A Multi-Modal Evaluation of GPS Assisted Rapid Multi-Cam Photogrammetry

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Abstract

Mobile multicam photogrammetry systems offer a number of advantages over other 3d imaging modalities, including rapid acquisition speed, low cost sensors, and the availability of mature open-source software systems for photogrammetric alignment and reconstruction.. Through a number of case studies we compare the Looq, a home-grown GPS enabled multi-cam mobile mapping system, to colocated models from terrestrial photogrammetry, aerial photogrammetry, two terrestrial LiDAR systems, and two SLAM LiDAR systems. We evaluate these systems across varied urban and natural environments, in GPS enabled and denied environments, tight interior spaces, and open landscapes in Europe and North America. The comparative performance of these systems is described qualitatively and quantitatively.

1. Introduction

Mobile mapping systems (MMS) offer rapid documentation of large and complex spaces. In this paper, we perform rigorous analysis to evaluate a novel GPS-enabled multi-cam photogrammetry MMS (Meyer, 2021) which seeks to minimize hardware cost/complexity, and provide high spatial accuracy in environments which are generally subject to drift error. (Meyer 2020), with statistical analysis and methodological comparisons between several simultaneous localization and mapping (SLAM) based mobile lidar systems, common single-camera aerial and terrestrial photogrammetric methodologies, and stationary terrestrial LiDAR scanning (TLS). The comparison incorporates several diverse use cases in cultural heritage (Al-Bayari 2019), involving built and natural subterranean environments, open spaces, building interiors, and crowded city streets. We explore the key features and drawbacks of the three data capture modalities, along with the extensibility of data outputs towards state-of-the-art machine learning based segmentation methods.

2. GPS Multi-Camera System

The Looq qCam (figure 1.) is a handheld camera-based mobile mapping device with survey-grade Global Navigation Satellite System (GNSS) capabilities. It features four 5-megapixel (MP) global shutter machine vision cameras, oriented in forward, left, right, and angled upward directions, capturing a total of 20 MP imagery per-snapshot with a 270° × 150° field of view and adaptive frame rate. Integrated strobe LEDs may be toggled to facilitate image capture in low-light environments. The system also incorporates an inertial measurement unit (IMU) and a GNSS receiver, achieving sub-centimeter in-model precision and a global accuracy of 3–5 cm under favorable satellite conditions (Furby 2024). Captured data is encrypted and uploaded directly to Looq's proprietary qAI cloud-based photogrammetric processing stack, which generates AI-segmented and classified point clouds (LAZ), top-down (nadir) orthomosaic imagery (GeoTIFF), and 270° panoramas (JPEG). These data products may then be viewed and analyzed on the qApp web application or exported for additional analysis.

Figure 1. Looq qCam system

3. Methodology and Case Studies

In this analysis we employ a diverse set of use cases involving both ideal and challenging test environments, to effectively compare the overall performance of documentation systems. Data sets are made publicly available for external testing, and validation of study results. Data sets are compared against references of known accuracy, and are evaluated through several key factors, including: precision, accuracy, coverage, density, acquisition time, and processing time (Elhashash, 2022). Additionally, we evaluate the effectiveness of corresponding software-dependent features offering the segmentation, masking, and removal of unwanted features.

3.1 Director's House, UC San Diego

This two-story seaside wooden house was built in 1913 and has served several residential and administrative purposes at the University of California San Diego's Scripps Institution of Oceanography (SIO), leading up to its current role as a common space for SIO faculty. Undergoing a renovation in 2017, the interior features custom wooden fixtures, furniture, and panelling. To document this structure, and provide foundational reference for facilities and maintenance professionals, a series of 3D surveys were conducted. First, a campus-wide aerial photogrammetry survey, then terrestrial photogrammetry (1,979 photos), terrestrial LiDAR with the Leica RTC 360 (69 scans), and one 17 minute Looq survey starting on the exterior, looping through the interior, and ending outside (Rocca, 2025). The RTC 360 constitutes a benchmark system, generating data of high quality with well documented functionality (Conti, 2024). With the Looq, it is generally recommended to start in a GPS accessible area, if continuing into a GPS denied environment, or else the model may not have reference for scale and inclination. This case study constitutes the main local metrological use case, as the simple geometric makeup of this building and its furnishings were easiest to track. Models were aligned in CloudCompare (2025) using the point pair picker, choosing 5 matching features for each floor, and visualized with Potree (Schutz 2016). The results of these alignments show a root mean square (RMS) error of 2.3 cm for the ground floor (figure 2), and a 1.1cm RMS error for the 2nd floor (figure 3).

