

APPENDIX E: MOBILE TERRESTRIAL LASER SCANNER (MTLS) SPECIFICATIONS MANUAL

MOBILE TERRESTRIAL LASER SCANNER (MTLS) SPECIFICATIONS MANUAL
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A. PURPOSE OF THIS MANUAL

The **Mobile Terrestrial Laser Scanning (MTLS) Specifications Manual** defines standards and procedures for preparing, collecting, editing, delivering, exploiting, and archiving electronic mapping data that is produced for the Indiana Department of Transportation (INDOT). These standards apply to all projects delivered to INDOT by contracted consulting firms, or exchanged internally within INDOT.

The purpose of the standards and procedures within this manual is to obtain an optimal degree of statewide uniformity within INDOT's combined Aerial/Ground Survey process, to establish and maintain MTLS Standards for INDOT and contracted consultants, and to allow for all of the project data to be effectively managed from conception to completion. These standards apply to any MTLS technology, regardless of vendor or make.

The work that was done to support the development of this Mobile Terrestrial Laser Scanning (MTLS) Specifications Manual is described in the research report titled *Laser Mobile Mapping Standards and Applications in Transportation* (Johnson, Bethel, Supunyachotsakul, & Peterson, 2016). The work includes experiments that were done, data that was collected, analysis that was carried out, and conclusions that were drawn about the accuracy of Mobile Terrestrial Laser Scanning (MTLS) systems. The findings and knowledge obtained from this research project were essential in the development of this MTLS Specifications Manual. This is because many of the technically related numbers and values, as well as other insights presented in the MTLS Specifications Manual, are substantiated and justified through these findings.

B. GENERAL

LiDAR (Light Detection and Ranging) is a technology that uses laser scanner(s) to obtain geospatial positions and signal reflectivity of points on the objects being surveyed. The fundamental result is a point cloud that contains three dimensional position (X, Y, Z) and intensity data. The intensity data gives information about the reflectivity of the survey objects' surface at each point captured in the scanning environment.

Mobile Terrestrial Laser Scanning (MTLS) is a system that uses LiDAR scanner(s) supported by one or more digital cameras, a Global Navigation Satellite System (GNSS) receiver, an Inertial Measurement Unit (IMU), a Distance Measurement Indicator (DMI), and ancillary devices to display, process, and record the navigation and geospatial data. The system is mounted on a moving terrestrial platform. Typically vehicles including vans and trucks are used, but boats, and rail vehicles may be used as dictated by the scanning environment. The Mobile Terrestrial Laser Scanner (MTLS) is often referred to as a Mobile Laser Scanner (MLS) and the whole system that deploys MTLS technology is conventionally known as a Mobile Mapping System (MMS).

B.1 Components of Mobile Mapping System

The Mobile Mapping System (MMS) can be configured in variety of ways depending on different vendors, requirements, and makes. The performance of the MMS itself depends on the specifications of the fundamental or main components which can be itemized as follows:

- Laser Scanner (active ranging sensor with steering optics)
- Digital Cameras
- Global Navigation Satellite System (GNSS) Receivers
- Inertial Navigation System (INS) incorporating the Inertial Measurement Unit (IMU) with onboard software displaying navigation, estimation, and error propagation solutions
- Distance Measurement Indicator (DMI) or Wheel Revolution Counter
- Rigid Platform for stable geometric calibration of the components
- Ancillary Devices for solution display, system control, and data storage

Table B.1 lists selected major attributes which comprise the specifications of the laser scanner, digital cameras, GNSS receivers, and INS which directly relate to the overall performance of a Mobile Mapping System.

It should be noted that the units listed in Table B.1 are the conventionally used units; there may be variability in the specifications listed by different vendors and manufacturers.

B.2 Working Scheme of the Mobile Mapping System (MMS)

In general, there are two different technologies that laser scanners use to determine the range to the scanned targets, *time of flight* and *phase* technology. The time of flight technology scanners typically have a longer range compared to those using the phase technology; however, the phase technology is generally faster than the time of flight technology.

The laser scanner in a Mobile Mapping System uses the time-of-flight technology to determine the range to the scanned targets. The rotating laser scanner also measures the angular direction of the range line using high resolution angle encoders. With range and angular direction measurements to the targets, the coordinates of scanned points are then computed in the scanner reference coordinate frame.

The point cloud coordinates in the scanner frame can be transformed to the IMU body frame if the rotation parameters and the translation parameters are known by calibration. The so-called "boresight angles" are the orientations of the scanner frame with respect to the IMU body frame and the "lever arm offsets" are the three dimensional offsets from the scanner frame origin to the IMU body frame origin.

The Inertial Measurement Unit (IMU) instantaneously reports the orientations of the IMU body frame (roll, pitch and heading) with respect to a reference frame known as "Instantaneous Local Level Frame" that has the origin aligned with IMU body's origin.

TABLE B.1
Examples of some major specifications of laser scanner, digital cameras, GNSS receivers, and INS.

