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16. ABSTRACT

The California Department of Transportation (Caltrans) continually seeks ways to deliver transportation projects more safely and efficiently. To produce high-quality projects and optimize limited transportation dollars, Caltrans needs to continually innovate and improve existing processes and procedures. Identifying which tools are best to use for specific purposes and how to integrate data collected from various platforms can help in determining the safest and most cost-efficient way of doing business. Caltrans, via research Task 3179 under Contract 65A0749, established a Geospatial Technology Proving Ground (GTPG) facility to support the integration of mobile mapping and Light Detecting and Ranging (LiDAR)-based data collection systems into Caltrans' business practices. The Caltrans Survey Program and other Caltrans Divisions have a need for research to capitalize on the efficiencies gained through a "collect once, use it many times" best practice. With limited resources and higher public expectations, the current lack of collaboration among all parties involved in Caltrans' highway construction and asset management projects contributes to inefficient delivery of transportation projects. This report documents the research to leverage the existing GTPG facility and the new Caltrans-owned Trimble MX9 and MX50 Mobile Terrestrial Laser

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Research and Development of the Caltrans' Geospatial Technology Proving Ground

Kin S. Yen, Anh P. Duong, Dave Torick, Ty A. Lasky &
Iman Soltani: Principal Investigator

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July 31, 2025

California Department of Transportation

Division of Research, Innovation and System Information

Executive Summary

The results of this research helped the California Department of Transportation (Caltrans) Survey Program deliver a better product aligned with the department's Enterprise Statewide Field Data Collection efforts. Caltrans Surveys can help the department attain its goal of "collect once, use it many times" for all geospatial data, while producing known safety, efficiency, and cost benefits.

Problem, Need, and Purpose of Research

Minimizing risk to workers and the traveling public during Caltrans' operations is an on-going priority. Mobile Terrestrial Laser Scanning (MTLS) is a generational transformative technology for surveying. MTLS collects high resolution and accurate survey data quickly and safely for both workers and the travelling public. Caltrans previously established a Geospatial Technology Proving Ground (GTPG) facility to support the integration of MTLS data collection systems into Caltrans' business practices. The Caltrans Survey Program and other divisions needed research to capitalize on the efficiencies gained through a "collect once, use it many times" best practice. With limited resources and higher public expectations, the current lack of collaboration among all parties involved in Caltrans' highway construction and asset management projects contributes to inefficient delivery of transportation projects. The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center leveraged the existing GTPG facility and the new Caltrans-owned Trimble MX9 and MX50 MTLS systems to provide Caltrans with the needed capabilities.

Overview of the Work

This research included the following tasks:

- Deployment support for the new Caltrans MX9 MTLS system
- Investigate time-based vs. distance-based MTLS target spacing
- As-built survey pilot projects and recommend best platform for digital as-builts
- Explore means to improve the cross-functional programmatic collection of data
- Evaluate the use of MX9 for Americans with Disabilities Act (ADA) ramp survey

- Support Caltrans Office of Land Surveys (OLS) to update Caltrans MTLS Guidelines, including additional workflows for Caltrans MTLS units

Major Results and Recommendations

This project provided invaluable support for continual active deployment of MTLS technology within Caltrans. Key contributions of this research project included:

- Assisted OLS in the installation and deployment of new Trimble MX systems.
- Continued deployment support for six MTLS vehicles and support Trimble and California Surveying & Drafting Supply (CSDS) in troubleshooting and parts replacement of Caltrans MX systems.
- Performed testing and data analysis relationship between time-based and distance-based ground control point spacing with MTLS vertical and horizontal accuracy.
- Created documentation for MX system operation, maintenance plan, system installation, and vehicle integration.
- Demonstrated successful integration of a high-resolution camera with the MX systems. The MX system external sensor port may be used to trigger specialty external sensors data capturing and accurate geo-reference external sensors data. Infrared cameras, ground penetrating radar, and pavement polarized cameras for better crack detections are potential sensors useful for Department of Transportation (DOT) applications.
- Evaluated Trimble MX publisher, a web-based software for general users to view MTLS data in point cloud and imagery, for OLS.
- Assessed MTLS accuracy for ADA ramp slope measurements and developed best practices for MTLS ADA ramp data collection to ensure sufficient high point density and quality data for ADA ramp inspections.

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Acronyms and Abbreviations

Acronym	Definition
ADA	Americans with Disabilities Act
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
ASPRS	American Society of Photogrammetry and Remote Sensing
CAD	Computer-aided design
Caltrans	California Department of Transportation
CSDS	California Surveying & Drafting Supply
CU	Compute Unit
DMI	Distance Measuring Instrument
DOE	Division of Equipment
DOP	Dilution-of-Precision
DOT	Department of Transportation
DRISI	Division of Research, Innovation and System Information
DWS	Detectable Warning Surface
fps	Frames per second
GAMS	GNSS Azimuth Measurement Subsystem
GB	Gigabyte
Gb	Gigabit
GCP	Ground Control Point
GNSS	Global Navigation Satellite System
GPS	Global Positioning System

Acronym	Definition
GTPG	Geospatial Technology Proving Ground
GUI	Graphical User Interface
HDPE	High-density polyethylene
HTML	HyperText Markup Language
IMU	Inertial Measurement Unit
IP	Internet Protocol
JPEG	Joint Photographic Experts Group
kg	Kilograms
km	Kilometers
LAN	Local Area Network
LAS	LASer
LCC	Lens Cast Calibration
LiDAR	Light Detecting and Ranging
lbs	Pounds
LED	Light-Emitting Diode
MMS	Mobile Mapping Suite
MP	Megapixel
MPH	Miles Per Hour
MTLS	Mobile Terrestrial Laser Scanning
OLS	Office of Land Surveys
OSM	Open Street Map
PETG	Polyethylene Terephthalate Glycol

Acronym	Definition
POS	Position and Orientation System
RMS	Root Mean Square
RMSE	Root Mean Square Error
RWLS	Right of Way and Land Surveys
SFP+	Small Form-Factor Pluggable
SSD	Solid State Drive
SUV	Sport Utility Vehicle
TB	Terabyte
TBC	Trimble Business Center
TRCPS	Trimble Reality Capture Platform Service
TLS	Terrestrial Laser Scanning
TMI	Trimble Mobile Imaging
UHMW	Ultra-High Molecular Weight
USB	Universal Serial Bus

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Chapter 1: Introduction

Problem

The California Department of Transportation (Caltrans) continually seeks ways to deliver transportation projects more safely and efficiently. To produce high-quality projects and optimize limited transportation dollars, Caltrans needs to continually innovate and improve existing processes and procedures. In addition, the department needs to evaluate methods to lower project support costs, accelerate project schedules, minimize rework, and be transparent and accountable to taxpayers.

Minimizing risk to workers and the traveling public during Caltrans' operations is an on-going priority. Mobile Terrestrial Laser Scanning (MTLS) is a generational transformative technology for surveying. MTLS collects high resolution and accurate survey data quickly and safely for both workers and the travelling public. Caltrans previously established a Geospatial Technology Proving Ground (GTPG) facility to support the integration of MTLS data collection systems into Caltrans' business practices. The Caltrans Survey Program and other divisions needed research to capitalize on the efficiencies gained through a "collect once, use it many times" best practice. With limited resources and higher public expectations, the current lack of collaboration among all parties involved in Caltrans' highway construction and asset management projects contributes to inefficient delivery of transportation projects.

Objectives and Scope

The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center leveraged the existing GTPG facilities at Timbuctoo and Highway 113 with the new Caltrans-owned Trimble MX9 and MX50 MTLS systems to provide Caltrans with the needed capabilities.

Expected Benefit

The results of this research will help the Survey Program to deliver a better product that is aligned with the department's Enterprise Statewide Field Data Collection efforts. Caltrans Surveys can help the department attain its goal of "collect once, use it many times" for all geospatial data, while producing known safety, efficiency, and cost benefits.

Research Methodology

The research involved the following tasks:

- Task 1: Manage project
- Task 2: Deployment support for the new Caltrans MX9/MX50 MTLS systems
- Task 3: Investigate time-based vs. distance-based MTLS target spacing
- Task 4: As-built survey pilot projects and recommend best platform for digital as-builts
- Task 5: Explore means to improve the cross-functional programmatic collection of data
- Task 6: Evaluate use of MX9 for Americans with Disabilities Act (ADA) ramp survey
- Task 7: Support Caltrans Office of Land Surveys (OLS) to update Caltrans MTLS Guidelines, including additional workflows for Caltrans MTLS units
- Task 8: Develop final report

Overview of Research Results and Benefits

The key deliverables of this project include:

- Documentation of MX9/MX50 support efforts, including any updated workflow recommendations
- Documentation of recommendations for time-based vs. distance-based MTLS target spacing
- Documentation of lessons learned and best practices as well as recommendations for the best platform for digital as-builts
- Documentation of resulting means to improve cross-functional programmatic collection of data
- Documentation of evaluation of MX9 use for ADA ramp surveys
- Recommendations for OLS updates to the Caltrans MTLS Guidelines, including additional data collection methods, software, processing, data archiving, and file compression for Caltrans MTLS units
- Recommendations for OLS updates to Chapter 15 of the Caltrans Surveys manual as needed to reflect workflow improvements discovered in this research

Chapter 2:
Deployment Support for the New Caltrans MX9 and MX50 MTLS Systems

AHMCT researchers provided ongoing deployment support to Caltrans' Office of Land Surveys (OLS) for their use of the newly procured Trimble MX9 and MX50 MTLS systems. This work included field support for data collection as well as supporting Caltrans OLS update data collection workflow documents. It also included support for safe storage of District 3's MX9 at the AHMCT research center when the system is not in use.

This task included:

- Assisting OLS and Caltrans' Division of Equipment (DOE) to install and deploy five new MX9 systems and one MX50 system.
- Decommissioning the old Trimble MX8 and Riegl VMX-1HA systems. AHMCT researchers removed both MX8 and VMX-1HA MTLS units from the Caltrans vehicles so that the old MTLS vehicles can be reused for the new MX50 and MX9 system installations.
- Measuring sensor offsets and conducting system testing before deploying new MX systems to Districts.
- Designing, fabricating, and installing lens cover and its support structure for 360-degree camera.
- Procuring and installing vinyl covers for front planar cameras.
- Reporting any system errors along with system log files downloaded from MX9/MX50 systems to Trimble and CSDS technical supports.
- Conducting any repairs and component replacements as needed.
- Assisting Trimble, CSDS, and OLS with performing a major software and hardware upgrade to three MX9 systems and one MX50 system at the AHMCT shop.

MX System Installation

A Chevrolet Tahoe or Suburban is used for the MX system vehicle. These vehicles have rear passenger air conditioning for better cooling of the MX system computer(s) inside the MX Compute Unit (CU). DOE designed and fabricated custom vehicle roof racks for the MX9 systems. In addition, the DOE team designed and fabricated custom window pass-throughs for the MX system sensor cables. DOE personnel have also installed mounting platforms for the MX

system power supplies and CU boxes. Furthermore, DOE personnel mounted the Trimble T100 tablet on the center consoles.

All Caltrans MX system vehicles have vertical clearances between 9.5' to 10'. The custom roof rack for all the MX systems is made using by 2" x 1" tubing. Each custom roof rack has a mount for a front Global Navigation Satellite System (GNSS) antenna. Detailed MX system installation and deployment checklists are available in the Caltrans Trimble MX System Data Collection Workflow, Installation, Troubleshooting, and Maintenance Guide document.

Dual Battery Upgrade and Setup

Trimble recommended that the MX system vehicles should have dual batteries installed. The Tahoe and Suburban have physical space and battery mounting infrastructure under the hood for a secondary battery. A Group 96R battery fits the Tahoe's secondary battery bay. Secondary batteries were added to the MX system vehicles if the vehicles did not have a secondary battery installed.

Planar Camera Cap

Planar camera caps were added to cover the two MX9 front planar cameras to keep the camera lenses clean during transit to project sites. The Trimble MX9 planar camera cap is made of flexible vinyl caps (McMaster.com part #:9753K96 https://www.mcmaster.com/9753K96/) for a 3" to 3-1/16" outside diameter tube. It is available in black or red. A 3" diameter clear acrylic disc was fixed using double sided tape to the inside of the vinyl cap to prevent wind from pushing the flat vinyl area and contacting the camera lens. The 3" acrylic disc is available from Amazon (https://www.amazon.com/gp/product/B0932RM4WZ/ref=ppx_yo_dt_b_search_asin_title?ie=UTF8&th=1).

Design and Fabrication of MX 360-degree Camera Cover and Mounting Hardware

A 360-degree camera cap is needed to keep the 360-degree camera lens clean and protected during transit to the project sites. AHMCT researchers custom designed the 360-degree camera cap and mounting structure for the MX system. Computer-aided design (CAD) models and assembly, as shown in Figure 2.1, are available with detailed dimensions. The 360-degree camera caps are 3D printed with PETG filament plastics as shown in Figure 2.2. The 3D printed caps are each composed of two parts joined together using epoxy as shown in Figure 2.3. Three thread studs are added to secure the cap to the mounting structure. The AHMCT research team fabricated six complete sets of

camera caps and mounting supports. One spare 360-degree camera cap remained at AHMCT.

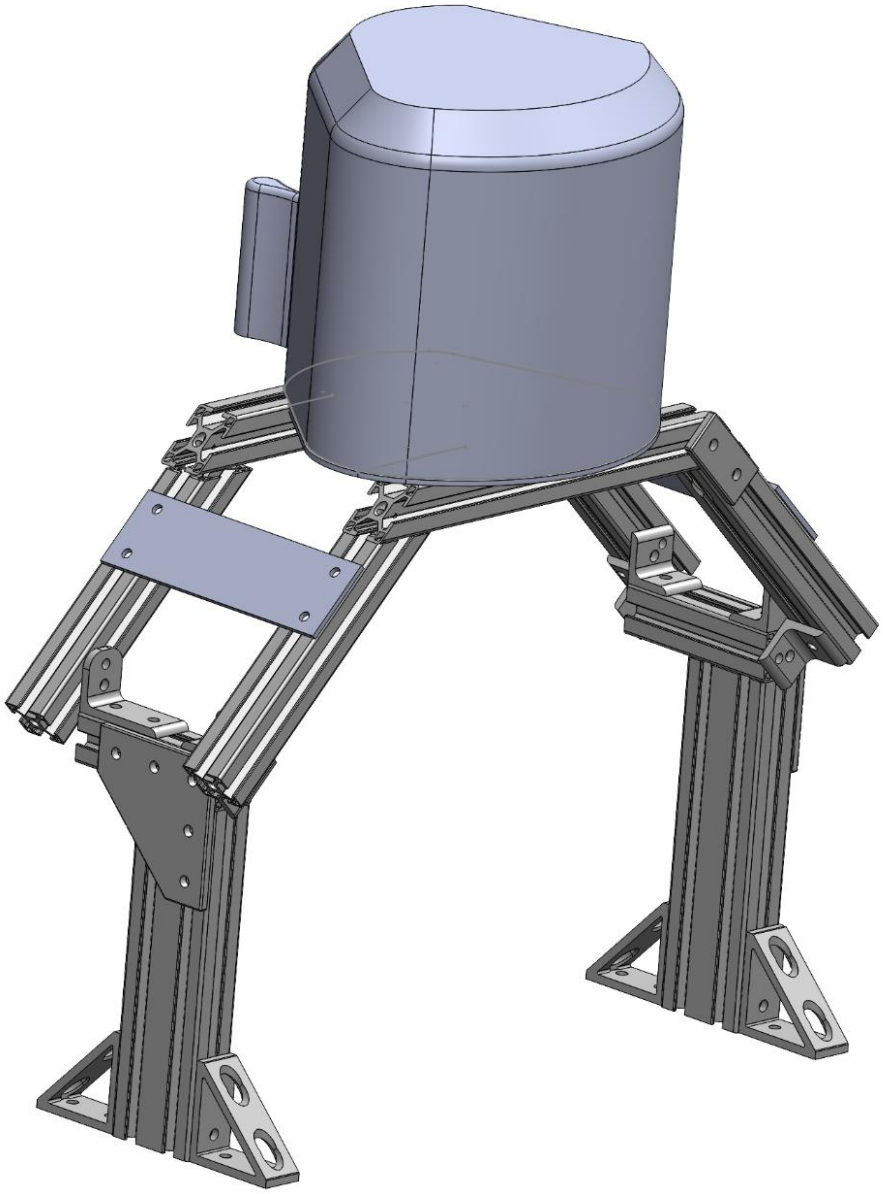


Figure 2.1: 360-degree camera cap and mounting support CAD model.

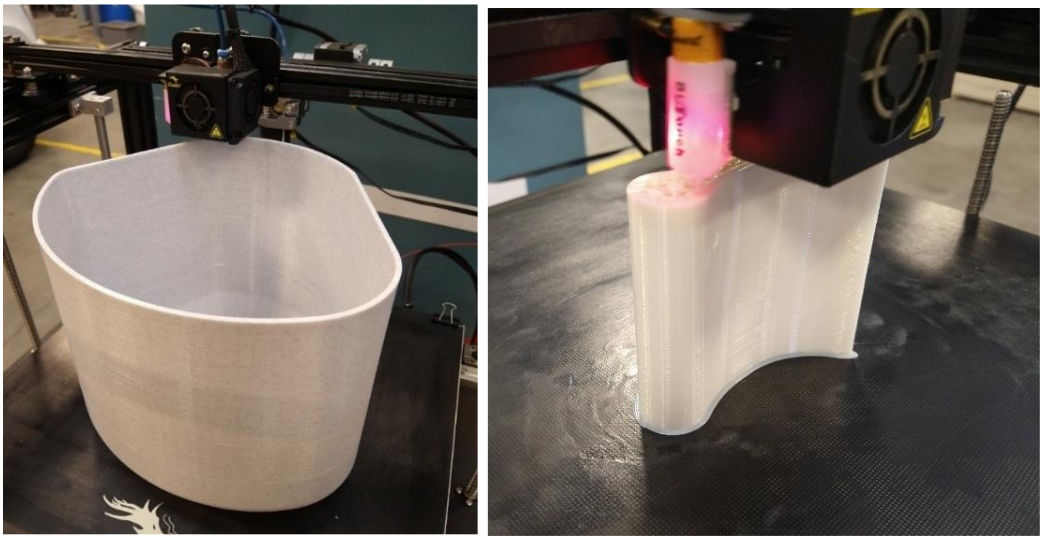


Figure 2.2: 360-degree camera cap parts being 3D printed. The cap is shown on the left; the cap handle is shown on the right.

Figure 2.3: Completed 360-degree camera caps. White protective paint was applied.

The camera cap support structure, consisting of COTS 3030 Aluminum T slot extrusion purchased from McMaster (https://www.mcmaster.com), is mounted to the MX Sensor Unit roof rack Aluminum Tslot extrusion made by Item (https://www.item24.com/en-us). All parts are either COTS or from modified COTS parts from McMaster. The modifications included cutting to length, drilling new holes, or countersinking existing holes from COTS parts.

Figure 2.4 shows two different 360-degree camera cap mounting structure designs. The initial design has a structural member partially blocking the view of the 360-degree camera. The revised 360-degree camera cap mounting structure reduces blockage of the camera's field of view as shown in Figures 2.5 and 2.6. The revised 360-degree camera cap mounting structures were installed on Districts 1, 3, 4, 6, and 11 MX system vehicles. The revised camera cap support was not installed on the District 8 MX9 system due to travel logistics and will be installed in the future.

The 360-degree camera cap and mounting structure installation and removal instructions are available in the Caltrans Trimble MX System Data Collection Workflow, Installation, Troubleshooting, and Maintenance Guide document.

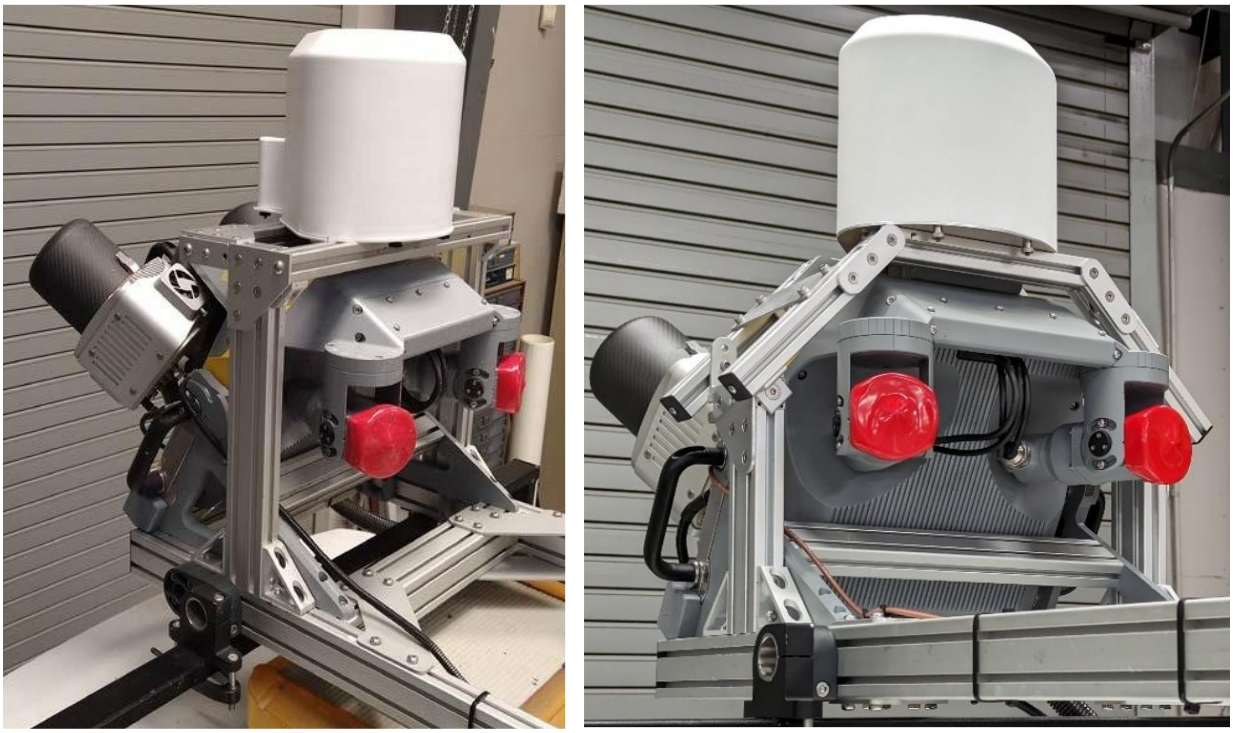


Figure 2.4: 360-degree camera cap mount designs. The initial design is shown on the left, and the final design is shown on the right.

Figure 2.5: Example panorama image from the 360-degree camera from version 1 of the camera cap mount. The red rectangles highlight the areas of the frame supports blocking the 360-camera field-of-view (FOV).

Figure 2.6: Example panorama image from the 360-degree camera from Version 2 camera cap mount. The Version 2 cap support reduces FOV blockage on both the sides of the vehicle.

The current cap design would not fit the new Trimble MX90 or MX60 360-degree camera. The 360-degree camera on the MX90 and MX60 is larger; therefore, modification to enlarge the cap design is required to fit over the large 360-degree camera installed on the MX90 and MX60 systems.

Figure 2.7: Examples of MX9 installation on Caltrans vehicles.

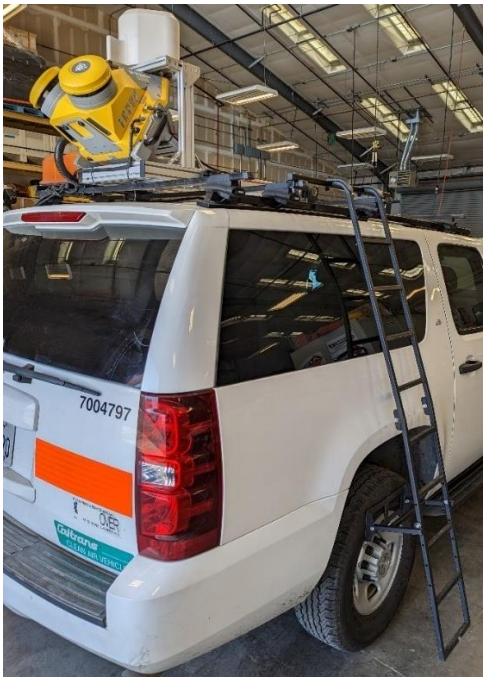


Figure 2.8: Caltrans MX50 installation with a custom side folding ladder.

Figure 2.9: Caltrans MX50 installation on a Suburban. MX8 system was previously installed on the vehicle.

DMI Rod Support Plate Modification

The distance measuring instrument (DMI) rod support plate shipped with the Applanix DMI kit is made from thin plastic. In the MX8 installation, the DMI rod wore through the DMI rod plate over several years, resulting in DMI damage. The modified DMI rod support plates are made of metal with rubber, plastic, or bronze brushings for smooth sliding of the DMI rod. The DMI rod support plate/brushing design is slightly different between MX9/MX50 systems. Some MX system DMI rod brushings are commercial-off-the-shelf (COTS), and one MX system DMI rod brushing has custom-made components using high-density polyethylene (HDPE). The brushing materials may be Ultra High Molecular Weight (UHMW) polyethylene, acetal/Delrin plastic, or bronze. Grease lubricants were applied to the sliding surfaces regularly to reduce wear and noise.

The DMI rod is made of a 10 mm diameter round aluminum rod as shown in Figure 2.10. Figures 2.10 and 2.12 show two DMI rod support designs. The DMI rod support plates were fastened to the bottom of the wheel well in both designs. Due to supply chain issues in 2020 and 2021, a custom HDPE brushing was fabricated to speed up the MX9 system deployment as shown on the left

side images of Figures 2.10 and 2.11. The custom HDPE brushing was designed to be compatible with was McMaster.com part #: 5912K79 (https://www.mcmaster.com/5912k79/). The custom HDPE brushing was later replaced with a McMaster part #: 5912K79 as shown on the right side image of Figure 2.10.

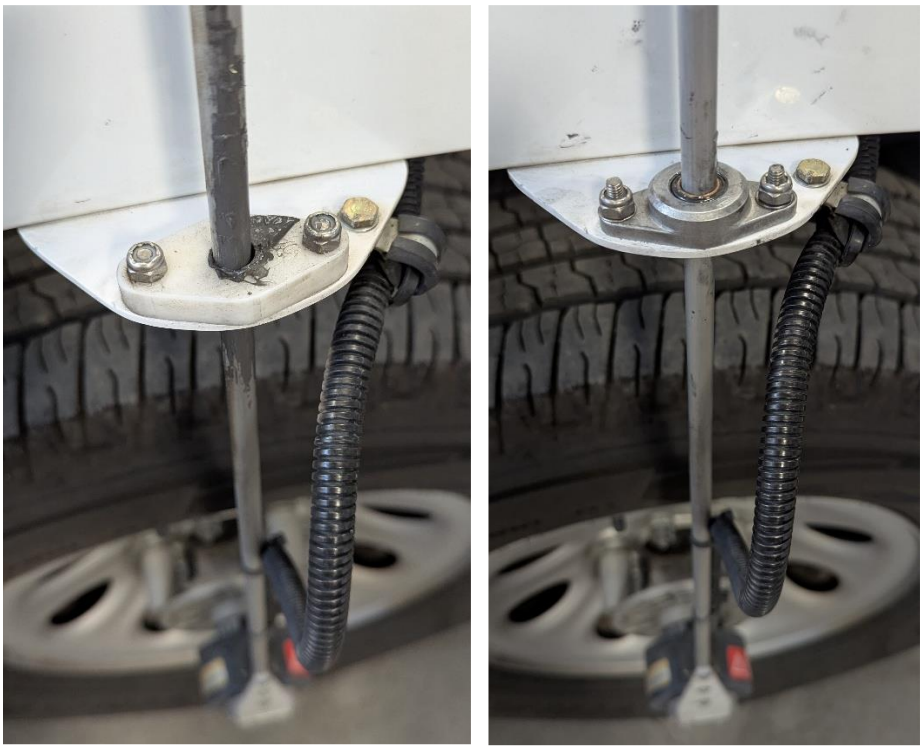


Figure 2.10: District 3's MX9 DMI rod support installation.

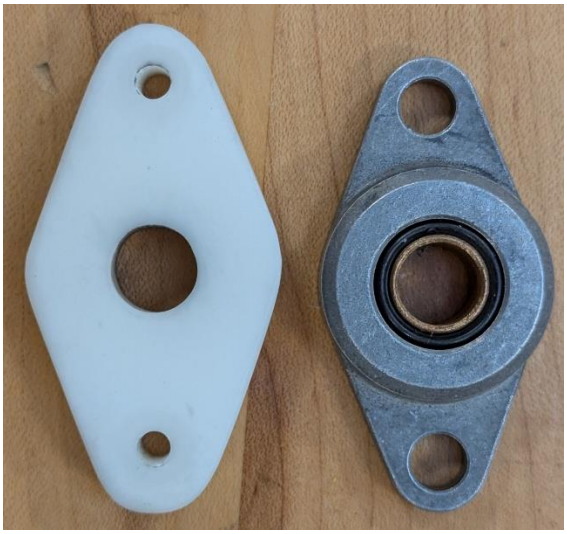


Figure 2.11: District 3's MX9 DMI rod brushings.

The second design, shown in Figure 2.12, uses a 5/8" right hand threaded rod end (McMaster.com part #: 60645K17 (https://www.mcmaster.com/60645K17/)) and a 7/16" inside diameter and 5/8" outside diameter bronze bearing (McMaster part #:6338K466 (https://www.mcmaster.com/6338K466/)). This design also required two 5/8"-18 nuts (McMaster.com part #: 95462A535 (https://www.mcmaster.com/95462A535/)). The 5/8"-18 nuts are used to adjust rod end hole position so that the DMI rod is vertical. The rod end allows for any small angular misalignment between the DMI rod and the rod end hole.

Figure 2.12: MX50 DMI rod support installation.