Figure 2. Director’s House 1st floor. TLS (left), Looq (right)

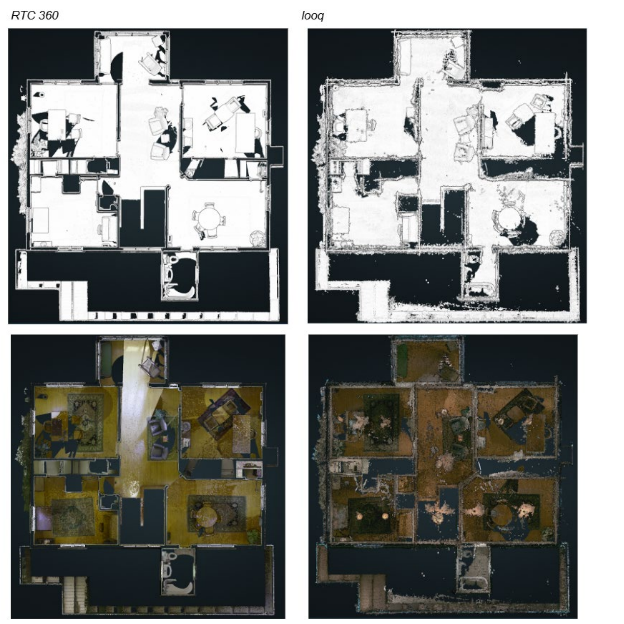

Figure 3. Director’s House 2nd floor. TLS (left), Looq (right)

The RTC 360 model possessed an average point density of approximately 3 mm, while the Looq point density was closer to 2cm. The surface quality of the look scan is notably rougher, with noticeable noise (figure 4). The overall color quality of the Looq data was more consistent than the RTC 360, though the scanner's high dynamic range (HDR) image option was not employed for this survey. Visible noise may be largely attributed to photogrammetry algorithms used by Looq’s proprietary processing pipeline, as well as its handling of significant noise present within the original imagery.

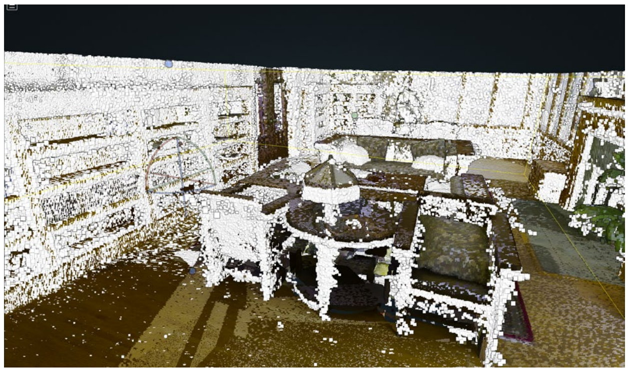

Figure 4. Looq data (white) overlaid with RTC 360 data (rgba)

3.2 Reggia Venaria Survey

The Reggia Venaria is a royal palace complex outside of Turin, Italy, with extensive gardens and vast interior spaces. The survey includes a chapel with high ceilings, a large gallery space, and extensive coverage of the palace exterior facade and surrounding gardens. The Reggia contains many windows, water features, and fine support netting beneath active conservation areas. Each of these present challenges for 3D reconstruction. These features were surveyed with the Looq multi-cam system, Stonex X40 go mobile SLAM LiDAR system, and Leica RTC 360 terrestrial laser scanner (McAvoy, 2025b).

This case study was intended to be the key metrological use case, but issues of data sharing between collaborators left us with only the Looq data for analysis. The study covered an area of over 9 kilometers of exterior garden (figure 6), along with two interior spaces (the church of San Uberto, and the white gallery). The dataset consists of 15 scans and over 40,000 individual images captured over a 2 day period.

