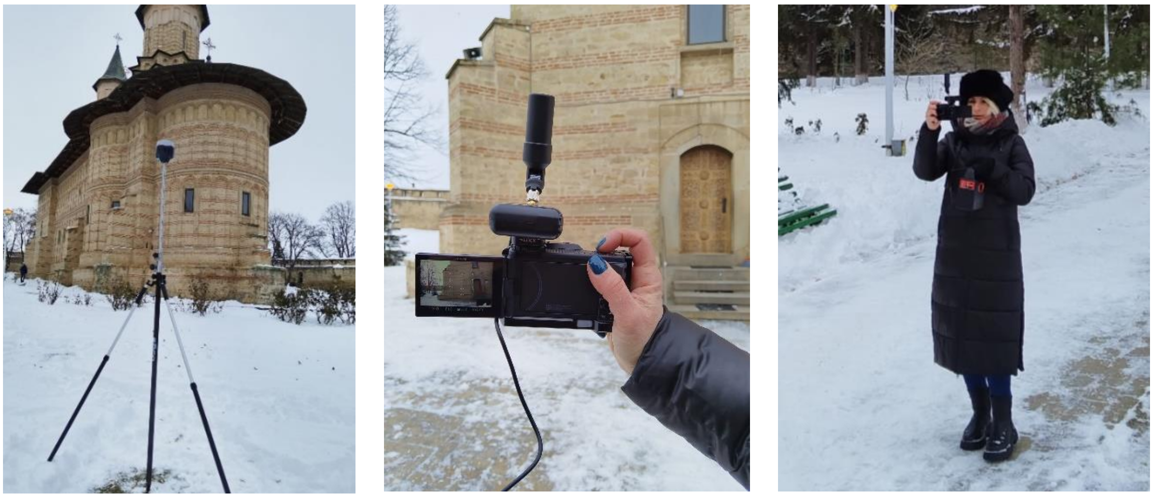
Each image acquisition position is measured with GNSS-RTK using a three-second average.

(a) (b) (c)

Figure 6. *Acquiring images with the S1 system*

A total of 68 images were captured with the S2 system, at a distance of approximately 15 m from the facade (with a spatial resolution of about 4 mm).

During the image acquisition process, an Emlid Reach RS2 GNSS receiver was configured as a base station for recording GNSS observations ***(Figure 7 a)***. The receiver's position was determined using GNSS-RTK technology at 2-minute intervals and a frequency of 5 Hz (601 measurements). Corrections were applied through the ROMPOS service, using data from the permanent reference station, particularly the Iași station in the national geodetic network, located 2.2 km away from the study area.



(a) (b) (c)

Figure 7. *Acquiring images with the S2 system: (a) the Emlid Reach RS2 receiver placed as a base, (b), (c) acquiring images for the 3D reconstruction of the building.*

2. Rural study area of the project

To test the accuracy of the S2 system in the rural study area of the project, 74 images were captured for a house whose rear part is obstructed by trees and is not visible in the UAS images ***(Figure 8 a,b,c).***

(a) (b) (c)

Figure 8. *Acquiring images with the S2 system for extracting topographic details not visible in the UAS images.*

To assess the accuracy of the results, 3 plexiglass plates representing checkpoints were placed ***(Figure 9)***.

Figure 9. *Checkpoint for the results obtained with the S2 system, materialized by a plexiglass plate.*

A.2.3 Image processing

1. <u>Study area, Galata Church</u>

The images captured with the S1 system are processed in Agisoft Metashape, using the 3D coordinates of the camera's optical center (CoP - Center of Projection) for each camera position as constraints in the image block adjustment (BBA) process. The offset along the vertical axis between the phase center of the GNSS antenna and CoP, as illustrated in Figure 1, is directly subtracted from the measured Z coordinates, considering that the antenna height is set to 0 when the camera positions are recorded on the ground. Additionally, the horizontal offset of 9 mm is applied along the X axis using the camera calibration menu in Agisoft Metashape before image processing. The positions and orientations of the images captured with the S1 system in relation to the ground coordinate system, as well as the sparse point cloud, can be observed in ***Figure 10***.