MMS Main Components	Major Specifications
Laser Scanner	<ul style="list-style-type: none"> • Point Repetition Rate (PRR) (measurements/sec or Hz) • Line Scan Speed (LSS) (lines/sec or rotation rate) • (PRP and LSS determine the overall measurement rate) • Range • Accuracy (length unit, mm for absolute comparison) • Precision (length unit, mm for repeatability) • Least Count of Angle Measuring Device
Digital Camera	<ul style="list-style-type: none"> • Resolution (pixels per frame) • Frame Rate (frames/sec) • Exposure (micro sec or sec) • Field of View (deg in H x deg in V) • Degree of Compression
Global Navigation Satellite System (GNSS) Receivers	<ul style="list-style-type: none"> • Data Rate (Hz) • Tracking (GPS, GPS & GLONASS) • Reacquisition (sec) • Kinematic processing with multiple base station
Inertial Navigation System (INS)	<ul style="list-style-type: none"> • IMU Data Rate (Hz) • IMU Drift Rate (deg/hr) • Gyro Bias (deg/h) • Accelerometer Bias (μg or mg)

The coordinates measured and transformed into the IMU body frame can be then transformed to the Instantaneous Local Level Frame.

The GNSS receiver mounted on the vehicle is continuously collecting time-tagged data for the Instantaneous Local Level Frame's position. The GNSS data logs obtained from the GNSS receiver mounted on the MMS vehicle and the data from receivers occupying a project base station(s) are then post-processed to arrive at the instantaneous position of the Instantaneous Local Level Frame with respect to an Earth-centered-earth-fixed (ECEF) project datum frame. The point cloud data in the Instantaneous Local Level Frame can then be transformed to the ECEF frame (geo-referenced).

B.3 Mobile Mapping System (MMS) Error Sources

The errors present in a Mobile Mapping System can be categorized into two main sources: instrumental errors and operational errors.

B.3.1 Instrumental Errors

The physical components of a MMS and the calibrated relationships among them contribute to the instrumental errors of the MMS itself. The following is a summary of error sources in the principal components of an MMS.

Laser Scanner Errors. The laser scanner of an MMS uses time-of-flight technology to determine the range to the scanned points. The laser scanner also makes

angular readings to the points using angle encoders. With range and angular measurements to the targets, the locations of scanned points are then determined. The errors in range and angular measurements are a contributing cause of the uncertainty in locating the actual positions of the scanned objects.

Global Navigation Satellite System (GNSS) Errors. GNSS error sources include the satellite and receiver clock errors, orbit errors, the atmospheric delays, and random noise. These errors may be modeled in the GNSS solution or compensated by differencing techniques relative to fixed control stations. The GNSS solution determines the project datum coordinate system of the scanned object points. Residual GNSS errors contribute to the relative positional errors between points and the absolute positional errors in the final coordinate system.

IMU Attitude Errors. The principal role of the IMU is to provide angular velocity observations which can be integrated into angular position information (roll, pitch, and heading) of the IMU body frame with respect to the Instantaneous Local Level Frame. Together with position data, this enables the point data in the Instantaneous Local Level Frame to be transformed into the ECEF frame. Thus all points in the point cloud are brought into a common reference frame. Knowledge of the sensor attitude with respect to the local level frame, via IMU data, affects every point. Therefore any uncompensated errors from the IMU will have direct impact on the geometric quality of the point cloud.

Boresight Alignment Errors (body frame / scanner frame angles and offsets). The orientation of the scanner frame with respect to the IMU body frame is expressed through boresight angles and lever arm offsets. The boresight angles cannot be observed by direct measurements, therefore these values are obtained indirectly through a calibration process. There are inevitable residual adjustment errors present in the alignment estimates.

The lever arm offset values can be obtained either through calibration or by measurements or both. Note that the values required are vector components, not just lengths, so some realization of the relevant coordinate systems is necessary.

B.3.2 Operational Errors

In addition to the errors from the MMS's instruments that directly contribute to overall errors, the way the system is operated also plays a vital role in the resulting MMS error budget. System operation procedures also affect the completeness and the quality of the scanned data.

GNSS Signal Multipath. The structures in the vicinity of the GNSS receiver can cause multipath interferences of GNSS signals resulting in decreased accuracy of the positions. The multipath effect can be quite severe especially in urban areas (urban canyons) where there are many tall building structures.

GNSS Signal Obstruction. The structures or objects in the vicinity of the GNSS receiver can cause an obstruction between the GNSS receiver and some or all satellites. This forces the receiver to estimate position with fewer satellites available in the viewing window resulting in geometrically weaker positioning solutions of the MMS. The obstruction effect is quite severe especially in urban areas (urban canyons) where there are many tall building structures.

Loss of GNSS Signal Lock. Closely related to signal obstruction is "momentary obstruction" resulting in loss of lock, or discontinuities in signal tracking. It differs from the obstructions mentioned above, in that it is momentary rather than persistent. The loss of GNSS signal lock greatly affects the positioning of the MMS. The loss of GNSS signal lock is mainly caused by obstruction features such as trees, bridges, vehicles, etc.

Traffic Conditions. A heavy traffic conditions during the MMS data collection causes vehicle and pedestrian shadows or occlusions in the resulting point cloud. Note that some of these conditions can be mitigated by having the MMS vehicle make multiple passes.

Weather Conditions. Rain or snow during the MMS data collection process can be very detrimental to the data quality due to the fact that the rain droplets or snowflakes themselves behave as scatterers with

unpredictable corruption of the point cloud. Recent rain can be an issue if there are significant puddles or standing water, as these will cause specular reflections of the laser energy. This has two deleterious effects: it prevents properly detecting the ground surface under the puddle, and it may introduce spurious points via the reflection (we could also call this multipath of the scanner itself).