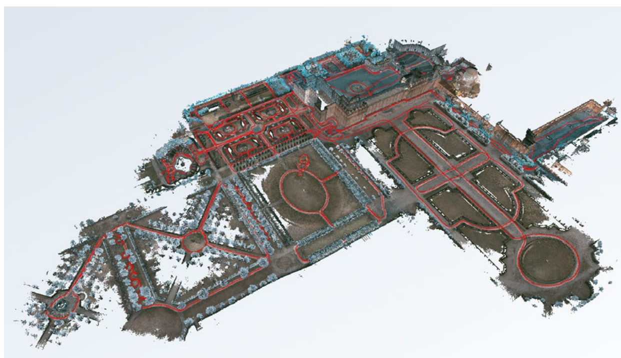

Figure 5. Outdoor study area and capture pathways Reggia Venaria, Italy

One important observation concerning the Looq performance, was its failure to resolve camera positions in one case going for 18 minutes over a 1.7km stretch (figure 6.) This issue might have been further exacerbated by the lack of high certain contrast fixed features, as the landscape was composed of grass, water, and trees.

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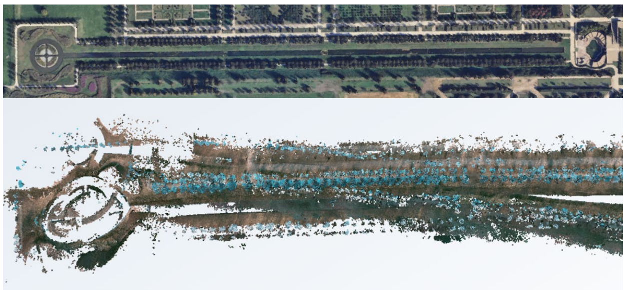


Figure 6. Google Earth Imagery (above) Looq scan over-time error (below)

3.3 Salvation Mountain

Salvation Mountain is a folk art site built by artist Leonard Knight near Niland, California. It is situated on the edges of the Salton Sea and Mojave Desert (figure 7). The man-made hill is constructed from a straw and clay adobe, sourced from the neighboring hillside. It is an eclectic earthen structure, including many found objects as both artistic and structural elements. Parts of the structure have begun to sag as rare extreme weather events in 2023 and 2024 caused significant erosion and structural stresses which can be seen through a time series of collected data. The subtleties of this transformation are the subject of our multi-modal comparison here, to evaluate system suitability for monitoring of non-traditional architectures. A professional survey was conducted (Chiabrando, 2023) using terrestrial LiDAR captured with the RTC 360, mobile SLAM LiDAR with the Stonex X200, aerial surveys with DJI phantom 3, along with the Looq system.

This case study constitutes our main global metrological example, as we possess multiple layers of geolocated data over time.

Figure 7. Multi-modal survey, Salvation Mountain, California USA

The focus of this analysis is on the “Museum” structure (figure 8), a 10 meter tall, vaulted building composed of hay bales, adobe coating, and painted surfaces. The building is supported by a range of found materials, including tires, tree branches, telephone poles, trucking cinches, and rope. The Museum has undergone significant deterioration over the two previous years, exposed to violent storms which were previously rare to the area. The survey team used the Looq to capture 1430 snapshots at 2 frames per second, for a scan lasting approximately 12 minutes, and 47 scans with the RTC360 taking 4 hours 42 minutes to complete.

Figure 8. Museum Structure at Salvation Mountain

The structure is organic and complex, and we have little confidence that any single feature has remained in its original place since the initial survey in 2023. Many of the hay bales have fallen, and the front entryway was beginning to collapse, falling forward by over 50cm, now stabilized with a pillar and rendering the entrance unpassable (McAvoy, 2025c). For these reasons we focus on comparisons to the foundation, drawing a horizontal cross section 10 centimeters above the ground inside the museum (figure 9).

