FINAL REPORT:
SLAM POSITIONING SYSTEM ASSESSMENT

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14. ABSTRACT

The U.S. Army Engineering and Support Center, Huntsville's Environmental and Munitions Center of Expertise demonstrated that simultaneous location and mapping system (SLAM) technology is viable for munitions response geophysical operations in global navigation satellite systems (GNSS) denied areas. SLAM system precision achieves that of high accuracy GNSS (e.g. real-time kinematic differential global positioning systems (RTK-DGPS)) when acquisition procedures are tailored to maximize the SLAM system's performance.

Two assessments were performed, one to compare SLAM positions to high accuracy RTK-DGPS positions and one to assess repeatability along the same track in a GNSS denied area. The assessment to compare SLAM to RTK-DGPS positions shows the SLAM track plot being almost indistinguishable from that of the RTK-DGPS after factoring for RTK-DGPS imprecision of several centimeters and the fact data was acquired dynamically on a cart not engineered to mitigate platform tilt, which added another two to three centimeters to the total RTK-DGPS error budget.

The repeatability assessment performed in a GNSS denied area shows SLAM system repeatability is very high when operated over long distances and long periods of time between control points. Sections repeated multiple times during the same sortie showed internal repeatability within the ±10 to 15cm error in repeating the same path as estimated by the operator during the sortie. Repeatability between an initial mapping survey and the repeat sortie was in the range of 30 to 50 centimeters on average. Significantly better results should be expected when the rotation and translation procedure used to compare the two datasets uses accurate control point data, which were not available for this assessment. This assessment used a low-quality GNSS data point that negatively affected the Kaarta® Engine's functionality

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Executive Summary

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Two assessments were performed, one to compare SLAM positions to high accuracy RTK-DGPS positions and one to assess repeatability along the same track in a GNSS denied area. The assessment to compare SLAM to RTK-DGPS positions shows the SLAM track plot being almost indistinguishable from that of the RTK-DGPS after factoring for RTK-DGPS imprecision of several centimeters and the fact data was acquired dynamically on a cart not engineered to mitigate platform tilt, which added another two to three centimeters to the total RTK-DGPS error budget.

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List of Acronyms

AGC	Advanced geophysical classification
COTS	Commercial off the shelf
GNSS	Global Navigation Satellite System
GPS	Global Positioning System (often synonymous with GNSS)
IMU	Inertial measurement unit
LiDAR	Light detection and ranging
MMRP	Military Munitions Response Program
RTK DGPS	Real-time kinematic differential GPS
SLAM	Simultaneous location and mapping
USAESCH	U.S. Army Engineering and Support Center, Huntsville
VSP	Visual Sample Plan

Glossary

Accuracy. In the context of this assessment, accuracy is how well a positioning system can register where measurements were taken with respect to a geographic coordinate system. This term is used to define how close reported coordinates are to the actual, physical locations on the Earth where the measurements were taken.

GNSS denied area. An area where centimeter-level GNSS accuracy cannot be maintained for the purpose of MMRP geophysical activities. This is normally due to the inability of an RTK DGPS instrument to maintain continuous lock on four or more GNSS satellites.

Point Cloud. The Wikipedia definition of point cloud is, "A **point cloud** is a set of data points in space. Point clouds are generally produced by 3D scanners, which measure many points on the external surfaces of objects around them. "

Precision. In the context of this assessment, precision refers to how well a positioning system can register where one location measurement was taken with respect to all other neighboring locations measurements. Error in precision is the error in the polar distance between two points.

1.0 INTRODUCTION

The U.S. Army Engineering & Support Center, Huntsville (USAESCH) performed an initial, independent assessment of simultaneous location and mapping (SLAM) technology for its applicability to geophysical mapping for advanced geophysical classification (AGC) operations in global navigation satellite system (GNSS) denied areas. AGC operations in GNSS denied areas are currently restricted to robotic total station navigation and positioning, which has production rates on the order of a quarter acre per day in forested areas[1]. Typical AGC production rates for similar systems operated in GNSS accessible areas range between one and two acres per day.

SLAM technology presents an opportunity to increase AGC productivity in GNSS-denied areas.

The SLAM system assessed herein was Stencil 2, manufactured by Kaarta, Inc. The USACE used a Stencil 2 unit rented from the manufacturer.

Stencil 2 uses a Velodyne VLP16 LiDAR and the Kaarta Engine for real-time SLAM processing. Engineers and programmers from Kaarta, Inc. assisted in setting-up connectivity between the Stencil 2 and the USAESCH's GNSS system, and in re-playing the SLAM data for initial post-processing to correct procedural errors made by USAESCH during data acquisition.

All positioning assessments were performed independently by the USAESCH.

1.1 BACKGROUND

SLAM technology uses measurements of the environment to build a three-dimensional map of the surrounding environment and at the same time locate where the measurement instrument is located as it is moved, or navigated, through the environment. This technology is used widely in robot autonomy to perform various tasks such as retrieving or restocking supplies in warehouses, and self-driving vehicles.

1.2 OBJECTIVE OF THE DEMONSTRATION

The purpose of this assessment was to learn how a commercial off the shelf (COTS) SLAM system operates, to compare the trajectory it produces against real-time kinematic differential global positioning system (RTK DGPS) technology; and in RTK DGPS denied areas (e.g. forest), to assess the SLAM system's repeatability over moderately long distances and time intervals.