B.4 Factors Affecting the Selection of Mobile Mapping as Survey Method

There are many factors to be considered in deciding if MMS is the appropriate technology for data collection for a project. Below is a list of the major factors to be considered:

- Size of the project; in terms of area and length
- Nature of the project area (urban area, flat open area, mountainous area, etc.—i.e., is it easily accessible via smooth roads or smooth surfaces which will support the vehicle?)
- Safety
 - Accessibility
 - Environmental issues in the project area (severe weather zone, extreme temperature, extreme condition (wind, visibility issue), etc.)
 - The laser scanner must be operated in a way to ensure the eye safety of the travelling public, pedestrians and animals
- Availability of unobstructed GNSS signals, for example interior of a parking garage would present difficulties.
- Desired products (deliverables) of the project.
- Project time constraints
- Project budgets
- Could the project be achieved at lower cost by static scanning, photogrammetry, or conventional surveying or kinematic GPS?

C. DATA AND METADATA

A Mobile Mapping System (MMS) produces a great deal of data in addition to the fundamental object point cloud. Users should be familiar with the data that may be available as an aid in quality acceptance and control and in developing additional applications using the data set. This chapter will cover characteristics of the data obtained from a Mobile Mapping System (MMS), conventional formats, and accompanying Metadata or support data.

C.1 Data Obtained from Mobile Mapping System (MMS)

C.1.1 Raw Sensor Data

The raw sensor data obtained from a Mobile Mapping System (MMS) can be varied and is typically stored in a proprietary format which depends on the sensors and components of the MMS used in data

acquisition process. If any of these data are wanted, then prior negotiations with the vendor for tools or translators will be necessary.

The raw sensor data typically includes the following:

- Readings from each laser scanner—the angles and ranges for a pulsed laser scanner or the angles and phases readings from a full waveform scanners
- Digital images taken from digital cameras and/or video files from a video recording system
- Distance readings from DMI
- GNSS readings which are the positioning data obtained from the GPS receiver
- IMU readings

To be useful, it is important that the raw sensor data listed is appropriately time-tagged.

C.1.2 Raw Point Cloud and Imagery

The aforementioned raw sensor data must be integrated and processed to arrive at a point cloud and imagery in an arbitrary reference frame of convenience. The point cloud at this stage is conventionally known as a raw point clouds. Because raw point clouds have not undergone any correction procedure though the use of project control points or reconciliation with overlapping point clouds, users may easily detect or visualize separations (misalignments or mismatches) between clouds from different scanning paths. Users are likely to also be able to visualize misalignment between raw point clouds and raw images.

C.1.3 Corrected Point Cloud and Imagery

The corrected or controlled point clouds are the raw point clouds that have been corrected through the use of project control points, and/or other overlapping point clouds. Assuming that raw point clouds and raw images have been properly corrected, the separations between point clouds from different scanning paths will be greatly reduced and the images will be consistent with each other and with the corresponding point clouds. The point clouds and images that have been projected through the use of project control points into an established project coordinate system are known as the registered, geo-referenced, or corrected point clouds and images.

C.1.4 Trajectory Files

The post-processing of the GNSS position data combined with IMU trajectory data and distance readings from the DMI results in the final trajectory of each MMS vehicle pass. The data sets and results of the trajectory determination are often collected into a trajectory file. For users of Applanix navigation equipment this file has a standard, proprietary format known as “Smoothed Best Estimate of Trajectory (SBET).”

C.1.5 Value-Added Products (Derived Products)

For particular applications with unique objectives, a variety of filters and processors can be applied to the point cloud. For example, object classification, vegetation removal, vehicle removal, feature extraction, terrain modeling, etc. may be applied to point clouds to produce specific types of value-added products. These are referred to as derived datasets or extracted features or dimensions. Examples of such derived datasets include cross sections, profiles, contours, utility locations, and bridge clearances.

Derived datasets can be obtained not only from manipulations applied to the point cloud data itself, but they can also be obtained through the manipulations of point clouds and other relevant information such as registered imagery.

C.2 Auxiliary Information for Mobile Mapping System (MMS) Data

Along with the data itself, several types of auxiliary data is usually provided as well. This can include a Project Narrative, and also Metadata or support data needed to fully exploit the point cloud. It is important to stress that the Project Narrative and the Metadata are not the same thing and should not be considered interchangeable. The Metadata is the data about the MMS data itself. This might include format specifications, unit descriptions, trajectory data, index files, or information about the imagery.

The Project Narrative report itself should provide the general information about the data collection. This could include notes taken at the time of the collection regarding date, time, weather, traffic, personnel, condition of roadway, condition of targets, etc. It may also include narratives about processing steps, GNSS adjustments, fitting of overlapping point clouds to one another, or fitting of point clouds to targeted project control points. Depending on organization details of the Narrative Report, there may be supplementary reports about some specific topics.

C.3 Conventional File Formats for Mobile Mapping System (MMS) Data

Conventional file formats for MMS data are listed in Table C.1. Users typically will be dealing with the point clouds, imagery, and derived data (value-added products) in common, open formats. Therefore, these conventional formats are listed in the table. In some projects, the raw sensor data may be part of the required deliverables and some typical formats of proprietary, raw sensor data obtained from a Mobile Mapping System (MMS) are included; however, raw data are system dependent and are stored in the hardware-specific formats. Some typical file formats of value-added products are included, but the list is not exhaustive.

TABLE C.1
Conventional file formats of mobile mapping system data.