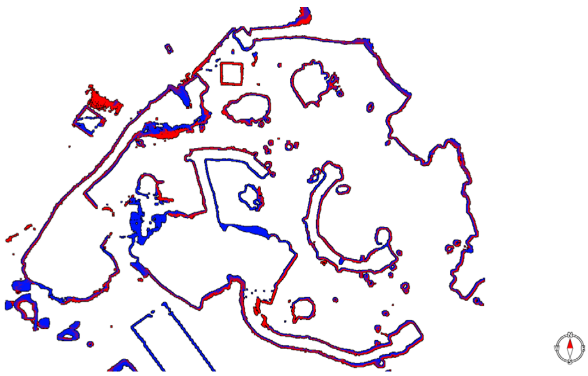


Figure 9. horizontal cross section of Museum structure

We first begin by comparing the 2025 Looq scan to the 2023 terrestrial LiDAR scan. Comparing the global alignment, the Looq’s on board GPS with the GNSS RTK survey completed in 2023, we observe a consistent 4cm eastern offset. Compared locally, the RMS of the cloud-to-cloud alignment was within 2.2cm (figure 10).

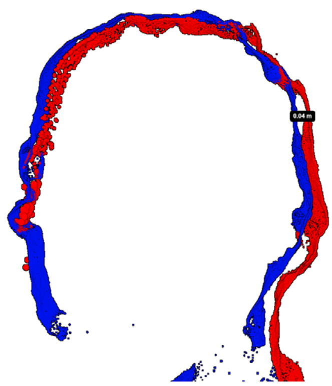


Figure 10. Looq 2025 scan in red to 2023 gnss/rtk in blue

A second comparison is performed between the Looq scan and 2023 surveys performed with the Stonex x120 go SLAM LiDAR

MMS system which had been aligned using the same 2023 control points as the RTC 360 survey. As coverage for the Stonex scanner was lacking within the Museum, we decided to analyze another smaller interior structure called the "Hogan" (figure 11).

Figure 11. Hogan structure, Salvation Mountain

A comparison of the horizontal cross section, of the 5m x 2.5m interior, again placed 10cm above ground, showed an average global offset of 2 cm to the east. A local alignment returned an RMS error of 1.3 cm (figure 12)

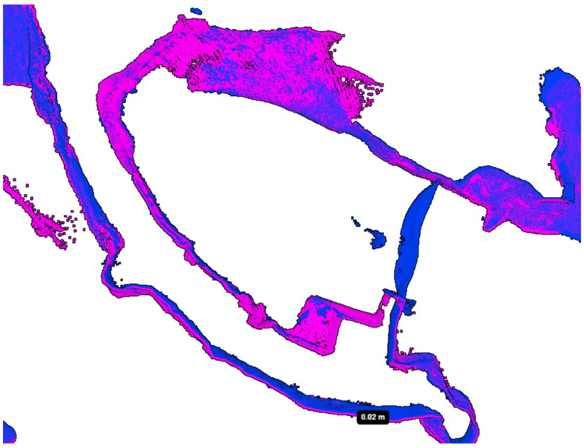


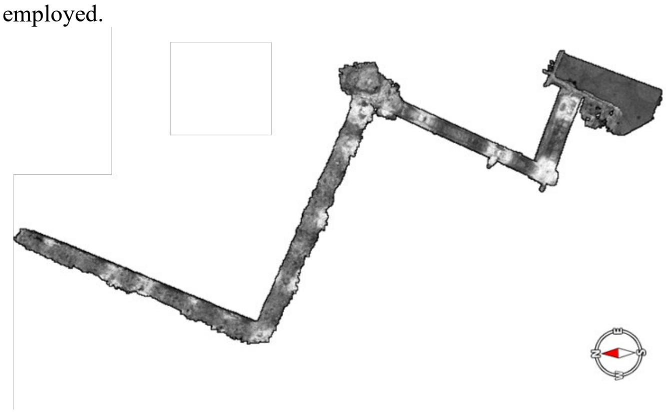
Figure 12. Looq Scan in blue, StoneX LiDAR in magenta

Surface quality of the Looq was better, with less visible noise, and surface density for both systems were approximately 1 cm, as the space was tight.

