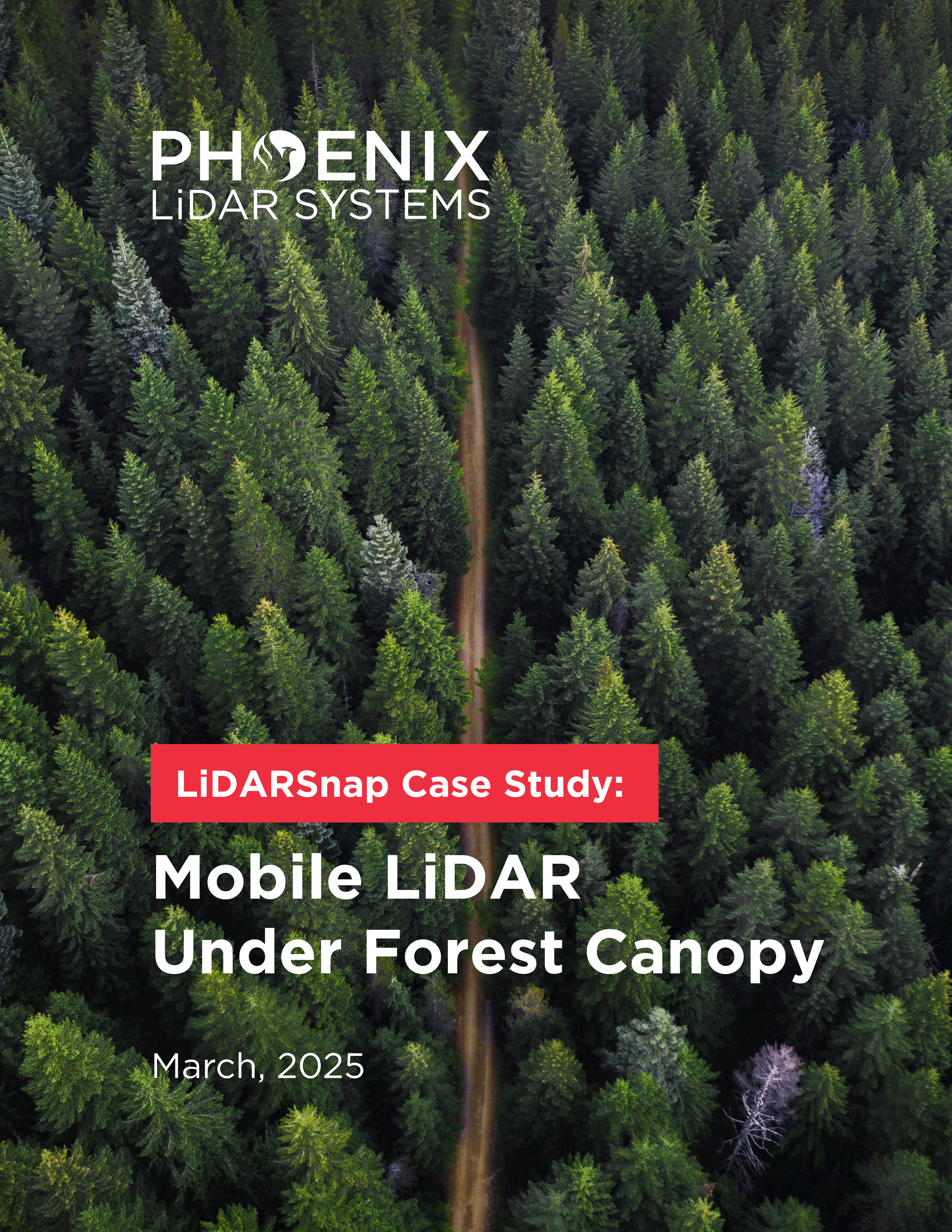

PHOENIX LiDAR SYSTEMS

LiDARSnap Case Study:

Mobile LiDAR Under Forest Canopy

March, 2025

Introduction

Phoenix LiDAR's LiDARSnap strip alignment tool was tested using a challenging mobile LiDAR data set. The data set was collected along a rural state road, Natchez Trace Parkway, near Mathiston, Mississippi. About 17.5 km of Natchez Trace Parkway was mapped using the RANGER Flex dual-head mobile LiDAR mapping system.