MX System Support

Working with OLS, district surveyors, CSDS, and Trimble technical support, AHMCT researchers developed supports for five MX9 systems and one MX50 system deployment. Support activities included:

- Reported issues encountered by MX system operators to OLS, Trimble, and CSDS
    - Downloaded MX system logfiles for error reporting to Trimble technical support
    - Performed diagnostic on DMI failure and replaced DMI cable or DMI unit
    - Repaired broken Trimble T100 tablet stylus
    - Reported solid state drive (SSD) write speed degradation issues
- Updated new Trimble Mobile Imaging (TMI) firmware when available

- Provided technical support for District 4 in GNSS/IMU POSPac data post-processing
- Attended Trimble webinars for Trimble Business Center MTLS data post-processing
- Updated Trimble T100 tablets' Windows operating system and its Chrome browser
- Connected Trimble T100 tablets to MX systems using wired Ethernet via a USB C Ethernet adapter to improve network connection reliability

MX System Upgrade

Working with OLS, district surveyors, and CSDS and Trimble technical support, AHMCT researchers hosted an on-site MX system upgrade event from June 10 to June 13, 2024, at the AHMCT vehicle shop. District surveyors drove one MX50 and three MX9 systems to the AHMCT vehicle shop for servicing. The sensor units and CUs were removed from the vehicles. Comprehensive hardware and software upgrades were performed on the sensor units and CUs including:

- Network cable replacement in sensor units and CUs
- Sensor unit embedded computer operating system and TMI firmware upgrades
- Upgrade CU computers' Windows operating system
- Replaced removable SSD drive dock and cables

System verification tests were conducted on all units before installing the MX units onto the vehicles. The writing speeds of all SSDs were tested. After the MX systems were reinstalled onto the vehicles, the MX systems were driven for more than two hours and collected sensor data at their highest collection settings for final system verification.

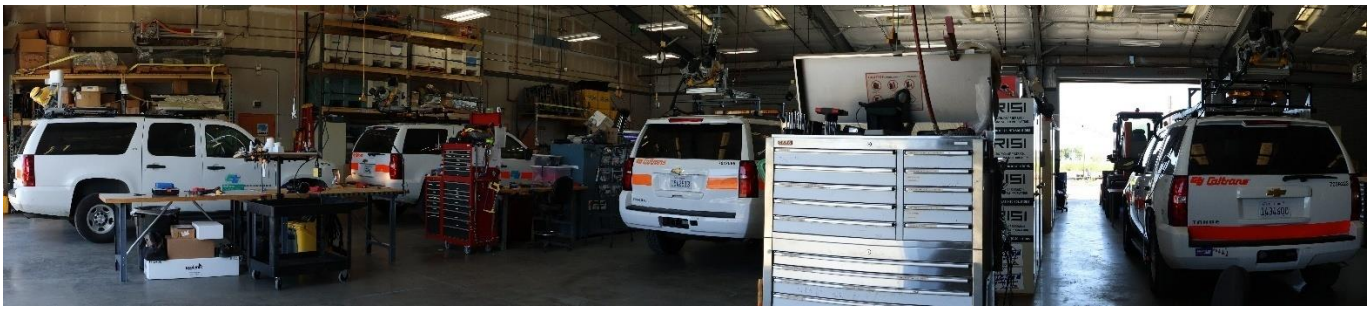


Figure 2.13: Four MX systems at AHMCT shop for major system upgrade.

Chapter 3:
Time-Based vs. Distance-Based MTLS Target Spacing

AHMCT researchers investigated the possibility of time-based MTLS data collection to modify target spacing requirements. This effort leveraged the Caltrans MX9 MTLS system and the GTPG. In a previous project, AHMCT researchers and Caltrans have investigated distance-based MTLS target spacing vs MTLS point cloud vertical accuracy using the Trimble MX8 system.[1] The new Trimble MX9 system has better system performance over the old MX8 system, which warranted repeating the target spacing experiment.

Experiment Design

Test site

The test site is located at California Highway 20 near Timbuctoo, California. Figure 3.1 shows a satellite image of the test site with ground control points (GCP) overlaid and represented by green dots. Figure 3.2 shows the test site topography map overlaid with GCP locations and GCP number on ArcGIS Pro software. The test site is composed of two segments: a western segment with target spacing of 250' and an eastern segment with GCP spacing of 500'. The western and eastern segments are separated by a bridge in the middle of the site. The GCP target was not placed on the narrow bridge shoulder. The western segment has GCPs numbered from 100 to 115, and the eastern segment GCPs are numbered from 116 to 147. There are 24 GCPs on each side of the highway shoulder (48 GCPs total). The GCP targets are white reflective thermal plastic rectangles that are 18" x 24" as shown in Figure 3.3.

[1] *Support for Caltrans Statewide Mobile Terrestrial Laser Scanning (MTLS) System Usage* (https://ahmct.ucdavis.edu/sites/g/files/dgvnsk8581/files/inline-files/UCD-ARR-20-08-31-01.pdf)

Figure 3.1: Satellite image of the test site overlayed with GCP on Google Earth. Green dots represent the GCPs locations. Background satellite images courtesy of Google Earth.

Figure 3.2: Test site topography map overlayed with GCP locations and GCP number using ArcGIS Pro software. Background topographic map image courtesy of ArcGIS Pro, ESRI.

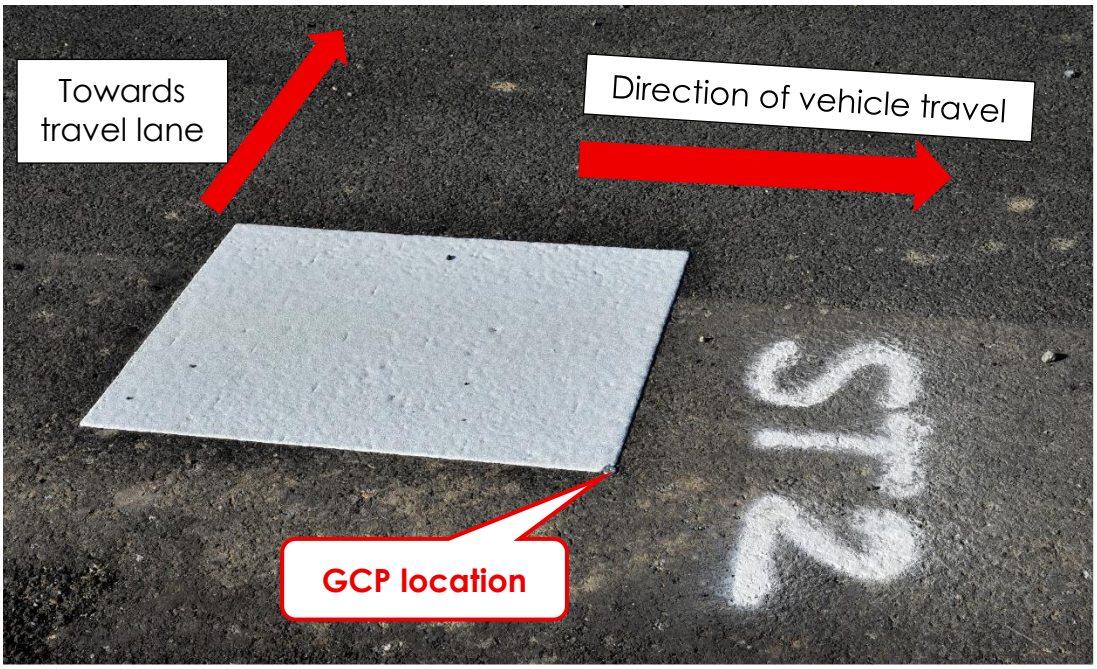


Figure 3.3: GCP target at the test site.

GCP Survey

Caltrans North Region Survey District 3 surveyors conducted the GCP survey using GNSS receivers and digital levels based on requirements specified in Caltrans Survey Manual Chapter 15. Due to local earth movement discovered after the first GCP survey, the survey was repeated six months before MTLS data collection.

Data Collection

A Caltrans Trimble MX9 Gen2 MTLS system was used to collect data on July 25, 2024. A total of 18 runs were recorded — nine in each direction (westbound and eastbound) — at varying speeds. The targeted vehicle speeds for data collection were 50, 55, and 60 miles per hour (MPH) and repeated three times during the entire data collection session. The MTLS vehicle driver experienced difficulty in maintaining a constant vehicle speed due to the hilly terrain of the test site.

Results

GNSS IMU Data Post-processing

The MX9 GNSS Inertial Measurement Unit (IMU) data were post-processed using Applanix POSPac MMS software with a Caltrans local permanent GNSS base station labelled TMB2 at the test site as shown in Figure 3.4. The maximum

baseline length is less than 3.1 kilometers (km). The test site GNSS base station log data contained only GPS and GLONASS data. Thus, Galileo GNSS was not employed during post-processing. GAMS was disabled, and DMI was enabled in POSPac MMS post-processing.

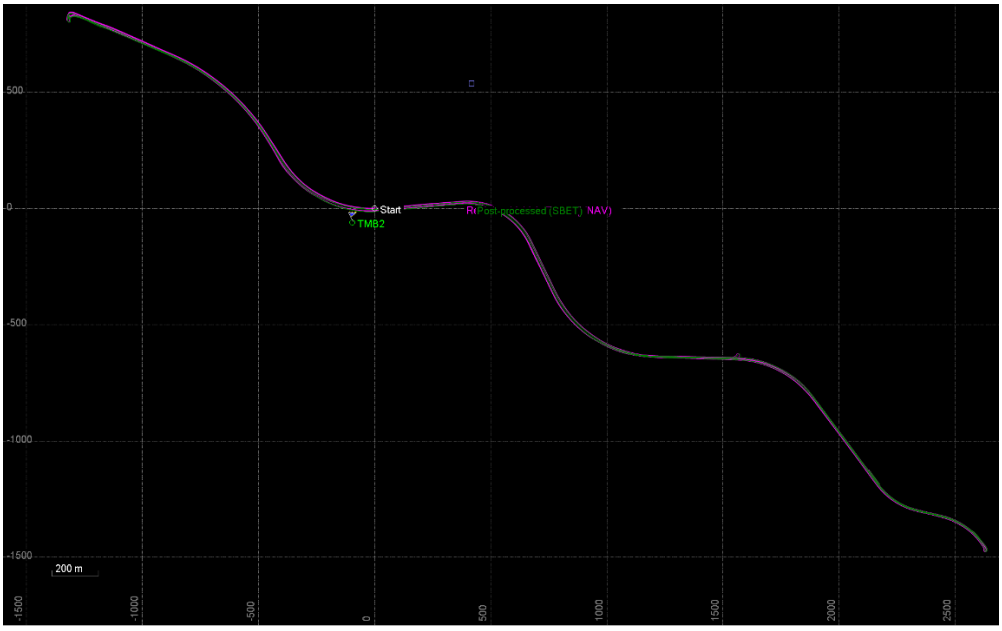


Figure 3.4: MX9 vehicle trajectory and GNSS base station location (labeled as TMB2) shown in POSPac MMS software.

The test site does not have any overpasses that completely block the GNSS signal temporarily. The northing, easting, and elevation error estimates, shown in Figure 3.5, are consistent throughout the entire session with small fluctuations that were caused by GNSS signal blockage due to trees and the terrain.

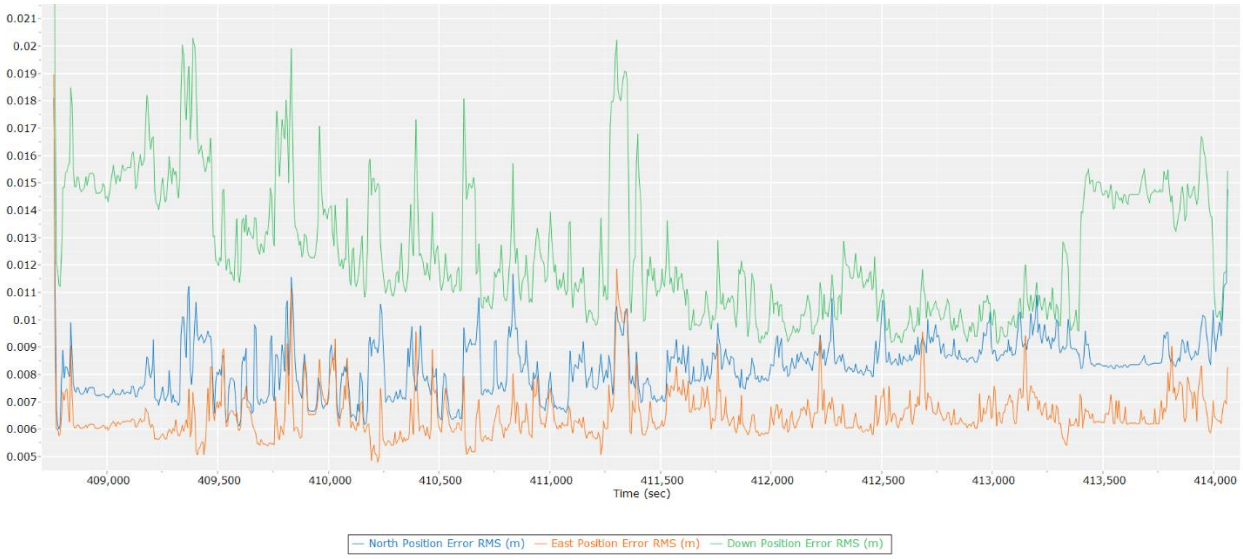


Figure 3.5: POSPac MMS smoothed solution accuracy estimate results.

Timing Between GCP Targets

Since constant vehicle speed was not achieved during each recorded run, the time elapse between GCPs was not constant and therefore must be calculated individually. The vehicle trajectory solution from the POSPac MMS was exported to a text file with 1-meter spacing decimation. The exported text file contains GPS time, x, y, z position, and orientations in tab separated text format. At 50 MPH (22.35 m/s), the time spacing between two 1-meter points is about 0.045 seconds. Thus, the timing error in subsequent GCP time spacing calculation is about 0.045 seconds.

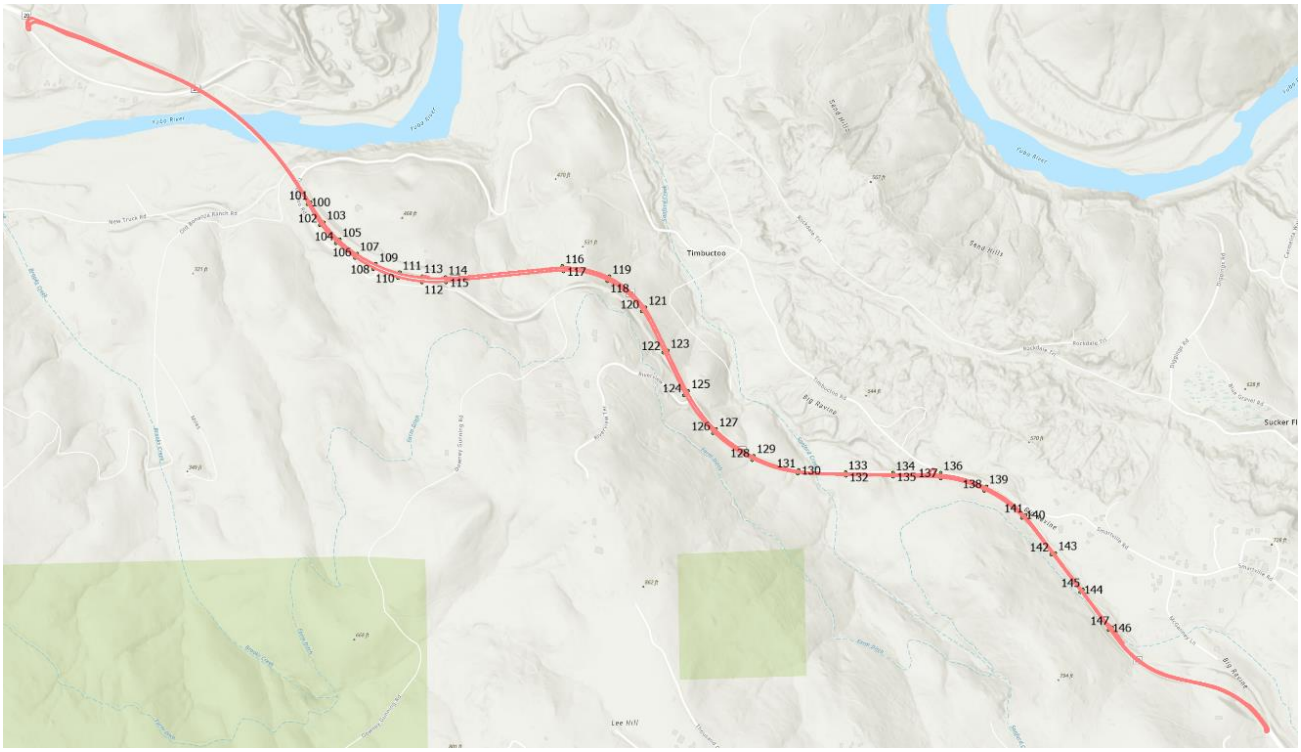


Figure 3.6: POSPac best smooth vehicle trajectory solution exported to ArcGIS Pro to determine time elapse between GCPs. Background topographic map image courtesy of ArcGIS Pro, ESRI.

The exported vehicle trajectory text files and GCP file were imported into ArcGIS Pro, as shown in Figures 3.6 and 3.7, for further processing. ArcGIS Pro was first used to filter out vehicle trajectory points within 9 meters away from a GCP. The distance for each of the remaining points to the closest GCP was calculated using the ArcGIS Pro software function. Next, the remaining points were exported to Excel for further sorting and filtering. A point for each MTLS record run closest to each GCP was manually selected in Excel. Then, the time elapsed GCPs were calculated using GPS time difference subsequent points within the same MTLS record run. The resulting Excel table was then imported in

ArcGIS Pro for visual verification and check for any human error as shown in Figure 3.8.

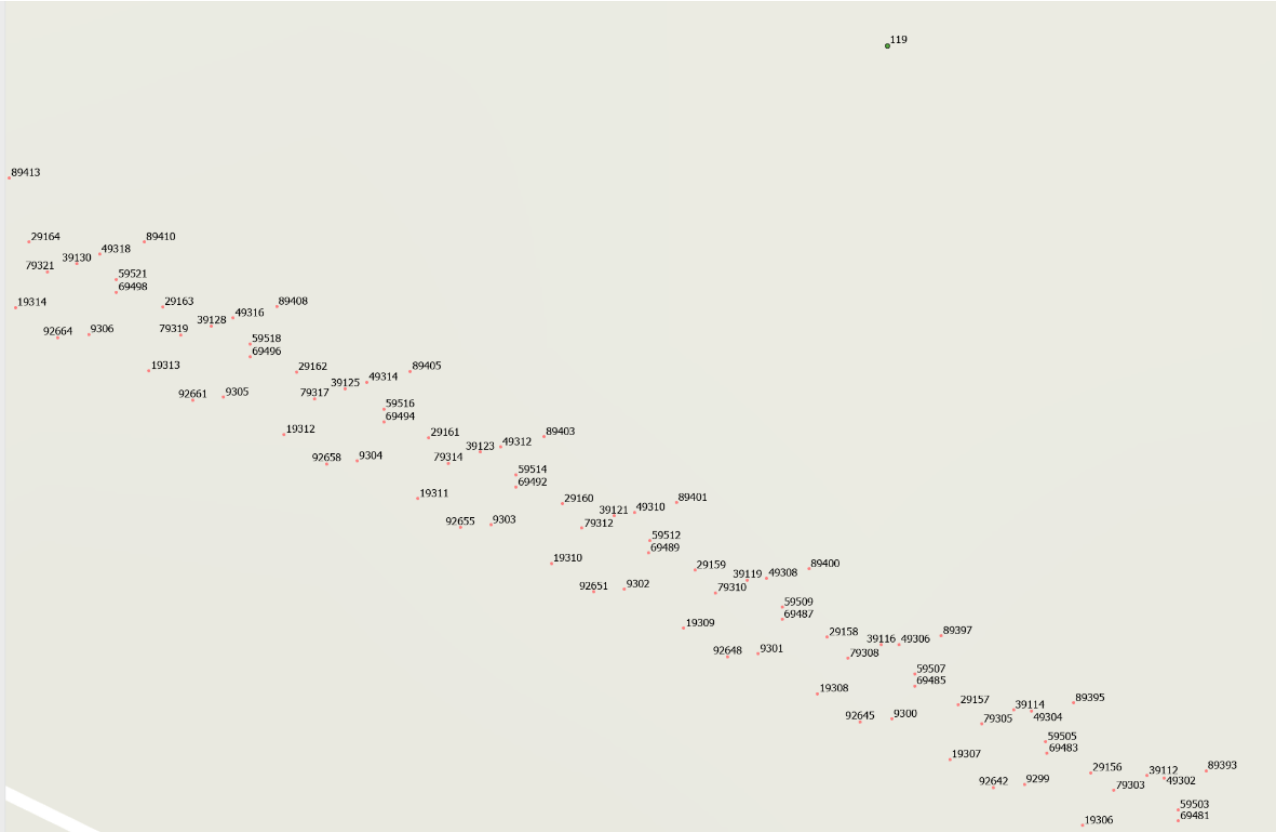


Figure 3.7: Zoom in view of the exported vehicle trajectory points (pink dots) at GCP number 119 (green dots). The labels on the vehicle trajectory points are the GPS time. Background topographic map image courtesy of ArcGIS Pro, ESRI.

Figure 3.8: Vehicle trajectory points for each MTLS record run closest to GCP number 119 plotted on ArcGIS Pro. The points were labeled with the point's GPS time (in seconds) in the left image. The points were labeled with time elapsed from previous GCP (in seconds) in the right image.

Trimble Business Center (TBC) MTLS Data Post-processing

TBC software was used to post-process and register each MX9 MTLS recorded run. Figure 3.9 shows the test site point cloud (in black and white gray scale) generated and overlayed with GCPs (white triangle shapes) and MTLS recorded run trajectories (in yellow and orange) in TBC. TBC's mobile mapping registration function was used to register the recorded runs and determine the root mean square errors (RMSE) in the x, y, and z direction, with different GCP registration spacing in time and distance.

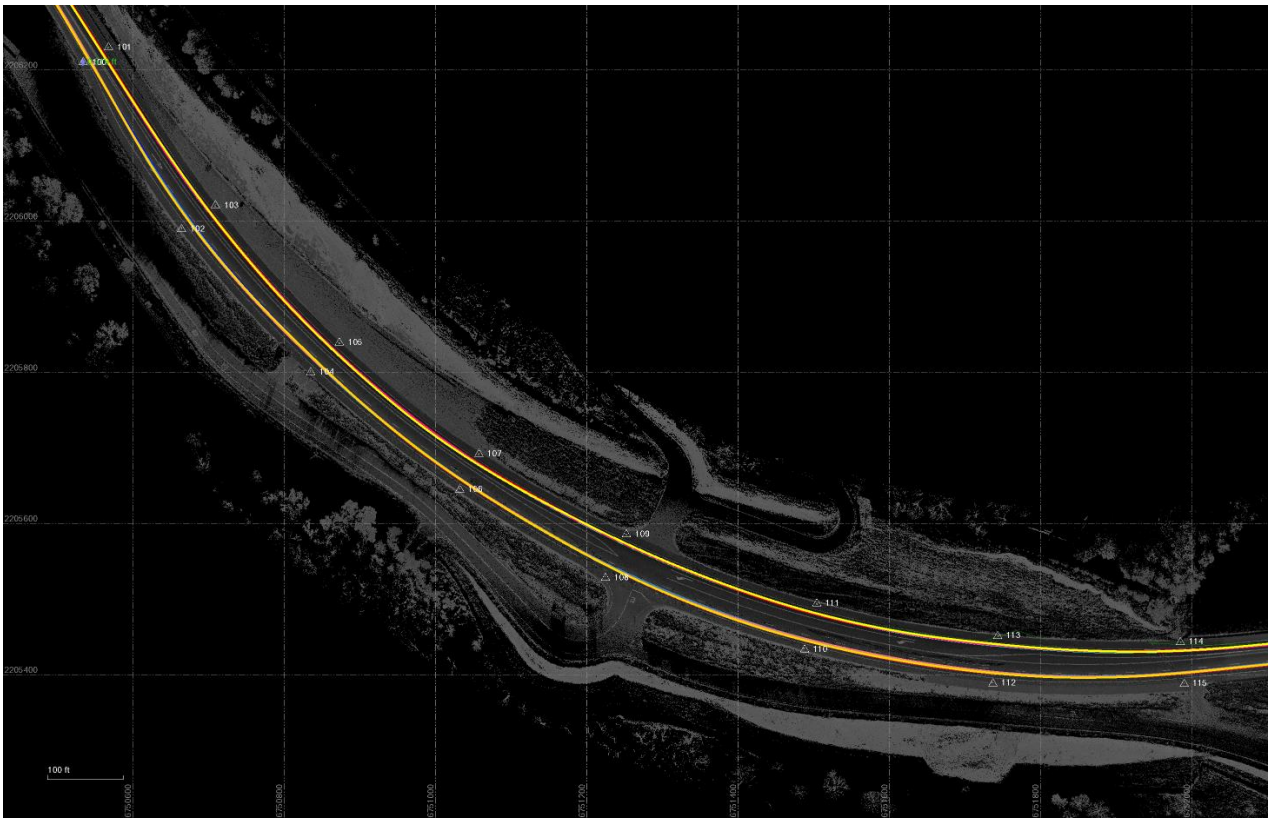


Figure 3.9: Western segment of test site point cloud (in black and white gray scale) generated in TBC overlayed with GCPs (white triangles) and MTLS record run trajectories (in yellow and orange)

Figure 3.10 shows an example of a GCP target point cloud (top view). The GCP target reference position is located on the corner of the rectangle furthest from the direction of travel, and the user stands facing the GCP target in the direction of travel as illustrated in Figure 3.9. The GCP target reference position is the location of the GCP in relation to the physical GCP target. Before any GCP registration, there is a systematic lateral error of about 0.4' as shown in Figure 3.10.

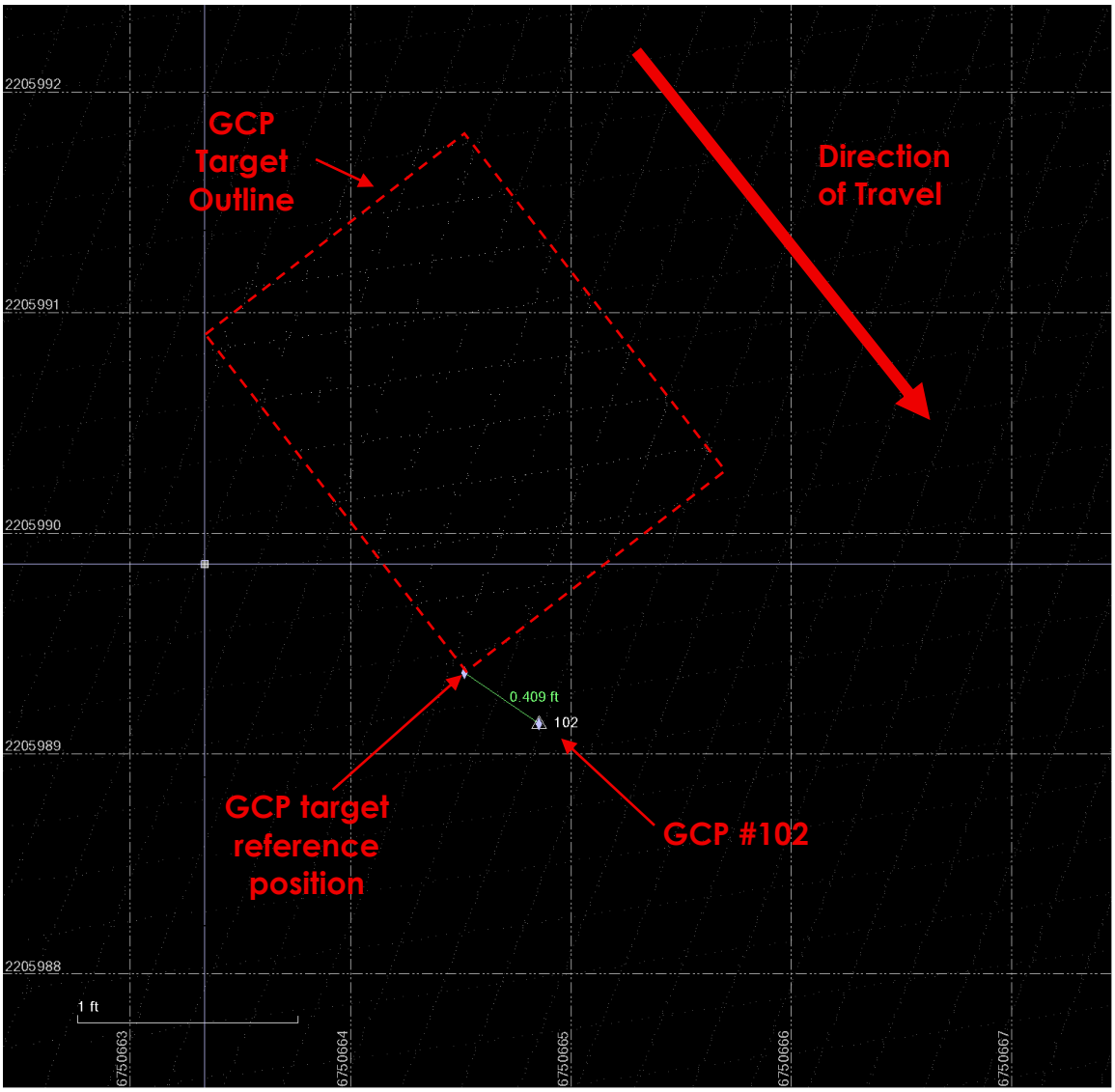


Figure 3.10: Example point cloud of a GCP target next to GCP #102. The unit displayed is in US survey feet.

Registration

TBC was used to perform manual picking of all the GCP target reference positions from all record runs. TBC provides visual feedback on the selected GCP reference position in relation to the surrounding point cloud. Picked points with large vertical errors (higher than 0.1') are double checked for pick accuracy. A total of 432 GCP target reference positions were selected from all 18 recorded runs. By selecting some GCPs for use in registration points and some GCPs for check points, the TBC registration report could provide the X, Y, and Z error for the check points. A "global and then local" registration method was used for all recorded runs.

The GCPs (100,101,114,115, 116, 117, 146, and 147) at the beginning and end of both the western and eastern segments were always used as registration points in all registration scenarios. Each recorded run was registered using six different scenarios of registration and check point combinations. Figure 3.11 shows several registration scenario examples for recorded run number 18. In the recorded run number 18, the vehicle is traveling in the westbound direction. The GCPs located on the westbound shoulder are used for registration and check points. Thus, Figure 3.11 only shows GCPs located on the westbound shoulder. GCPs number 100, 115, 117, and 146 are located on the eastbound shoulder, and therefore they are not shown in Figure 3.11. For odd number record runs (vehicle traveling in the eastbound direction), the GCPs located on eastbound shoulder are used for registration and check points.