The root mean square errors calculated by comparing the estimated positions of the checkpoints (ChPs) in the image block with the measured coordinates using GNSS-RTK technology have values of 1.6 cm, 2.4 cm, and 1.7 cm in the X, Y, and Z directions, respectively. After the image orientation process, a dense point cloud was generated ***(Figure 11)***, resulting in a total of 12,056,374 points.

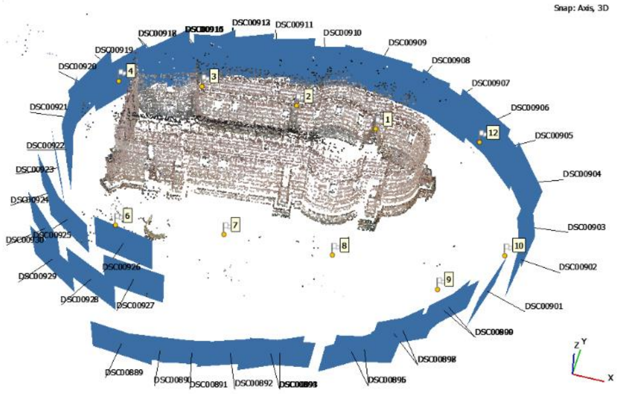


Figure 10. *The positions and orientations of the images captured with the S1 system in relation to the ground coordinate system*

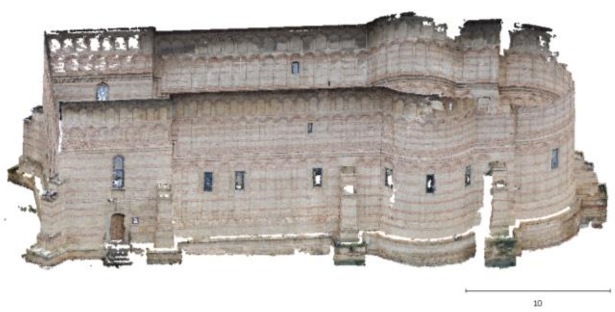


Figure 11. *The dense point cloud obtained using the S1 system*

The trajectory of the GNSS-PPK system was calculated following the same steps as in the system calibration process. The base station is the Emlid Reach RS2 GNSS antenna mounted in the churchyard, and the solution is 100% fixed ***(Figure 12)***. The 68 images captured with the proposed GNSS-PPK device were processed in Agisoft Metashape without using GCPs. The 3D coordinates of each CoP served as constraints in the image block adjustment (BBA) process ***(Figure 13)***. Before image processing, calibration parameters, namely the offsets calculated between the CoP and the phase center of the antenna, are applied using the camera calibration menu in Agisoft Metashape. After the image orientation process, a dense point cloud was generated ***(Figure 14).***

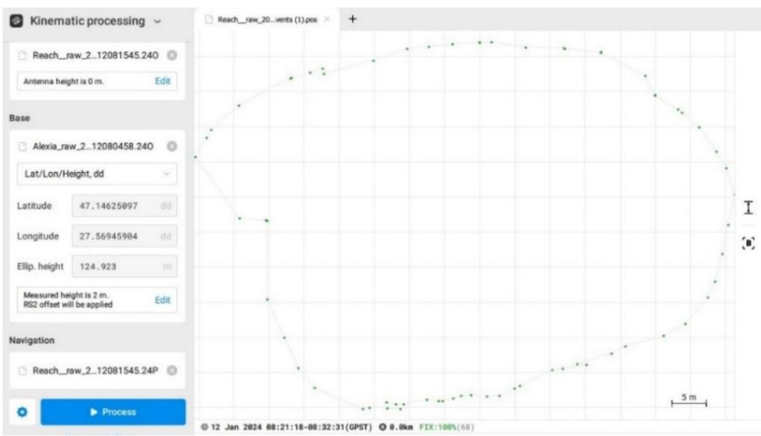


Figure 12. *The kinematic processing of the GNSS-PPK device trajectory with Emlid Studio 1.7 software: the calculated positions for each image acquisition position.*

