PHOENIX LiDAR SYSTEMS

A PHOENIX LiDAR CASE STUDY | MAY 2025

RANGER-FLEX Calibration Stability Analysis

INTRODUCTION

MODULARITY IS A KEY FEATURE OF THE RANGER-FLEX LASER MAPPING PRODUCT LINE. These systems can be quickly reconfigured, with sensors added and/or removed, to allow for optimized utilization on a variety of vehicle types. Modularity also presents a challenge: How can a system calibration, which is a cornerstone of data accuracy, be preserved if laser scanners and cameras are routinely separated from each other and from the navigation system? The **RANGER-FLEX** has been engineered to specifically address this, and a series of datasets were collected to test the stability of its calibration.

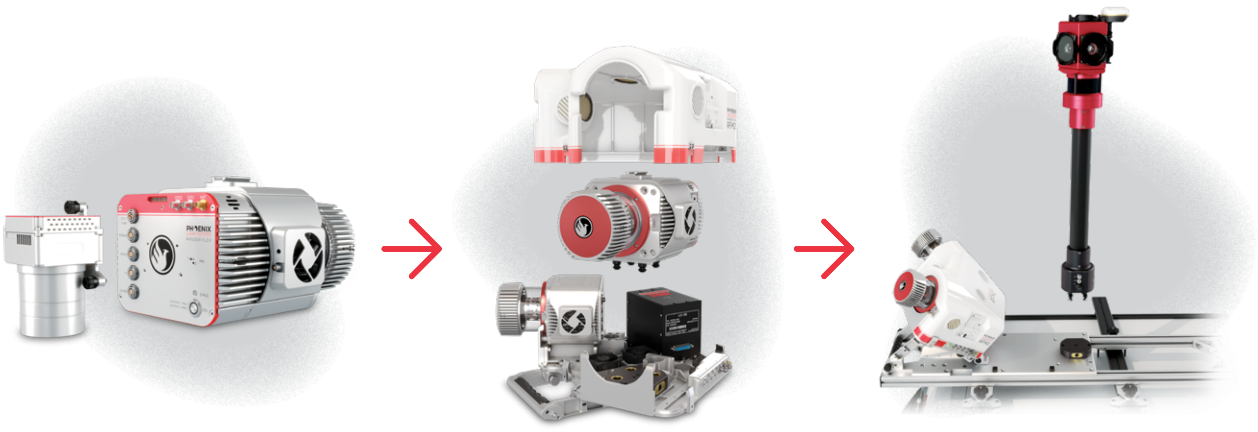


FIGURE 1: *An example of the modularity of the RANGER-FLEX System*

SYSTEM CALIBRATION

Sensor calibration, in the context of kinematic LiDAR data production, refers to a sensor's calibration in respect to the LiDAR system's inertial navigation system (INS). LiDAR points collected by the LiDAR sensor are georeferenced using a vehicle trajectory created by the INS. To accurately georeference these points, the location and orientation of the LiDAR sensor in respect to the INS must be known and controlled for. Orientation values are of particular concern, as angular misalignment between the INS and LiDAR results in significant point-cloud georeferencing error. This precise angular alignment of the LiDAR sensor with the INS is often referred to as a "boresight" or simply "calibration."

Pre-calibrated values (degrees)	Post-calibrated values (degrees)
X: 90.000°	X: 89.721°
Y: 0.000°	Y: 0.173°
Z: 180.000°	Z: 179.888°

FIGURE 2: *Example LiDAR sensor calibration values are shown. Initially, coarse, pre-calibration values are extracted from mechanical CAD drawings. These values are then refined through a software routine for each system.*

Robust system calibrations are determined through the collection and analysis of purpose designed projects. The targets utilized and the perspectives from which they are measured affect the observables that are required to solve for systemic calibration parameters, like rotational corrections around the yaw, pitch, and roll axis.

System calibrations are computed by the LiDAR post-processing software, in this case LiDARSnap. LiDARSnap and other similar software routines typically solve for these calibration values using a least squares parameter estimation method. This means that the software produces calibration values which best reduce observed residuals. In this context, residuals are essentially the alignment error between different passes of LiDAR data on hard surfaces, like the roadway and buildings (i.e. strip alignment errors). Residuals may remain even after this least squares optimization, such as residuals that are due to trajectory error. It's also important to keep in mind that the estimated calibration values are determined from the observations in the data set, so values will change slightly between different data sets.