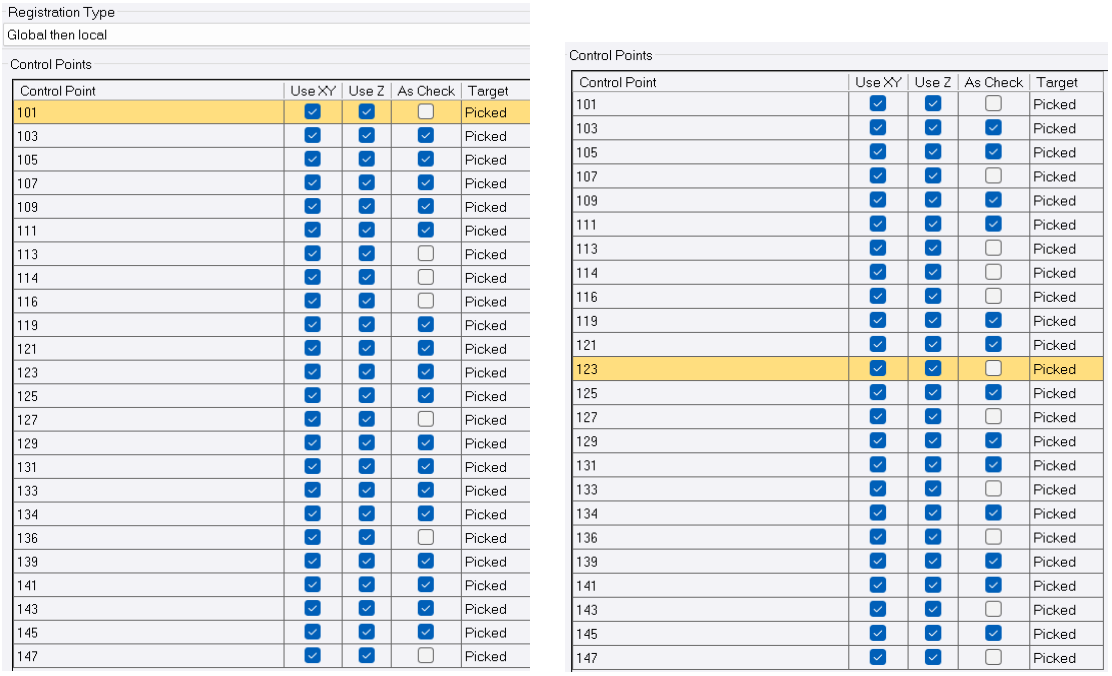


Figure 3.11: TBC screenshots of examples registration scenario for record run #18.

TBC can generate and export a registration report in HyperText Markup Language (HTML) file format. The registration report contains all recorded run registration scenario results in the TBC project. The registration report provides tables of the GCPs used for registration and the resulting check points' XYZ errors for every registration in the TBC project. Figure 3.12 shows an example of the tabulated results for a single registration from the TBC registration report.

All tabulated registration results were copied to Microsoft Excel for the following analysis:

- Calculate X, Y, and Z RMSE for check point(s) between two registration points.
- Determine the distance spacing between two registration points.

- Calculate the time spacing between two registration points using the GCPs elapsed time results from previous analysis.
- Tabulate RMSE, time spacing, and distance spacing in a single table.
- Sort data based on time spacing and distance spacing.
- Calculate RMSE statistics and plot results.

Run 18 Trajectory2

Control points:

Name	Registration type	Type	Control point easting (US survey foot)	Control point northing (US survey foot)	Control point elevation (US survey foot)	Target easting (US survey foot)	Target northing (US survey foot)	Target elevation (US survey foot)
147	GlobalThenLocal	Control	6758987.228	2201766.190	600.069	6758986.858	2201766.488	600.044
145	GlobalThenLocal	Validation	6758680.135	2202162.483	584.652	6758679.733	2202162.747	584.847
143	GlobalThenLocal	Validation	6758392.054	2202549.110	564.801	6758391.728	2202549.408	564.704
141	GlobalThenLocal	Validation	6758079.980	2202948.221	552.663	6758079.610	2202948.487	552.651
139	GlobalThenLocal	Validation	6757667.638	2203247.384	536.338	6757667.294	2203247.630	536.281
136	GlobalThenLocal	Control	6757188.057	2203392.563	511.381	6757187.763	2203392.796	511.222
134	GlobalThenLocal	Validation	6756687.316	2203390.038	481.537	6756686.979	2203390.341	481.509
133	GlobalThenLocal	Validation	6756189.074	2203397.075	454.795	6756188.749	2203397.431	454.710
131	GlobalThenLocal	Validation	6755693.147	2203418.977	444.715	6755692.809	2203419.306	444.706
129	GlobalThenLocal	Validation	6755226.142	2203567.887	460.302	6755225.781	2203568.207	460.220
127	GlobalThenLocal	Control	6754829.454	2203848.632	476.422	6754829.124	2203848.949	476.356
125	GlobalThenLocal	Validation	6754535.543	2204250.067	491.713	6754535.253	2204250.444	491.771
123	GlobalThenLocal	Validation	6754320.517	2204675.104	496.508	6754320.211	2204675.480	496.566
121	GlobalThenLocal	Validation	6754085.427	2205127.778	496.770	6754085.068	2205128.143	496.789
119	GlobalThenLocal	Validation	6753706.020	2205453.132	493.326	6753705.616	2205453.466	493.282
116	GlobalThenLocal	Control	6753213.974	2205561.085	480.857	6753213.580	2205561.394	480.912
114	GlobalThenLocal	Control	6751984.661	2205443.442	415.383	6751984.318	2205443.731	415.333
113	GlobalThenLocal	Control	6751743.285	2205451.397	398.811	6751742.958	2205451.719	398.770
111	GlobalThenLocal	Validation	6751504.145	2205494.111	381.566	6751503.818	2205494.472	381.490
109	GlobalThenLocal	Validation	6751252.501	2205585.843	362.522	6751252.123	2205586.197	362.464
107	GlobalThenLocal	Validation	6751057.543	2205691.915	347.118	6751057.188	2205692.280	346.994
105	GlobalThenLocal	Validation	6750873.410	2205838.990	330.221	6750873.048	2205839.323	330.164
103	GlobalThenLocal	Validation	6750709.444	2206020.425	314.363	6750709.093	2206020.747	314.286
101	GlobalThenLocal	Control	6750567.957	2206229.456	302.167	6750567.624	2206229.764	302.119

Name	Adjustment type	Adjusted target easting (US survey foot)	Adjusted target northing (US survey foot)	Adjusted target elevation (US survey foot)	Adjustment easting (US survey foot)	Adjustment northing (US survey foot)	Adjustment elevation (US survey foot)	Residual easting (US survey foot)	Residual northing (US survey foot)	Residual elevation (US survey foot)
147	XYZ	6758987.228	2201766.190	600.069	0.370	0.298	0.025	0.000	0.000	0.000
145	XYZ	6758680.087	2202162.463	584.900	0.402	0.264	0.195	0.048	0.020	0.248
143	XYZ	6758392.068	2202549.136	564.781	0.326	0.298	0.097	0.014	0.026	0.020
141	XYZ	6758079.935	2202948.228	552.755	0.370	0.266	0.012	0.045	0.007	0.092
139	XYZ	6757667.603	2203247.384	536.413	0.344	0.246	0.057	0.035	0.000	0.075
136	XYZ	6757188.057	2203392.563	511.381	0.294	0.233	0.159	0.000	0.000	0.000
134	XYZ	6756687.280	2203390.092	481.649	0.337	0.303	0.028	0.036	0.054	0.112
133	XYZ	6756189.057	2203397.165	454.832	0.325	0.356	0.085	0.017	0.090	0.037
131	XYZ	6755693.125	2203419.023	444.809	0.338	0.329	0.009	0.022	0.046	0.094
129	XYZ	6755226.104	2203567.907	460.304	0.361	0.320	0.082	0.038	0.020	0.002
127	XYZ	6754829.454	2203848.632	476.422	0.330	0.317	0.066	0.000	0.000	0.000
125	XYZ	6754535.596	2204250.129	491.813	0.290	0.377	0.058	0.053	0.062	0.100
123	XYZ	6754320.566	2204675.166	496.584	0.306	0.376	0.058	0.049	0.062	0.076
121	XYZ	6754085.436	2205127.831	496.784	0.359	0.365	0.019	0.009	0.053	0.014
119	XYZ	6753705.997	2205453.155	493.252	0.404	0.334	0.044	0.023	0.023	0.074
116	XYZ	6753213.974	2205561.085	480.857	0.394	0.309	0.055	0.000	0.000	0.000
114	XYZ	6751984.661	2205443.442	415.383	0.343	0.289	0.050	0.000	0.000	0.000
113	XYZ	6751743.285	2205451.397	398.811	0.327	0.322	0.041	0.000	0.000	0.000
111	XYZ	6751504.145	2205494.153	381.532	0.327	0.361	0.076	0.000	0.042	0.034
109	XYZ	6751252.452	2205585.881	362.507	0.378	0.354	0.058	0.049	0.038	0.015
107	XYZ	6751057.518	2205691.966	347.038	0.355	0.365	0.124	0.025	0.051	0.080
105	XYZ	6750873.379	2205839.011	330.210	0.362	0.333	0.057	0.031	0.021	0.011
103	XYZ	6750709.425	2206020.437	314.332	0.351	0.322	0.077	0.019	0.012	0.031
101	XYZ	6750567.957	2206229.456	302.167	0.333	0.308	0.048	0.000	0.000	0.000

Figure 3.12: Example TBC registration report result tables screenshots.

Time-based and Distance-based GCP Errors

A total of 454 data points with various time and distance spacing was available for statistical analysis. Various plots were made to check for any human error or outliners in data processing. Figures 3.13, 3.14, and 3.15 show the large horizonal and elevation errors from recorded run 16. The large vertical error points in Figure 3.13 from recorded run 16 does not correspond to the large X error points from recorded run 16. In other words, the large vertical error points are not associated with the points with large X error in the run. The GCP reference point selections in recorded run 16 were double checked in TBC to make sure human error was not the cause for the X error. Subsequent analysis was conducted with and without the large error from recorded run 16. AHMCT researchers found no significant difference in the results. Therefore, all the following results and analyses included all data from recorded run 16.

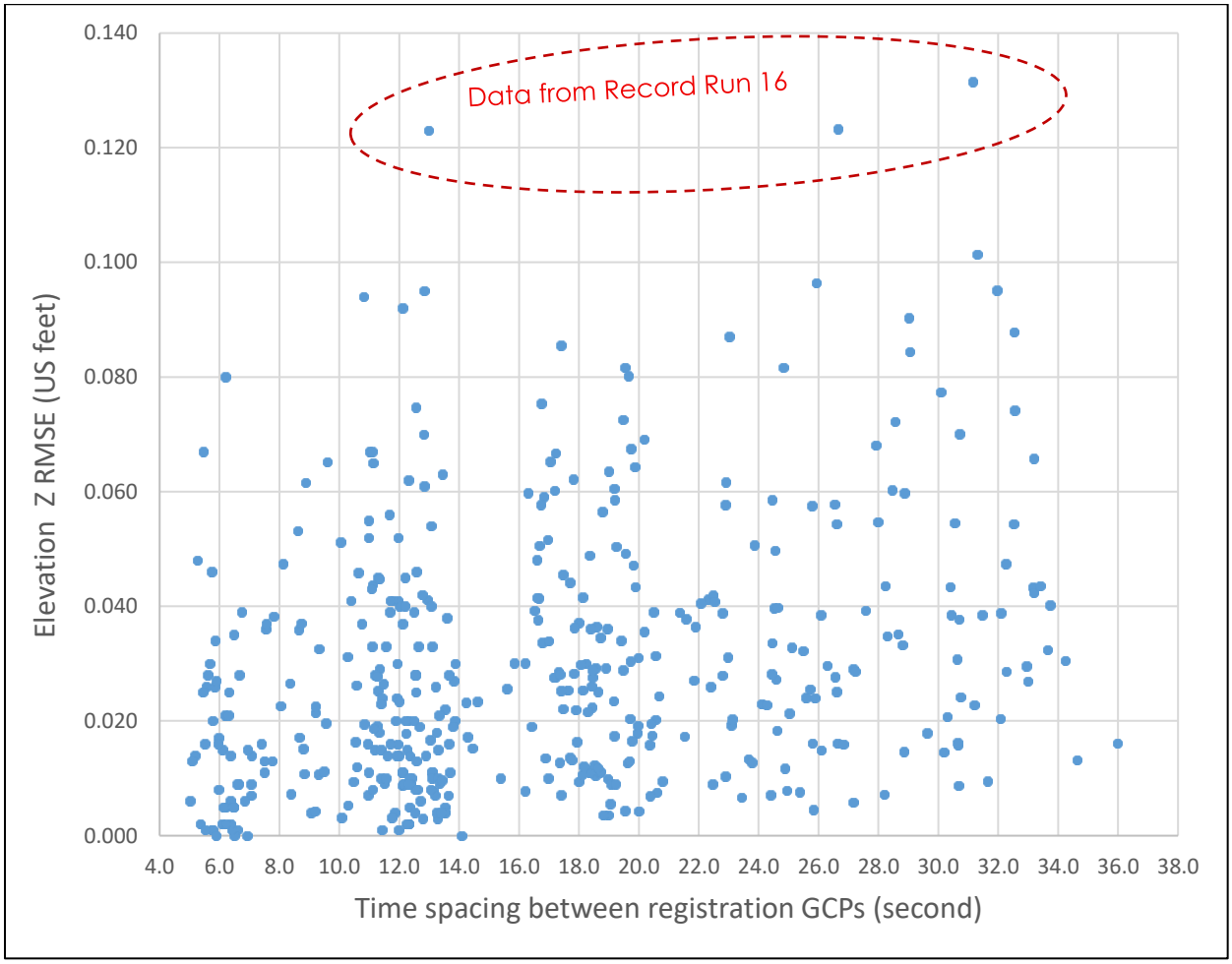


Figure 3.13: Elevation Z RMSE vs time spacing between registration GCPs for all 454 data points.

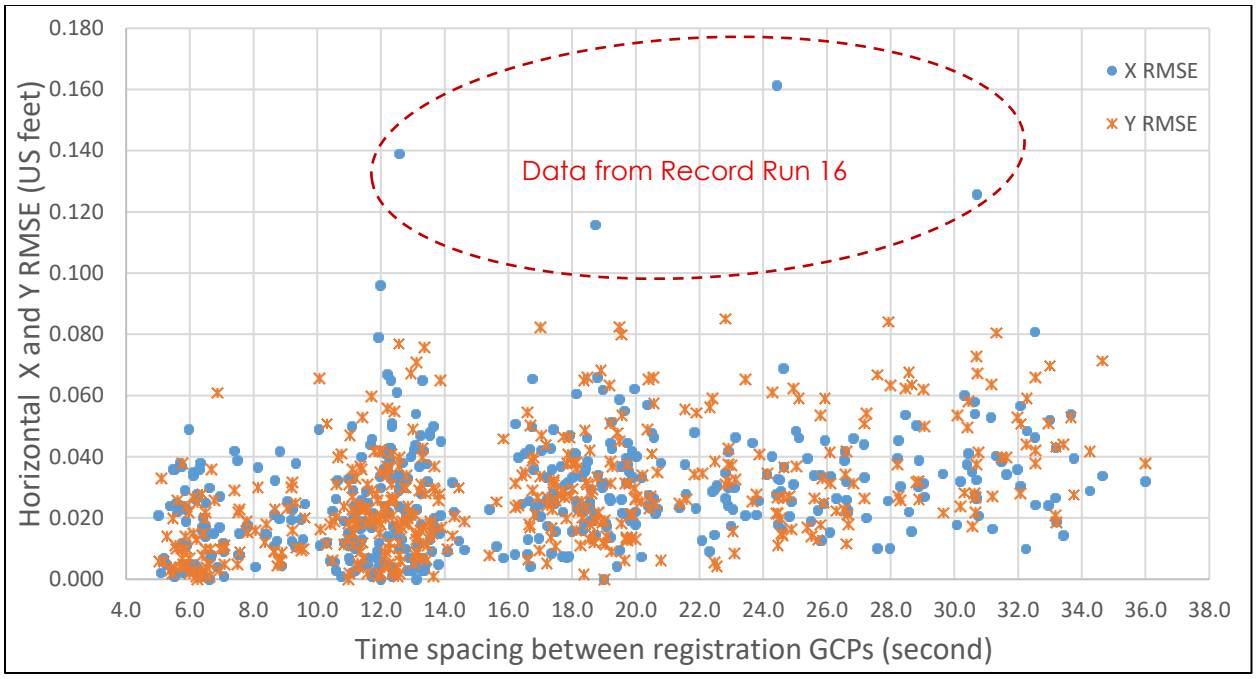


Figure 3.14: Horizontal X and Y RMSE vs time spacing between registration GCPs for all 454 data points.

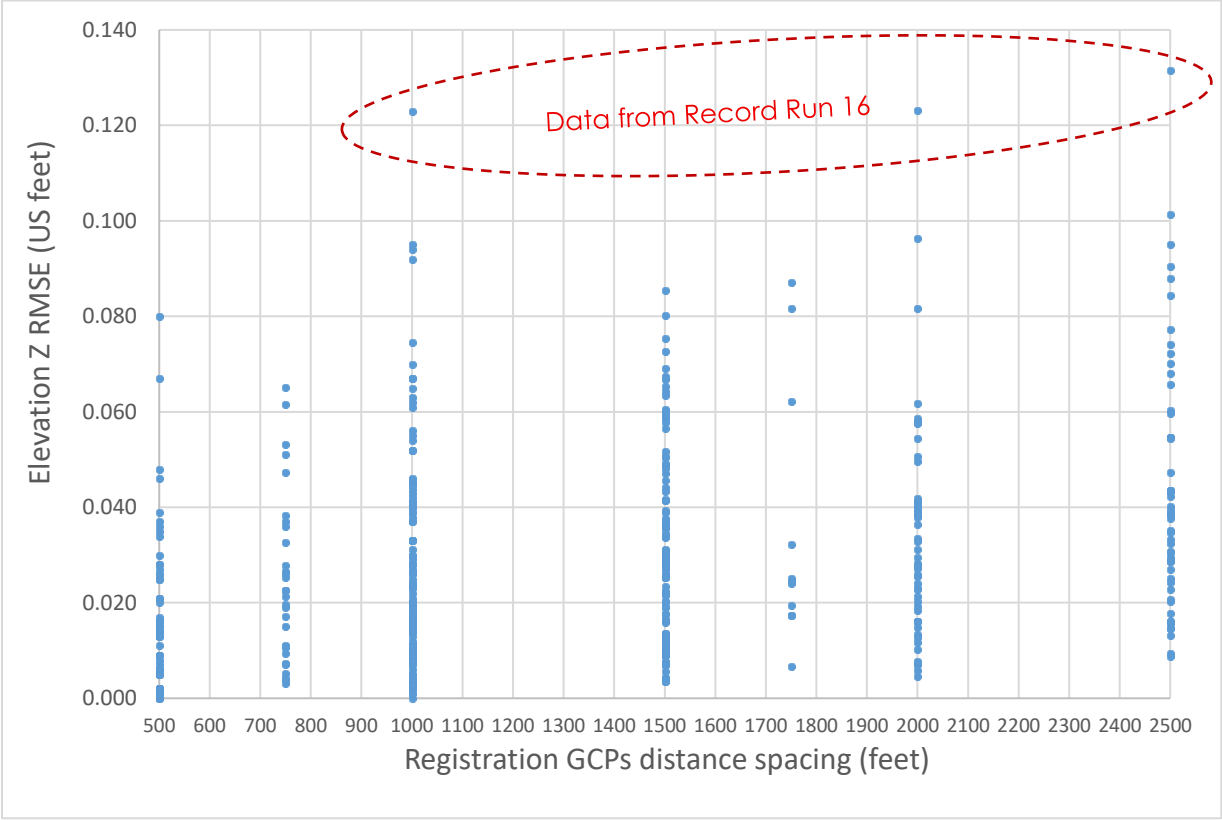


Figure 3.15: Elevation Z RMSE vs distance spacing between registration GCPs for all 454 data points.

Time-based GCP Spacing RMSE Results

Figure 3.13 does not show a clear trend relationship between time-based GCP spacing vs. vertical RMSE error. The 454 raw data points were first sorted by time spacing from smallest to largest and then grouped in bins of 30 and 44 points with consecutive time spacing. The last bin (points with the largest time spacing) has 34 points for a bin size of 30, and the last bin has 58 points for a bin size of 44. Next, the average time, X, Y, and Z RMSE values of each bin were calculated and tabulated. The use of two different bin sizes allowed for evaluating the effect of bin size on the analysis. Figure 3.16 shows elevation Z RMSE vs average time spacing between registration GCPs with a bin size of 30 and 44. Linear, polynomial, and natural logarithmic best fit curves were applied to the data in Figure 3.15 to determine trendlines. AHMCT researchers found that the logarithmic curve produced the best data fit compared to linear or polynomial curves. The resulting best fit logarithmic curves (bin size 30 and 44) are almost identical as shown in Figure 3.16. The larger bin size (44) data points are closer to the best fit curve. However, a larger bin size would result in fewer data points.

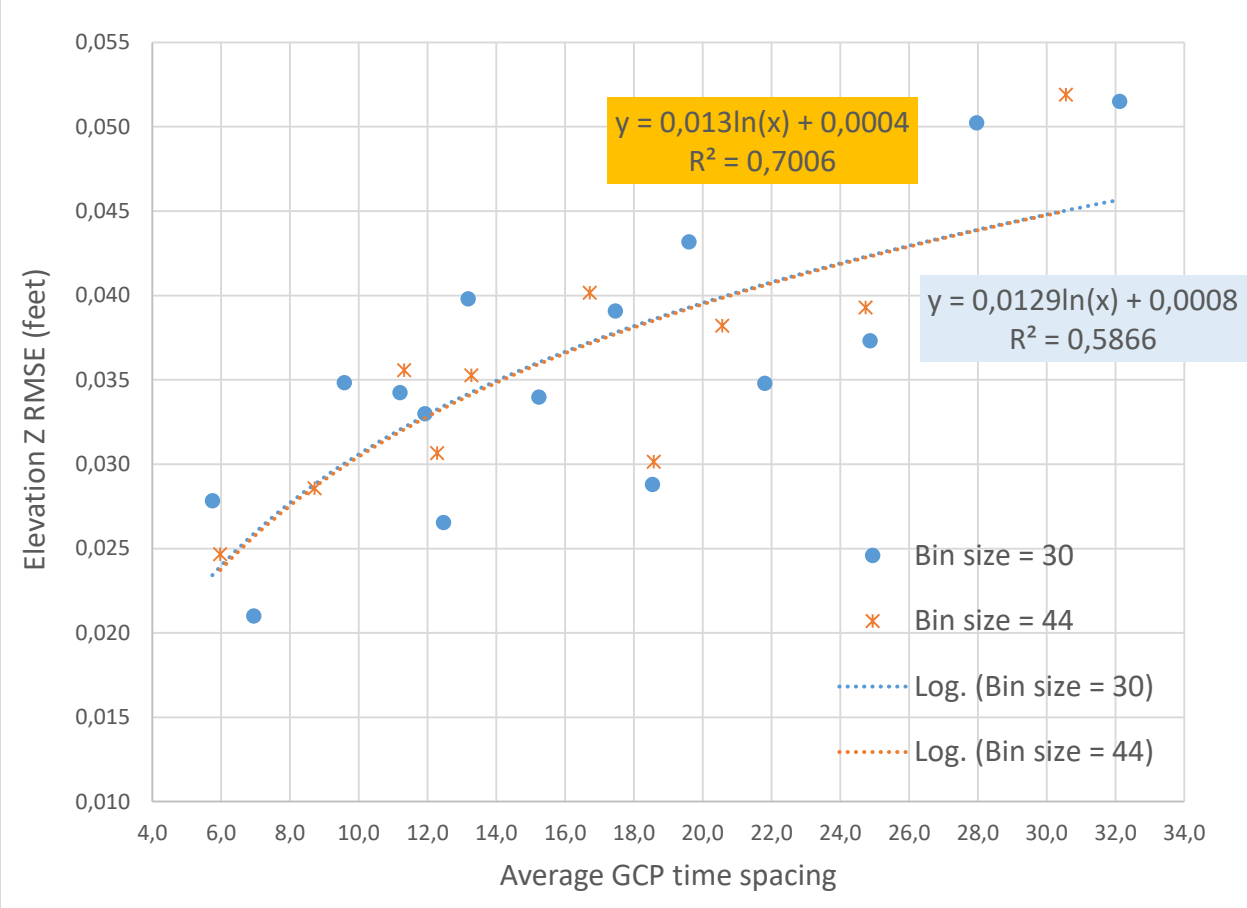


Figure 3.16: Elevation Z RMSE vs average time spacing between registration GCPs.

Figure 3.17 shows horizontal X and Y RMSE vs average time spacing between registration GCPs with a bin size of 30. The X and Y RMSE behavior are similar to that of elevation Z RMSE data. AHMCT researchers found that the logarithmic curve produced the best data fit compared to linear or polynomial curves in Figure 3.17. The "Y" in the best fit equations in Figure 3.16 and 3.17 is the RMSE (y-axis), and the "X" in the best fit equations is the average time spacing between registration GCPs (x-axis).

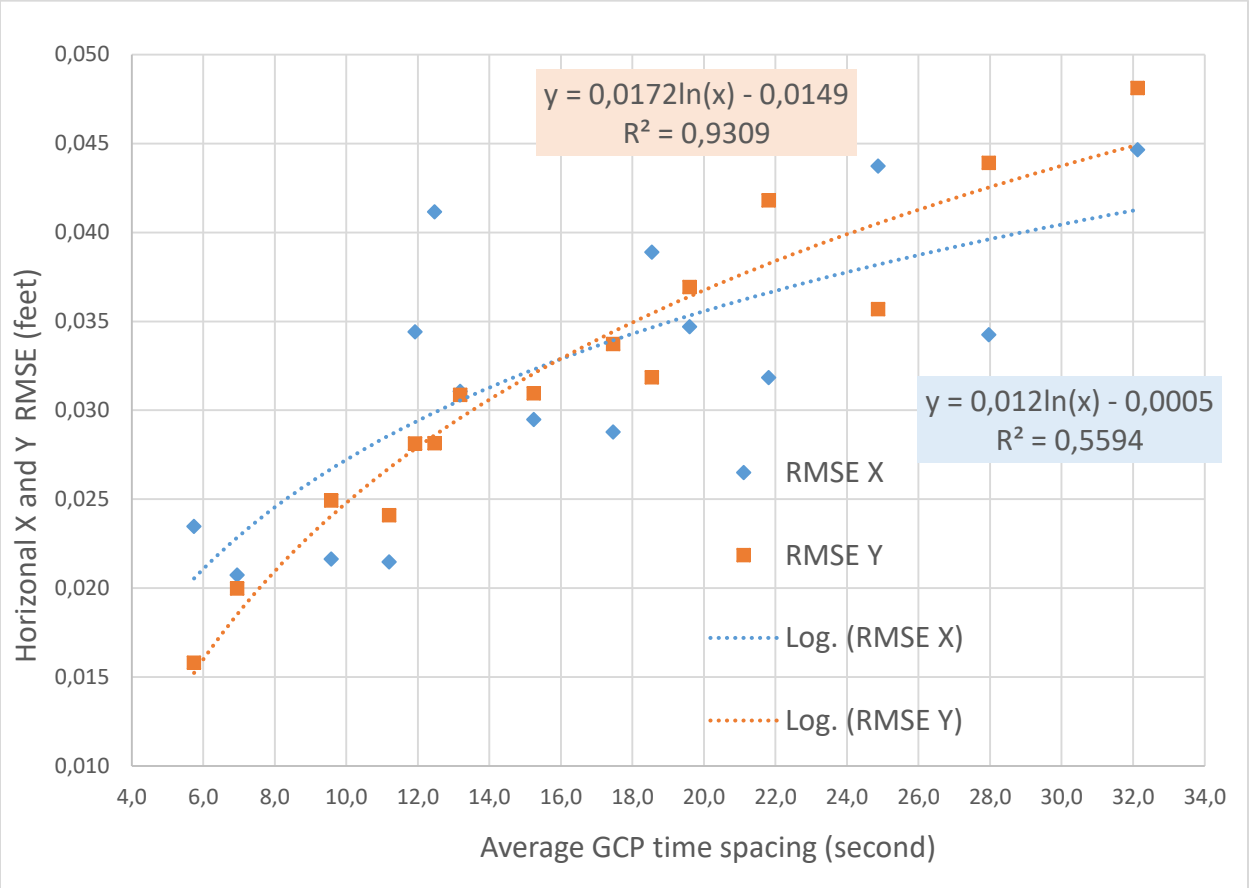


Figure 3.17: Horizonal X and Y RMSE vs time spacing between registration GCPs.

MTLS users may select the appropriate time spacing between GCPs based on the accuracy requirement for the survey project using Figure 3.16 and 3.17. Users should be aware that project sites with degraded GNSS signal conditions would decrease system accuracy. The authors rated test site GNSS signal condition as good to excellent.

Distance-based GCP Spacing RMSE Results

All 454 data points were sorted using the registration GCP distance spacing. The X, Y, and Z RMSE values were calculated using all the points with the same registration GCP distance spacing. Figure 3.18 shows elevation Z RMSE vs distance spacing between registration GCPs. AHMCT researchers found that the logarithmic curve produced the best data fit compared to linear or polynomial curves. The distance-based data points are a closer fit ($R^2 = 0.91$) to its best fit curve compared to time-based spacing data points ($R^2 = 0.70$ with bin size = 44) as shown in Figure 3.16.