MMS Data	Conventional File Format	Remarks (ASCII /Binary)	Commonly Used Software to Read and/or Process
The Raw Sensor Data			
GNSS Data	RINEX	ASCII	Text Editor (Notepad, WordPad)
Digital Images	TIFF, JPEG, PNG	Binary	Photoshop
Digital Video	AVI, MOV, MPG	Binary	Media Player, Quicktime
Point Cloud and Imagery			
Raw Point Clouds	LAS, PTX, XYZ	LAS: binary standard, PTX, XYZ ASCII open	TopoDot, Terrasolid, Pointools, Leica Cyclone, Faro Scene, Scene LT
Raw Digital Images	TIFF, JPEG, PNG	Binary	Photoshop
Corrected Point Clouds	LAS, PTX, XYZ	LAS: binary standard, PTX, XYZ ASCII open	TopoDot, Terrasolid, Pointools, Leica Cyclone, Faro Scene, Scene LT
Corrected Digital Images	TIFF, JPEG, PNG	Binary	Photoshop
Trajectory File	SBET, SHP KMZ, TXT	Binary ASCII	Text Editor for ASCII
The Derived Dataset			
Cross sections, contours, bridge clearances	CAD formats (e.g., DGN, DXF, DWG)	Binary, ASCII	MicroStation, AutoCAD

D. ACCURACY, RESOLUTION, AND COMPLETENESS OF MMS DATA

The accuracy of an MMS dataset depends on several factors which can be categorized into the groups as follows:

- Hardware and specifications of the Mobile Mapping System used
- Usage of the control points, and the quality and distribution of control points
- Data collection parameters (range, incident angles, speed of vehicle, etc.)
- Data collection environment (the nature of the scanning area (urban area or open area, weather, temperature, traffic conditions, etc.)
- Data processing techniques

The horizontal accuracy and vertical accuracy are handled separately as they often have different accuracy requirements; however, they are of course geometrically related. The horizontal accuracy of MMS data is tested by comparing the planimetric coordinates of well-defined validation points extracted from the MMS dataset against the coordinates of the same points obtained independently from a higher accuracy ground survey. Similar to the case of horizontal accuracy testing, the vertical accuracy testing compares the elevations at validation points and independently surveyed elevations.

D.1 Accuracy Specifications

There are two types of MMS dataset accuracies that must be addressed: (1) the absolute accuracy, sometimes referred to as the network accuracy, and (2) the relative accuracy, sometimes referred to as the local accuracy.

D.1.1 Absolute Accuracy (Network Accuracy)

The absolute accuracy is a value that represents the uncertainty in the planimetric coordinates (horizontal position) and the elevation (vertical position) of a point in the point cloud. The absolute accuracy is evaluated by testing horizontal and vertical position discrepancies at project validation points. Project control points should be referenced to the National Spatial Reference System (NSRS) which is defined, maintained and published by the National Geodetic Survey (NGS). NAD 83(2007) is the geodetic datum recommended for horizontal control. NGVD 88 and orthometric (sea level) heights is recommended for vertical control. In a case where ellipsoid heights are used, the former horizontal datum suffices for both horizontal and vertical accuracy.

D.1.2 Relative Accuracy (Local Accuracy)

Relative accuracy is a value that represents the uncertainty in the *difference* in the planimetric coordinates (horizontal position) and elevation (vertical position) between points in the point cloud. Experience has shown that for MMS data, since it is continuously registered to the absolute coordinate reference system during collection, relative accuracy computed for a set of validation points distributed throughout the point cloud is the same as absolute accuracy. Therefore, we do not tabulate a relative accuracy specification for the validation points. A specification for the vertical difference between closely spaced adjacent points is tabulated. For some applications such as design and construction work high absolute accuracy is critical, in contrast, for some applications such as bridge clearance measurement, a high relative accuracy is sufficient.

D.2 Accuracy Reporting Standard

MMS data accuracy reporting should conform to the following items:

- Use root-mean-square error (RMSE) to compute the positional accuracy of a dataset
- Positional accuracy (both horizontal and vertical) shall be reported at the 95% confidence level
- Positional accuracy (both horizontal and vertical) shall be reported in ground units
- The unit shall be the same as the unit of the MMS dataset coordinates
- The number of digits to the right of the decimal point for reported accuracy shall be equal to the number of digits to the right of the decimal point for the MMS dataset coordinates

For more details about how the root-mean-square error (RMSE) and the 95% confidence level are computed to represent the positional accuracy of the dataset, see Appendix A.

D.3 Accuracy Requirements

TABLE D.1
95% critical values for testing MMS absolute results.

Absolute Accuracy	Design	Asset
Horizontal	95% of tested points <8 cm discrepancy from reference position	95% of tested points <18 cm discrepancy from reference position
Vertical	95% of tested points <5 cm discrepancy from reference elevation	95% of tested points <24 cm discrepancy from reference elevation

TABLE D.2
95% critical values for testing MMS relative vertical results.

Relative Accuracy	Design	Asset
Vertical difference between closely space points	95% of tested dV <5 cm discrepancy from reference dV	95% of tested dV <6 cm discrepancy from reference dV

D.4 Range Effect

The range between the laser scanner and the target objects or terrain plays a vital role in the positional accuracy of the scanned points. Although the accuracy of the range itself may be largely independent of range, the coordinate values of the scanned points depend on both measured length and the measured direction of the range line. It is the latter angular solution that makes point coordinate accuracies range dependent. It is important to not only specify the required accuracy

for the delivered point cloud but to also specify the required accuracy within a required range (e.g. the delivered point clouds shall have the accuracy of X.X cm within 20 m range)

Since accuracy of the point coordinates degrades when the range between the laser scanner and the point increases, some vendors may specify an effective range or a range limit and exclude all the points that get scanned beyond the specified range to ensure a consistent level of accuracy.