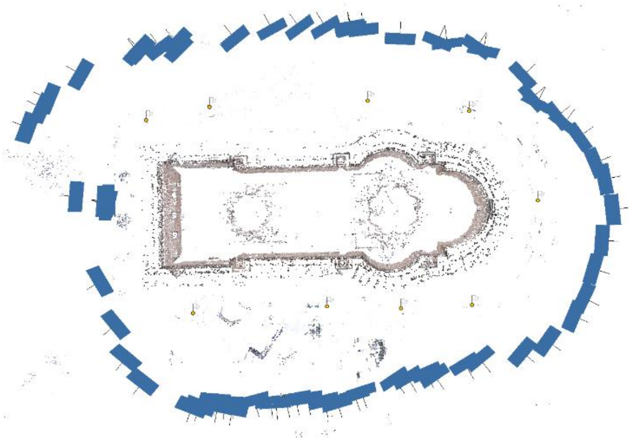


__Figure 13.__ The positions and orientations of the images captured with the S2 system in relation to the ground coordinate system

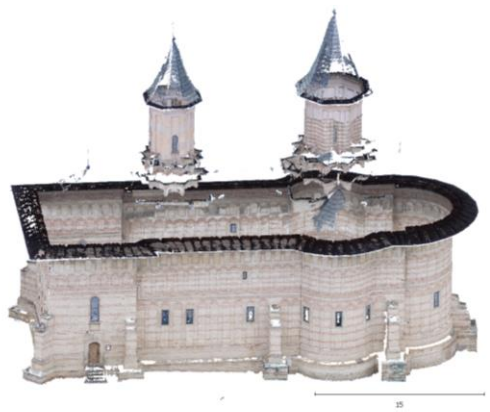


__Figure 14.__ The dense point cloud obtained using the S2 system

The residual errors of the camera positions are 0.8 cm on the X-axis, 0.7 cm on the Y-axis, and 1.2 cm on the Z-axis. The RMSE values for the checkpoints are 1.5 cm in the X direction, 2.4 cm in the Y direction, and 1.7 cm in the Z direction, with a total error of 3.3 cm. The results are consistent with those obtained with the S1 GNSS-RTK system. However, the accuracy of RTK measurements can be influenced by various factors, including ionospheric errors, tropospheric errors, signal obstructions, and multipath errors. These errors can occur due to objects close to the receiver, such as tree canopies and tall buildings, affecting the measurement accuracy. Therefore, it is important to mention that the checkpoints were strategically positioned in the church vicinity to ensure visibility in the images acquired with both systems. Additionally, the churchyard has tall trees, which can influence GNSS measurements and should be taken into account.

3. Rural study area of the project

The trajectory of the GNSS-PPK system was calculated using the IASI station from the national GNSS network as the base station, and the solution is 95.9% fixed, with only 3 camera positions being "float" ***(Figure 15)***. The 74 images acquired with the proposed GNSS-PPK device were processed in Agisoft Metashape without using GCPs. The 3D coordinates of each CoP served as constraints in the image bundle block adjustment (BBA) process ***(Figure 16)***. Before image processing, calibration parameters, namely the offsets calculated between the CoP and the phase center of the antenna, are applied using the camera calibration menu in Agisoft Metashape.