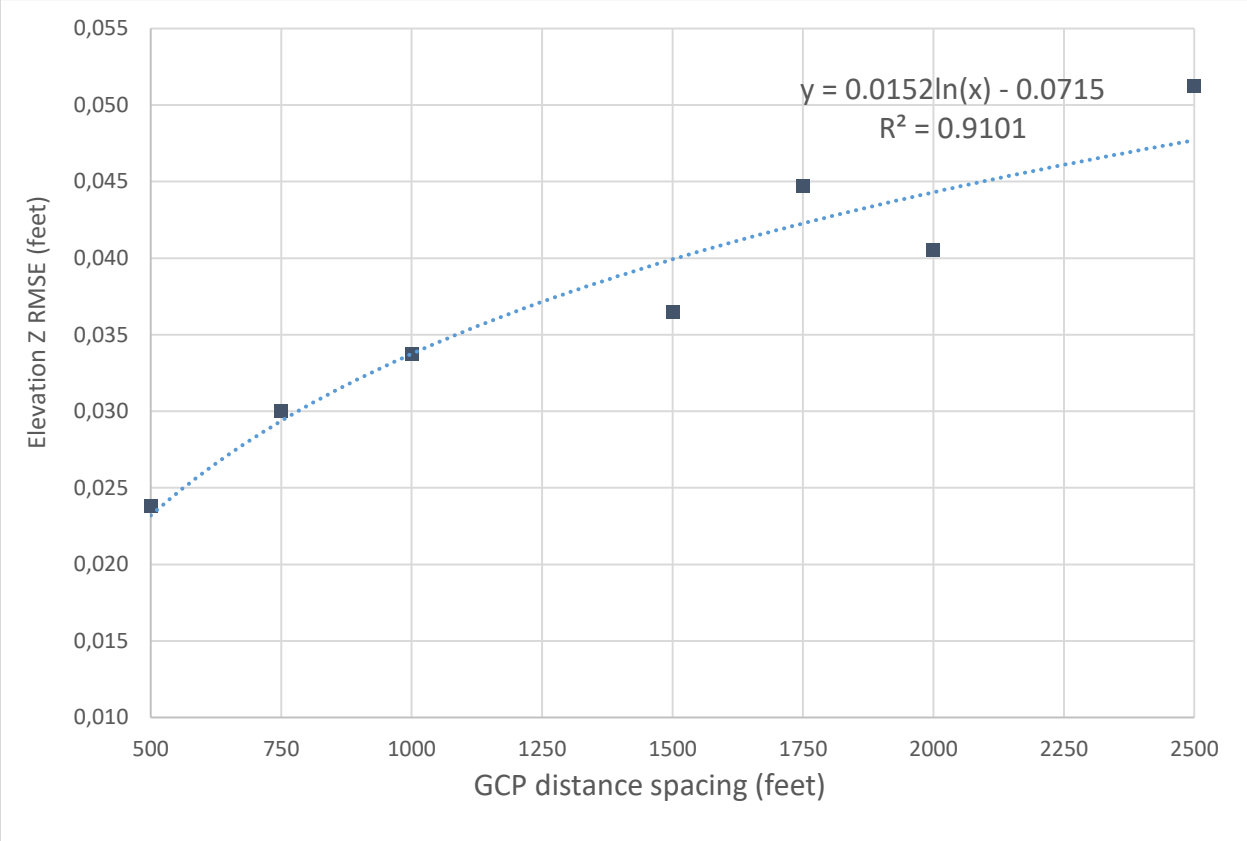


Figure 3.18: Elevation Z RMSE vs distance spacing between registration GCPs.

Figure 3.19 shows horizontal X and Y RMSE vs distance spacing between registration GCPs. The X and Y RMSE behavior are similar to that of elevation Z RMSE.

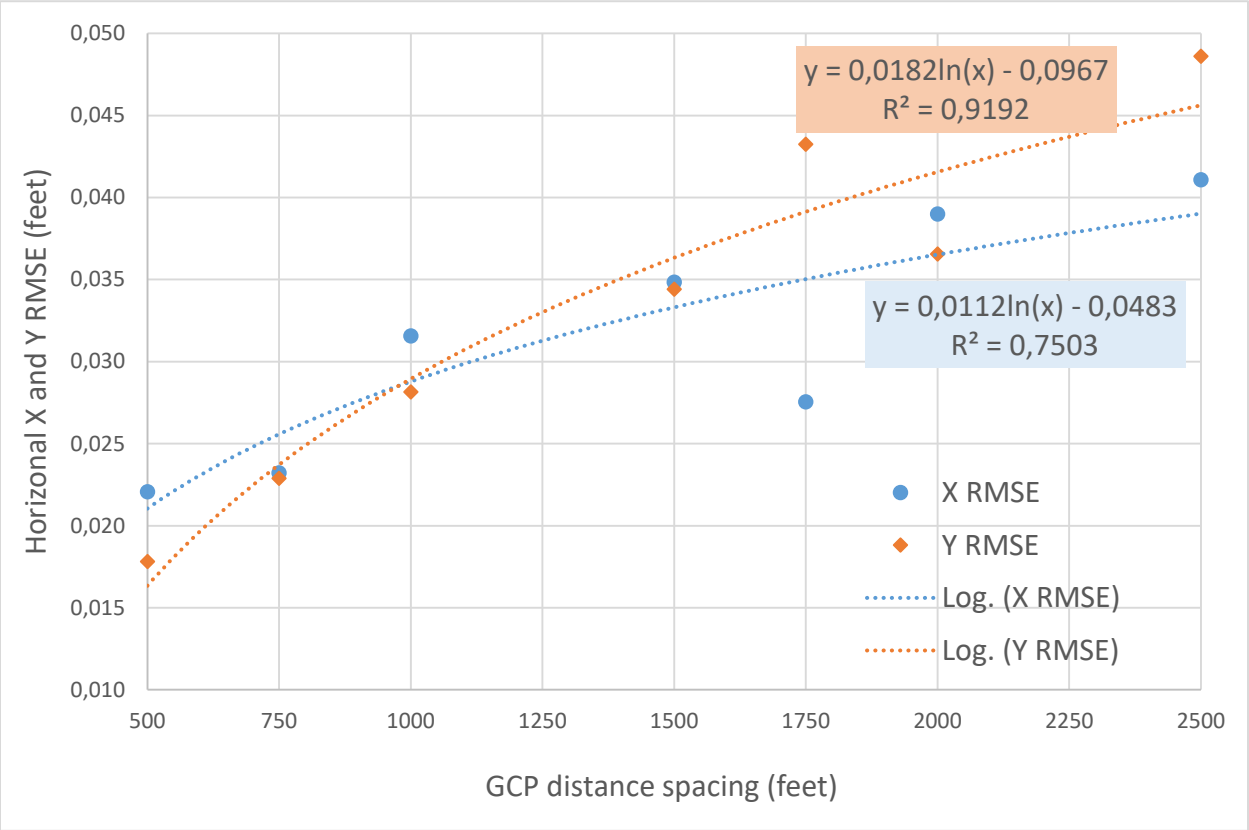


Figure 3.19: Horizonal X and Y RMSE vs distance spacing between registration GCPs.

Conclusion

- Some uncertainties and inaccuracies exist when picking the GCP target reference point location from the point cloud, particularly when the target point density is low due to higher vehicle speeds.
- The inclusion or exclusion of a small number of large errors from recorded run 16 did not make a significant difference in the result.
- The distance-based GCP spacing data points show a clear trendline compared to time-based GCP spacing data points.
- The results are based on vehicle speeds between 50 to 65 MPH with good GNSS signal condition. Due to safety concerns, AHMCT researchers did not attempt to scan the test site below 45 MPH.
- The time-based GCP spacing approach is logical, particularly when MTLS vehicle speeds are much slower at highway exits, on-ramps, and city streets. The distance-based GCP spacing approach may be more practical when communicating with survey crews with limited understanding of MTLS

technologies. Using a time-based GCP spacing approach, MTLS GCPs should become denser at highway exits, on-ramps, and city streets.

- Different DOTs and survey projects may have different accuracy requirements. MTLS surveyors must apply their best judgment based on the project accuracy requirements and project site conditions, including terrain, urban canyon, and long GNSS baseline lengths, which may degrade system GNSS performance. Figures 3.16 to 3.19 provide guidance for selecting appropriate GCP spacing based on time or distance.
- Most Caltrans MTLS projects consist of a highway mainline. The vehicle scanning speed is usually between 50 to 65 MPH. With a relatively small MTLS vehicle scanning speed variation, specifying GCP spacing using distance-based or time-based makes little difference. AHMCT researchers believe the distance-based GCP spacing approach is simple to follow for all surveyors with or without in-depth MTLS experience.

Chapter 4:
Platform for Sharing Digital As-Builts

Objectives

The objective of this task was to facilitate distribution of as-built data from MTLS to other data customers within Caltrans. Allowing as-built data users to view and study the point clouds and images directly, data customers can make data driven decisions immediately. Viewing point cloud data and georeferenced ground images often requires specialized software and high-end workstations which are not widely available to all Caltrans staff. This task evaluated the efficacy of Trimble MX publisher software which was designed for general users to view point clouds and georeferenced images using a web browser.

North Region Surveys was interested in sharing MTLS data at Fort Jones, California with District 2 Planning & Local Assistance. The AHMCT research team used this opportunity to test and evaluate Trimble MX publisher software for this use case.

Trimble MX Publisher Evaluation

Trimble MX Publisher is a platform that was tested for sharing MTLS data with project stakeholders. The MTLS data is streamed to the end user's web browser for viewing, navigating, and extracting features and measurements using basic tools. The MTLS data is hosted on either a premises-based or cloud-based server. Trimble MX publisher also supports other datasets, such as aerial images, point clouds from aerial platforms, terrestrial laser scanners, and handheld laser scanners. It provides a simple user-friendly web-based interface for general users who may have limited experience with complex data structures from MTLS systems.

A dedicated x86 windows server was used for hosting the Trimble MX Publisher server software. The server was connected to the University of California Davis network with a one Gigabit per second (Gbps) link. The MTLS data was stored locally on an SSD. This setup was meant for a short-term evaluation of the MX Publisher software. Factors related to Caltrans enterprise level deployment considerations were not prioritized.

Trimble MX Publisher Installation

Trimble provided detailed MX Publisher installation steps and licenses for activation. AHMCT researchers installed and set up the software by following

Trimble's instructions and support clarification emails. The software installation is more complex than simply double-clicking an installation file. However, the instructions are clear and straightforward. After installing and starting the MX Publisher webserver, the user may administer the software from a web browser.

Trimble MX Publisher Data Pre-processed

Trimble Business Center (TBC) software is used to post-process the MX9 and MX50 MTLS data to georeferenced point clouds and images. TBC has an export preset specifically for MX Publisher. The Fort Jones MTLS dataset was exported for MX Publisher import. Figure 4.1 shows the file and folder structure of the Fort Jones exported dataset from TBC. The vehicle scan trajectory data are stored in the trajectory.csv text file. Both left and right laser point cloud clouds are stored in open American Society for Photogrammetry and Remote Sensing (ASPRS) LASer (LAS) format files within the laser folder. Each LAS file has an associated text file, as shown in Figure 4.2, specifying the LAS file datum and Geoid model used. This information is useful when setting up a project in MX publisher.

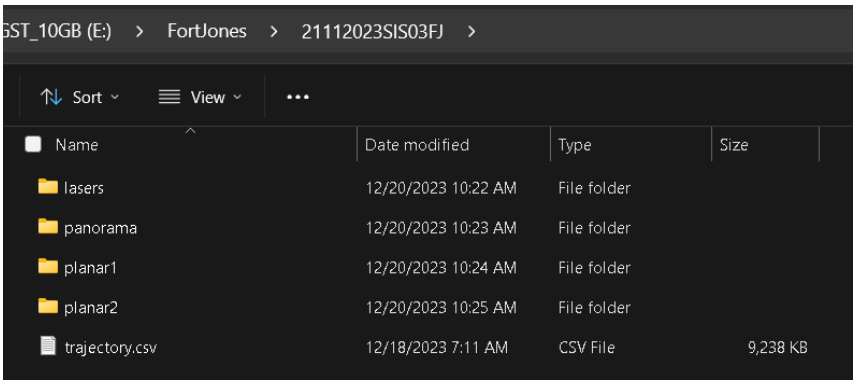


Figure 4.1: TBC MX Publisher exported file structure (Fort Jones dataset).

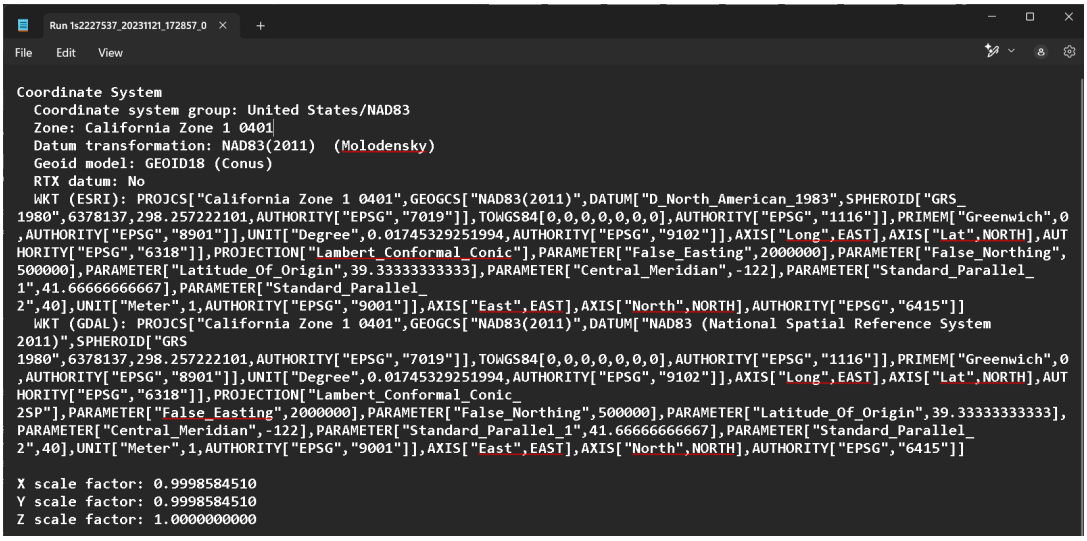
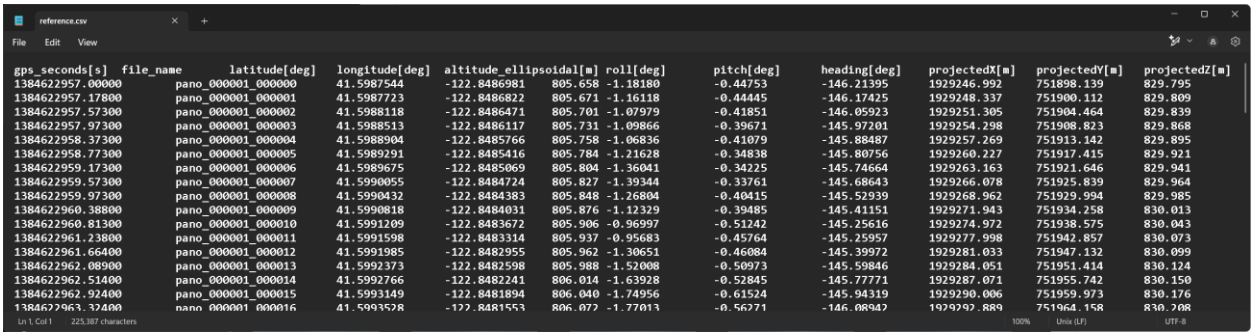


Figure 4.2: Associated LAS text file storing the LAS file's datum and Geoid model.

The camera images were stored in the panorama, planar1, and planar2 folders. The image files are in Joint Photographic Experts Group (JPEG) format. Each camera image folder also contains a reference.csv text file, as shown in Figure 4.3, containing each image's time, position, and orientation data.



reference.csv

File Edit View

gps_seconds[s]	file_name	latitude[deg]	longitude[deg]	altitude_ellipsoidal[m]	roll[deg]	pitch[deg]	heading[deg]	projectedX[m]	projectedY[m]	projectedZ[m]
1384622957.00000	pano_000001_000000	41.5987544	-122.8486981	805.658	-1.18180	-0.44753	-146.21395	1929246.992	751898.139	829.795
1384622957.17800	pano_000001_000001	41.5987723	-122.8486822	805.671	-1.16118	-0.44445	-146.17425	1929248.337	751900.112	829.809
1384622957.57300	pano_000001_000002	41.5988118	-122.8486471	805.701	-1.07979	-0.41851	-146.05923	1929251.305	751904.464	829.839
1384622957.97300	pano_000001_000003	41.5988513	-122.8486117	805.731	-1.09866	-0.39671	-145.97201	1929254.298	751908.823	829.868
1384622958.37300	pano_000001_000004	41.5988904	-122.8485766	805.758	-1.06836	-0.41079	-145.88487	1929257.269	751913.142	829.895
1384622958.77300	pano_000001_000005	41.5989291	-122.8485416	805.784	-1.21628	-0.34838	-145.80756	1929260.227	751917.415	829.921
1384622959.17300	pano_000001_000006	41.5989675	-122.8485069	805.804	-1.36041	-0.34225	-145.74664	1929263.163	751921.646	829.941
1384622959.57300	pano_000001_000007	41.5990055	-122.8484724	805.827	-1.39344	-0.33761	-145.68643	1929266.078	751925.839	829.964
1384622959.97300	pano_000001_000008	41.5990432	-122.8484383	805.848	-1.26804	-0.40415	-145.52939	1929268.962	751929.994	829.985
1384622960.38800	pano_000001_000009	41.5990818	-122.8484031	805.876	-1.12329	-0.39485	-145.41151	1929271.943	751934.258	830.013
1384622960.81300	pano_000001_000010	41.5991209	-122.8483672	805.906	-0.96997	-0.51242	-145.25616	1929274.972	751938.575	830.043
1384622961.23800	pano_000001_000011	41.5991598	-122.8483314	805.937	-0.95683	-0.45764	-145.25957	1929277.998	751942.857	830.073
1384622961.66400	pano_000001_000012	41.5991985	-122.8482955	805.962	-1.30651	-0.46084	-145.39972	1929281.033	751947.132	830.099
1384622962.08900	pano_000001_000013	41.5992373	-122.8482598	805.988	-1.52008	-0.50973	-145.59846	1929284.051	751951.414	830.124
1384622962.51400	pano_000001_000014	41.5992766	-122.8482241	806.014	-1.63928	-0.52845	-145.77771	1929287.071	751955.742	830.150
1384622962.92400	pano_000001_000015	41.5993149	-122.8481894	806.040	-1.74956	-0.61524	-145.94319	1929290.006	751959.973	830.176
1384622963.32400	pano_000001_000016	41.5993528	-122.8481553	806.072	-1.77013	-0.56771	-146.08942	1929292.889	751964.158	830.208

Ln 1, Col 1 225,387 characters 100% Unix (LF) UTF-8

Figure 4.3: Image folder reference.csv text file storing each image's time, position, and orientation data.

Trimble MX Import and Upload Tool

The Trimble MX Import and Upload Tool was used to convert the TBC exported data to Trimble MX Publisher's proprietary data format. The proprietary data format was designed for streaming the data to an end user's web browser viewer efficiently and minimizing end user wait time for data to appear on display. Figure 4.4 shows the Trimble MX Import and Upload Tool graphical user interface (GUI). The software shows the location of the data overlaying on maps, which ensures that the proper map datum and geoid were selected correctly. The Geoid model file was downloaded separately from the installation files.

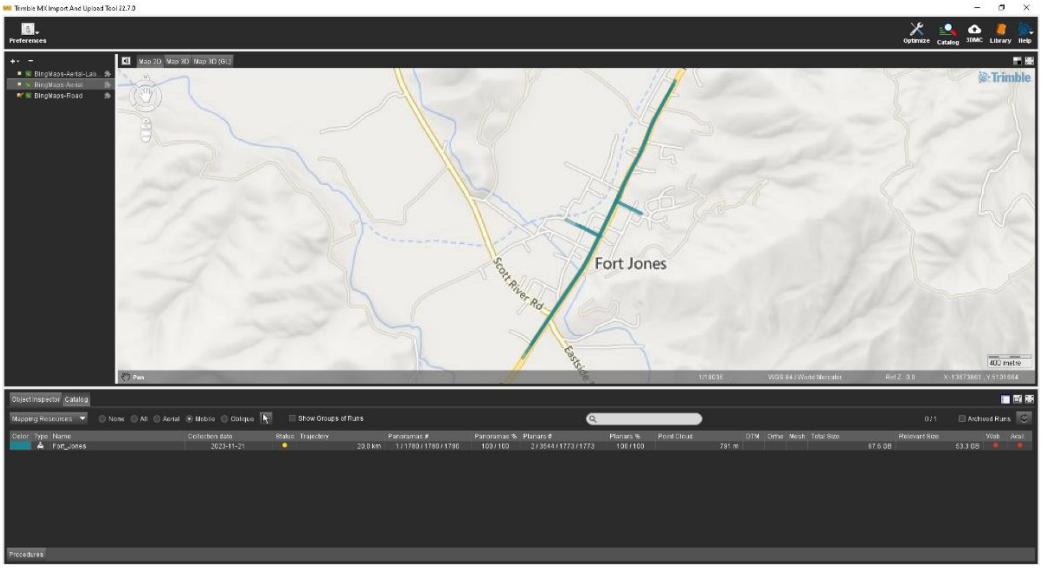


Figure 4.4: Trimble MX Import and Upload Tool GUI.

After that, the TBC exported data may be converted to the MX publisher's proprietary data format. MX publisher uses the term "optimize" instead of "convert" as shown in Figure 4.5. Figure 4.6 shows the optimize MX publisher Fort Jones dataset files and folders that were then copied to the MX publisher server's SSD.

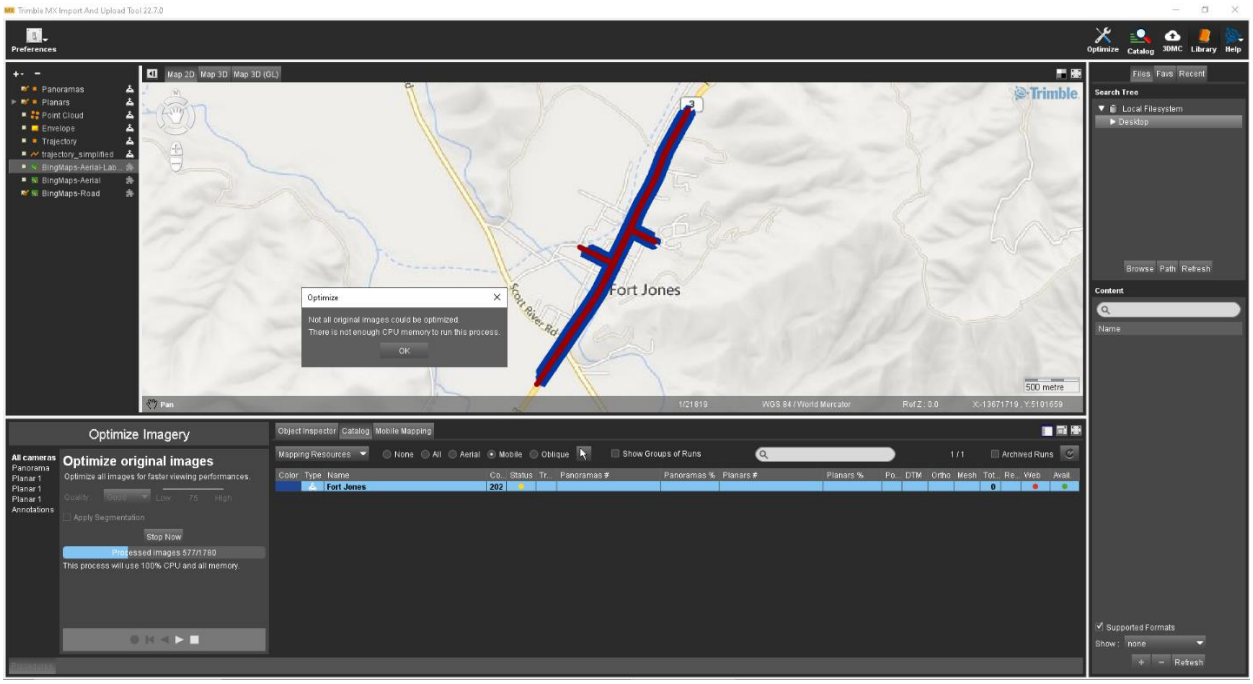


Figure 4.5: Trimble MX Import and Upload Tool optimize the MTLS data for MX Publisher.

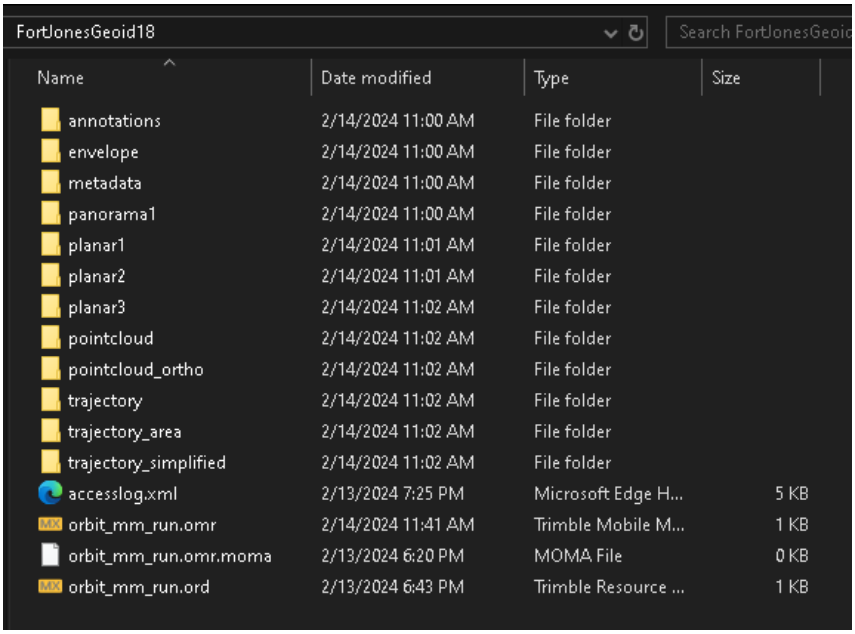


Figure 4.6: Trimble MX Publisher data files structure.

Trimble MX Publisher Administration

MX Publisher's administration was conducted using its web GUI. After changing the MX Publisher web server administrator's password, new users and their permissions were then added as shown in Figures 4.8 and 4.9. User groups were created after creating all new users with passwords. User groups were then assigned to access different datasets (Resources / Resources groups in MX Publisher's term).

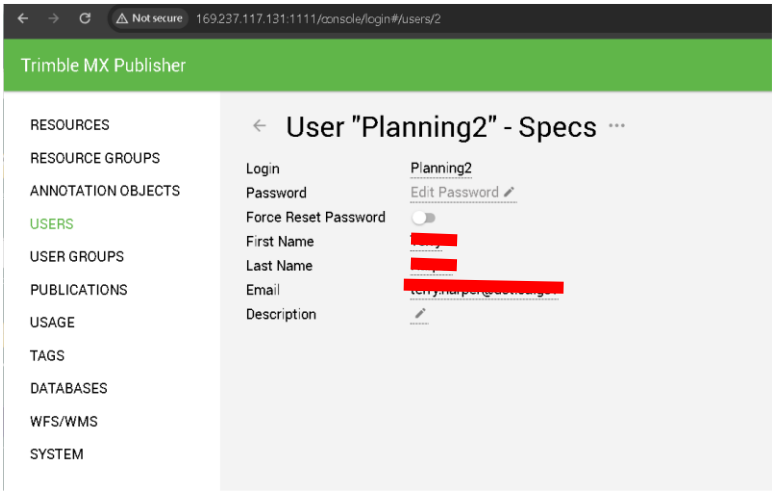


Figure 4.8: MX Publisher user administration web GUI.

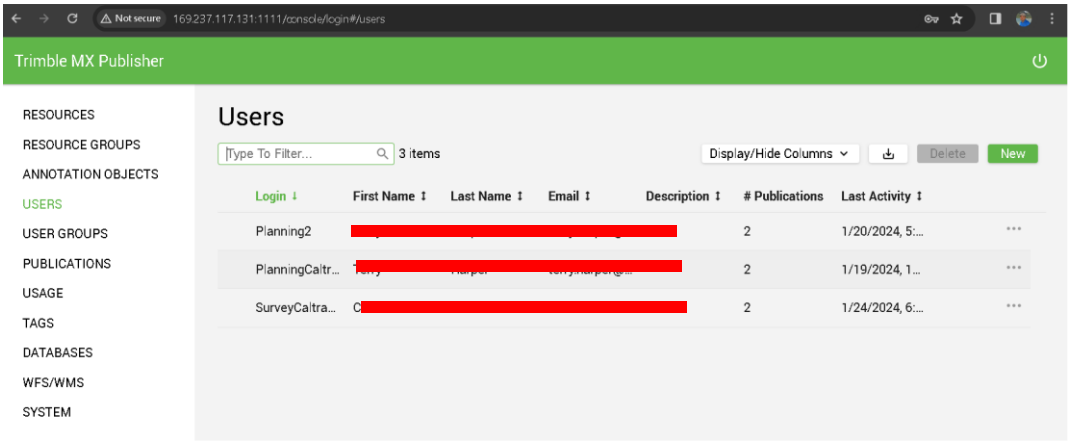


Figure 4.9: MX Publisher users overview administration web GUI.

Figures 4.10 and 4.11 show the MX Publisher Resource setup GUI. Administrators entered the MX Publisher dataset file location and associated meta data. Bing Map background resources must be created using the included *.otm files in the MX Publisher folder. Bing Map backgrounds are not available by default. Users can provide their own map tile server to support custom maps.

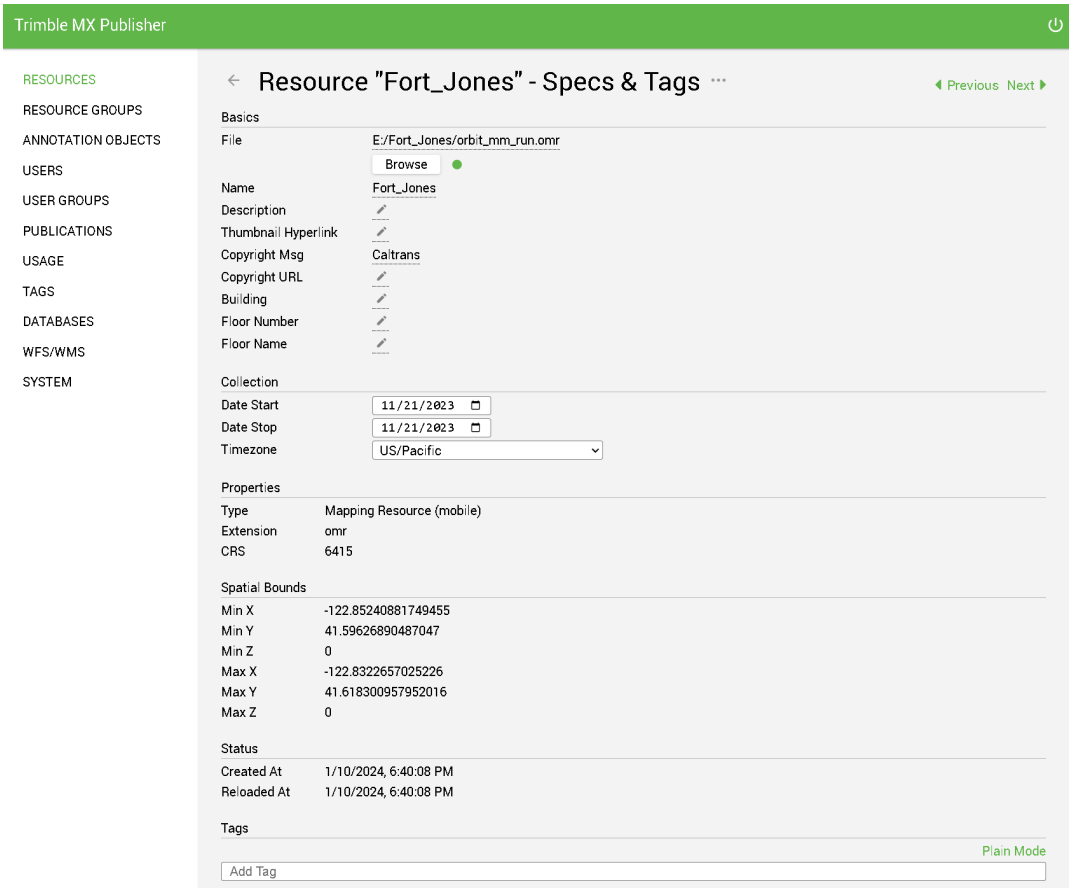


Figure 4.10: MX Publisher Resources administration web GUI.