Of the 17.5 km mapped, nearly 85% was covered by a dense tree canopy. This dense tree canopy presented an accuracy challenge, as GNSS signals were mostly unavailable. LiDARSnap was used to not only calibrate the relative accuracy of the two passes, but also to georeference the scan in respect to leveled control. This paper discusses the processing workflow, results, and capabilities of LiDARSnap in challenging, GNSS-denied environments.

The Data Set

The RANGER-Flex RFM2 Mobile Mapper

The RANGER Flex RFM2 system was used to map Natchez Trace Parkway, near Mathiston, Mississippi. This RFM2 system utilizes two Riegl VUX-1UAV sensors, along with a Ladybug5+ panoramic camera, and is designed for high accuracy mobile LiDAR mapping. The VUX-1 sensors recorded lidar data at 1200 kHz each, resulting in a single-pass point density on the road surface of approximately 5000 points per square meter. For navigation and positioning, the RFM2 utilized a fiber-optic gyro IMU and a NovAtel GNSS receiver.

Figure 1
RANGER Flex RFM2 Mobile LiDAR System

Natchez Trace Parkway

Natchez Trace Parkway is a two-lane road with dense tree cover throughout most of the road. This dense tree canopy creates a significant positioning challenge.

Figure 2
Natchez Trace Parkway as seen from the Ladybug5+ mapping camera. Trees line the road on both sides.

Both lanes of Natchez Trace Parkway were mapped at an average speed of 45 mph, and in total approximately 35 km of lane-miles of LiDAR data were collected in about 1 hour.

Processing Workflow

Trajectory Processing

An initial trajectory was computed using Novatel's Inertial-Explorer. The quality of this trajectory was far from suitable for mapping grade LiDAR production. Throughout the data set, the navigation system tracked mostly a single-digit number of satellites, or no satellites at all. Several periods of complete loss of GNSS satellites were experienced, the longest of which lasted over 300 seconds. This lack of GNSS data was the primary challenge of the data set, and produced horizontal and vertical positioning errors over several meters.

Pointcloud Production and Calibration

Due to the poor accuracy of the initial trajectory, pointcloud relative accuracy (strip-to-strip) was also very poor. Many areas of the data set had strip-to-strip separation of several meters:

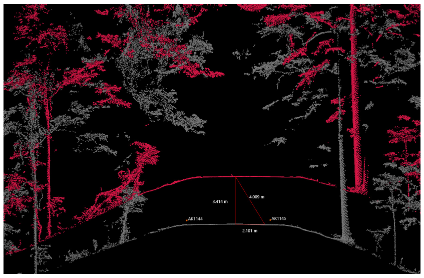

Figure 4
In many areas, strips were misaligned by more than 3 meters vertically, as well as horizontally misaligned by about 1 meter.

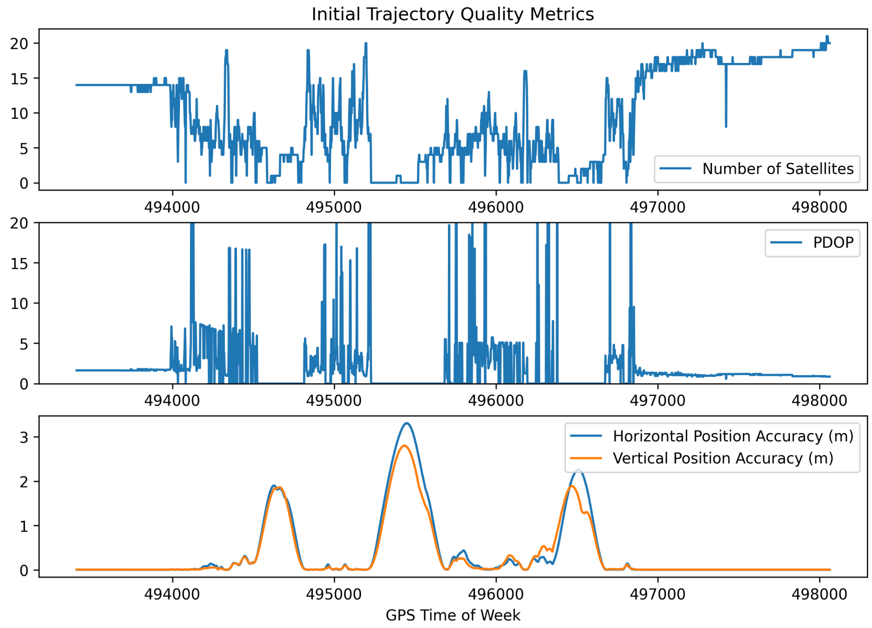

Figure 3
Number of satellites, PDOP, and position accuracy. Position accuracy defined as the standard deviation of the position solution components (horizontal and vertical).