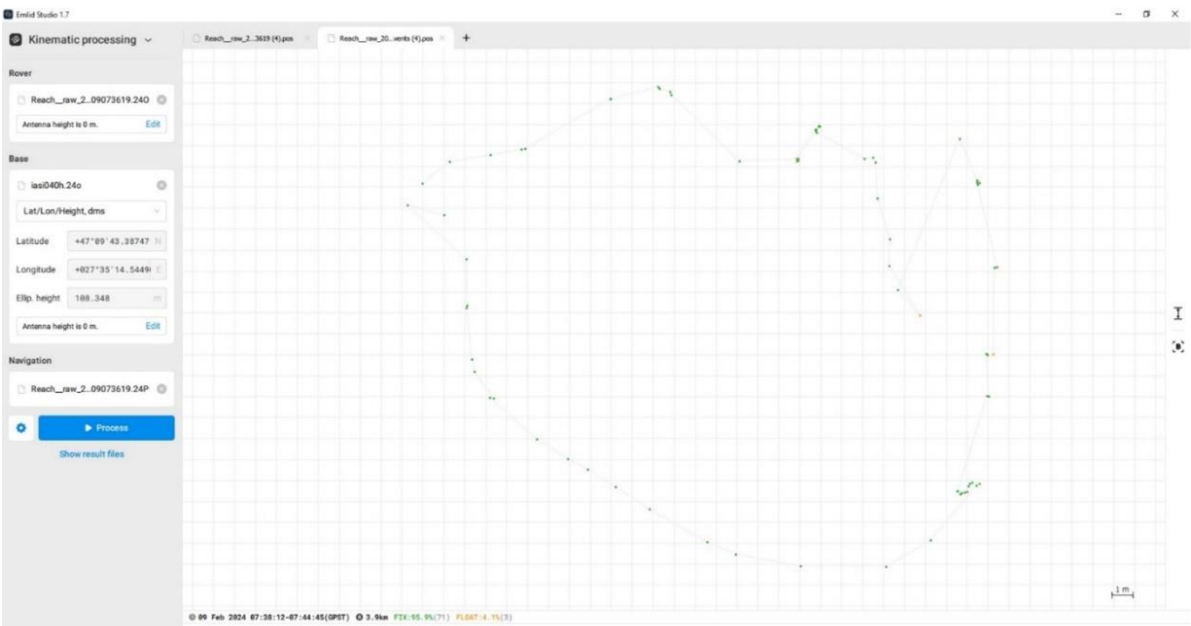


__Figure 15.__ The kinematic processing of the GNSS-PPK device trajectory with Emlid Studio 1.7 software: the calculated positions for each image acquisition position.

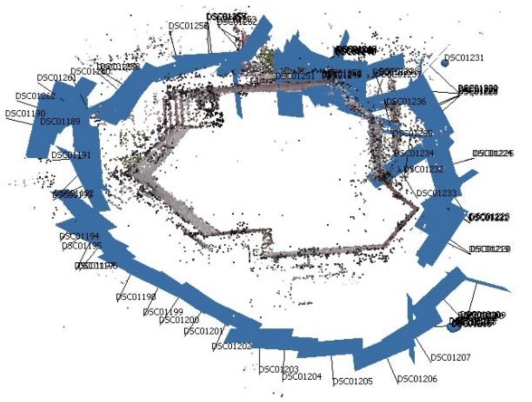
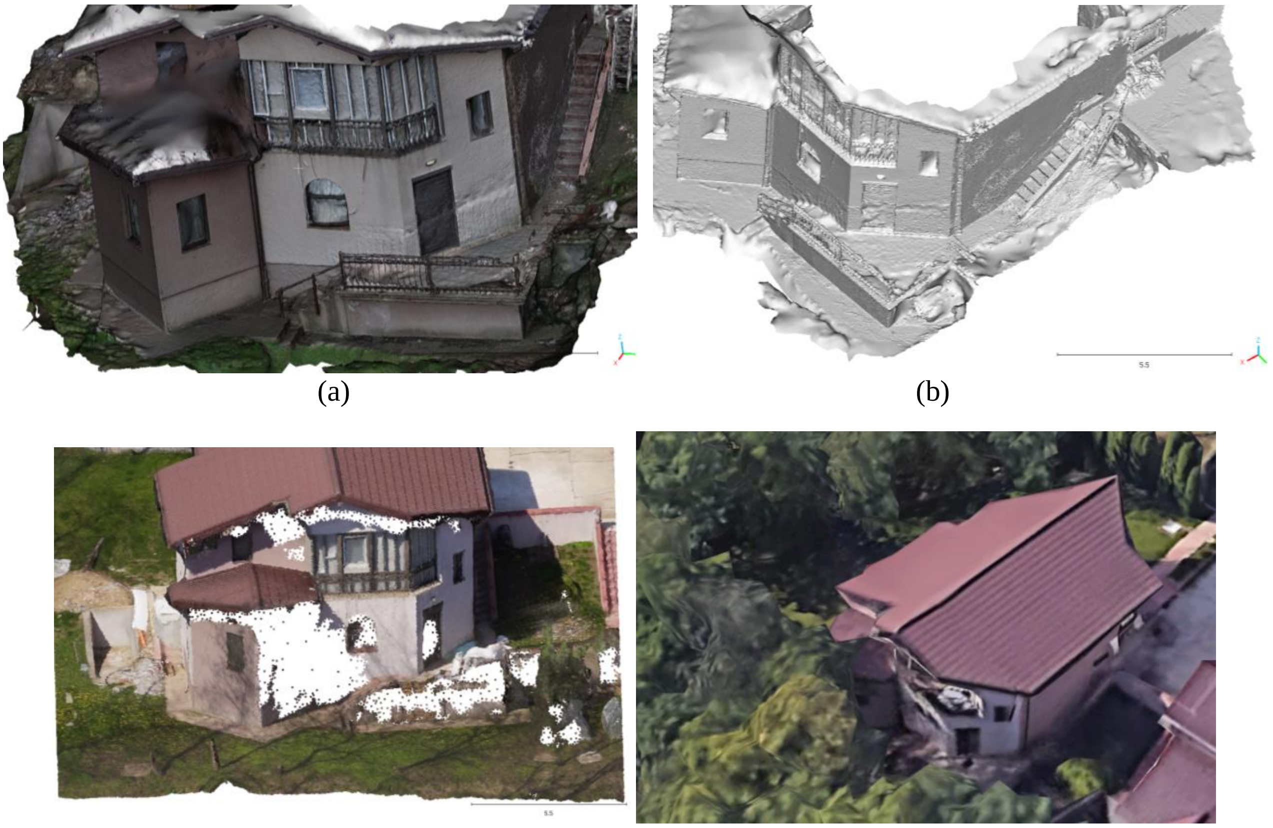