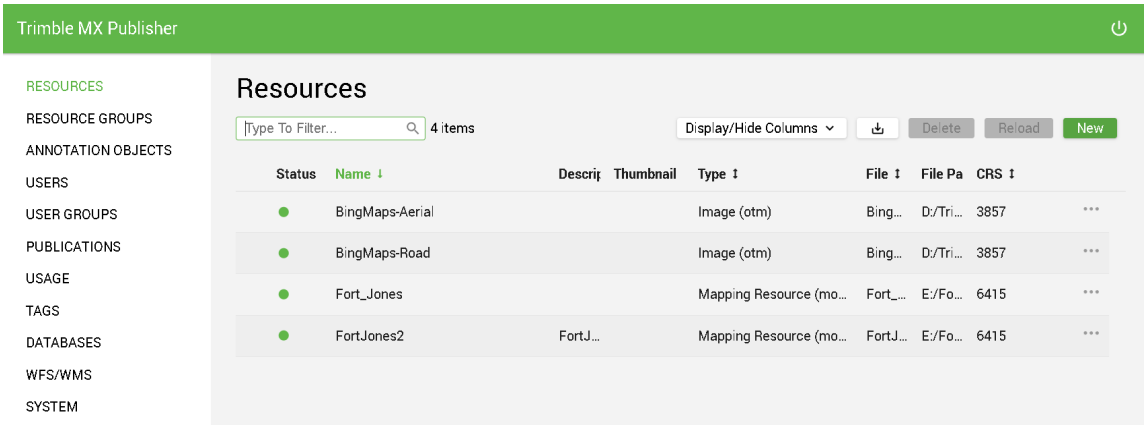


Figure 4.11: MX Publisher Resources administration web GUI. List of created resources are shown.

After that, the administrator produced publication using previously created resources as shown in Figure 4.12. The previously created users were then assigned to the available publications as shown in Figure 4.13.

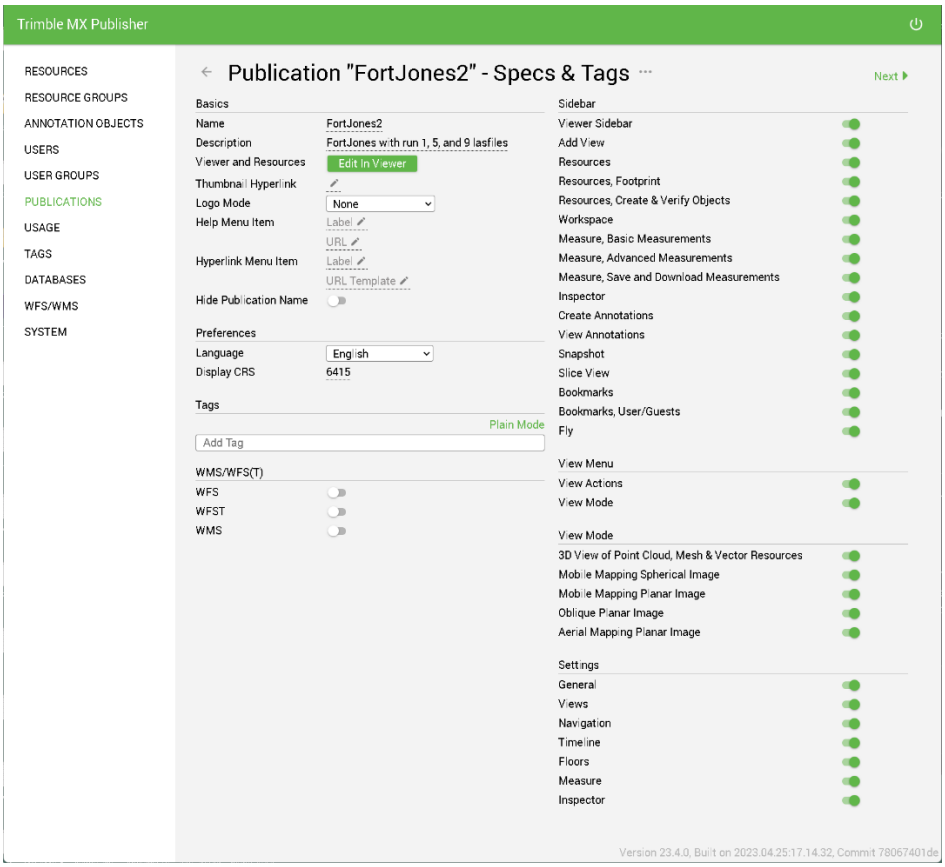


Figure 4.12: MX Publisher individual publications administration web GUI.

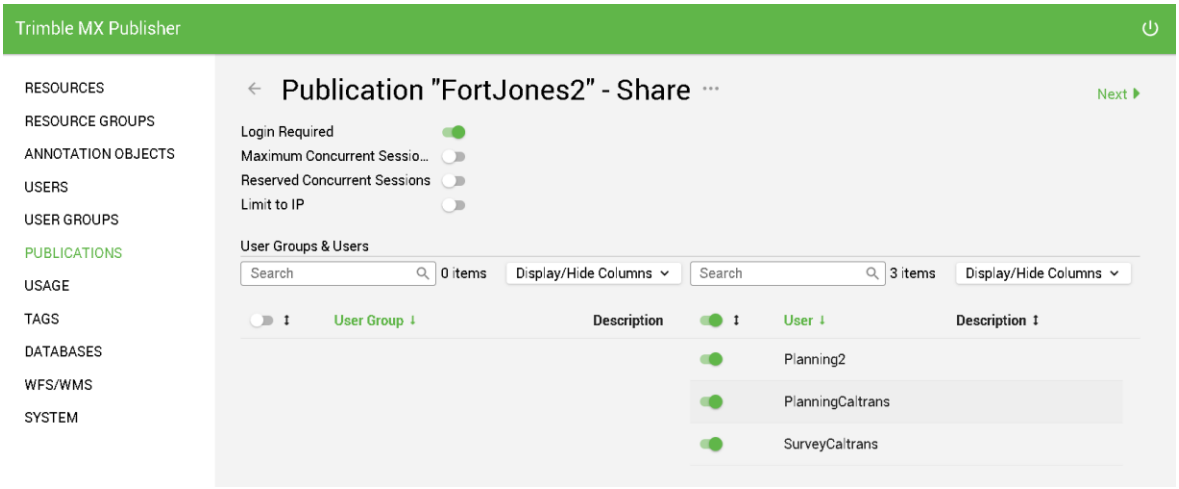


Figure 4.13: MX Publisher publications users permission administration web GUI.

Trimble provided three days of training for AHMCT researchers and Caltrans personnel on MX publisher administration. AHMCT researchers were able to complete much of the setup prior to training using available instructions. However, the training highlighted the need to download and set up the Continental United State GEOID18 file to ensure that the point cloud elevation data are displayed correctly.

Trimble MX Publisher Web User Interface

After completing all setups on the MX Publisher administrator web GUI, the end user web GUI was then customized by the administrator. Customization includes making resources visible, as shown in Figures 4.14, 4.15, and 4.16, by default as well as the display layout as shown in Figure 4.17.

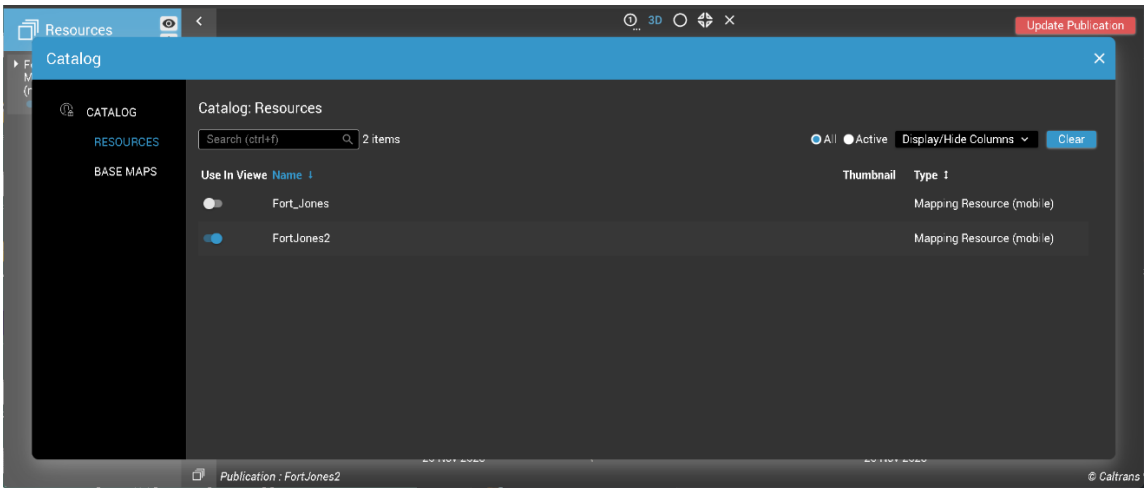


Figure 4.14: MX Publisher end user resources web GUI.

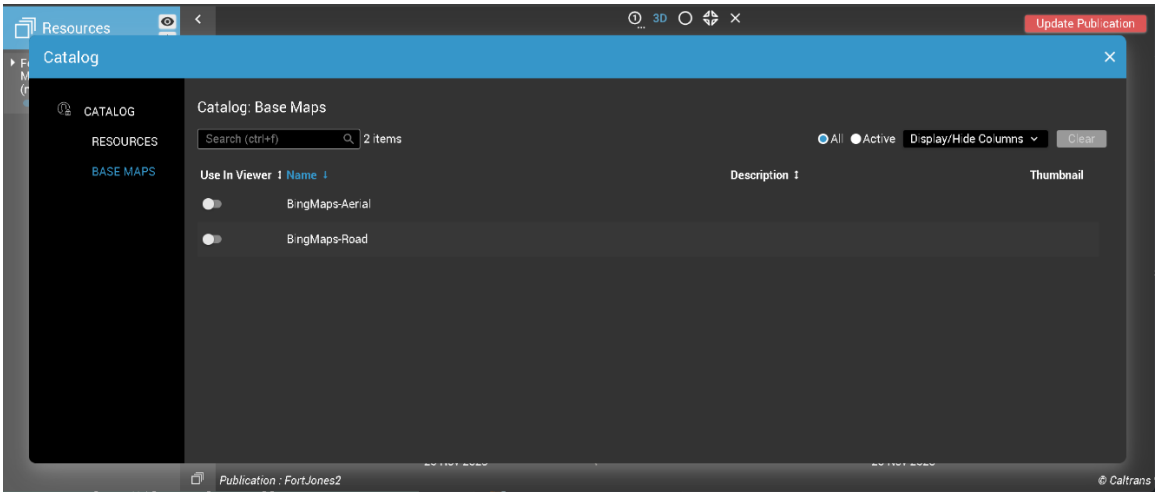


Figure 4.15: MX Publisher end user base map web GUI.

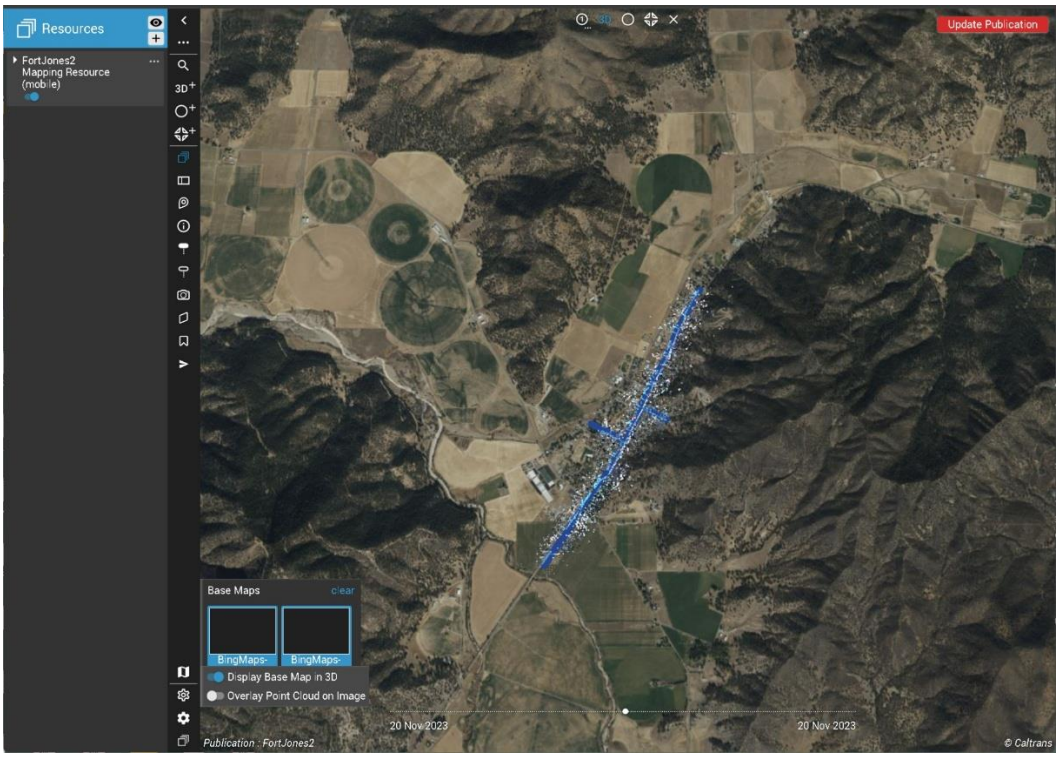


Figure 4.16: MX Publisher end user single tile web GUI.

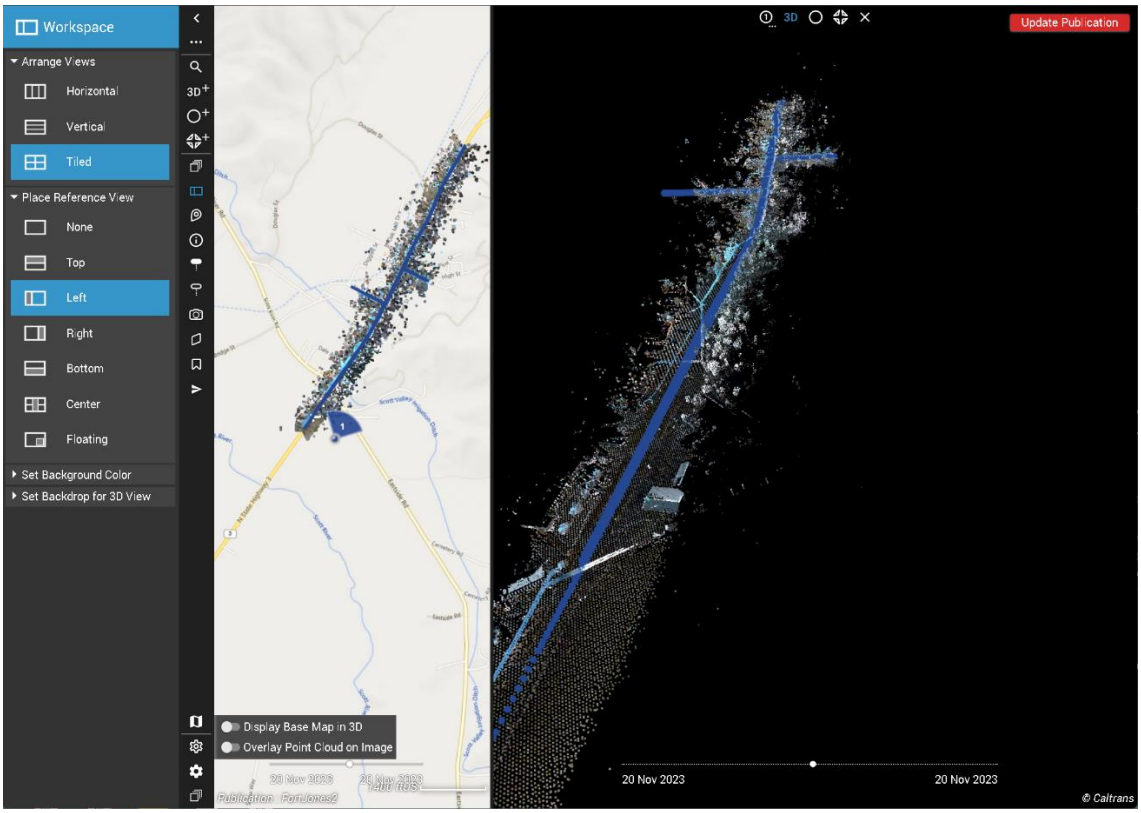


Figure 4.17: MX Publisher end user tile configuration web GUI.

Figure 4.17 shows different layout arrangement options available. A layout with more view panels allows end users to view more data simultaneously. However, users with low-resolution displays may not favor this layout view. Figures 4.18 and 4.19 show the final customized layout and interface setup for end users. The top right view window shows the image from the 360-degree camera, and the top middle view window shows MTLS point cloud colored using the 360-degree images by default. The end user has the option to change the point cloud display to intensity-based view. Images from the planar cameras are displayed on the bottom two view windows. The left view window shows the aerial map view.

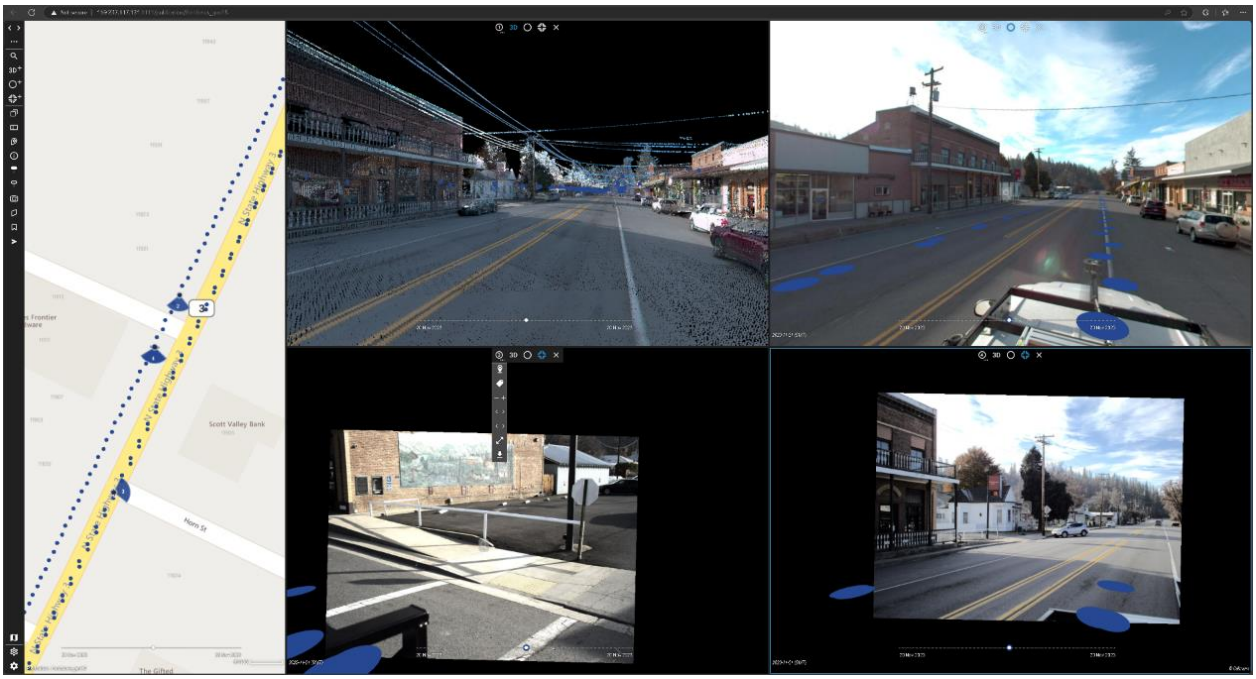


Figure 4.18: MX Publisher end user multiple tiles web GUI. The map view on the left shows camera image position overlay on top of street map tiles.

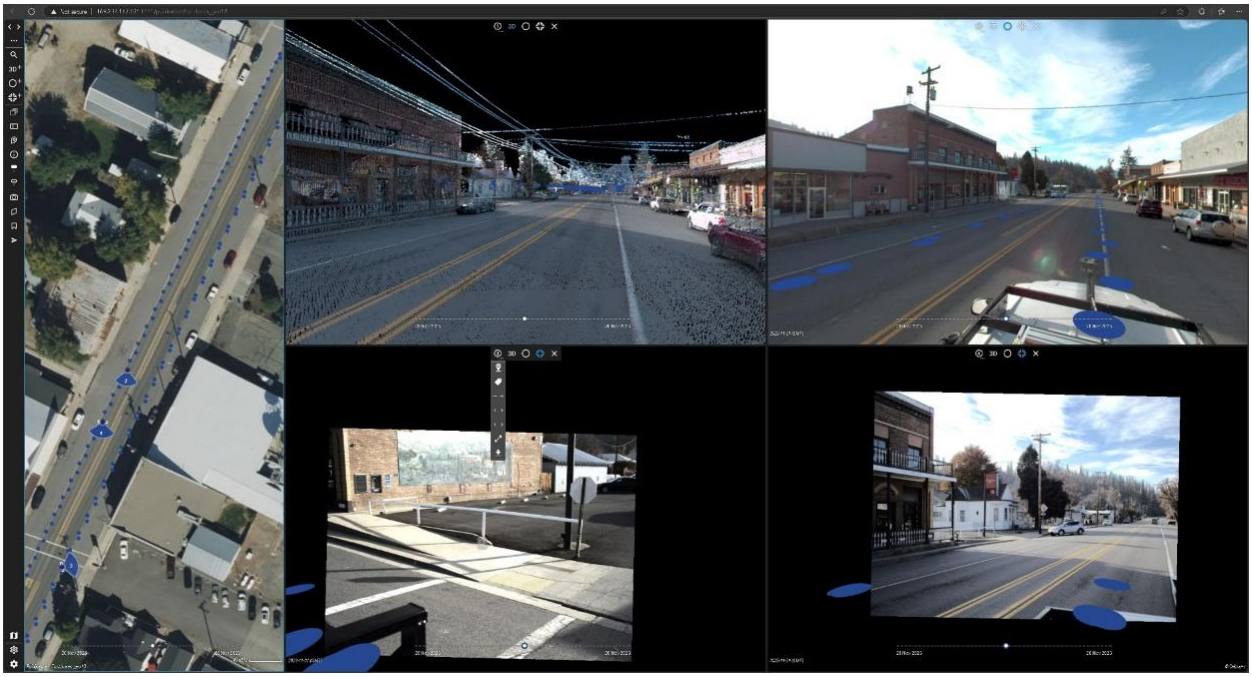


Figure 4.19: MX Publisher end user multiple tiles web GUI. The map view on the left shows camera image position overlay on top of satellite imagery.

Results

The software was successfully installed and worked as intended. AHMCT researchers have also evaluated the web interface using the Fort Jones dataset via a 1 Gbps ethernet to the server. The loading data speed was acceptable. North Region and OLS personnel were among the first test users to assess MX Publisher's usability. The web link and login were then shared with Planning personnel for their evaluation. The evaluation was carried out when most people were on a hybrid work schedule. Therefore, the available broadband bandwidth might have varied from different users.

The lack of positive user feedback was mostly due to slow loading data and slow navigation. Slow broadband speed can negatively impact the navigation and data loading performance. In general, users find the web interface intuitive and the overall concept appealing.

Trimble was developing a desktop version of the MX publisher that would speed up data loading and navigation with data since the data are stored locally on SSDs. Recently, Trimble Clarity software was made available to work with Trimble Connect Cloud services to enable sharing of 3D geospatial data, including point clouds and models. Stakeholders may view MTLS data via a web browser. Using Trimble Connect integrated cloud services would reduce standalone software and setup complexities from third-party cloud services.

Trimble Reality Capture Platform Service (TRCPS)[2] may also be a viable tool to serve similar purposes. TRCPS delivers point clouds and 360-degree imagery directly alongside detailed design data to end users using secure Trimble Connect Cloud services. TRCPS facilitates collaboration between infrastructure stakeholders while maintaining original data accuracy.

[2] Trimble Reality Capture Platform Service (https://geospatial.trimble.com/en/resources/home/introducing-the-trimble-reality-capture-platform-service-unlocking-reality-data-through-seamless-collaboration).

Chapter 5:
Improve Cross-Functional Programmatic Collection of Data

AHMCT researchers explored means to improve the cross-functional programmatic collection of data and achieve the "collect once, use it many times" best practice aspired to by Caltrans. The objective is to maximize the benefit of geospatial data collection and leverage its use across various disciplines.

In support of California's goal to expand broadband deployment statewide, Caltrans is making its right of way available for broadband infrastructure. High resolution images along selected highway routes would enable Caltrans Division of Environmental to better assess environmental impacts for broadband infrastructure expansion. AHMCT researchers investigated the impact of adding a high-resolution camera to the MX9 system to collect high resolution roadside images along with point cloud data for Division of Environmental to assist with environmental impact studies. Phase One GS120 camera was integrated with a Caltrans MX9 system in this task.

Phase One GS120 Camera Integration with MX9 system

Phase One GS120 Camera has a medium format 120 Megapixel (MP) image sensor, and it can capture full resolution images at 7 frames per second (fps). Detail GS120 camera specification is available at Phase One (https://www.phaseone.com/). Its high-resolution images would enable detailed environmental impact analyses to be performed safely in the office. Caltrans plans to use the 120 MP camera to photograph 15' to 50' beyond the edge of pavement for environmental applications.

AHMCT researchers completed design and fabrication mounts for the Phase One GS120 Camera for the MX9 MTLS system as shown in Figures 5.1, 5.2, and 5.3. A CAD model was developed as shown in Figure 5.4. The camera mount is made of 3060 and 2020 aluminum T-slot extrusion. At the rear of the camera body, the GS120 camera has one power input port, one USB C data port, and external camera triggering ports A and B as shown in Figure 5.1. The GS120 camera is mounted with a 36 degrees tilt from horizontal on the passenger side facing directly to the shoulder.

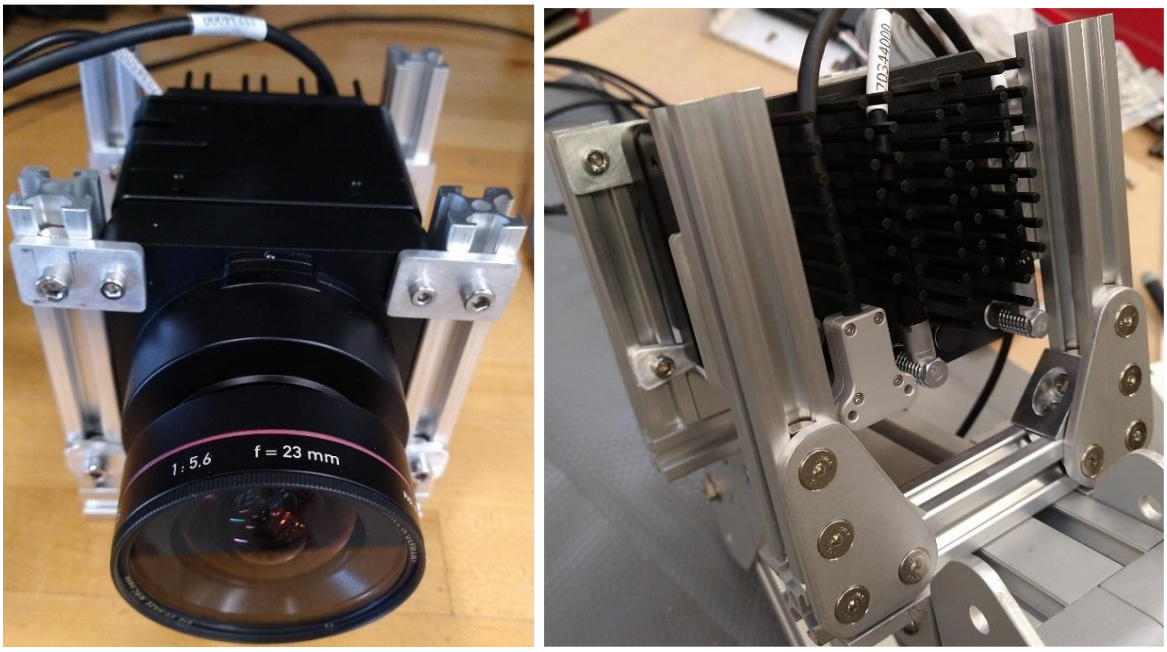


Figure 5.1: GS120 camera mount.

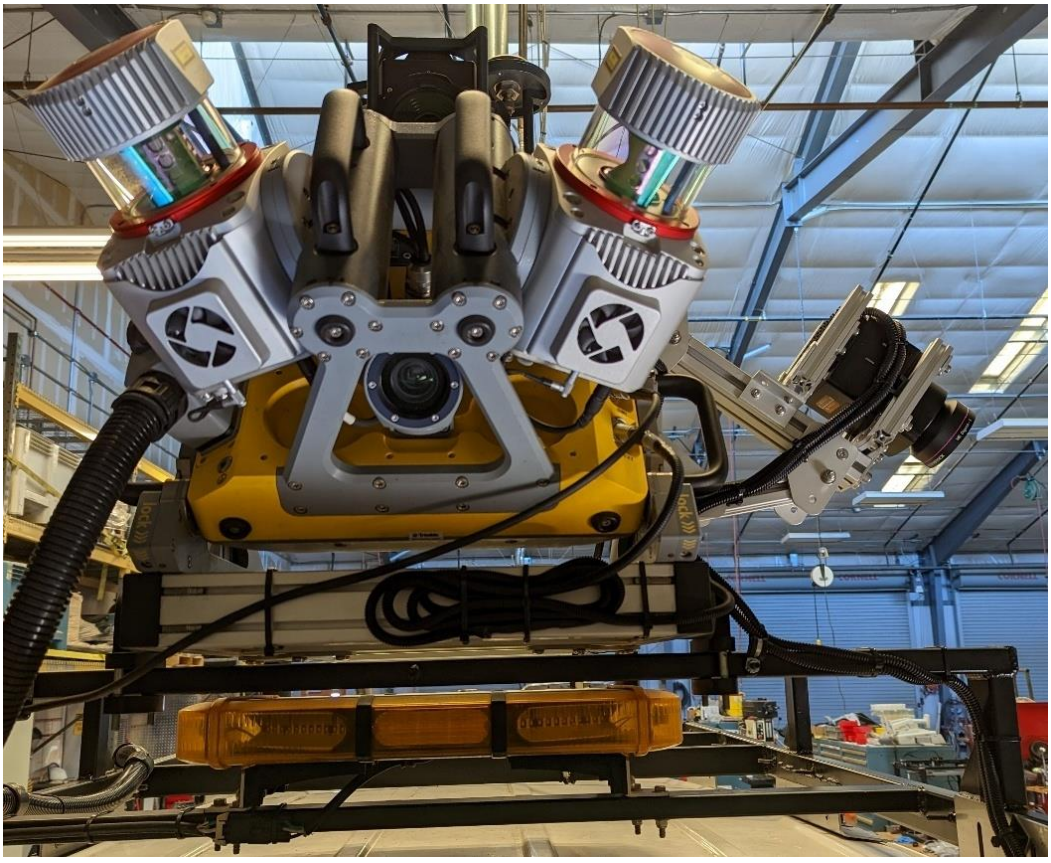


Figure 5.2: GS120 camera mount on MX9 sensor unit.