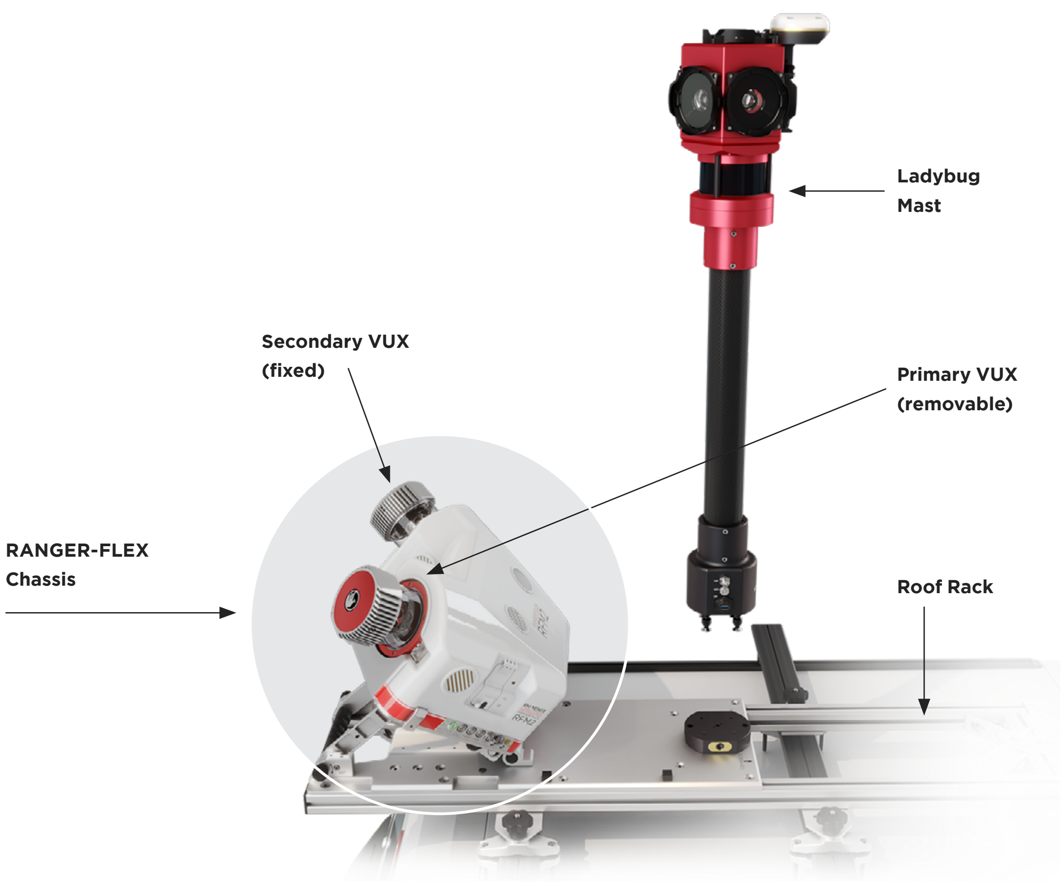
Generally, system calibrations are not performed at the same time as mapping projects, especially in mobile LiDAR mapping, because the content of a scanned area may not contain sufficient surfaces to solve for all angular boresight parameters. Attempting to solve for yaw misalignment along a mostly featureless highway is a case in point. In order to achieve high efficiency over the course of multiple mapping missions, it is highly advantageous to avoid the need for regularly recurring system calibrations.

HARDWARE DESIGN

The **RANGER-FLEX** has unique mounts designed for maintaining the calibration of its modular components. Removable components on the RFM2 mapping system use a locking sensor mount to ensure calibration stability. This mount uses four pull studs, which are seated and secured via a locking mechanism. The locking mechanism is engaged with a torque specification to ensure repeatability during mounting.

Removable components on the RFM2 include the primary LiDAR sensor and 360° spherical camera mast. This enables the primary LiDAR sensor, which houses the data recorder and navigation system, to be used for other LiDAR applications, typically UAV LiDAR acquisition. Removal of the Ladybug camera facilitates easy storage and transport of the system.