Figure 16. *The positions and orientations of the images captured with the S2 system in relation to the ground coordinate system*

Figure 17. *The dense point cloud obtained using the S2 system*

The 3D reconstruction of the house in the rural study area was complete, including the stairs represented with a high level of detail, as can be seen in ***Figure 18 a, b***. As for the 3D model of the house based on images captured with the SHARE camera, it is incomplete, showing information gaps in areas obstructed by trees, as depicted in ***Figure 18 b, c***.



(a) (b)

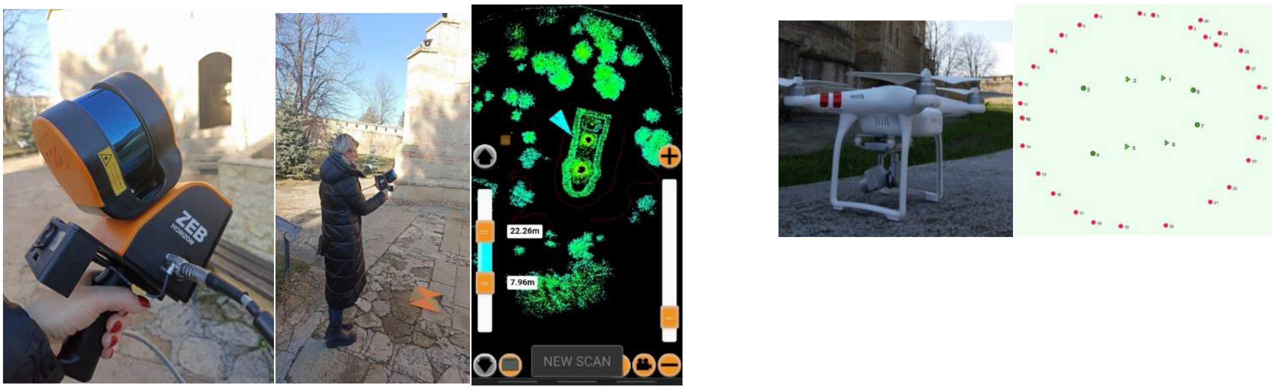
(c) (d)

Figure 18. *Textured 3D model of the house based on images acquired with the S2 system (detail with the rear part obstructed by trees) (a), shaded representation (b), 3D model of the house based on images acquired with the SHARE camera (c), visualization in Google Earth with the house under study obstructed by trees (d).*