D.5 Resolution (Point Density) of MMS Dataset

The resolution of the MMS dataset is characterized in terms of point density which is the number of points in a given unit area (points/m² or points/ft²). The point density varies within the point cloud and is affected by the following project factors:

- Scanner specifications (Point Repetition Rate and Line Scan Speed)
- Nominal distance from the scanner
- Vehicle speed
- Number of scanning passes
- Obstructions

A point density value by itself is not a complete piece of information. It is important that the point density information be accompanied by the distance from the scanner and the location where it was evaluated (e.g., the point density of 1000 points/m² evaluated on the (horizontal) pavement surface at 3 meters away from the scanner, the point density of 100 points/m² evaluated on the (vertical) building wall at 20 meters away from the scanner).

Point density plays an important role in feature extraction from scanned point clouds. A contractor shall ensure that the point density within a point cloud is sufficient to permit the extraction of features of interest (e.g., lines, spheres, cylinders, planes, poles, etc.) at the specified level of accuracy within the specified distance from scanner.

Scanning the scene using the maximum sampling rate of the laser scanner to achieve point clouds with maximum possible density often seems to be the best practice. However, some vendors have commented that using the maximum scan rate may produce noisy point clouds for some specific features. Discussions with the vendor prior to scanning can be useful here.

D.6 Multiple Scan Passes and Overlapping Scans

The same scene (roads, buildings, etc.) is often scanned with multiple scanning passes to ensure high quality of the scanned point cloud (increase point density, fill the shadow gaps, create good geometry of scanned points on the feature of interests for feature extraction) or to cover larger areas with side overlapping scans. There is no specific rule about the minimum percentage of point cloud overlap. Disregarding costs, more overlap means more redundancy

which is beneficial. A practical rule would be that every point in the scene should be seen by at least 2 scan heads on different passes. In general, looking at consistency or non-consistency (gaps) between data on the same feature from separate passes is an ideal way to judge many aspects of the whole post processing effort (multiple cloud reconciliation, enforcement of control point positions, etc.).

E. CONTROL AND VALIDATION SURVEY

MMS service providers and vendors should be responsible for any control surveys that are needed. Often they subcontract this activity to local surveying firms, working to their specifications. Vendors may have the control survey and target placement done by INDOT. INDOT must consider the responsibility and liability for control accuracy affecting the delivered products.

On the other hand, INDOT may very well wish to take responsibility for validation surveys, as this gives them a way to quantitatively evaluate the quality of the delivered products against requirements for accuracy. Checkpoints or validation points and off-road targets provide a way to implement such a validation survey, in which the control values are withheld from the MMS vendors, and are only used by INDOT to check the delivered data quality.

E.1 GNSS Base Stations

GNSS observations at fixed base receiver(s) and the receiver mounted on vehicle are used in the kinematic post-processing of the GNSS data to reference the point cloud to the project coordinate system. Vendors typically set up their own GNSS base stations for a project to ensure that the baselines to the vehicle are short and hence will not degrade the post-processing kinematic solutions. INDOT may share knowledge of network ground control points in the proximity of the project. INDOT may occupy the control points and supply the raw GNSS data streams to the vendor.

Considerations for setting up project GNSS base stations include the following:

- Keep baselines from base receiver to vehicle receiver short for the differential GNSS solution. A single base receiver station, centrally located, may be sufficient for small project areas.
- Multiple GNSS base station receivers may be distributed over large project areas. For linear roadway projects, a minimum is to place at least one GNSS base station at the beginning and one at the end of the project.
- Multiple GNSS base station receivers increase redundancy in case of an accident, receiver error, human error in setting base stations, or other possible error.
- The GNSS base stations must conform to Chapter 25, GPS Survey Control Network of the INDOT Design Manual.

E.2 Project Control and Validation Points

The raw MMS dataset must be adjusted to the project control coordinate datum. Project control points are used to solve for the parameters of a coordinate transformation from the raw dataset coordinate system to the project coordinate datum. Validation points are established to make an independent evaluation of accuracy of the delivered products. Validation point coordinates should be withheld from the solution and not used in post processing. Project control points and validation points are the well-defined points and their coordinates are independently surveyed from a higher accuracy surveying method.

Project control points are often designed by the vendor, and they are typically placed within the road right of way. Validation points are often established by the client and may be in the roadway or adjacent to the roadway. The points must be identifiable in the point cloud. This is accomplished by placing reflective targets on the roadway (crosses, squares, chevron) or placing reflective objects (sphere for example) plumbed over points off the roadway. The target position on the surveyed point is established by processing the intensity signal from shapes on the roadway or by processing the geometry of points on the target object.

Considerations for establishing project control and validation points include the following:

- Control and validation points must be independently surveyed to a higher accuracy than the MMS data.
- Control points can either be a point in the permanent local control network or they can be connected to the local control network and placed for a specific project
- Control and validation points must be uniquely identifiable and visible in the point cloud. When control points are targeted, consider target size, shape, and reflectivity in the final point cloud.
- The control points should be placed over the scanned area in a well distributed manner and at a spacing adequate to meet the accuracy requirement of the final point cloud.
- Validation points should be placed at locations approximately midway between adjacent control points.
- If the scans include roadways, the control points should be placed on both sides of the roadway as well as on the centerline or median area (without safety being compromised) in a well distributed manner.
- The control points which are set by using GPS must conform to Chapter 25, GPS Survey Control Network of the INDOT Design Manual.

F. QUALITY MANAGEMENT

Quality management involves tasks performed before and during MMS data acquisition and data processing to proactively monitor and ensure the quality of the MMS datasets. The planned tasks are documented in what is known as Quality Management Plan (QMP) and the major tasks in quality management can be categorized into quality assurance (QA) and quality control (QC) tasks.