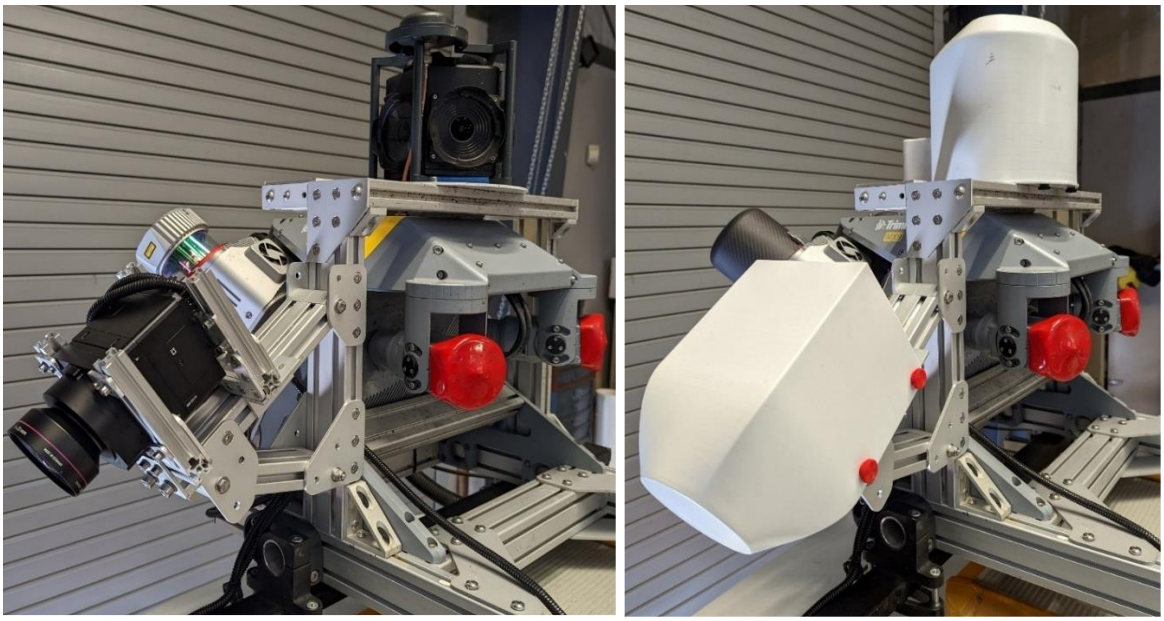


Figure 5.3: GS120 camera mount on MX9 sensor unit. A 3D printer protective GS120 camera cover is shown on the right.

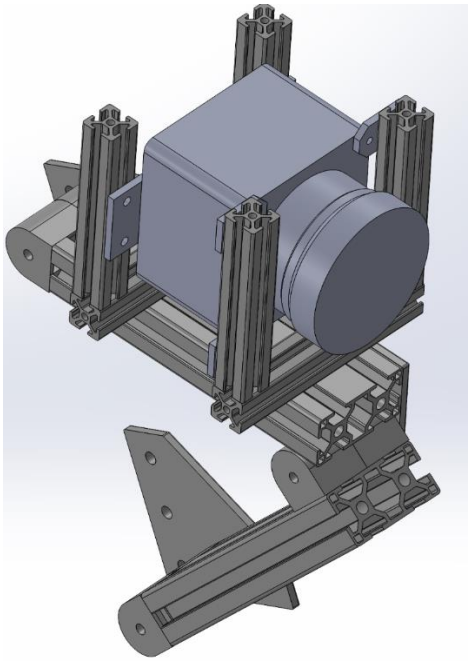


Figure 5.4: GS120 camera mount CAD model.

The GS120 camera is paired with a Phase One iX controller, as shown in Figure 5.5, for controlling the camera as well as storing image data from the GS120 camera. The iX controller requires a 24-30 VDC 150 Watts power supply. The iX controller and GS120 camera kit does not come with any vehicle power supply. A CUI inc. VHK200W-Q24-S24, purchased from Mouser Electronics, was used to convert vehicle 12 VDC to the required 28 VDC for the iX controller. A

trim resister was added to increase the VHK200W-Q24-S24 voltage output from 24 VDC to 28 VDC. The iX controller is connected to the GS120 camera via a USB 3.0 data connection. It also supplies power to the GS120 camera via a separate power cable. Figure 5.6 shows the iX controller mounted on the support frame, made of 3060 Aluminum T-Slot extrusions, next to the MX9 CU. The iX controller power supply and main power switch are also mounted on the support frame.

Figure 5.5: iX Capture controller.

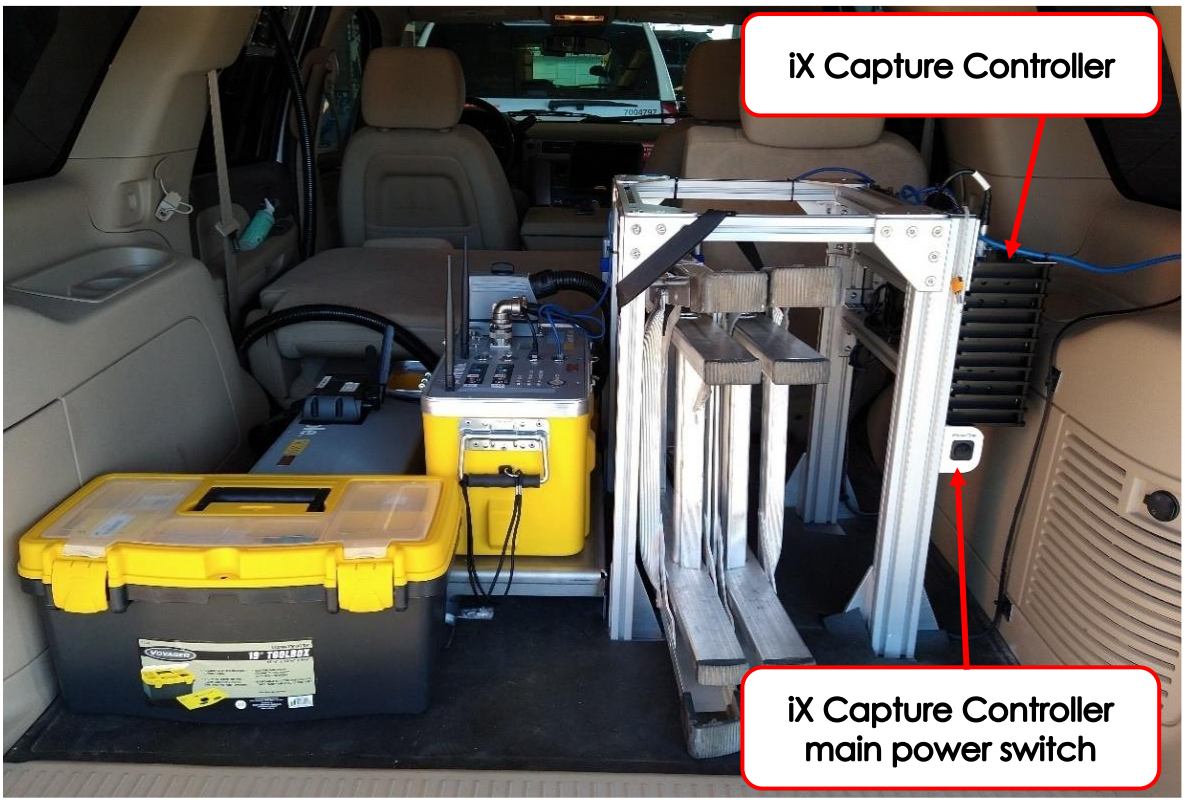


Figure 5.6: iX Capture controller mounted inside an MX9 system vehicle.

The MX9 Sensor Unit external sensor interface port is connected to the GS120 camera's external camera triggering ports A using a cable custom made by AHMCT researchers following instructions from Trimble and Phase One technical support. For the MX9 Sensor Unit, the external sensor interface port may be connected using a LEMO FGG.2K.314 connector. The GS120 port A may be connected using a LEMO FGG.0B.309 connector. MX9 TMI software settings were changed to support triggering the external GS120 camera. The GS120 provides an event trigger to the MX9 GNSS/IMU system at every mid-exposure of image capture. The TMI settings are shown in Table 5.2.

Table 5.1: MX9 to GS120 triggering cable pinout and function.

Trimble MX9 Sensor Unit LEMO FGG.2k.314.CLAC85				**GS120 Camera Port A LEMO FGG.0B.309**	
Pin No.	Name	Type	Comment	Pin No.	Description
1	Trigger 1	5V TTL	Output		
2	GND		Trigger 1 Ground		
3	Event 3	High > 4 VDC Low < 0.8 VDC	Opto-isolated Input	**7**	Mid-Exposure Pulse
4	GND		Trigger 3 Ground	**8 & 9**	Reserved & Common
5	Trigger 2	5V TTL	Output	**4**	Trigger in
6	GND		Trigger 2 Ground	**8 & 9**	Reserved & Common
7	Trigger 4	High > 4 VDC Low < 0.8 VDC	Opto-isolated Input		
8	GND		Trigger 4 Ground		
9	Com 4 RX	RS232	Receive		
10	Com 4 TX	RS232	Transmit	**5**	RS232 RX
11	GND		RS232 Ground	**8 & 9**	Reserved & Common
12	PPS 1	5V TTL	Output		
13	PPS 1	5V TTL	Output		
14	GND	Ground			

Table 5.2: MX9 TMI software external sensor settings for triggering GS120 camera image capture and time synchronization.

TMI Settings	TMI setting Value
Trigger 1:	Enable and Falling Edge
Event 3	Enable and Falling Edge
Guard Time	10
COM Port	Enable
COM Port Baud rate	115200
Update Rate	10 Hz
NMEA Messages	EVT3

An AHMCT researcher installed and tested the GS120 camera and the iX controller. Field tests showed that the setup does not support the desired image frame rate (~5 fps) using the iX controller. The system was able to sustain an image capture rate of 1.25 to 1.5 fps. Both the USB 3 and SATA storage are limiting the high data collection rate required to sustain 5 fps or about 600 MB/s data rate. GS120 camera raw images are stored in either compressed raw (~ 63 MB) or uncompressed raw format (~ 130 MB). Phase One technical support suggested using the GS120 camera's 10 Gigabit (Gb) Ethernet data interface instead of the USB interface to achieve 5 fps or higher image capture rate.

Figure 5.8 shows the GS120 10 Gb Ethernet interface location. A 10 Gb Small Form-Factor Pluggable (SFP+) to Optical Ethernet Fiber transceiver was installed into the GS120 camera 10 Gb Ethernet interface as shown on the right side of Figure 5.8. A fiber optic cable is more flexible compared to twin copper coax 10 Gb Ethernet cable. Figure 5.9 shows a fiber optic cable installed onto the SFP+ optical transceiver port.

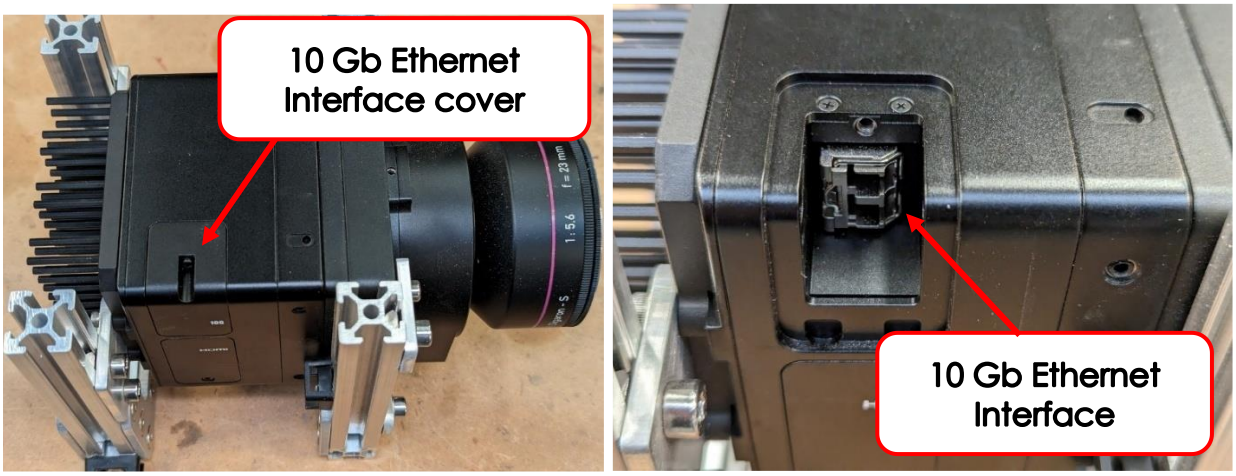


Figure 5.8: GS120 10 Gb Ethernet interface location.

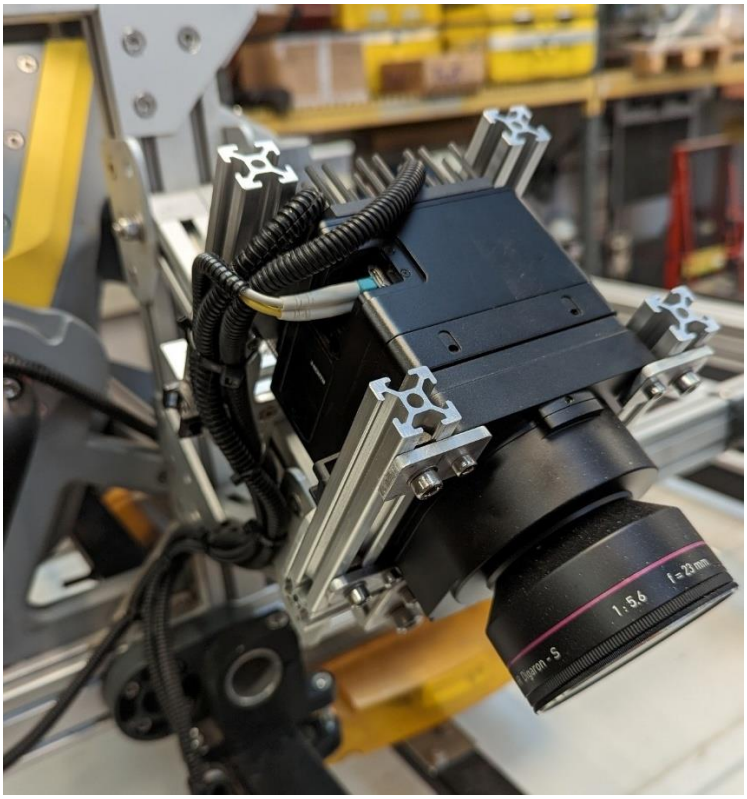


Figure 5.9: GS120 Camera with a 10 Gb Ethernet fiber optic cable installed.

The iX controller does not support adding a10 Gb Ethernet interface. AHMCT researchers redesigned the data capture system using an Intel NUC RNUC12WSKi7 computer with a Sonnet Solo10 Gb SFP+ Thunderbolt 3 adapter with a Short-Range SFP+ fiber transceiver. The Intel NUC computer has an i7-1206P processor and 32 Gigabytes (GB) of memory and a 4 terabyte (TB) SSD with two Thunderbolt 4 ports. The CUI inc. VHK200W-Q24-S24 power supply was reconfigured with a different trim resister to output 20 VDC for the Intel NUC computer and the GS120 camera. A 10-meter long 10 Gb Ethernet fiber optic cable was used to connect the GS120 camera SFP+ transceiver module to the Solo 10 Gb SFP+ transceiver module in the 10 Gb Ethernet to Thunderbolt port adapter as shown in Figures 5.9 and 5.10. The captured images are stored in the internal 4 TB SSD during data collection. The computer and GS120 camera were assigned fixed IP addresses with the same subnet of the GS120 camera. Phase One technical support assisted AHMCT researchers in upgrading the GS120 camera firmware to the latest version.

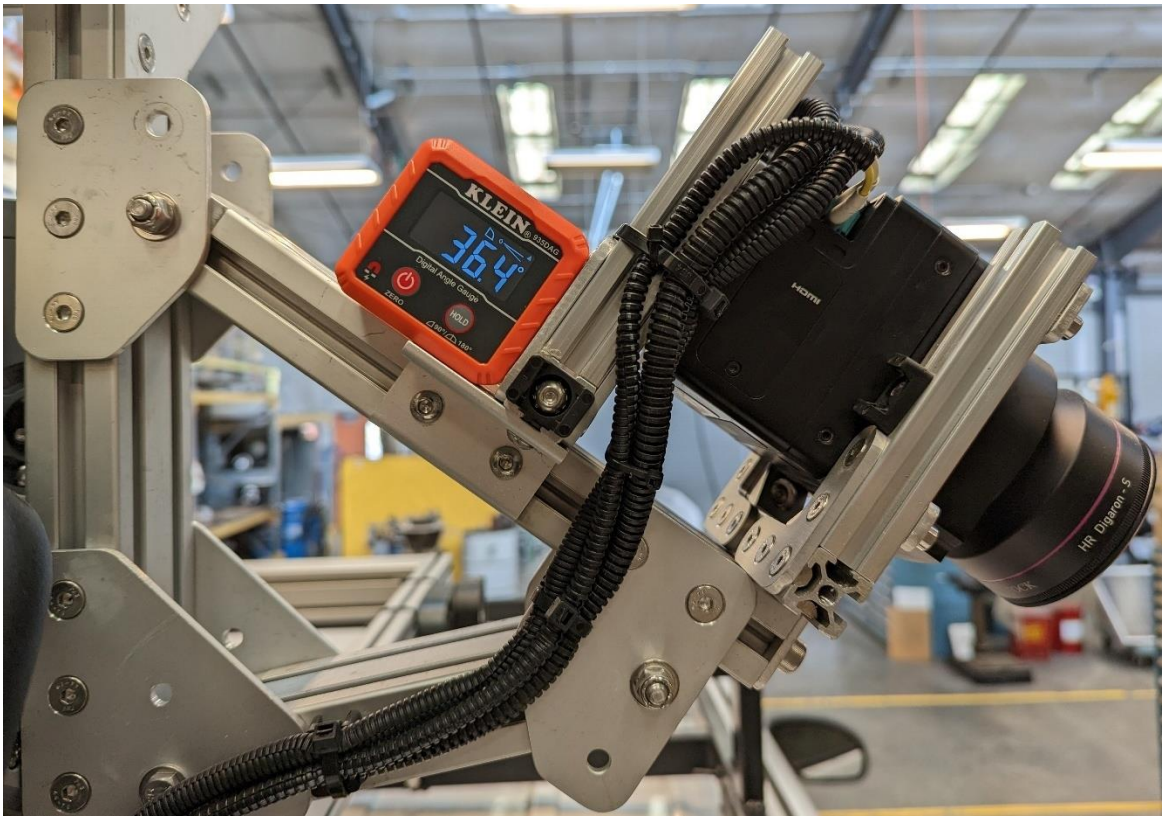


Figure 5.10: GS120 Camera with a 10 Gb Ethernet fiber optic cable installed.

iX Capture Software User Interface

Phase One iX Capture Software, running on Windows operating system, is used to control and adjust the GS120 camera settings and image capture parameters. Figures 5.11 and 5.12 show the software GUI. The MX9 tablet was used to run a remote desktop client and log remotely onto the Intel NUC computer running the iX Capture software. The software can control the image trigger methods, exposure settings (shutter speed, aperture, and ISO speed), file format, and GPS COM port settings. The IIQ S compress format, which utilizes Phase One proprietary file compression, was recommended by Phase One. The iX Capture user interface is straightforward and easy to use.

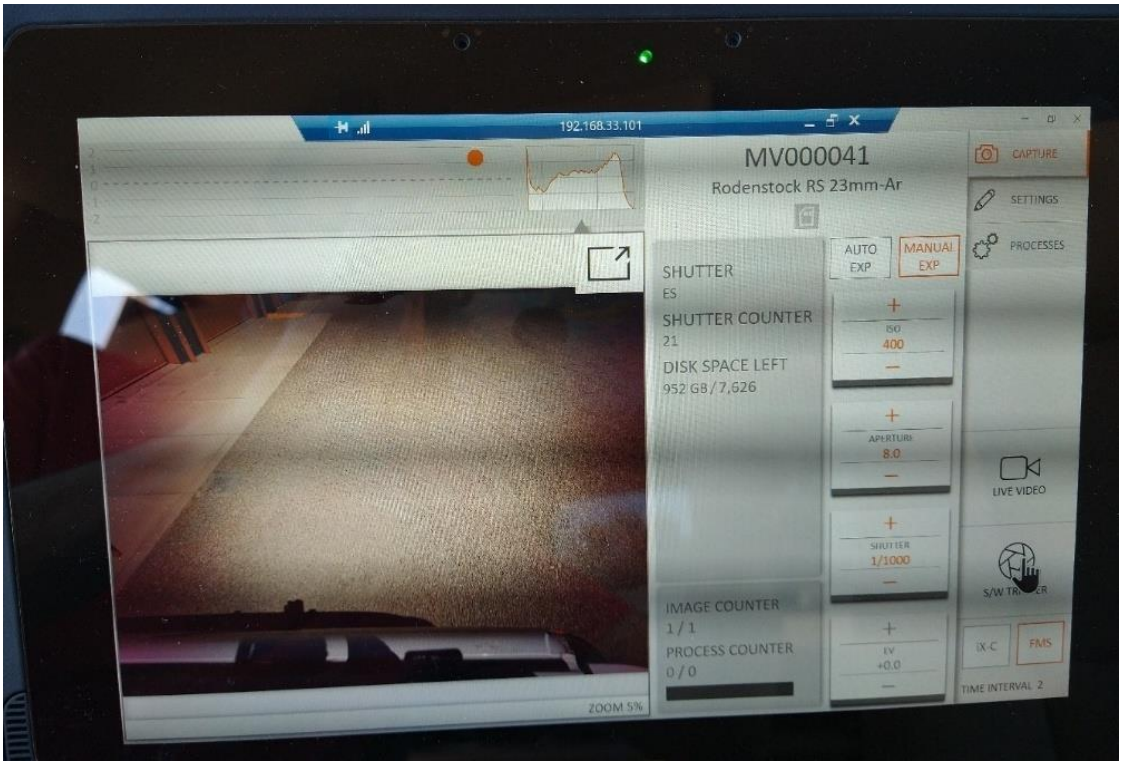


Figure 5.11: Phase One iX Capture software GUI controlling the image exposure settings.

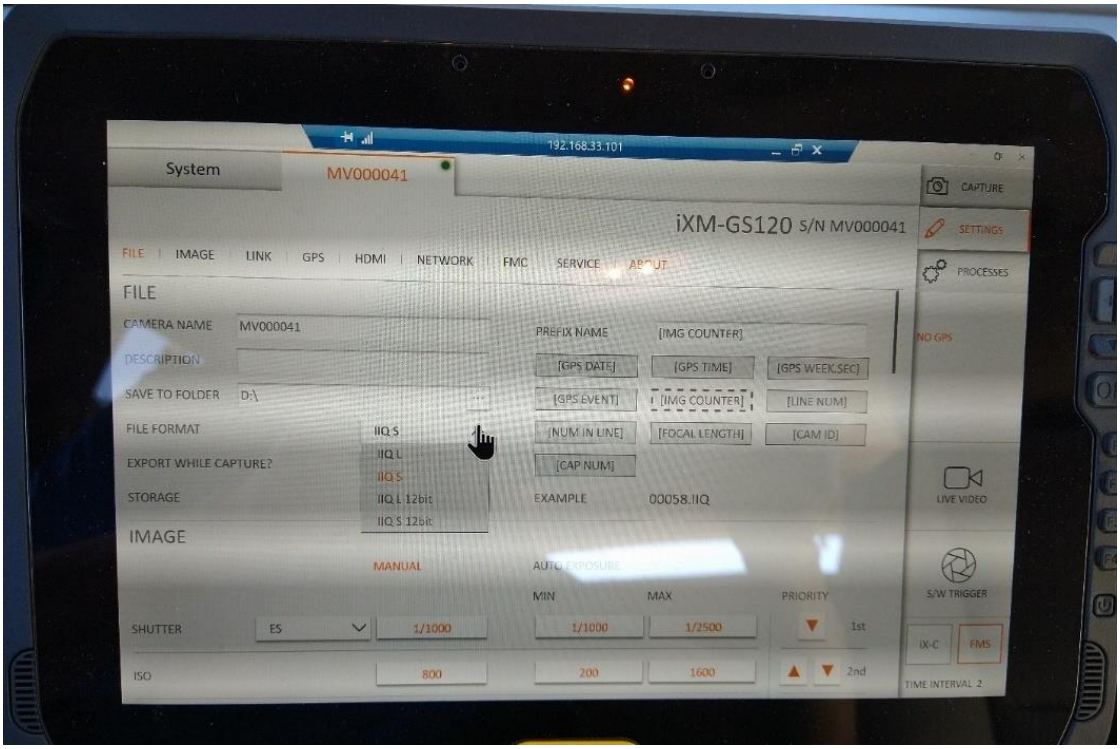


Figure 5.12: Phase One iX Capture software GUI controlling the image file format and location.

Test Results

MX9 GS120 Integration Testing

AHMCT researchers conducted a few field tests on different roadways using the camera's USB C and 10 Gb Ethernet connection. The camera shutter speed was set to 1/2000 seconds (electronic shutter) so that sufficient time between image frames was available for data transfer from the camera to the computer. High shutter speed (small exposure time) reduces motion blur on images as well. The lens aperture ratio was set to either F5.6 or F8 lens aperture. Higher lens aperture ratios (F number) yield higher image depth of view. Higher depth of view results in a sharper image for objects throughout different distances from the camera. The camera sensor sensitivity was set to ISO400. Higher sensor sensitivity settings result in higher noise in the image and reduce image quality. Users must tradeoff between shutter speed, aperture ratio, and sensor sensitivity settings to capture clear images based on the available light. The image files were stored using the Phase One compress raw image format.

In the first test using the USB C data connection, about 4,500 images were captured. The second and third tests using the 10 Gb Ethernet data connection, about 500 and 1,500 images were triggered by the MX9 system at a 5-meter distance interval with vehicle speeds between 45 to 55 MPH. The second and third tests were successful at capturing images at a 5-meter spacing (~5 fps at 45 to 55 MPH) with only two skipped images out of ~1,500 images captured in one session. The cause of the missing capture images is unknown. There may be a temporary slowdown in data transfer to the SSD or the computer. Extensive computer system resource monitoring would be required to determine the root cause.

Phase One Capture One Software Post-processing

Phase One Capture One software is required to post-process the raw image files as well as export them to commonly used file formats such as .jpg. Figures 5.14, 5.16, and 5.17 are sample images collected from field tests. The image examples all show lens and optical vignetting. Vignetting is a reduction of an image's brightness toward the periphery of the image. Optical vignetting can be reduced by decreasing the lens aperture (increase F number). However, a smaller lens aperture must be compensated by increasing the exposure time (reducing the shutter speed) and/or increasing the image sensor sensitivity. In addition, the image samples exhibited a magenta cast toward the periphery. According to the Phase One website, "Lens cast is a result of the sensor being exposed to light from a very sharp angle and will typically occur as a green cast in one corner of the image, stretching into a magenta cast in the

opposite corner." The Phase One support website (https://support.phaseone.com/knowledgebase/article/KA-01239/en-us) provides instructions for lens cast calibration (LCC) to mitigate the effect of lens cast. In addition, the Phase One Capture One software LCC tool can correct for more uniform light caused by lens vignetting.

Phase One provided the LCC plate, a white translucent plastic plate, to AHMCT researchers for LCC. The LCC plate was placed flat against the front of the camera lens, and images, as shown in Figure 5.13, were taken at a few different shutter speeds with the same lens aperture setting for capturing all other images. Capture One software was then used to create the LCC profile for correcting the lens cast on all images. The LCC tool improved the image quality. However, the images still exhibited noticeable, yet smaller, effects of lens cast and vignetting at the edge of the image. Figures 5.14 and 5.15 show an example image before and after LCC was applied. The image with LCC applied shows some magenta at the left and right edges as well as a green tint on the top and bottom edges. Figure 5.15 shows minimal vignetting. Phase One Capture One software has extensive image post-processing tools. AHMCT researchers are not Capture One software expert users. There may be other Capture One tools and workflow that could yield better correction results as shown in Figure 5.15.

Figure 5.13: Example LCC image from the GS120 camera with its 23 mm lens.

Lens casting is caused by the super wide-angle lens (23 mm focal length). The super wide-angle lens provides a large FOV image, resulting in a larger image coverage area. The shorter focal length lens provides a larger FOV. However, wide-angle lenses that are not designed to accommodate the large GS120 image sensor could cause lens casting and vignetting in the image. The 23 mm lens and GS120 camera combination was designed for black and white imagery for pavement analysis. The 23 mm lens is not recommended by Phase One for the GS120 camera. The widest FOV compatible lens with the GS120 camera, provided by Phase One camera, is a 35 mm focal length lens. The 35 mm lens has a smaller FOV than that of the 23 mm lens. The vignetting and magenta color cast are the results of improper matching of the lens and camera, and the defects are not the result of the lens or the camera.

Figure 5.14: Example GS120 camera image without LCC applied.

Figure 5.15: Example GS120 camera image with LCC applied.

Sample Images

Figures 5.16 to 5.21 are sample images collected with exposure settings of F8 aperture, 1/2000 second shutter speed, and ISO400 sensitivity. LCC was not applied to the sample images provided. Figures 5.17, 5.19, and 5.21 are image crops of the area highlighted with a rectangle with the red dotted lines in Figures 5.16, 5.18, and 5.20, respectively. The 120 MP image provides high resolution details in small areas far away from the camera or vehicle. The sample images show that the user can read small letters in signs clearly. The image quality is degraded by motion blur due to the vehicle traveling at about 45 to 55 MPH. The motion blur effect is higher since the camera is mounted orthogonal to the vehicle travel direction. Motion blur may be reduced by decreasing the vehicle speed and/or increasing the camera shutter speed. The operator will need to balance the tradeoff between motion blur, available light, and data collection duration by adjusting the vehicle speed accordingly.