3.4 Tunnels and Cave Systems, Mexico

Subterranean structures feature a range of logistical and morphological challenges for 3d documentation, making mobile mapping systems attractive options for documentation. In a number of cave entrances relating to the Maya site of Chichen Itza in Yucatan (McAvoy, 2023), and the Sac Actun Cave system in Quintana Roo, Mexico, several surveys were performed incorporating the Hovermap 100 SLAM mobile LiDAR system (Rissolo, 2024), the Leica BLK 360 g2 and Looq multi-cam system (figure 13).

Beneath the pyramid of El Castillo at the Maya site of Chichen Itza, are two tunnels dug in the early 20th century in order to locate the sub-pyramid below. We performed comparative analysis of these tunnel scans (McAvoy, 2025a). The southern tunnel begins on the eastern side of the southern stairway, is about 50 meters long, 1 meter wide, and 1.8 meters tall (figure 14). There is no light and the Looq's strobe feature was employed.



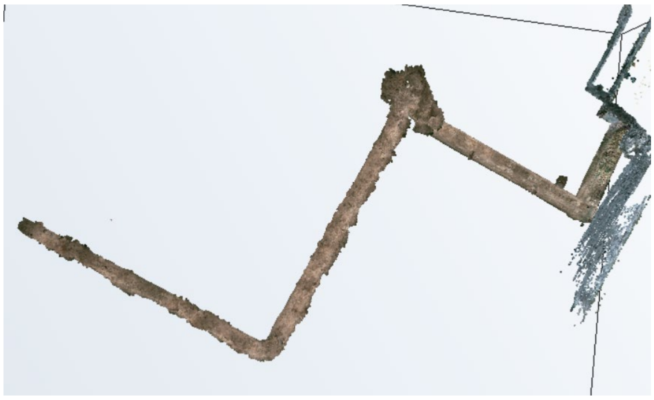


Figure 13. El Castillo south tunnel BLK 360g2 above, Looq scan below.

The tight space proved to be a problem for the BLK 360, which created blank spots for areas too close to the sensor, and warping vortexes of white (high intensity) points around them, deforming the surface by up to 2 cm (figure 14.).

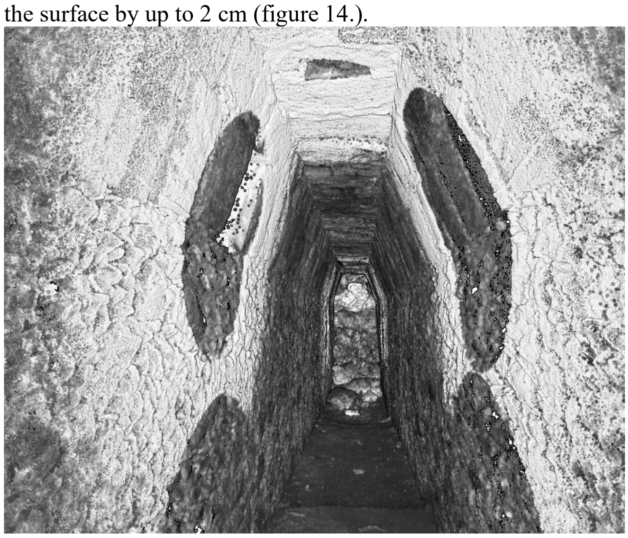


Figure 14. El Castillo South Tunnel interior, featuring distance-based deformations

The Looq captured the walls without issue, but the dark distant points left some black noise in the center of the tunnel and had some green color shift towards the edges of the light falloff (figure 15).

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Figure 15. Looq Interior El Castillo south tunnel

Several scans in Yucatan are incorrectly tilted (figure 16).. We have observed this issue with the Looq, but also using 3D scans performed with non-rtk enabled drones. For this reason, we are inclined to blame some unknown GPS network related issue rather than the Looq system itself. We are currently unsure of the cause of the issue, and we are forced to correct our scans against a 1 meter resolution fixed wing aerial LiDAR basemap.

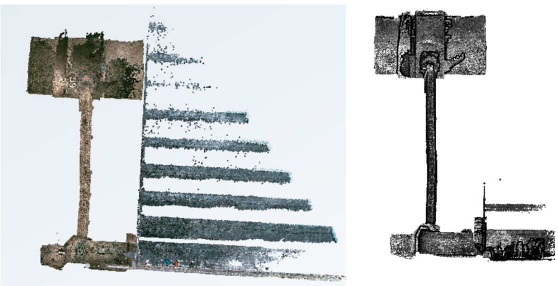

Figure 16. GPS errors, 2 degree downward tilt from west to east (left) correct positioning Hovermap (right).