FIGURE 3: *The RANGER-FLEX modular sensor mounting system*



REPEATABILITY EXPERIMENT

To test the calibration stability of the locking sensor mount system, several data sets were collected using a calibration designed drive pattern at a calibration site, and then analyzed.

1. Baseline: The 1st mission collected data that was used to determine a baseline system calibration.

2. Control: The 2nd and 3rd data sets were collected as experimental control, without removing any hardware. The purpose of these were to observe the jitter (or variance around a mean) in computed calibration values, even when the system is not physically changed.

3. Experiment: A 4th mission was conducted to acquire the calibration stability experimental dataset. Prior to data acquisition the primary scanner, VUX0, was removed from the system chassis to introduce the zero-point mount as a variable.

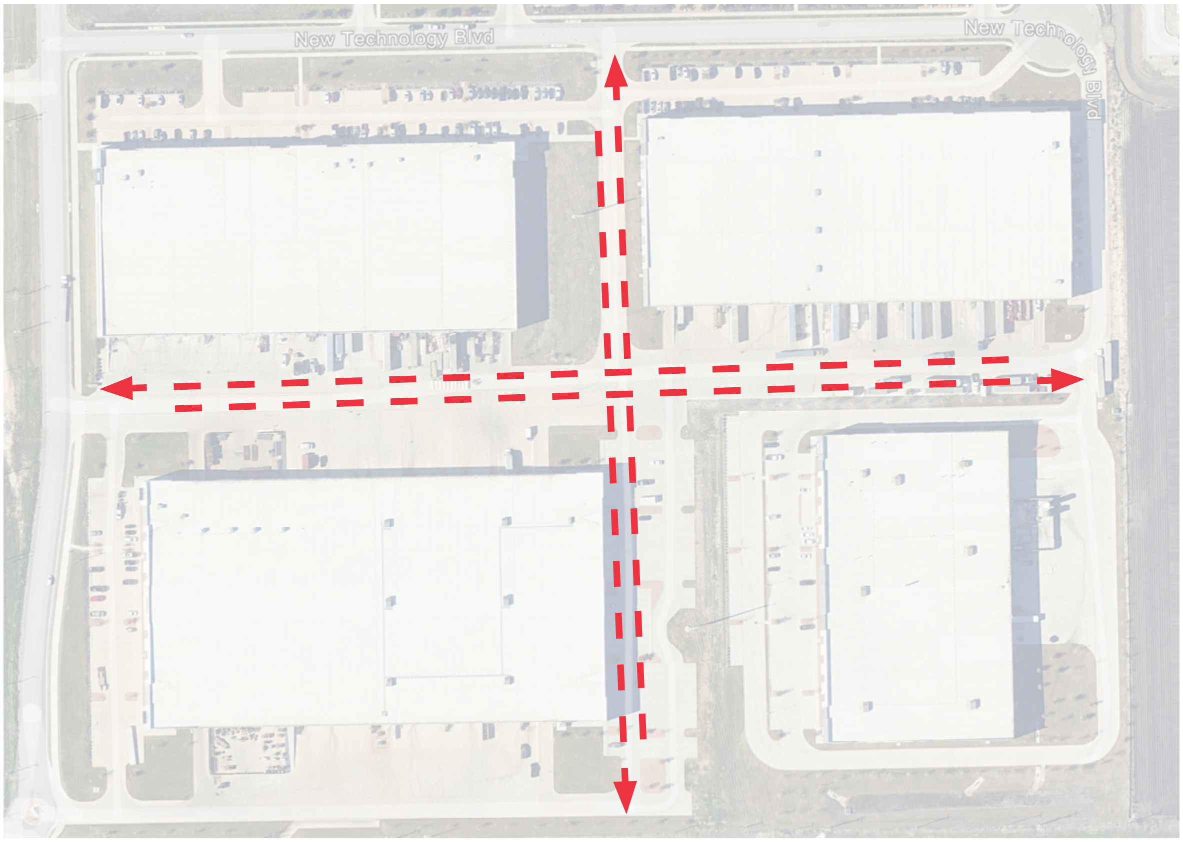


Figure 4: *The calibration site and path used during all missions.*

REPEATABILITY EXPERIMENT

Each of the 4 missions were separately processed in SpatialExplorer, and LiDARSnap was used to determine unique sensor calibrations. No trajectory optimization was used during this experiment. The resulting calibration values for the **control** and the **experiment** dataset were compared to the **baseline** dataset's values. Specifically, the comparison of the calibration values between missions was performed along IMU axes (X, Y, and Z), and from these individual components a total magnitude rotation vector was computed. This total magnitude value summarizes how much adjustment of the baseline calibration was required to optimally align it with the IMU frame per mission. The changes in estimated calibration values are summarized below in table 1.