F.1 Quality Assurance (QA)

Quality assurance (QA) refers to the planning of the tasks *prior to any collection activity* to manage the overall quality of the project. The QA program is planned by the vendor to ensure quality in the data collection and data processing activities. The QA report should be included in the project deliverables. Examples of QA activities will include: recent system calibrations, planning for multiple passes, planning for any special driving maneuvers at corners, planning for project control, planning optimal vehicle velocities and settable parameters, monitoring expected weather, etc.

F.2 Quality Control (QC)

Quality control (QC) refers to the check procedures and evaluations performed during stages of the project to detect any problems. QC may indicate needed corrections for ensuring the quality of products in intermediate stages and the quality of the final products. The QC report should be included in the project deliverables. Examples of QC activity include: monitoring PDOP metrics for the GNSS constellation, monitoring unexpected obstructions which may require re-executing the pass, monitoring adjustment statistics when merging overlapping point clouds, monitoring adjustment statistics (discrepancies) when fitting point cloud to project control, carrying out any independent validation point evaluation, etc.

The quality control planned tasks shall include but not be limited to the procedures described in Part F.2.1 through F.2.4.

F.2.1 Alignment Evaluation of Overlapping Point Clouds from Different Passes

In general, the overlapping scanned point clouds from different scanning passes are not well aligned without an adjustment through the use of project control points and/or cloud-to-cloud registration algorithms. These adjustment processes can dramatically improve the alignment between overlapping clouds from different passes. The misalignments between scanning passes are visualized through the vertical separations (difference in elevation data) between clouds. Note that horizontal misalignments (in non-horizontal planar data) also manifest themselves as vertical separations. The proposed procedures for comparing the elevation data (vertical separation) of overlapping point clouds from different passes must be documented and included in the Quality Management Plan (QMP).

F.2.2 Adjustment of the Raw MMS Dataset

The raw MMS dataset is adjusted and registered to the project control points through a coordinate transformation adjustment. The descriptions of the proposed type of transformation (i.e. the mathematical

model, rigid body, seven parameter, rigid body without scale, etc.) to be used and the selected control points to be used must be documented and included in the Quality Management Plan (QMP).

F.2.3 Accuracy Evaluation of Corrected Point Clouds

As previously discussed in Part D, the accuracy evaluation of the MMS corrected point clouds is performed by comparing the coordinates of project validation points from the MMS dataset against the coordinates of the same points obtained independently from a higher accuracy survey. Validation points cannot have been used in the previously mentioned transformations. The descriptions of the proposed accuracy evaluation process of corrected point clouds must be documented and included in the Quality Management Plan (QMP). INDOT may decide whether to require the vendor to make a validation check or do it themselves independently.

F.2.4 Accuracy Evaluation of Other Derived Products

Besides the accuracy evaluation performed directly on the corrected point clouds, the accuracy of any required derived dataset or derived products must also be evaluated. A suitable method of evaluating the accuracy of a derived product is dependent on the type of product. The description details of the proposed method used in the accuracy evaluation process of the derived products must be documented and included in the Quality Management Plan (QMP).

F.3 Quality Management Plan (QMP)

The quality management plan (QMP) shall include the description of the proposed QA and QC plans, and it shall be submitted for review and approval before the start of the project. During the QMP review, INDOT may request some amendments applied to the QMP before approving the plan. The suggested contents of QMP are discussed in Part G.1.4.

G. DELIVERABLES AND DOCUMENTATIONS

The deliverables and documentation of projects depend on the type of projects and their associated workflows or procedures to arrive at the final products. It is not feasible to list deliverables and documentation for each specific type of project; therefore, minimum required deliverables and documentation for all MMS projects will be summarized and the optional deliverables that may be considered for specific applications must be agreed upon in the contract.

G.1 Fundamental Deliverables and Documentation

The following deliverables and documentation should be delivered for all projects. The recommended

formats of Fundamental Deliverables and Documentation are listed in Table G.1.

G.1.1 Point Clouds, Imagery and Videos

- Corrected point cloud
- Corrected imagery and videos

The point cloud data, imagery and videos must be delivered in agreed upon project reference coordinate system. It is desirable to also require the delivery of raw point cloud data and imagery in order to monitor the extent of the correction and refinement steps. However INDOT may choose to not make this mandatory.

The delivered data should be clean and free from the erroneous points caused by signal scattering, signal processing, and background reflections.

G.1.2 Derived Data (Value-Added Products/Modeled Point Clouds)

The required delivered products are not limited to only observed point clouds and imagery; the derived datasets are project dependent and vary among types of projects. The point cloud may be classified into different types of features of interest such as the cross sections or profiles of roads, the clearance of surveyed bridges, the extracted drainage lines, the locations of utilities, the modeling/extraction of power lines are examples of possible derived products for some projects. The required deliverable data for each project must be specified in the agreement.

The required file formats of the delivered data are to be clearly specified in the contract agreement. For some common products, unless specified otherwise in the contract agreement recommended files formats can be found in Table C.1.

G.1.3 System Calibration Report

A system calibration report provides verification of recent/current calibration of the geometric relationship between the laser scanner and INS unit (boresight calibration, lever arm offsets calibrations), camera calibration (parameters of every camera used in the system to obtain images), and other ancillary device calibration. As a minimum, the report must describe the date, extent, and result summary for any relevant calibration processes. The report should also include some statements about the authority and qualifications of the individuals or service providers who have made the calibration. It is desirable to include the calibration results and their associated statistics in detail, although this may be considered proprietary information by some vendors.