A.2.4 Accuracy assessment of the information extracted from georeferenced images

1. Study area, Galata Church

To evaluate the accuracy of the information extracted from the georeferenced images, the point clouds resulting from processing the images acquired with the two systems were compared with a reference point cloud. To obtain the reference point cloud, the church was scanned for approximately 10 minutes using the hand-held scanner GeoSLAM Zeb Horizon ***(Figure 19a)***. While the facades were fully scanned, there are information gaps for the towers and the roof surface. Thus, a UAS flight was conducted using the low-cost DJI Phantom 3 Standard system, acquiring 31 images manually from approximately 20 meters above ground level ***(Figure 19b).***



(a) (b)

Figure 19. *(a) Scanning the church with the GeoSLAM scanner, (b) Acquiring the UAS images with the DJI Phantom 3 system*

For calculating the trajectory of the scanning system, GeoSLAM Hub 6.3 software was used, resulting in a point cloud of approximately 82 million points in a local coordinate system. To bring the point cloud into the Stereo-70 coordinate system, the Helmert transformation method was employed. The accuracy assessment of the georeferencing process for the GeoSLAM point cloud was performed based on 3 ground control points (GCPs), resulting in the following errors: 4 mm on the X-axis, 2.2 cm on the Y-axis, and 1.7 cm on the Z-axis.

To evaluate the accuracy of the indirect georeferencing process of the UAS images, 8 ground control points were placed around the church, with 4 serving as GCPs and 4 as checkpoint points (ChPs). This resulted in a root mean square error (RMSE) of 1.9 cm on the X-axis, 1.0 cm on the Y-axis, and 3.3 cm on the Z-axis after processing them with Reality Capture software.

(a) (b)

Figure 20. *The GeoSLAM dense point cloud, (a) the UAS point cloud*

Considering that the UAS flight and the GeoSLAM system scanning were conducted on different days and processed with a different number of GCPs, it was necessary to align the two point clouds. Following a point-to-point comparison of the UAS and GeoSLAM point clouds using the M3C2 distance implemented in CloudCompare software, a standard deviation of 5.3 cm was observed ***(figure 21)***. Additionally, cross-sectional and longitudinal analyses of the point clouds revealed some discrepancies between GeoSLAM and UAS data. Therefore, to enhance the alignment of the two point clouds, the Iterative Closest Point (ICP) algorithm available in OPALS (2024) was used. After five iterations, the standard deviation was reduced to 2.5 cm ***(figure 21)***.

Following alignment with the ICP algorithm, the two point clouds were once again compared using the M3C2 distance. A threshold value of 2.5 cm was set, and points exceeding this threshold were exported and integrated with the GeoSLAM point cloud. The resulting point cloud is illustrated in ***figure 21***.