Figure 5.16: Example one of images from GS120 using a 23 mm lens. LCC correction was not applied.

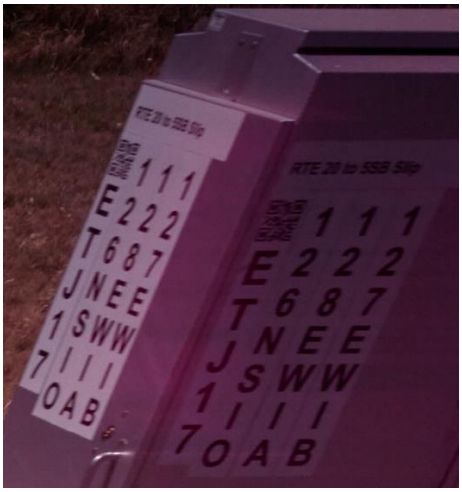


Figure 5.17: Full resolution view of the red rectangle area in the image above. LCC correction was not applied.

Figure 5.18: Example two images from GS120 using a 23 mm lens. LCC correction was not applied.

Figure 5.19: Full resolution view of the red rectangle area in the image above. LCC correction was not applied.

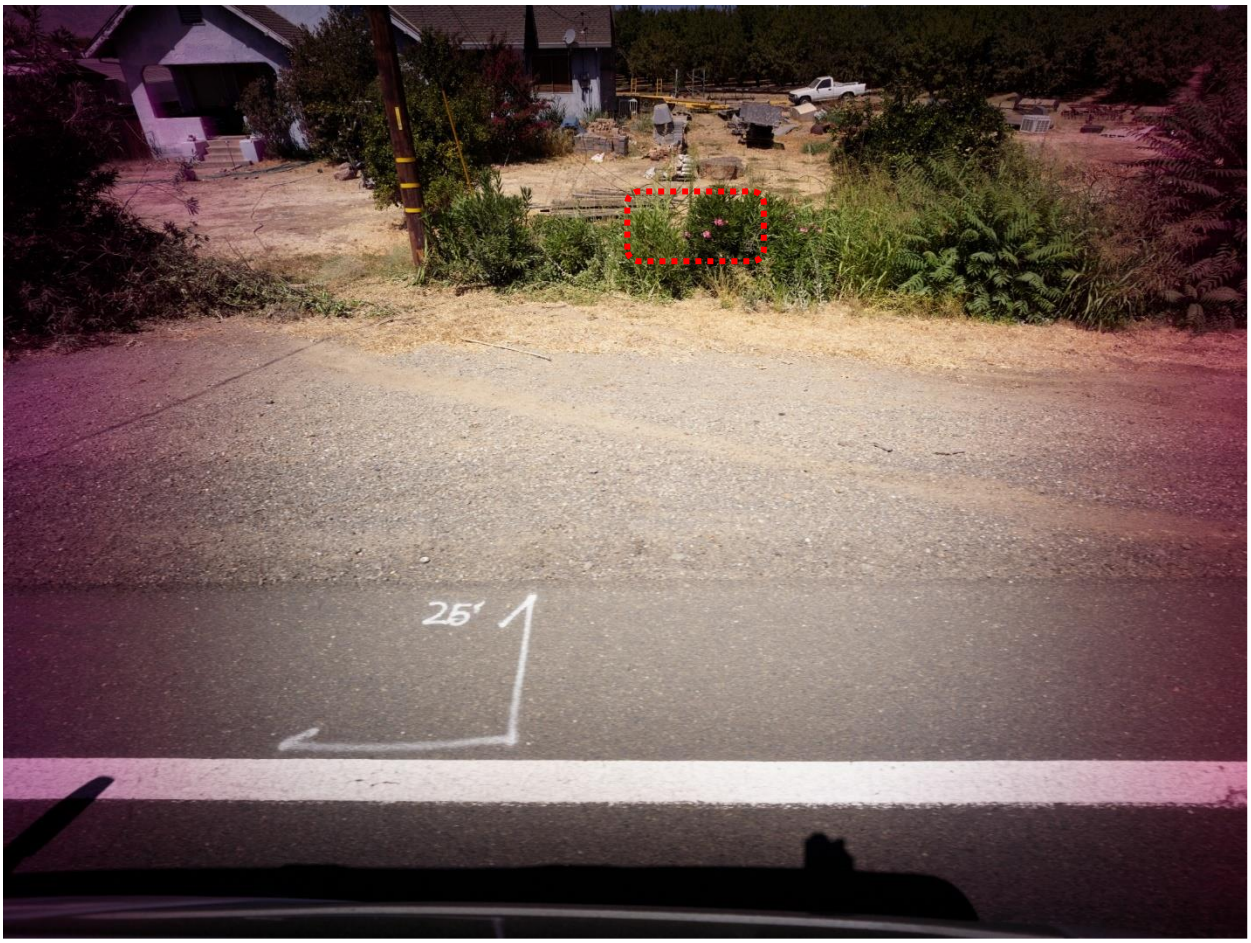


Figure 5.20: Example three images from GS120 using a 23 mm lens. LCC correction was not applied.

Figure 5.21: Full resolution view of the red rectangle area in the image above. LCC correction was not applied.

Conclusion

The GS120 camera integration with the MX9 system is a proof-of-concept prototype. The results demonstrated:

- The technical feasibility of using the MX9 system to trigger distance-based image capture with GS120 high resolution camera. In addition, the camera successfully provided event trigger to the GNSS/IMU system to precisely timestamp and geolocate the exact position and orientation of the camera for each image.
- The integrated system can collect 120 MP images every 5 meters at 55 MPH.
- The GS120 120 MP images provide high resolution detail to clearly identify letters on signs, vegetation species, and other roadside features. The high-resolution images greatly supplement MX9 cameras.
- The GS120 global electronic shutter system yields clear images without any spatial distortion typical from a rolling shutter camera. Most high-resolution cameras use rolling shutters.

Challenges and Future Works

- Large 120 MP image file size can present IT challenges in data storage, data transfer, and image post-processing.
- Powerful workstations are required to load, post-process, export, and review large images quickly. Depending on the objects or features the users are interested in, machine learning technology may be needed to extract data efficiently from the thousands of images collected.
- Short exposure time (1/2000 or shorter) is recommended to reduce motion blur in capture images. The aperture should be set to F5.6 or F8 to increase the depth of field. Due to these constraints, image collection may be limited to days with a lot of available sunlight.
- While wide angle lenses provide wide field of view, improper matching of lens and camera sensors can result in poor image quality with color cast and vignetting.
- The MX9 external sensor port may be used to trigger and geo-reference external sensors, such as infrared cameras, ground penetrating radar, and pavement cameras.

Chapter 6:
Evaluation of MX9 and MX50 use for Americans with Disabilities Act (ADA) Ramp Surveys

AHMCT researchers evaluated the use of MX9 and MX50 for ADA ramp surveys. ADA ramps have stringent requirements. AHMCT researchers analyzed data from the MX9 and MX50 to assess whether using the MTLS system to perform ADA ramp surveys is feasible. AHMCT provided MTLS data collection workflow recommendations on scanning ADA ramp surveys. This study focused on ADA ramps on sidewalks and does not include other ADA features for building and facility access.

Background

ADA requirement documents are widely available on the World Wide Web. Caltrans divisions have also published ADA-related documents specific to Caltrans. The Caltrans Division of Design published Pedestrian Accessibility Guidelines for Highway Projects[3], and the Caltrans Division of Construction created Permanent Pedestrian Facilities ADA Compliance Handbook[4]. Caltrans Division of Right of Way and Land Surveys made public their Americans with Disabilities Act (ADA) Surveys[5], which provide guidelines for Caltrans surveyors conducting pavement elevation surveys at ADA ramps. These documents are vital in understanding ADA ramp requirements. Caltrans ADA requirements may be more stringent than the US national ADA standard requirements.

Traditionally, ADA ramp inspection surveys are conducted using digital levels and measuring tape. Specifically, 48-inch-long and 24-inch-long digital levels, as shown in Figures 6.1 and 6.2, were used to measure ramp running slope, cross slope, gutter slope, and flare slope. Horizontal ADA ramp dimensions are measured using measuring tape. Caltrans Division of Construction has developed custom ADA ramp inspection CME-5773* forms, available on

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[3] Caltrans Division of Design published Pedestrian Accessibility Guidelines For Highway Projects (https://dot.ca.gov/-/media/dot-media/programs/design/documents/dib82-06-a11y.pdf)

[4] Permanent Pedestrian Facilities Ada Compliance Handbook (https://dot.ca.gov/-/media/dot-media/programs/design/documents/dib82-06-a11y.pdf)

[5] Caltrans Division of Right of Way and Land Survey made public their Americans with Disabilities Act (ADA) Surveys (https://dot.ca.gov/-/media/dot-media/programs/right-of-way/documents/ls-manual/ada-sib-18-01-attachment-a11y.pdf)

Caltrans Division of Construction Forms website[6], for various types (Case A, B, C, D, E, F, G, CH, CM, and non-standard plan) to determine the ADA compliance of curb ramps. The Caltrans CME-5773* forms guide inspectors to make all the necessary measurements for documenting each ADA ramp inspection. For example, the CME-5773ADE form is used for Case A, D, and E ADA ramps. The Ohio and Colorado Departments of Transportation have developed their own curb and ramp measurement guide using digital levels available on their websites[7].

The traditional ADA ramp inspection method using digital levels and measuring tape is labor intensive and time consuming. AHMCT researchers were trained and performed several ADA ramp inspections using the CME-5773ADE form on Case A ramps to better understand the processes. Two AHMCT researchers took 10 to 15 minutes to perform all measurements for a Case A ADA ramp. This time does not include transit time between ramps. Transit time between ramps varies depending on the distance between ramps and nearby parking location availability. Manual measurements are prone to human error, often requiring revisits to the ramp location to repeat measurements. The digital level cost ranges from $100 to $400.

Figure 6.1: Example 48" digital level

Figure 6.2: Example 24" digital level

Terrestrial Laser Scanning (TLS) and MTLS may be used to collect high density accurate as-built point clouds of ADA ramps. The advantages of using MTLS in ADA ramp survey include:

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[6] Caltrans Division of Construction Forms (https://dot.ca.gov/programs/construction/forms)

[7] OHIO_ODOT_Curb_Ramp_Measuring_Guide_5-27-2021.pdf https://www.transportation.ohio.gov/wps/wcm/connect/gov/97d290c3-edde-437c-96c3-0f3243947ffb/ODOT_Curb_Ramp_Measuring_Guide_5-27-2021.pdf?MOD=AJPERES&CONVERT_TO=url&CACHEID=ROOTWORKSPACE.Z18_K9I401S01H7F40QBNJU3SO1F56-97d290c3-edde-437c-96c3-0f3243947ffb-o1cnUkZ and COLORADO_CurbRampMeasurementGuide.pdf https://www.codot.gov/business/civilrights/ada/assets/curbrampmeasuringguidelines_v1_01-20.pdf/@@download/file/CurbRampMeasurementGuide.pdf

- The high-resolution ADA ramp point cloud provides a digital as-built record for facilitating any future disputes resolution.
- MTLS data collection speed is the highest compared to TLS and traditional methods, resulting in shorter field data collection time and eliminating the need for repeated site visits. The MTLS ADA ramp survey method does not require temporary closure of the ADA ramp area except in areas with a high density of pedestrian traffic.
- ADA ramp measurements may be extracted from the point cloud in the office with post-processing software. The measurements can be overlaid onto the point cloud, enabling quality control and quality assurance of ADA ramp measurements while reducing human error.
- MTLS is suitable for surveying numerous ramps near each other. On the other hand, TLS or digital level methods may be more advantageous for single or non-standard ADA ramp inspections.

Slope Measurements Accuracy

Stabila Tech 196M digital level, commonly used for ADA ramp slope measurements, has a published inclination measurement accuracy on their website[8]. Stabila Tech 196M digital level has an inclination measurement accuracy of ± 0.05° at 0° and 90° and ± 0.10° at 1° to 89°. As a result, Stabila Tech 196M digital level theoretically has a cross slope measurement accuracy of ± 0.05° and running slope measurement accuracy of ± 0.10°.

Trimble MX9 and MX50 with Applanix AP60 position and orientation system (POS), deployed in Caltrans, have a published roll and pitch accuracy of 0.005° (Root Mean Square [RMS]) and heading accuracy of 0.015° RMS in good GNSS signal environments using a post-processed solution with a GNSS base station within 15 km. Theoretically, the estimated slope measurement errors contributed by the POS roll and pitch errors are approximately equal to ± 0.007° (0.005*2^0.5) RMS.

The ADA ramp and landing width requirement is 48" (49.75" for Caltrans) or more. The ADA ramp and landing cross slope should be 2.08 % or 1.15° (1.7% or 0.97° for Caltrans) or less. The ADA ramp running slope should be 8.33%[9] or 4.74° (7.7% or 4.4° for Caltrans based on Caltrans Curb Ramp (Case A, D, or E) ADA

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[8] Stabila Tech 196M digital level specifications https://www.stabila.com/en/products/details/digital-spirit-level-tech-196m-dl.html

[9] Permanent Pedestrian Facilities Ada Compliance Handbook (https://dot.ca.gov/-/media/dot-media/programs/civil-rights/documents/permanent-pedestrian-facilities-ada-compliance-handbook-a11y.pdf)

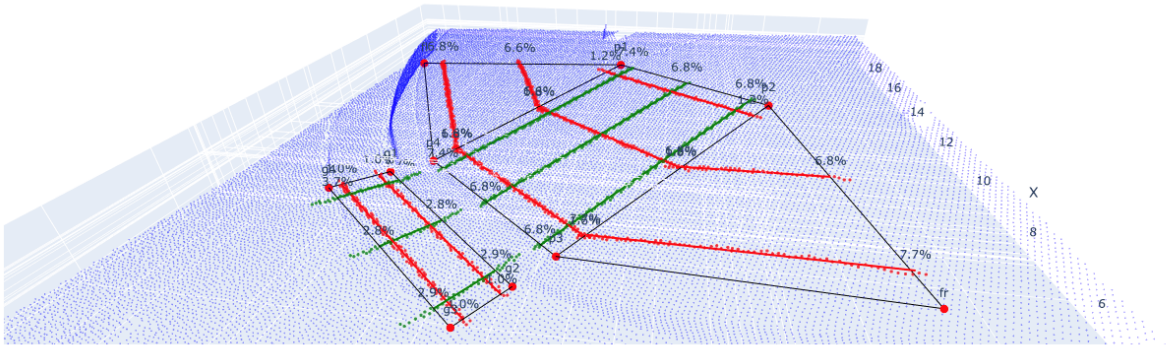
Compliance Inspection Report CEM5773ADE Form[10]) or less. U.S. Access Board (https://www.access-board.gov/) recommends running slope to be 7.5%[11] or less based on "Dimensional Tolerances in Construction and for Surface Accessibility" (https://www.access-board.gov/research/building/dimensional-tolerances/) by David Kent Ballast.

The Trimble MX9 and MX50 laser range precisions are 3 mm and 2.5 mm, respectively. Using a simple worst-case scenario of measuring slope using two points with a 3 mm vertical error at 2' apart to measure the slope, the laser range precision errors could result in a 0.4° error. The gutter counter slope measurement error would be higher due to the short gutter depth. If the slope measurement uses the two points at 4' apart, the slope measurement error would be half (0.2° or 0.35 % at a zero percent grade). This scenario resembles measuring cross slope and running slope on the ADA main ramp and landing. In practice, most ADA ramp slopes are measured utilizing a best fit straight line at or over 48" long using 10 or more points in a point cloud as shown in Figure 6.3. Therefore, the MX9 MTLS point cloud slope measurement errors should be less than 0.2° theoretically. ADA ramp slope measurements using digital levels and MTLS are compared in a later section.

[10] Caltrans Curb Ramp (Case A, D, or E) ADA Compliance Inspection Report CEM5773ADE Form (https://forms.dot.ca.gov/v2Forms/servlet/FormRenderer?frmid=DOTCEM5773ADE)

[11] Guide to the ADA Accessibility Standards (https://www.access-board.gov/ada/guides/chapter-4-ramps-and-curb-ramps/#transition-to-street)

ADA CURB RAMP FIELD MEASUREMENTS (Yub70_2_Right8.las)



Ramp Slope (x.x%)	Ramp Cross Slope (x.x%)	Ramp Width (inches)	Left Flare Slope at Back of Curb (x.x%)	Right Flare Slope at Back of Curb (x.x%)	Gutter Slope (x.x%)	Gutter Cross Slope (x.x%)
A1: 6.8%	B1: 1.6%	C1: 59.3"	D1: 6.8%	E1: 7.7%	F1: 1.0%	G1: 2.9%
A2: 6.8%	B2: 1.8%	C2: 59.6"			F2: 1.0%	G2: 2.8%
A3: 7.4%	B3: 1.2%	C3: 60.0"				G3: 3.7%
8.3% or less?	2.0% or less?	48" or greater?	10.0% or less?	10.0% or less?	2.0% or less?	5.0% or less?
Yes	Yes	Yes	Yes	Yes	Yes	Yes
ADA Standard 8.3% max	ADA Standard 2.0% max	ADA Standard 48" min	ADA Standard 10.0% max	ADA Standard 10.0% max	ADA Standard 2.0% max	ADA Standard 5.0% max

Figure 6.3: Best fit straight lines for slope measurement overlay on a Case A ADA ramp MTLS point cloud (blue dots) from an MX9 system. The red lines represent cross slope measurement locations, and the green lines represent running slope measurement locations. The red and green dots are points used to determine the corresponding best fit lines for slope and length measurements.

MTLS System's 360-degree Camera Role in ADA Ramp Survey

A detectable warning surface (DWS), which is required on all ADA ramps, is composed of a grid of truncated domes detectable by cane or underfoot that alert people with visual impairments of their approach to street crossings and hazardous drop-offs[12]. DWS are used to indicate the boundary between pedestrian and vehicular routes where there is a flush instead of a curbed connection. DWS are often colored yellow, orange, red, or black. However, there is no DWS color standard. The difference between laser reflectivity of the colored DWS and concrete pavement may be large or small. The presence of DWS can be difficult to identify in the point cloud in some cases.

[12] Public Right-of-Way Accessibility Guidelines https://www.access-board.gov/prowag/other/dw-update.html

The 360-degree images are more reliable for positively identifying the presence of DWS at an ADA ramp. Figures 6.4 and 6.5 show examples images from the 360-degree camera.

Figure 6.4: Example full size image of ADA ramps with yellow DWS at an intersection captured with a MX System 360-degree camera. ADA ramps are next to the stop sign on the ground.

Figure 6.5: Example of a "zoomed in" image of ADA ramps with yellow DWS captured by a MX System 360-degree camera.

The 360-degree camera image can also be used to colorize the point cloud. However, some slight misalignments typically appear in the color image of the point cloud. Figures 6.6 and 6.7 show an MX50 colorized point cloud and an intensity-based point cloud of a same ADA ramp. Figure 6.7 shows slight differences in point intensity valves between the DWS and the surrounding concrete surface, resulting in difficulty identifying DWS present on the ADA ramp. Figure 6.8 shows another ADA ramp intensity-based point cloud. The ADA ramp, shown in Figure 6.8, is located at Alturas, California near the ADA ramp shown in Figures 6.6 and 6.7. In this case, the DWS and surrounding concrete surface point reflectivity differences are larger.

Figure 6.6: Example ADA ramp (Case A) colorized point cloud from the MX50's left and right lasers. The ADA ramp is located at Alturas, California. The yellow DWS can be seen in the colorized point cloud.

Figure 6.7: Intensity-based rendering of the same ADA ramp shown in Figure 6.5. The DWS reflectivity is very close to the surrounding concrete surface.

MTLS Point Cloud Point Density

Figure 6.9 shows a point cloud (from both the left and right lasers) of an ADA ramp located on the opposite side of a two-lane road of the ADA ramp in Figure 6.8. Both point clouds in Figures 6.8 and 6.9 were collected and generated using an MX50 system with the same scanning session run. The point cloud point density, shown in Figure 6.9, is much lower than that of Figure 6.8 because the ADA ramp in Figure 6.9 is further away from the MX 50 vehicle's

travel path. Low point cloud density presents challenges in extracting the lateral dimensions of the ADA ramp. The point location accuracy decreases as the point is farther away from the vehicle path, resulting in higher measurement errors for horizontal dimensions and slopes.

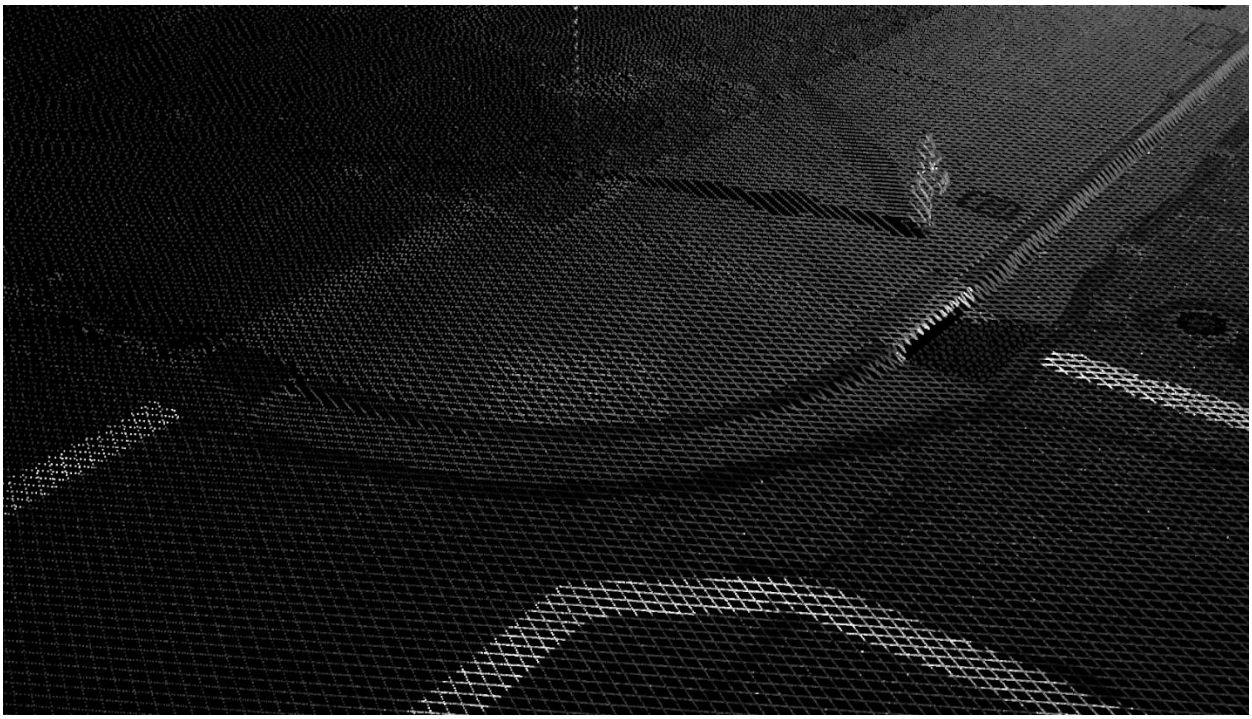


Figure 6.8: Example ADA ramp point cloud (intensity-based rendered, left and right lasers) collected from an MX50 system. The ADA ramp is located at Alturas California near the ADA ramp shown in Figures 6.6 and 6.7. In this case, the DWS and surrounding concrete surface reflectivity difference is larger.

Figure 6.9: Point cloud of an ADA ramp located on the opposite travel direction side of the ADA ramp shown in Figure 6.8 collected in the same scan session by an MX50 system.

Figures 6.10 and 6.11 show point clouds of the same ADA ramp captured using the MX9 Gen 2 system in a colorized point cloud and an intensity-based point cloud, respectively. The point clouds in Figures 6.10 and 6.11 were captured with both laser scanners set at 1.8 million points per second and a scan rate of 250 lines per second with a vehicle speed of about 15 to 20 MPH. Figure 6.10 shows a small misalignment between colorization and the points in point cloud. This misalignment is particularly apparent at the edge of the DWS. Users should not expect perfect alignment in the colorization. Figure 6.11 demonstrates that the DWS edges can be located in the intensity-based rendering point cloud. Figure 6.11 also shows that the MTLS point clouds do not provide sufficient point density and detail to identify individual truncated domes in a DWS.

Comparing the point clouds shown in Figures 6.7. 6.8, and 6.11 shows the MX9 can capture higher point density than the MX50. The concrete segment edges are easily identifiable as shown in Figure 6.11. Each concrete segment surface is not necessarily flat from edge to edge in an ADA ramp. Figure 6.11 also shows that a single, right laser point cloud may be sufficient for ADA ramp feature extraction for some ADA ramps. Since the left laser is usually farther from an ADA ramp, the left laser point cloud density on the ADA ramp is usually lower. Figures 6.12 and 6.13 show point clouds of the same ADA ramp on Highway 70 in Marysville, California captured with an MX9 system. The point cloud in Figure 6.12 combined points from both left and right laser scanners and has a higher point density than that of in Figure 6.13. The point cloud shown in Figure 6.13 consists of points from only the right laser scanner.

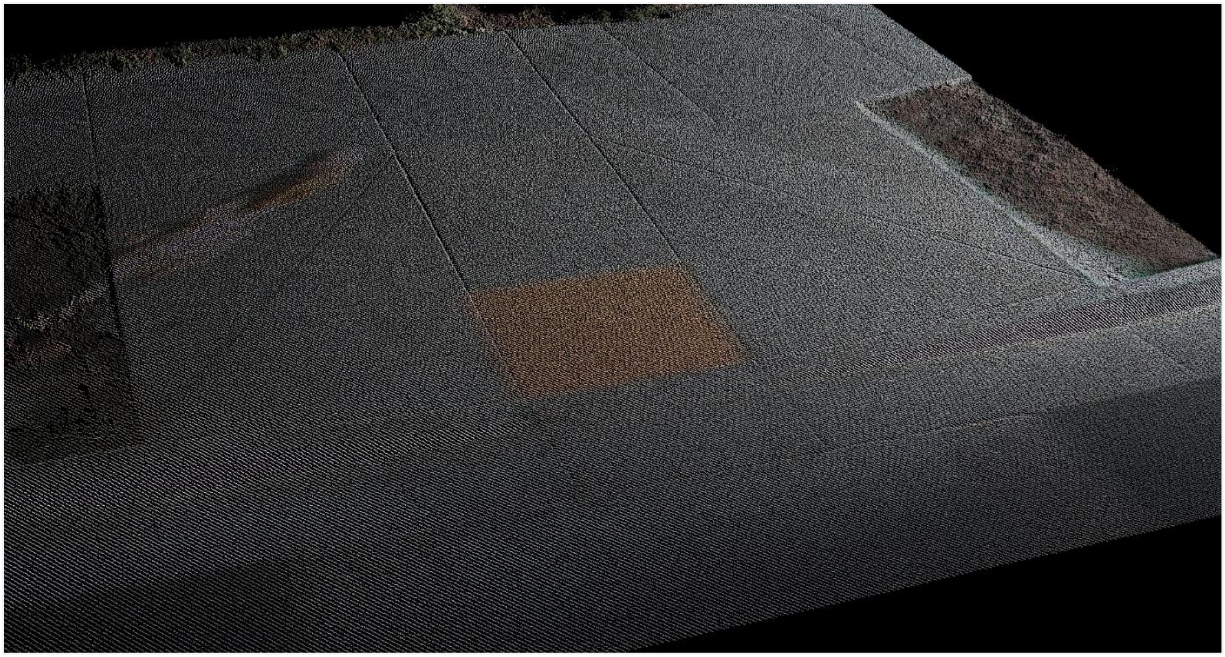


Figure 6.10: Colorized right laser point cloud of an ADA ramp collected from an MX9 Gen 2 system at Woodland, California. The laser sensors were set to collect at 1.8 million points per second with scan rate set at 250 lines per second. The vehicle data collection speed is about 15 MPH.

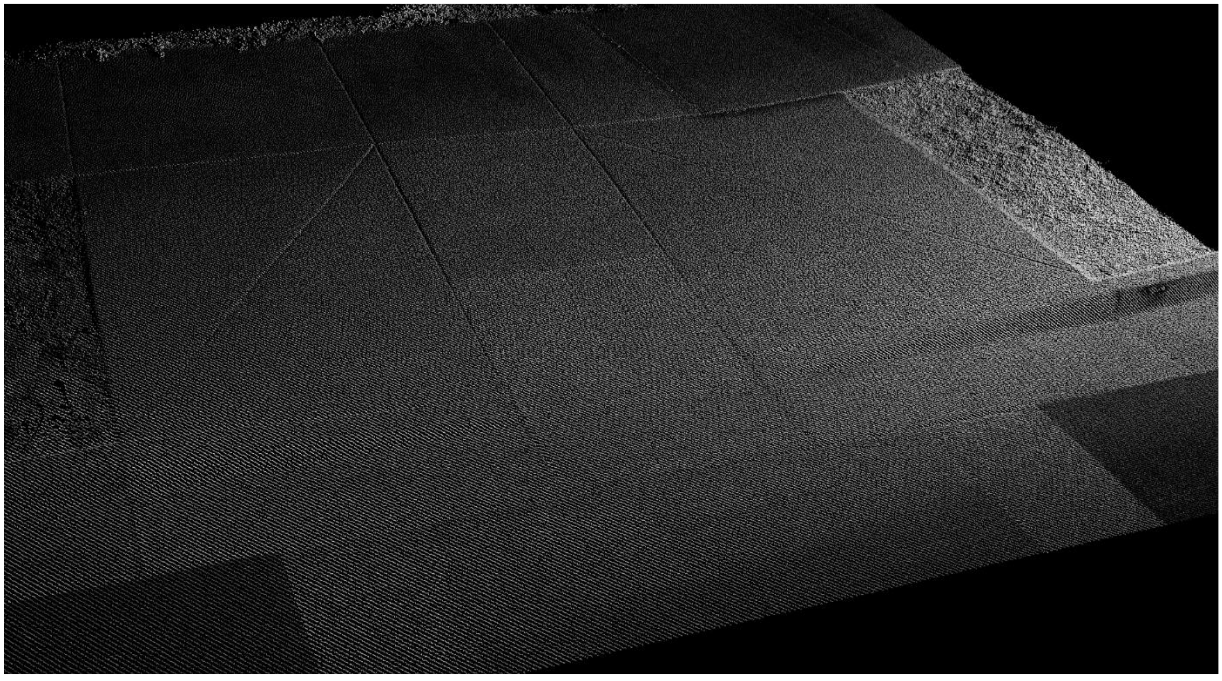


Figure 6.11: Intensity-based point cloud of the same colorized ADA ramp point cloud shown in Figure 6.10.