LiDARSnap was used to calibrate the data, resolve the strip-to-strip misalignment, and georeference the scan accurately in respect to ground control points (GCPs).

LiDARSnap and Correspondences

LiDARSnap is a LiDAR calibration tool. This means that LiDARSnap is used to adjust strips, or individual passes of LiDAR data, to improve relative and absolute accuracy. LiDARSnap uses observations in the data set, which can be either pointcloud observations or GCP-to-pointcloud corrections, and makes adjustments based on the available observations.

In a purely LiDAR use-case, with no available GCPs, LiDARSnap attempts to find matching surfaces in the pointcloud data which can be used to derive a correction. These matched surfaces, also known as a ***correspondence***, must be in the same general location and have the same orientation.

LiDARSnap searches for correspondence at a radius specified by the user, known as the ***Sampling Radius***. When sampling for correspondences, orientation of surfaces is determined by modeling the surface and projecting an orthogonal ***normal vector*** out from the surface:

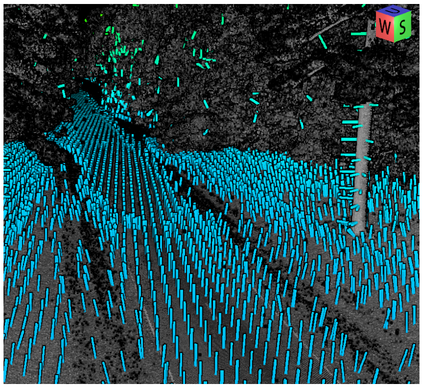

Figure 6
Correspondences detected on tree trunks and the road surface.

Adjustment Rate and Parameters

Once a sufficient number of correspondences are found in an area, LiDARSnap is able to

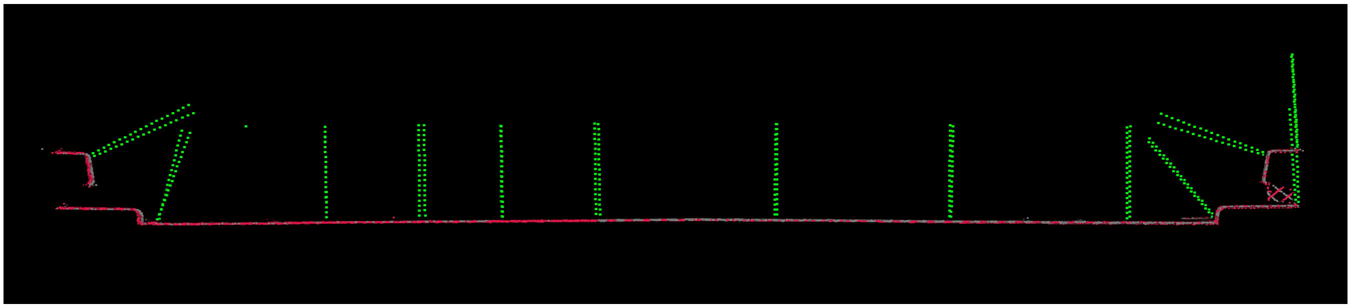

Figure 5
Normal vectors computed by LiDARSnap (green) are visualized on a bridge in profile view. The guard rail has normals at approximately 30 degrees, while the road surface has normal vectors at 90 degrees.