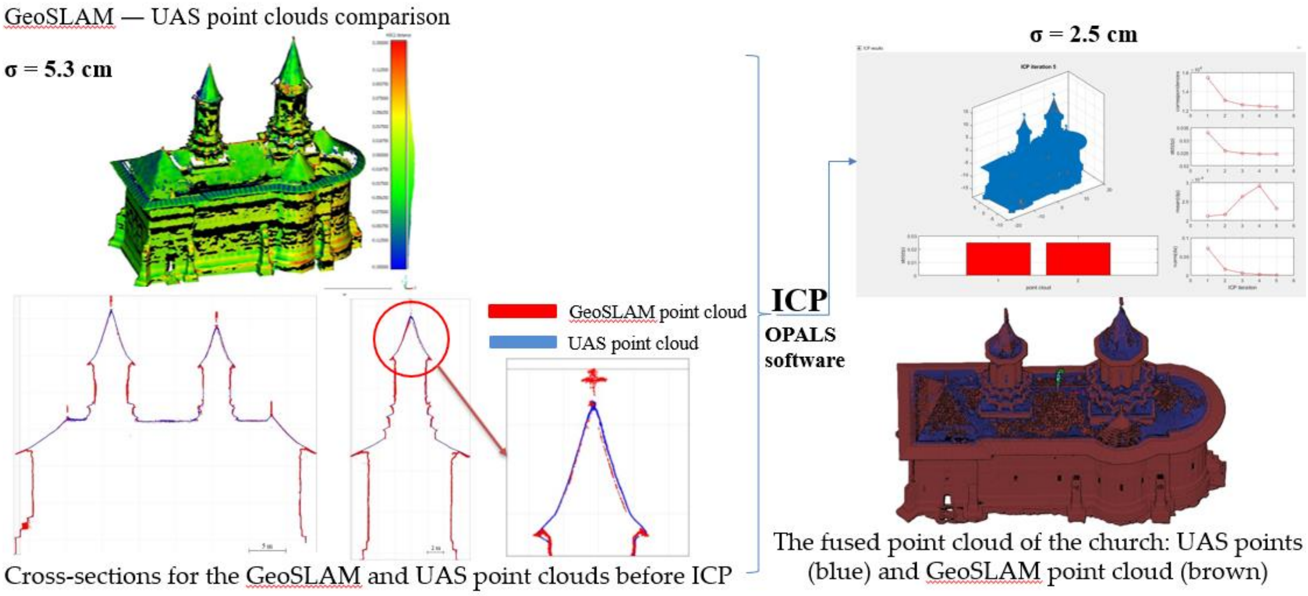
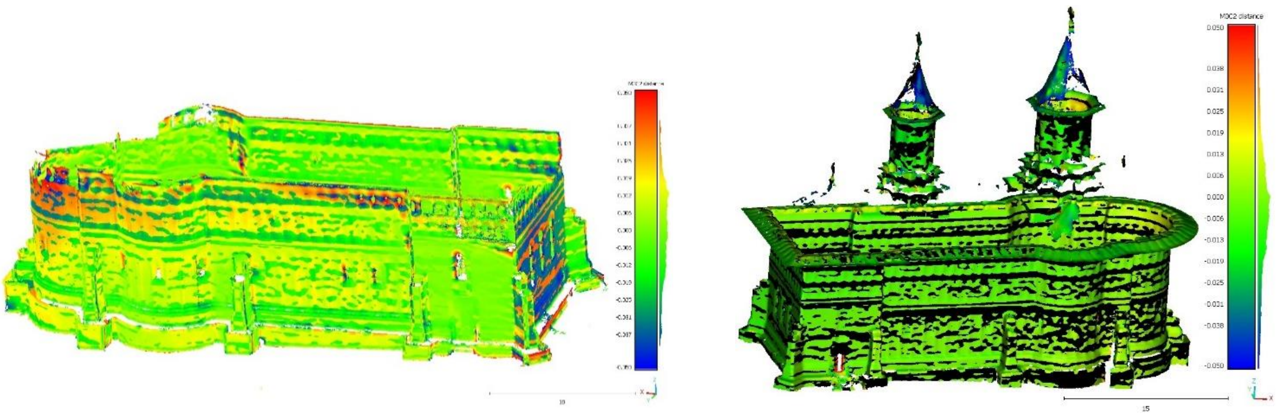


Figure 21. *Alignment of the GeoSLAM and UAS point clouds using the ICP algorithm and the resulting integrated point cloud, considered as reference.*

The point clouds obtained based on the images acquired with the two systems S1 and S2 are compared with the reference point cloud using the M3C2 distance, resulting in a standard deviation of 1.8 cm for the S1 system and 1.9 cm for the S2system ***(Figure 22).***



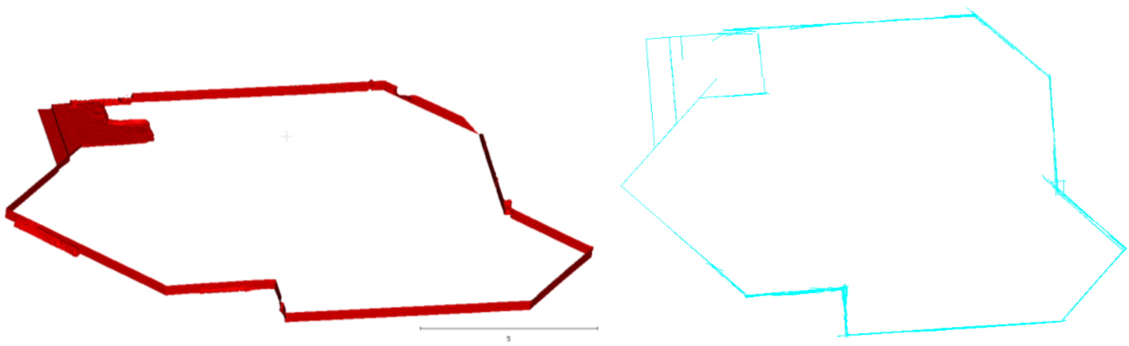
(a) (b)