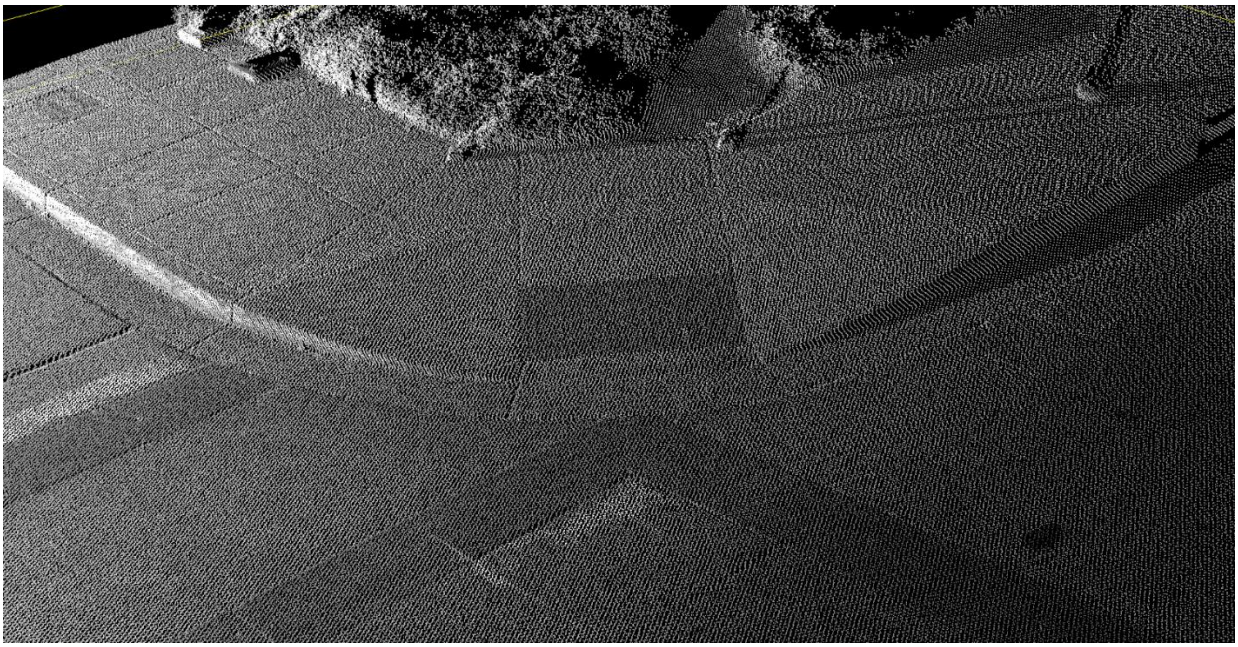


Figure 6.12: MX9 collected point cloud of an ADA ramp (LiDAR intensity view) using both right and left laser scanners.

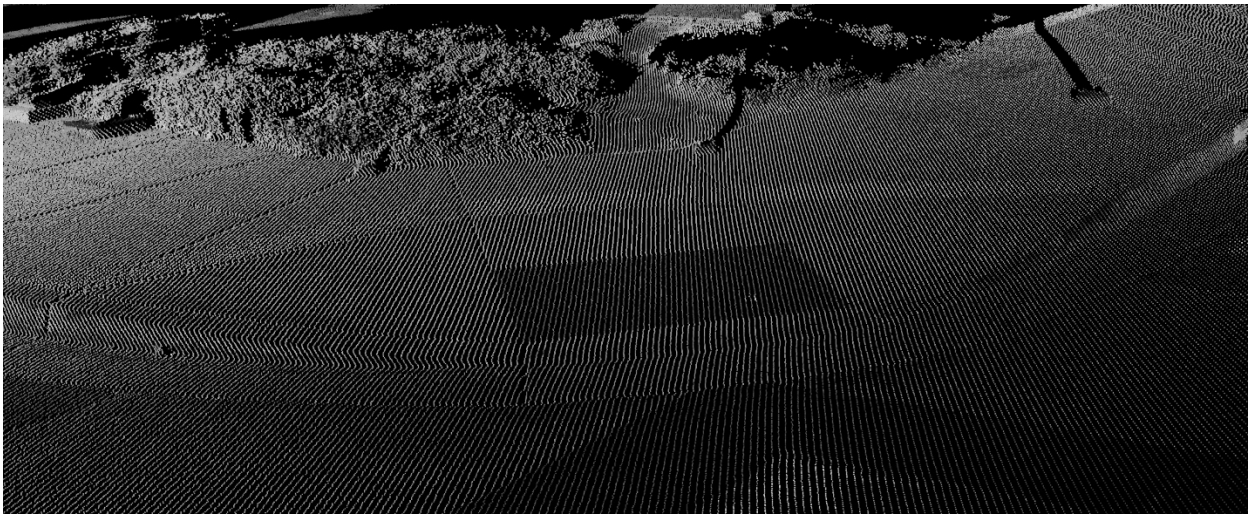


Figure 6.13: MX9 collected point cloud of an ADA ramp (LiDAR intensity view) using only the right laser scanner.

Figure 6.14 shows a Case F ADA ramp colorized point cloud from both left and right lasers. Figure 6.15 shows the left laser point cloud of the same Case F ADA ramp in Figure 6.14. The red dashed line circle in Figure 6.15 highlighted the area without any point measurements due to the shadow effect of the curb. Figure 6.15 also shows debris, circled with a green dashed line, accumulated at the right edge of the ADA ramp.

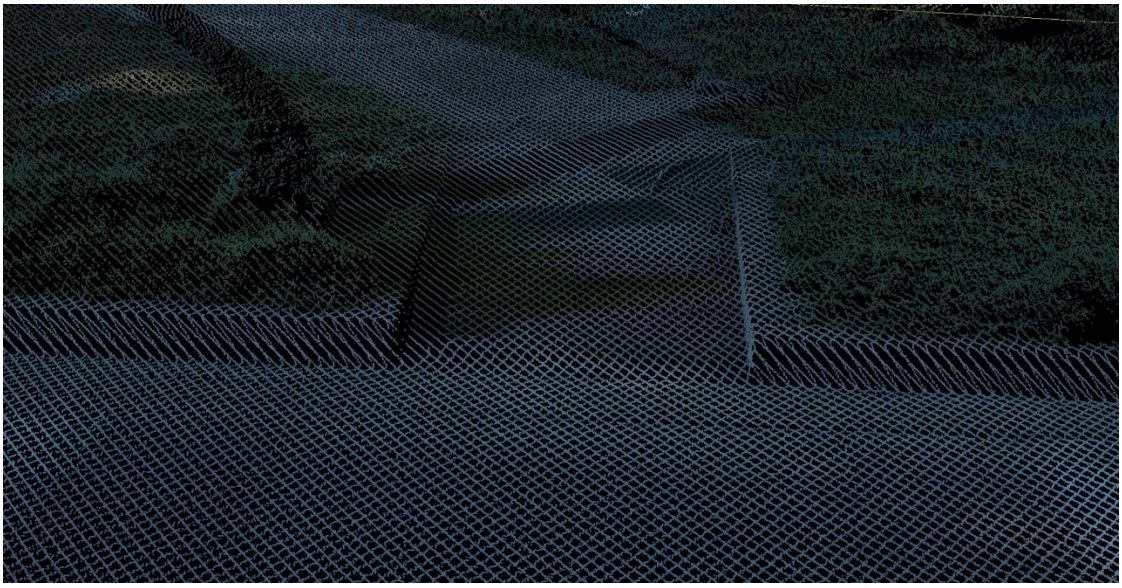


Figure 6.14: Example Case F ADA ramp, located on Highway 70 in Marysville, California, colorized point cloud with both left and right laser points.

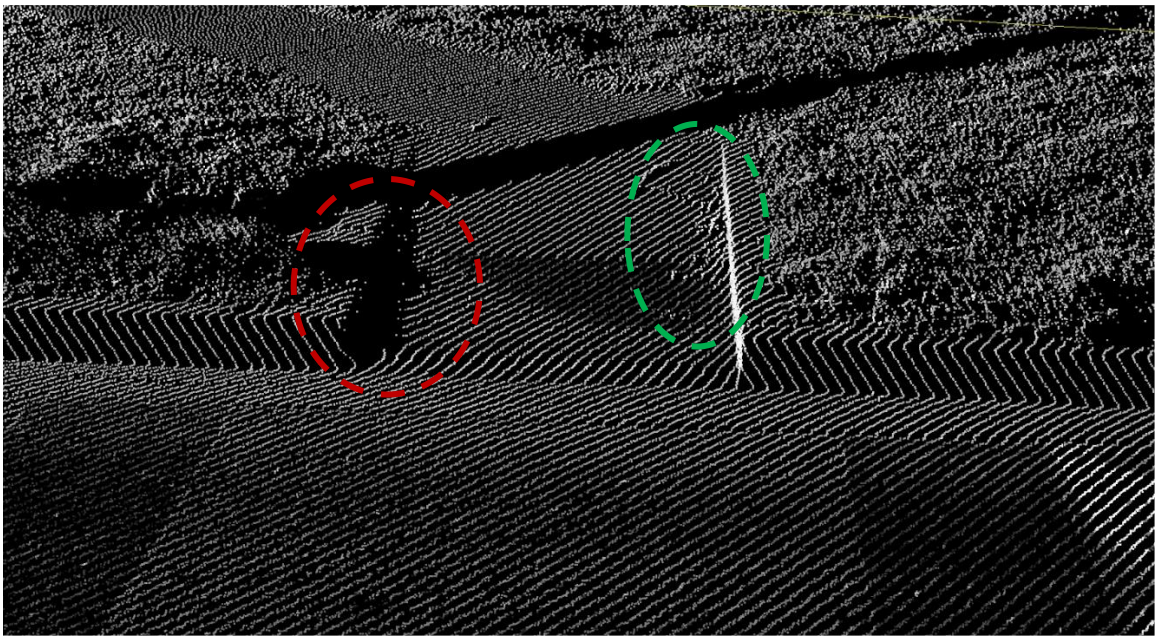


Figure 6.15: Left laser point cloud of the same Case F ADA ramp in Figure 6.14, The red dashed line circle highlighted area without any point measurement due to the shadow effect from the curb.

Figure 6.16 shows an island passageway point cloud captured by an MX9 system. The red dashed line circle in Figure 6.16 highlights the area without any point measurements due to the shadow effect of the curb. Examples shown in Figures 6.14, 6.15, and 6.16 demonstrate the advantage of MTLS systems with a dual laser scanner configuration. This configuration reduces shadow effects

caused by curbs and objects at the ADA ramp. Figure 6.17 exhibits the detrimental effects of shadows (point data void) in the point cloud caused by the vehicle.

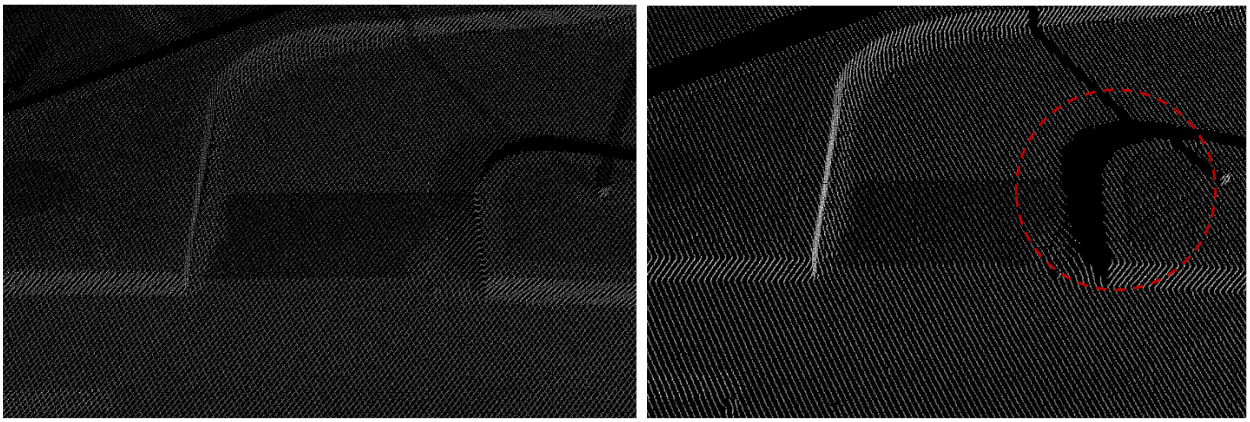


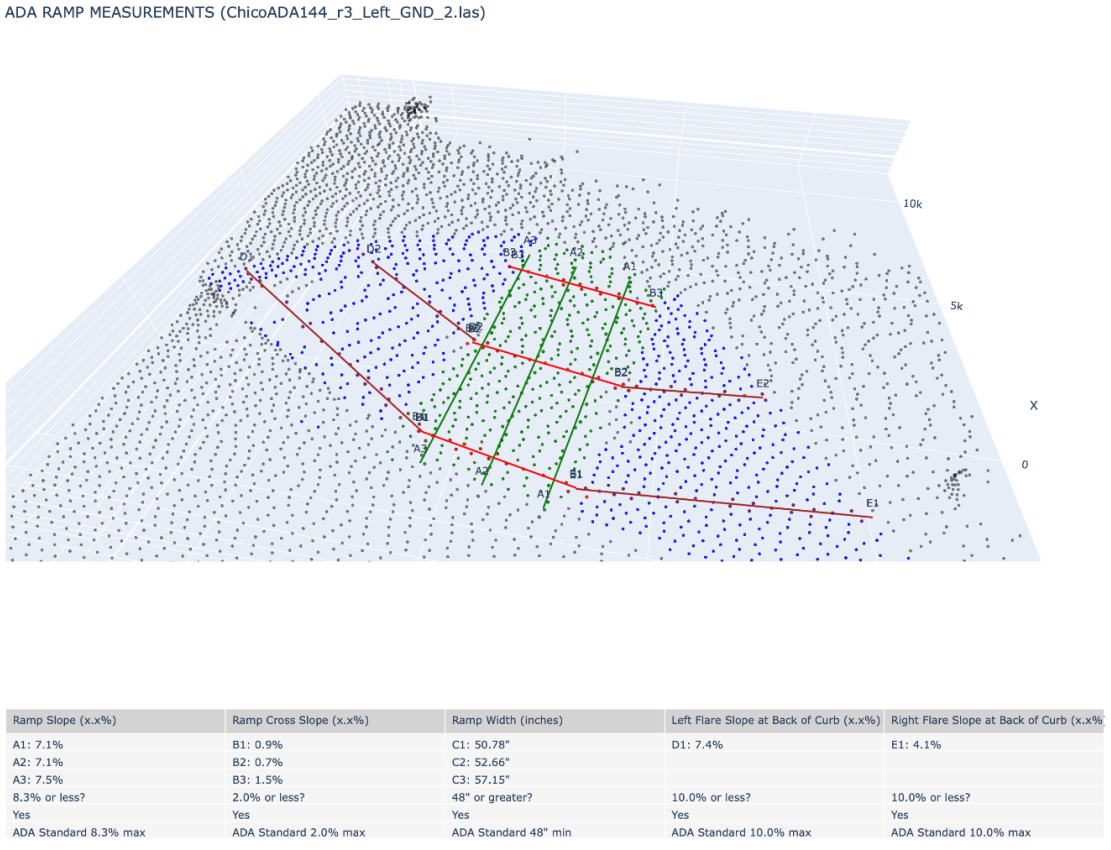
Figure 6.16: Example island passageway point cloud captured by an MX9 system. The point cloud on the left consists of points from both left and right laser scanners, and the point cloud on the right consists of points from the right laser scanner only.

Figure 6.17: Example ADA ramp point cloud with shadow (point data void) caused by vehicular traffic.

Comparison of MTLS and Manual Measurements

Twelve Case A ADA ramps' running and cross slopes, located in Woodland, California, were measured using Stabila Tech 196M 24" and 48" digital levels. The digital levels readings were checked for consistency by flipping the digital level 180 degrees. The ADA ramps at the same Woodland location were also scanned using an MX9 Gen 2 system with a vehicle speed of about 15 to 20 MPH and laser scanners set at 1.8 million points per second and 250 scan lines per second.

AHMCT researchers developed software to semi-automate the ADA ramp slope feature measurements. The custom developed software uses best plane and line fit methods to determine the running and cross slopes for flat surfaces. Figures 6.3 and 6.18 illustrate measurement outputs from the AHMCT custom software. The blue dots in Figure 6.18 represent the point cloud of the ADA ramp flare surface, and the green dots represent the point cloud of the ADA ramp surface. The red, green, and burgundy lines are best fit straight lines using points within 1" distance of the lines. The red, green, and burgundy points near the red, green, and burgundy lines are the points used for calculating the best fit lines.



Ramp Slope (x.x%)	Ramp Cross Slope (x.x%)	Ramp Width (inches)	Left Flare Slope at Back of Curb (x.x%)	Right Flare Slope at Back of Curb (x.x%
A1: 7.1%	B1: 0.9%	C1: 50.78"	D1: 7.4%	E1: 4.1%
A2: 7.1%	B2: 0.7%	C2: 52.66"		
A3: 7.5%	B3: 1.5%	C3: 57.15"		
8.3% or less?	2.0% or less?	48" or greater?	10.0% or less?	10.0% or less?
Yes	Yes	Yes	Yes	Yes
ADA Standard 8.3% max	ADA Standard 2.0% max	ADA Standard 48" min	ADA Standard 10.0% max	ADA Standard 10.0% max

Figure 6.18: Example Case A ADA ramp with fitted straight lines for slope measurement.

Each ADA measurement has a label and measurement location defined by the corresponding CEM-35773* form. For example, the CEM-35773ADE form defines the ADA ramp running slopes measurements as A1, A2, and A3, and cross slope measurements as B1, B2, and B3. The Case A ADA ramp landing running slopes are labelled as J1, J2, and J3, while the landing cross slopes are labelled as I1, I2, and I3. The ADA ramp flare slopes are labelled as D1 and E1. Running slope direction aligns with the direction of pedestrian travel.

Slope Measurement Difference Results and Discussion

Table 6.1 shows the statistics of the slope measurement differences between the manual digital level and AHMCT software estimates. The average differences of cross slope measurements (B1-B3 and I1-I3) are close to zero % grade (-0.05% and -0.06 %), and the standard deviation of cross slope differences is about 0.41% or 0.23°. The cross slope standard deviation differences agree with the theoretical estimate error of 0.35% or 0.2°. The average differences of flare slopes (D1 and E1) are also close to zero. The standard deviation differences in flare slopes are larger (0.43% and 0.59%) than that of the cross slope differences.

Table 6.1: Statistical differences between manual and auto-extracted ADA ramp slope measurements

ADA Measurements	A1 - A3 (% grade)	B1 - B3 (% grade)	D1 (% grade)	E1 (% grade)	I1 - I3 (% grade)	J1 - J3 (% grade)
Average Manual Measurement Value	7.89	0.66	6.89	7.15	0.73	1.4
Average Difference	0.39	-0.05	-0.03	0.01	-0.06	-0.56
Error Standard Deviation	0.56	0.41	0.43	0.59	0.32	0.50
Maximum Difference	1.55	0.76	0.77	1.32	0.62	0.12
Minimum Difference	-0.71	-0.91	-0.78	-0.83	-1.03	-1.78

The average differences between running slope measurements (A1-A3 and J1-J3) are non-zero and larger than expected. The standard deviation running

slope differences are about 1.6 times larger than the theoretical estimates. The larger error may be caused by:

- Errors in the automated feature extraction algorithm that resulted in large outlier estimates. Further software refinement and quality control should be pursued to locate any outliers and erroneous estimates.
- The digital level method measures the top of the ramp surface to obtain slope values, which can be different from averaging the point cloud surface to extract the slope values. The digital level method is subject to error caused by large local high or low spots on the concrete surface.

The slope measurement comparison data provides an estimated slope measurement error using an MTLS point cloud. Borderline cases may require a site visit to collect digital level measurements to determine pass or fail. The data presented provides a better understanding of the MTLS limitation when applied to the ADA ramp survey.

MTLS Best Practices for Collecting ADA Ramp Data

When collecting MTLS ADA ramp data, the MTLS operator should consider the following factors:

- Excessive debris at the ADA ramp can impede accurate data collection and extraction. Street sweepers can effectively remove debris from the curb flow line and on or near the ramp.

Figure 6.19: Example of area with too much debris that would obstruct MTLS feature extraction.

- Avoid sharp 90-degree turns.

- Avoid making U-turns when collecting data. The operator should consider driving past a ramp, stopping data collection, and then starting a new run after turning the vehicle around.

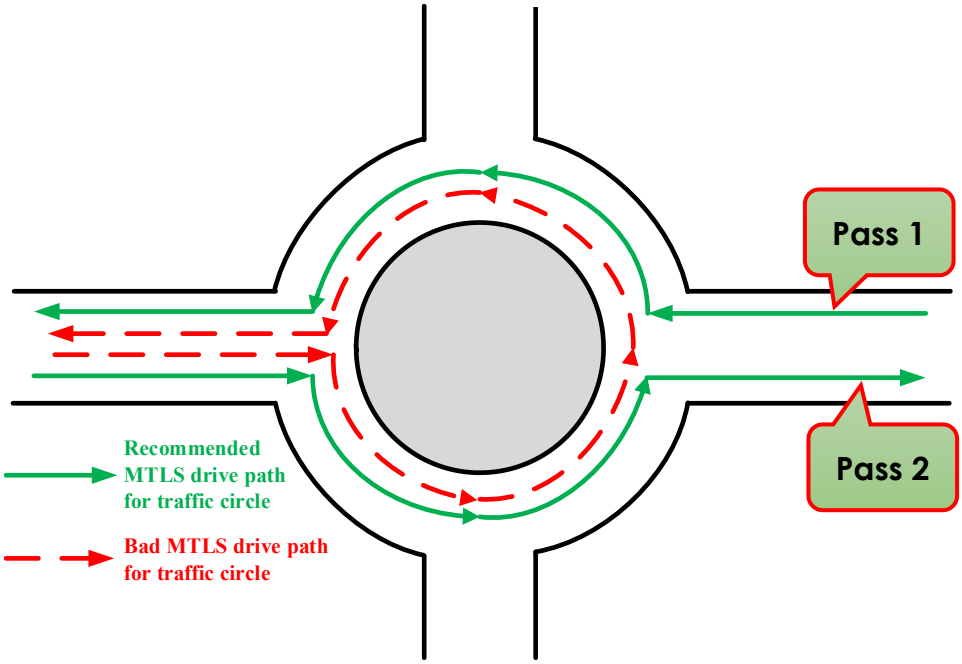


Figure 6.20: Recommended MTLS drive path for a traffic circle.

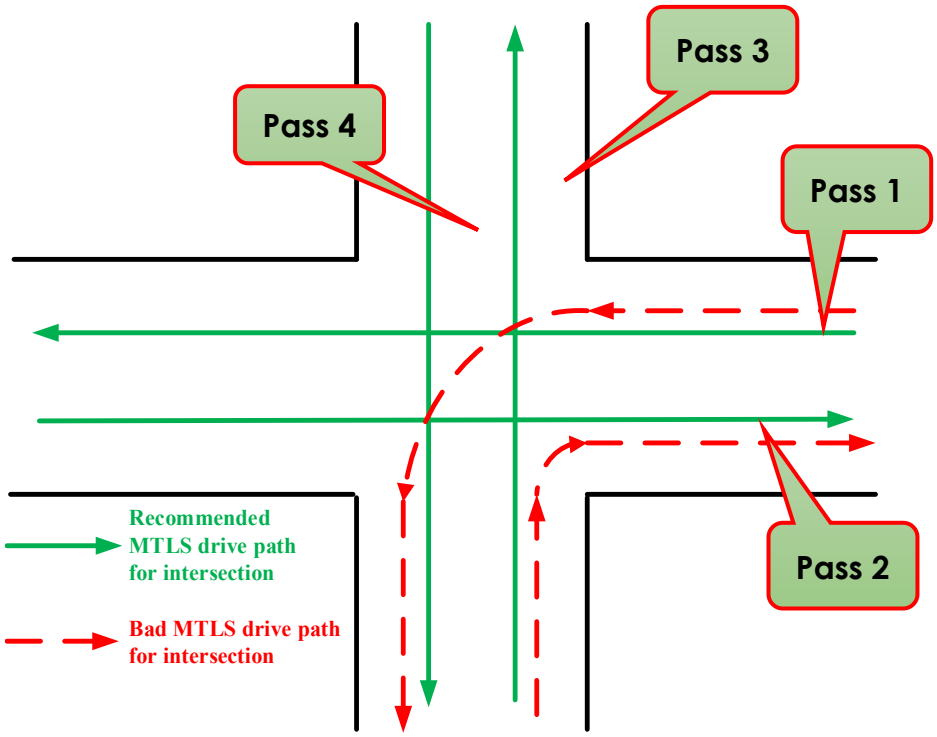


Figure 6.21: Recommended MTLS drive path for an intersection.

- Drive a straight path as much as possible. Figures 6.20 and 6.21 show recommended driving paths for scanning traffic circles and intersections.
- The MTLS vehicle travel path should be within 30' of the ADA ramp. Operators may consider driving slower (if it is safe to do so) to improve the point density of the point cloud.
- The maximum laser scanner data acquisition rate should be used.
- Plan for data collection to occur during low pedestrian and vehicular traffic times. Vehicles at or parking near ADA ramps can cause shadows in the data. Scanning during late nighttime may be a good option for high traffic urban areas.
- To ensure adequate point density, MX9 drivers should maintain a 25 MPH or lower vehicle speed if safe to do so. MX50 drivers should consider slowing down to 20 MPH or lower.
- When approaching a red stop light, the MTLS driver should stop short of the intersection. After the light turns green, the MTLS driver may then drive through the intersection in one continuous smooth vehicle motion.
- Color photos can help identify the presence of DWS. Capturing images at noon or on cloudy days would reduce shadows in images.

Challenges

This chapter did not cover all aspects of ADA ramp inspection and ADA ramp and requirements. To cover all the complexity of ADA inspections and requirements was beyond the scope of this task. ADA ramps with large gaps and discontinuity between concrete surfaces may not be adequately measured. MTLS is suitable for documenting newly built ADA ramps. Older ADA ramps with pavement gaps, cracks, and distressed surfaces are better suited for an in-person inspection by experienced ADA inspectors. Performing ADA ramp surveys using MX9 and MX50 MTLS systems are feasible but may not be suitable for use in all cases.

Current point cloud software tools available in ADA ramp measurement extraction from point clouds are limited. Better software tools would increase efficiency through reduced office time and improve cost savings.

Chapter 7:
Update Caltrans MTLS Workflows for Caltrans MX Systems

The goal of this task was to update existing Caltrans Trimble MX system data collection workflows for Caltrans MTLS units based on lessons learned from operating six Trimble MX systems on various projects in different Caltrans districts. AHMCT also provided recommendations to OLS in support of an update to Chapter 15 of the Caltrans Surveys manual. The target spacing recommendation may be updated in the future with technical advancements in post-processing software and GNSS/IMU systems.

Caltrans Trimble MX System Data Collection Workflow, Installation, Troubleshooting, and Maintenance Guide document was created and provided to OLS and Caltrans DRISI. The document includes:

- General description of the Caltrans Trimble MX systems
- Caltrans Trimble MX system operation and data collection procedures
- Caltrans Trimble MX system troubleshooting guide
- Caltrans specific Trimble MX system vehicle selection recommendations and installation details. It also includes 360-degree camera cover cap installation and removal instructions.
- Caltrans Trimble MX systems maintenance recommendations.

The recommendations and suggestions provided below are specific to Caltrans and its application of MX systems. They may not apply to other MX system users. It is a living document designed to preserve institutional knowledge on deploying and operating Trimble MX systems efficiently and sustainably.

Chapter 8: Deployment and Implementation (if applicable)

Problems and Issues that Affected Product Deployment

AHMCT does not foresee any major problems affecting deployment. Like any advanced complex system, the MTLS system requires periodic maintenance and occasional repair. Trimble and CSDS have been working closely with OLS to address any MX system issues.

Solutions to Noted Problems and Issues

None.

Issues Expected to Affect Full Implementation

AHMCT does not foresee any significant issues affecting full implementation. The issues encountered were minor and may decrease usage efficiency but nothing else.

Other Considerations for Reaching Full Product Deployment

Trimble has developed a new generation of MX systems for MTLS projects. The new generation MX system has a 360-degree camera with double the image resolution compared to the previous generation. The new 360-degree camera is larger and would require modification of the existing 360-degree camera lens cap design. Design changes to the lens cap mounting structure should be minimal.

Continuing effort in documenting institutional knowledge of MTLS deployment and lessons learned is also important moving forward. Continuous effort in personnel training is essential due to retirement and the promotion of trained surveyors.

Equipment Issues

Working with Trimble, OLS, and district surveyors, AHMCT researchers are evaluating version 2 CU to solve the deteriorating SSD write speed issues. Spare

drives are available in every MTLS vehicle. Surveyors may swap out drives if needed.

Operational Issues

None.

Policy Issues

Trimble has developed a software called LiDAR QC that can post-process MX system data, which results in better pass-to-pass matching of the point cloud data. The software is new and requires extensive testing and evaluation through multiple projects at different locations. LiDAR QC can potentially increase the ground control target spacing distance (reduce the number of required ground control points and targets per project). Consequently, the Caltrans Survey Manual Chapter 15 may need to be updated accordingly.

Chapter 9:
Conclusions and Future Research

Overview of Research Results and Benefits

This project provided invaluable support for continual active deployment of MTLS technology within Caltrans. Key contributions of this research project included:

- Assisted OLS in the installation and deployment of new Trimble MX systems.
- Continued support for six MTLS systems and vehicle deployments, along with assistance to Trimble and CSDS in troubleshooting and parts replacement for Caltrans MX systems.
- Performed testing and data analysis relationship between time-based and distance-based ground control point spacing with MTLS vertical and horizontal accuracy.
- Created documentation for MX system operation, maintenance plan, system installation, and vehicle integration.
- Demonstrated successful integration of a high-resolution camera with the MX systems. The MX system external sensor port may be used to trigger specialty external sensors and accurate geo-reference external sensors data. Infrared cameras, ground penetrating radar, and pavement polarized cameras for better crack detections are examples of potential sensors useful for DOT workflows.
- Evaluated Trimble MX publisher, a web-based software for general users to view MTLS data in point clouds and imagery, for OLS.
- Assessed MTLS accuracy for ADA ramp slope measurements and developed best practices for MTLS ADA ramp data collection to ensure sufficient high point density and quality data for ADA ramp inspections.

Future work includes:

- 360-camera cover cap design modification to accommodate the new, higher resolution 360-camera on new Trimble MX mobile mapping systems.
- Evaluate the effectiveness of LiDAR QC software in improving MTLS point cloud accuracy and reducing the need for ground control targets.