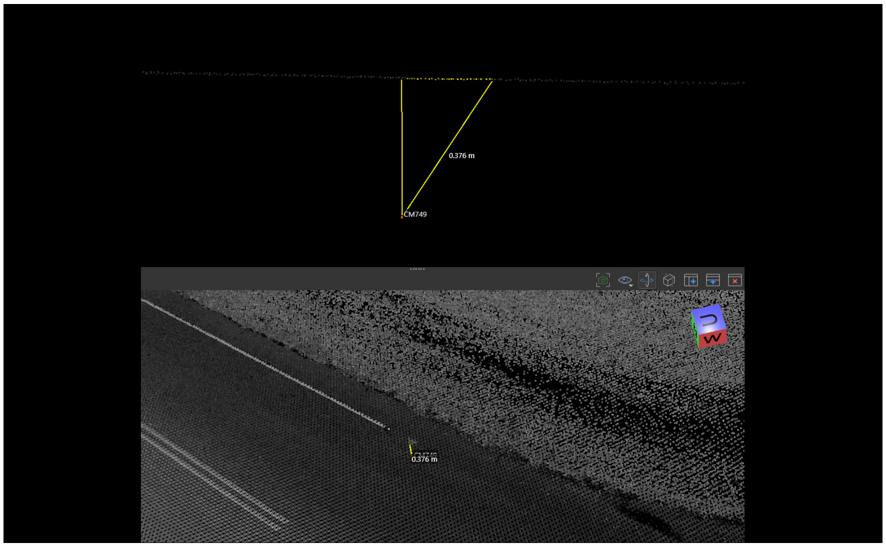

Figure 7
Small triangular targets along the roadway are identified in the LiDAR intensity data, and a 3D correction in respect to a GCP (CM749) is created.

compute an adjustment to reduce the residuals between all correspondences. A residual is the 3D distance between two matched surfaces, or between a GCP and a point in the pointcloud (more on GCPs in the next section).

Once a sufficient number of correspondences are observed in a given area, LiDARSnap should be capable of adjusting the trajectory so that the residuals are reduced. The ***Trajectory Adjustment Rate*** (TAR) parameter controls this functionality. During adjustment, the trajectory is divided into sections based on this parameter. Each individual section of trajectory can be adjusted independently of the other sections, which enables LiDARSnap to make the required variable adjustments throughout the data set.

At each of these sections, LiDARSnap is able to adjust only the parameters allowed by the user. At any given point along the trajectory, there are 6 adjustable parameters: **east, north, up, roll, pitch,** and **yaw**. East, north, and up indicate the position of the vehicle, while roll, pitch, and yaw collectively indicate the orientation of the vehicle.

Ground Control with LiDARSnap

GCPs can be integrated with LiDARSnap and function as observations, just like pointcloud correspondences, albeit with a different weighting during adjustments.

With a typical, less-challenging mobile data set, where GNSS positioning is relatively accurate, GCPs play a less involved role in the LiDAR calibration workflow. In such cases, calibration of the data is mainly a strip-to-strip exercise. GCPs may be used in some areas to help accurately georeference the data; however, they may not be needed throughout the entire data set, particularly in areas where the initial trajectory accuracy is high.

GCPs can be used either as vertical observations or as full observations (i.e. 3D observations, vertical and horizontal). If GCPs are used only as vertical observations, the vertical position of a GCP can be assumed as being the ground near the GCP, and it is not necessary to visually identify the GCP target within the pointcloud. If horizontal correction in respect to GCPs is required, a 3D correction must be created manually by the user. This workflow involves the user identifying the horizontal location of the GCP in the LiDAR data, typically by visualizing the LiDAR by its intensity values. This 3D correction method was used with the Natchez Trace Parkway data set; manual corrections can be seen visualized in 3D by a yellow correction vector.

In the case of a particularly challenging mobile data set, it may be necessary to create many manual corrections between GCPs and the cloud, to help tie down the cloud to the GCPs and achieve accurate absolute georeferencing of the pointcloud data.

Parameters Used

LiDARSnap was run using a 0.5 second trajectory optimization rate, with all parameters (north, east, up, roll, pitch, yaw) enabled for optimization. Corrections in respect to GCPs were made every 152 m (500 ft). The sampling radius for correspondences was set to 1 m, and normal search radius was set to 10 cm.