3.5 San Marino Seismic Studies

The historic city center of San Marino is at risk of seismic activity, with much of its monumental architecture placed along a cliffside with a vertical dropoff (figure 17). To identify architectural features related Documentation campaigns were conducted with the Leica BLK 360 terrestrial laser scanner, and the Looq multi-cam system The survey consisted of 9 Looq scans, consisting of approximately 27,000 geolocated photos over a 3.5 kilometer path, along with 484 terrestrial lidar scans, and 11,653 high resolution images captured with a Sony A7 R3 mirrorless camera (McAvoy, 2025d).

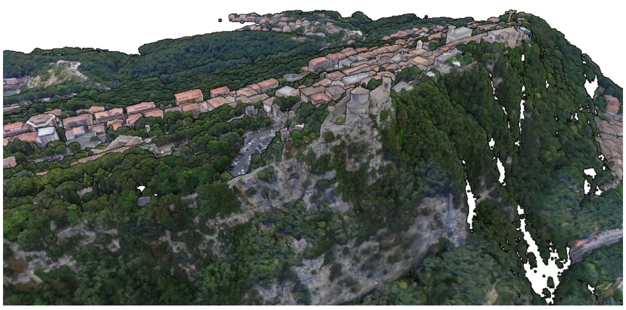

Figure 17. 2017 drone survey of San Marino Historic city center above (Lo, 2023)

Here, we compare the alignment of a Looq scan (figure 18) to drone photogrammetry. The drone survey was relatively low resolution, performed at a high altitude with a resolution of approximately 10cm. The Looq scan portrays an entirely different view of the city, made from ground-based observation, lacking the roofs, and sharing only features on the streets. An alignment showed a RMS error of approximately 21 cm, and a horizontal global shift was observed at 2.3 meters east to west.

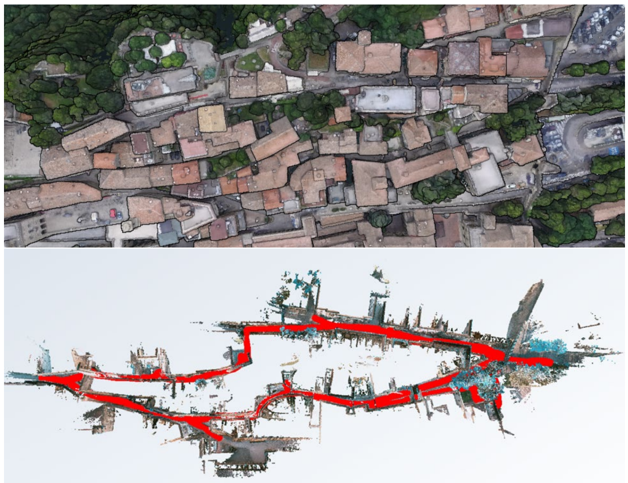

Figure 18. drone scan of Marino historic city center. Drone survey above, Looq survey below.

3.6 Florence Pedestrian Filters

and Florence, Italy, features densely packed urban environments with heavy tourist traffic. The presence of people and vehicles present challenges, both for reconstruction of 3D scenes, and present an ethical dilemma as we decide how to disseminate imagery featuring individuals who have not given their consent (figure 4). Though this may be legally defensible in many parts of the western world, many cultures have different understandings of privacy and public spaces, and it is generally considered best practice to remove humans from raw imagery (McAvoy, 2025b).

Figure 19. Photogrammetric model of Ponte Vecchio in Florence, Italy (left) and automatically masked image input, removing human (right)

4. Discussion

For precision mapping and ground truth use cases, terrestrial LiDAR and total station GNSS survey methods naturally remain the definitive baseline for achieving the greatest levels of accuracy and detail. However, recent mobile mapping systems as detailed here have exhibited demonstrable progress in becoming a viable alternative for regular survey tasks, especially in instances where time efficiency and accessibility remain high priorities. Such cases may include those where a high survey frequency is necessary in environments prone to continuous change, or those where time allocations and specialized training may need to be optimized.