Control datasets' differences were averaged to determine how much variance there is in calibration values even when the equipment is unchanged. The difference between the **experiment** data and baseline shows the stability of a system calibration when the removable scanner is detached from the FLEX RFM2 chassis recalibrated.

From the results we see that calibration values can vary by about 0.01°, even when the system is unchanged. This is evident in the two control drives, for which LiDARsnap computed calibration values which were about 0.01° different from the initial calibration. This variance can also be observed with the secondary VUX (VUX1) values observed in all data sets. The secondary VUX is permanently fixed to the RFM2 chassis, and its calibration values varied between data sets by about 0.01°. This shows that changes in calibration values cannot really be observed below 0.01°. When the removable scanner, VUX0, was removed and reinstalled, the calibration values changed by about 0.027°.

	VUX0 (removable sensor)				VUX1 (fixed sensor)			
DATASETS	X	Y	Z	**TOTAL**	X	Y	Z	**TOTAL**
Control 1 vs. Baseline	-0.0113°	0.0021°	-0.003°	**0.0120°**	-0.0067°	0.0016°	-0.0001°	**0.0069°**
Control 2 vs. Baseline	-0.0029°	-0.009°	-0.0006°	**0.0095°**	-0.0023°	0.0105°	-0.003°	**0.0112°**
Control average	-0.0071	-0.00345	-0.0018	**0.01075**	-0.0045	0.00605	-0.00155	**0.00905**
Experiment vs. Baseline	-0.0158°	0.0221°	-0.0021°	**0.0272°**	0.0055°	0.0103°	-0.0032°	**0.0121°**

Table 1: *Angular difference, in degrees, between calibrations computed in two different data sets. Per-axis (X,Y,Z) differences are shown along with a total angular magnitude.*

CONCLUSION

People who are familiar with LiDAR calibration may have a contextual understanding of how significant this 0.027° change is. However, LiDAR data providers typically seek to achieve certain accuracy standards in respect to strip-alignment, so placing this angular calibration stability in a more conventional accuracy context is important.

Relative Accuracy

RMSΔz		
Experiment dataset with baseline sensors calibration	Experiment dataset with recomputed sensors calibration	Overall system accuracy impact
0.0157 m	**0.0132 m**	**0.0025 m**

TABLE 2: *The relative accuracy of the experimental dataset using the baseline and an updated calibration.*

The experiment dataset was used to generate 2 different point clouds: 1 that used the baseline calibration values, and 1 with recomputed values. Each of these point clouds was evaluated with an automated reporting tool in SpatialExplorer which summarized their relative accuracies (alignment of data from different passes) as RMSΔz based on vertical differences between passes. In this context, the recalibration of our experiment dataset resulted in a 0.0025 m accuracy improvement. This means that the removal and reinstallation of VUX0 impacted the systems data quality by 2.5 mm.

CONCLUSION

Scan Range & Accuracy Standards

LiDAR error can come from many sources, but generally the trajectory and system calibration are the most common sources of error in a properly functioning system. Table 3 shows the scan range at which an angular calibration error of 0.027° allows a dataset to meet various accuracy standards. This method is idealized, as it assumes no trajectory error, but nonetheless it can be used to put into context the angular calibration stability value.

Accuracy standard		FLEX calibration stability	Range at which calibration stability impact exceeds accuracy standard	
ft	m		ft	m
0.020	0.006	0.027°	**42.44**	**12.93**
0.040	0.012	0.027°	**84.88**	**25.87**
0.060	0.018	0.027°	**127.32**	**38.81**

TABLE 3: *Data accuracy standards and extrapolated conforming scan ranges.*

For the most stringent accuracy standards, the conservative approach may be to recalibrate a system before each mission, however the **RANGER-FLEX** mount system ensures stability between calibrations, which is particularly helpful when data sets are not suitable themselves for sensor calibration.