G.1.4 Quality Management Plan Report

Quality management plan (QMP) must include the description of the proposed QA and QC plans. The

Quality management plan should include, but not be limited to the following:

- Descriptions and map of control points (same contents as Control Survey Report)
- Proposed procedures to be used in alignment evaluation of overlapping point clouds from different passes
- Proposed procedures to be used in the adjustment process of the raw MMS dataset
- Proposed procedures to be used for the accuracy evaluation of corrected point clouds
- GNSS PDOP values during data acquisition
- Descriptions and map of validation points
- Summaries of statistical and adjustment results for data merging, registration, and validation

Sections G.1.5 through G.1.8 summarize reports that are associated with the fundamental data processing procedures. Starting from the first step of the data acquisition process, until the production of deliverable products as specified in the project contract, many data processing and evaluation steps must occur. These steps should be summarized including basic procedures and results to complete the project documentation. If there are additional steps not itemized here, they should also be summarized in the same way.

G.1.5 Trajectory Analysis Report

The trajectory analysis report shall document the steps used for processing the GNSS and IMU readings in order to obtain the final trajectory of the MMS vehicle, typically expressed as the Smoothed Best Estimate of Trajectory (SBET file, or equivalent). The results and related statistics shall be documented in the trajectory analysis report.

G.1.6 Report of the Alignment Evaluation of Overlapping Point Clouds from Different Passes

The results from the process of comparing the elevation data (vertical separation) of overlapping point clouds from different passes and the results with their associated statistics as well as any other the related information must be documented and reported in detail. The results of this vertical separation analysis shall be reported whenever it occurs, both before and after fitting to control points.

G.1.7 Report of the Adjustment of the Raw MMS Data to Control Points

The statistical results from the adjustment process of fitting raw MMS data to project control points (transformation process) including related, supplementary information must be documented and reported in detail.

G.1.8 Modeled Dataset Report

The modeled dataset report should provide detailed information on how the final deliverables derived from

the point clouds were obtained. The underlying information includes the name of the software or analytical tools used to produce the deliverable, the steps or procedures, and any related statistics of the results. For example, if a Digital Terrain Model (DTM) is a required final product, this report should cover the name of the software packages and whatever is known about the algorithms employed. It should also briefly mention the workflow used to arrive at the final DTM. Additionally, it should also provide the information about the values of any adopted parameters used in DTM computations as well as the associated statistics of the result.

G.1.9 Report of the Corrected Point Clouds Accuracy Evaluations

The statistical results of the accuracy evaluation processes applied to the corrected point clouds as well as any related information must be documented and reported in detail.

G.1.10 Report of the Derived Products' Accuracy Evaluations

The statistical results of the accuracy evaluation processes applied to any derived products as well as any related information must be documented and reported in detail.

G.1.11 Project Narrative Report

The project narrative report should include the following information:

- Project name and location identifier
- Survey date, time, weather conditions, limits, purpose, personnel involved, contacts with customer personnel, log of activities with relevant details such as velocities, scan rates, etc.
- Project datum, epoch and units
- Survey control points found, held and set (see Control Survey Report)
- Personnel, equipment, and surveying methodology employed
- Problems encountered, if any
- Other supporting survey information such as GNSS observation logs
- Dated signature and seal (if licensure is required) of the surveyor/engineer in charge

G.1.12 Control Survey Report

Include a listing and map of project control point locations and type of signalization with relevant statistics from any adjustment procedures used to arrive at final project control coordinates. Specify the horizontal and vertical coordinate datum used for the final project control.

G.1.13 Metadata Files

As a minimum, include the adjusted trajectory file with information about how the adjustment was done.

G.1.14 Final Project Report

Include all of the items listed in this chapter G, organized in a readable fashion.

G.2 Optional Deliverables and Documentation

Besides the aforementioned fundamental deliverables and documentation, there may be other required deliverables and their related documentations based on the agreement of client and vendor. Table G.1 summarizes the list of deliverables below:

TABLE G.1
Deliverables list.

Fundamental Deliverables and Documentations	Point clouds, imagery and videos Derived data (modeled point clouds/value-added products) System calibration report Quality management plan report Fundamental Data Processing Documentations and Reports
	<ul style="list-style-type: none"> • Trajectory Analysis Report • Report of the Alignment Evaluation of Overlapping Point Clouds from Different Passes • Report of the Adjustment of the Raw MMS Data to CP's • Modeled / Derived Data Report
	<ul style="list-style-type: none"> Report of the Corrected Point Clouds Accuracy Evaluation Report of the Derived Products Accuracy Evaluation Project narrative report Control Survey Report Metadata Files Final Project Report
Optional Deliverables and Documentation	As specified in the contract

H. APPLICATIONS OF MOBILE TERRESTRIAL LASER SCANNING

The applications for mobile terrestrial laser scanning is a dynamic list as users refine existing applications and continue to develop new applications. Table H.1 incorporates the information in the paper by Williams, Olsen, Roe, and Glennie (2013) and then adds and/or modifies a number of the listed applications into the format shown. Of course there are overlaps with what could be accomplished using static terrestrial scanners or airborne scanners. Users must select the best method based on available equipment and resources and needs for accuracy, density, redundancy, and completeness.

TABLE H.1
General and related specific applications.