Results

LiDARSnap processing completed in approximately 2 hours. After running LiDARSnap, average error in respect to ground control was 0.009 m, compared to the unoptimized average error of 0.726 m. Relative accuracy, strip-to-strip residuals, also saw a drastic improvement, with the standard deviation of correspondence residuals being reduced from 0.879 m to 0.024 m. Results are summarized in the table below:

	Minimum GCP 3D residual (m)	Maximum GCP 3D residual (m)	Mean GCP 3D residual (m)	Standard deviation of cloud-to-cloud correspondences (m)
Before Optimization	**0.018**	**4.460**	**0.726**	**0.879**
After Optimization	**0.001**	**0.067**	**0.009**	**0.024**

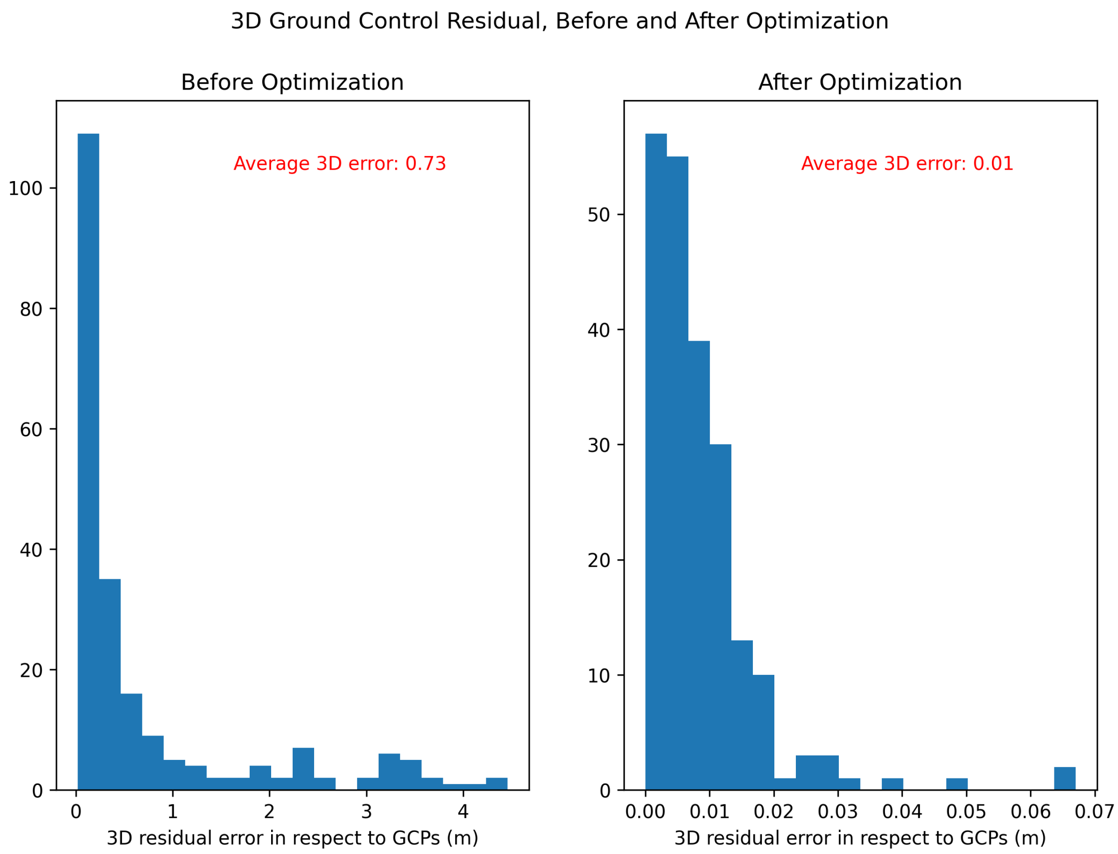

Figure 8
3D residual error in respect to GCPs, before and after optimization via LiDARSnap.

Cloud-to-cloud 3D residuals (i.e. relative misalignment between strips) improved as well. The standard deviation of the correspondence residuals decreased from 0.879 m pre-optimization to 0.024 m. Note that standard deviation is used when referring to cloud-to-cloud correspondences, because typically the mean residual is near-zero, due to half of the correspondences being negative, and half being positive.

Spatially, results were consistent, and the entire project area exhibited a low error in respect to control after adjustment:

Conclusion

Accurate LiDAR data production proved to be possible on Natchez Trail Parkway, despite the GNSS-denied, tree-tunnel conditions. The horizontal and vertical accuracy of the initial trajectory, produced by InertialExplorer, ranged between a few centimeters to several meters. Using an unoptimized trajectory, the average error in respect to control was 0.726 m, with residuals ranging from a few centimeters to over four meters. After running LiDARSnap, these GCP 3D residuals were reduced to an average of 0.009 m. LiDARSnap also improved the strip-to-strip, relative accuracy of the data, and reduced the standard deviation of cloud-to-cloud correspondence residuals from 0.879 m to 0.024 m.