Though the Looq software processes account for moving objects like cars and people, the weaknesses inherent to interval bases photogrammetric tie point matching cause significant error in vegetated environments. It leads to the suboptimal, scattered reconstruction (treeconstruction) of swaying vegetation, and potential deformation of entire scenes.

MMS-based surveys across our case studies have unanimously demonstrated greater time efficiency by several orders of magnitude, as well as significantly decreased requirements for per-scan setup and needs for manual processing intervention and complexity. TLS-based systems generally demand some degree of understanding of runtime settings configuration, capture methodologies and setup, and data processing techniques, including scan alignment, GNSS total station data registration, data exports, and visualization. Mobile mapping systems, such as the tested Stonex and Looq systems, attempt to streamline these processes to a maximal extent by means of automation. A typical Looq capture, for instance, involves a walkthrough of a site, ensuring the capture of features of interest on a live image preview, and uploading a proprietary (LMR) capture file to Looq's cloud platform for processing. Data products, including masked panoramas, ortho-mosaic imagery, capture tracks, and point clouds are made available automatically after completion of processing, generally within 24-72 hours of initial upload. By nature of their capture methodologies, the tested mobile mapping systems have also demonstrated significant reductions in data acquisition time for a given site of interest.

The ongoing shortcomings of MMS in comparison to traditional TLS / total station methods lie largely in processed data quality. Due to reductions in overall sampling compared to full TLS systems, LiDAR-based mobile mapping systems may yield a relatively sparse set of spatial features compared to TLS and even imaging-based systems. Imaging-based systems such as the Looq, meanwhile, may exhibit instances of undesirable noise within the final point reconstruction, as well as a similar sparseness and possible misalignments across textureless surfaces lacking in distinctive features for extraction (Figure 20).

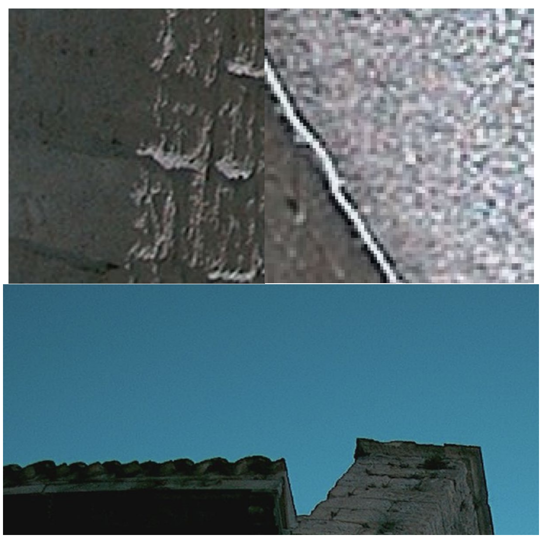

Figure 20. Samples of sensor noise and edge vignetting in Looq image data, leading to noise and chromatic artifacts in the final point cloud

We have observed some variance seen across Looq scans despite PPK corrections, and ground control points are still necessary to ensure accuracy. In some areas, we have observed significant deviation from our foundational basemaps, sometimes more than a meter. In many cases, especially regarding our use cases in Yucatan, we observe some tilting effect. In some cases, these issues are shared by other GPS positioned imaging systems, in some cases it's not. The error we observe is likely the combination of poor global signal quality, and the nature of our sites, further interrupting connections as we enter gps denied interior spaces, tight alleyways, caves… The requirements for the surveyed points are somewhat more relaxed with mobile mapping systems than for a full total station survey, but if we hope to use these data in future facing monitoring projects, it is at least necessary to have some sense of our expected accuracy. For the moment, given our range of test cases, we possess that confidence for GPS enabled environments within the United States but need to investigate further these issues we've observed elsewhere. Looq has begun to offer a new feature incorporating Post-Processed Kinematic (PPK) correction through the addition of a separate Rinex file. This feature is designed to compensate for the kinds of issues described above, but these integrations require further evaluation.

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