General Activity	Specific Application
Project Planning	Roadway Analysis Topographic Mapping, Digital Terrain Modeling Environmental Studies Surveying, Other Measurements Intersection Upgrade/Rehab Drainage Analysis Urban Feature Modeling/City Modeling/GIS
Project Development	3D Design, Clashes, Interferences Feature Extraction for CAD, Baseline Data
Construction	Progress Monitoring As-Built/Repair Documentation Machine Control and Construction Automation Post Construction QA/QC Pavement Smoothness Assessment Earthwork Quantities ADA Compliance
Maintenance	Bridge Inspection Pavement Inspection Power Line Clearance Above Ground Utility Inspection Vegetation Management Drainage/Flooding Assessment
Operations	Traffic Congestion/Parking Utilization Land Use/Zoning Compliance Tax Assessment Building Information Modeling (BIM) Bridge Information Modeling (BrIM) Emergency Response Clearances, Vertical & Horizontal (Bridges, Signs, Guardrails, ...)
Safety	Extraction of Geometric Properties & Features (Sightlines, Obstructions) Accident Investigation/Forensic Investigations Railroad Grad Crossing Inspection Facilitate Cooperative Operations with Trolleys, Trains, Light Rail, Aviation, Bikes, Pedestrians Driver Assistance, Autonomous Navigation
Asset Management	Inventory Mapping Modeling and Inspection Automated/Semi-Automated Sign Extraction Billboard Management Signals, Pavement Markings, Bike/Pedestrian Amenities
Tourism	Virtual Tour of Region Attractions Integration with Turn by Turn Driving Instructions Historical Baseline Survey & Preservation
Research	Unstable Slope Detection Landslide Assessment Coastal Erosion Useful Integrations of Point Cloud and Image Data Extraction of CAD Model from Point Cloud Use of Point Cloud Features to Control Imagery Virtual Reality (VR) interaction with Point Cloud Data Planning Drone Waypoints and Trajectories

It should also be recognized that the real value from mobile laser scanning is the registered point cloud. As imaging and computer vision capabilities advance, comparable point

clouds can in some cases be generated from imagery. This certainly is an area of active research. Some of the listed applications can best be accomplished by simply viewing

the point cloud or viewing an integrated display of the point cloud with associated imagery. Other applications may be best accomplished using software aids for automated or semi-automated extraction of features or dimensions. One of the exciting opportunities offered by laser scanning data is that multiple departments may be able to make use of the same data for quite different purposes. The data itself becomes a significant asset.

I. REFERENCES

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APPENDIX: ROOT MEAN SQUARE ERROR (RMSE) CALCULATION FOR REPRESENTING THE POSITIONAL ACCURACY OF A DATASET

This section illustrates the details of how the root mean square error (RMSE) is computed to represent the positional accuracy of the MMS dataset. The positional accuracy is evaluated by analyzing the coordinate discrepancies at validation checkpoints distributed throughout the point cloud.

Refer to the surveyed reference coordinates in Easting, Northing and Elevation of the i -th validation point as $(E_{Ref}, N_{Ref}, h_{Ref})_i$, and the observed coordinates of the same validation point obtained from the MMS dataset as $(E_{Det}, N_{Det}, h_{Det})_i$. Calculate the discrepancies in coordinates at each validation point. The coordinate discrepancy values are denoted dE_i , dN_i , and dh_i are the difference calculation shown in Equation A.1.

$$\begin{bmatrix} dE \\ dN \\ dh \end{bmatrix}_i = \begin{bmatrix} E_{Det} \\ N_{Det} \\ h_{Det} \end{bmatrix}_i - \begin{bmatrix} E_{Ref} \\ N_{Ref} \\ h_{Ref} \end{bmatrix}_i \quad (A.1)$$

For the i -th validation point the discrepancy, dP_i , in planimetric 2D position is calculated as shown in Equation A.2.

$$dP_i = \sqrt{dE_i^2 + dN_i^2} \quad (A.2)$$

For the i -th validation point the discrepancy, dQ_i , in 3D position is calculated as shown in Equation A.3.

$$dQ_i = \sqrt{dE_i^2 + dN_i^2 + dh_i^2} \quad (A.3)$$

Then the Root Mean Square Error in Easting, Northing, and Elevation of the MMS dataset can be computed using the coordinate discrepancy in of all n validation points as shown in Equations A.4, A.5 and A.6 respectively.

$$RMSE_E = \sqrt{\frac{\sum_{i=1}^n dE_i^2}{n}} \quad (A.4)$$

$$RMSE_N = \sqrt{\frac{\sum_{i=1}^n dN_i^2}{n}} \quad (A.5)$$

$$RMSE_h = \sqrt{\frac{\sum_{i=1}^n dh_i^2}{n}} \quad (A.6)$$

The Root Mean Square Error in planimetric 2D position can be computed from the Root Mean Square Error in the Easting and Northing coordinates as shown in Equation A.7.

$$RMSE_P = \sqrt{(RMSE_E)^2 + (RMSE_N)^2} \quad (A.7)$$

The Root Mean Square Error in 3D position can be computed from the Root Mean Square Error in Easting, Northing, and Elevation coordinates as shown in Equation A.8.

$$RMSE_Q = \sqrt{(RMSE_E)^2 + (RMSE_N)^2 + (RMSE_h)^2} \quad (A.8)$$

The RMSE computed values may be scaled to the 95% confidence range as shown below.

$$Error_{P-95} = RMSE_P \times 1.7308 \quad (A.9)$$

and

$$Error_{h-95} = RMSE_h \times 1.9600 \quad (A.10)$$

In general the accuracy of the dataset is separated into horizontal accuracy and vertical accuracy which are computed as RMSE values and then scaled to a 95% confidence range (see pages 10 and 11 in FGDC (1998)).