These results show that even with challenging, GNSS-denied data sets, LiDARSnap is able to achieve sub-centimeter absolute accuracy in respect to control.

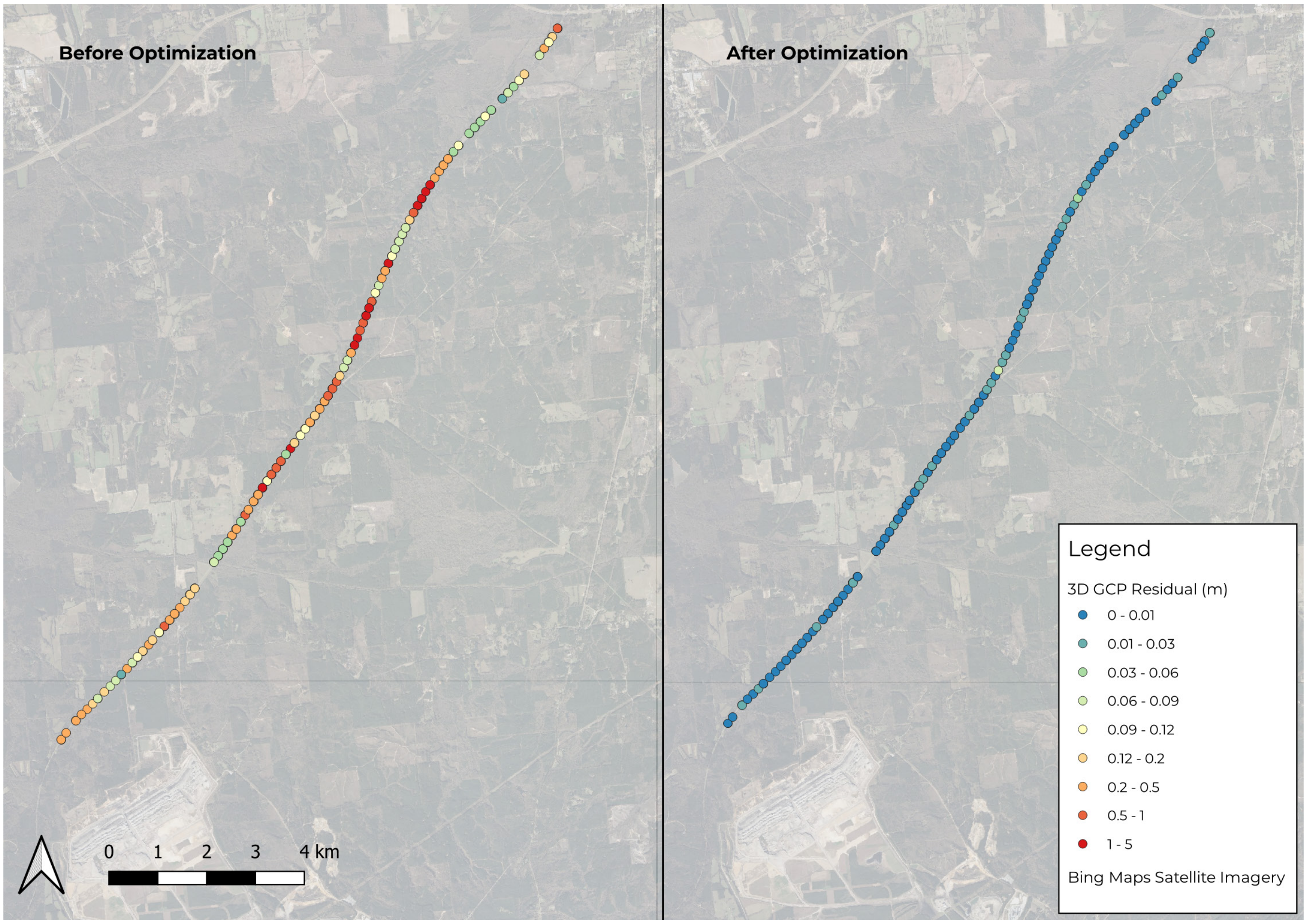

Figure 9
3D residual error in respect to control before and after optimization via LiDARSnap.