Figure 22. *The dense point cloud compared to the reference point cloud, colored based on the M3C2 distance values: (a) the cloud obtained with S1 system, (b) the cloud obtained with S2 system.*

2. Rural study area of the project

To evaluate the accuracy of the direct georeferencing process of the images acquired with the S2 system using GNSS-PPK technology, the root mean square error (RMSE) was calculated based on the differences between the coordinates of the 3 GCPs determined by GNSS-RTK measurements with the Emlid Reach RS2 receiver and those resulting from the direct georeferencing process of the images, considering the CoP as constraints in the BBA process. Thus, the RMSE values for the GCPs are 1.0 cm in the X direction, 2.4 cm in the Y direction, and 3.2 cm in the Z direction, with a total error of 4.1 cm. It should be noted that these errors are for the case where no GCPs are used in the BBA process of the interior and exterior orientation parameters. Additionally, the obtained errors are ideal for cadastral surveys.

Using AutoCAD Map 3D, a series of sections were made through the point cloud, starting from the ground level of the construction, at 0.5 m intervals. For each section, polylines were automatically extracted, and the result is presented in ***Figure 23***. The polyline representing the footprint of the building was manually identified.



(a) (b)

Figure 23. *Section through the point cloud (a), automatically extracted polylines based on the sections (b).*

For evaluating the accuracy of the building footprint obtained from the point cloud, distances between this polyline and the one obtained directly on the field by measuring the sides of the house with a distometer were measured. The differences can be visualized in ***figure 24*** and fall within tolerances.

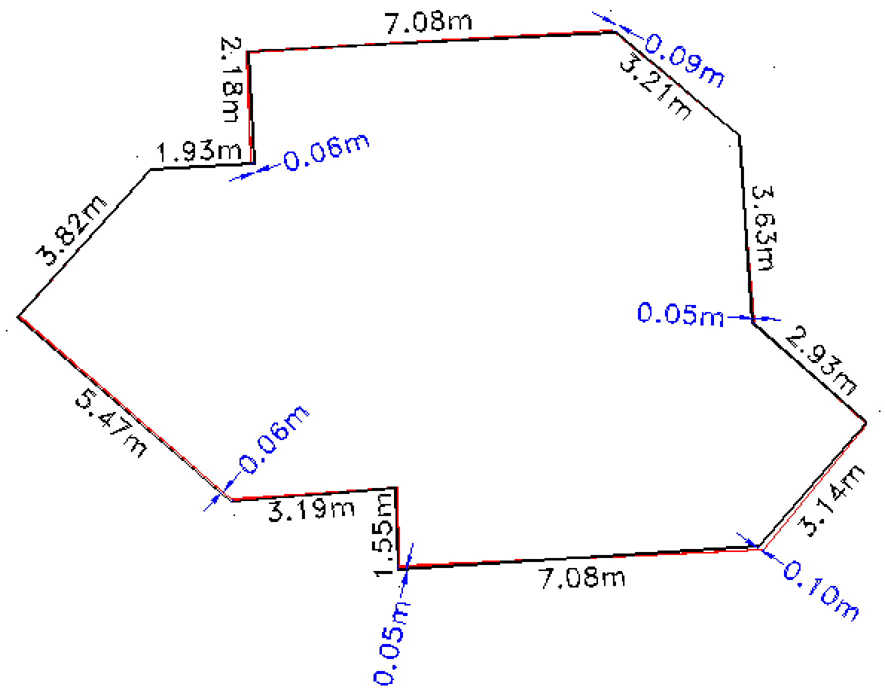


Figure 24. *The building footprint obtained through direct measurements with the distometer (black color), and based on the point cloud generated from the images taken with the S2 system (red color).*