1.3 TECHNOLOGY DESCRIPTION

The Kaarta Engine is software that uses data from LiDAR, IMU, and optionally camera imagery and GNSS data, to map the environment and to measure the trajectory of the hardware system as it is navigated through the environment. It should be noted that Stencil only collects GNSS in real time for use in its loop closure tool in postprocessing and is not used to actively correct any of the live scan results. Stencil contains a computer that runs the Kaarta Engine. It interfaces a Velodyne VLP16 LiDAR, internal IMU and external camera imagery with the software. The Stencil also has four USB 3 ports, two HDMI ports for external displays, and a Gigabit Ethernet connection. Figure 1-1 shows the Stencil unit used for this assessment.

The concept of operations for Stencil is to start a survey sortie in a stationary position as the Kaarta Engine builds an initial point cloud of the surrounding environment. Once an initial

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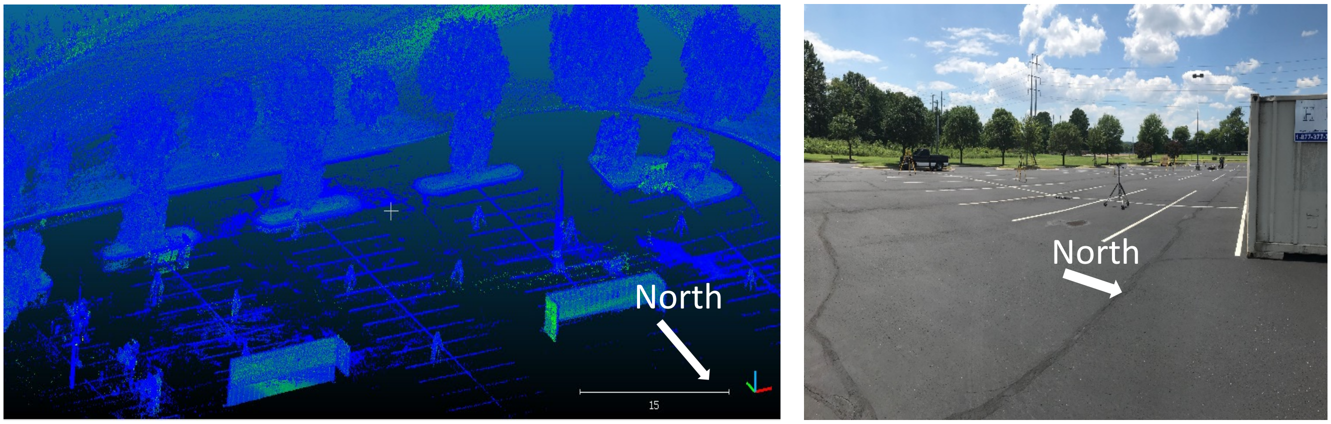
[1] Personal communication with USAESCH Geosciences Branch concerning AGC production rates at the Former Motlow Range FUDS in the summer of 2019.

point cloud is created, the system can be navigated through the environment. Data streams from the LiDAR, IMU, camera imagery and GNSS (camera and GNSS are not required) are then used in real-time to calculate where the system is located within the point cloud environment it has created. As the system moves, the point cloud is augmented and extended as new LiDAR information is acquired and registered. Figure 1-2 shows an example of a point cloud generated during this work, along with a photo of the same area.

Front View

Side View

Figure 1-1. Stencil SLAM system.



Stencil Point Cloud of Parking Lot area

Photo of Parking Lot area

Figure 1-2. Example of point cloud generated during Stencil survey of Parking Lot area.

1.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY CONCEPT

The advantages of the technology for use in the MMRP industry are its ability to provide precise relative location accuracy in GPS denied areas and to provide point-cloud data that can be used to easily and quickly identify and characterize data gaps. SLAM systems require surveyed monuments or temporary control points to provide absolute positioning in a geodetic coordinate system.

There are two types of limitations: 1) precision drift during a sortie; and 2) system precision performance as a positioning system for MMRP geophysical activities. The former is linear and is minimized via post-processing of recorded data. This report serves as an initial assessment for the latter.

2. Objectives of Assessment Activities

The objectives are listed in Table 2-1

Table 2-1
Assessment Objectives

Objective	Type	Measurement Method
Ease of operation	Qualitative	Operator feedback
Gain knowledge of system precision	Quantitative	Co-locate SLAM and RTK DGPS sensors and compare SLAM recorded survey track to RTK-DGPS recorded survey track
System repeatability in GNSS denied areas	Quantitative	Repeat the same survey path multiple times

2.1. Ease of Operation

Ease of operation is assessed qualitatively from operator feedback. Operators are expected to read the operator’s manual and to contact the manufacturer to answer questions.

2.2. Gain knowledge of system precision

The SLAM system is co-located immediately beneath an RTK DGPS and navigated throughout an area over parallel lines spaced approximately 60cm apart, mimicking a 100% coverage geophysical investigation. Post-processed track plots are reviewed and distances between the SLAM positions and the RTK DGPS track plot are measured.

2.3. System repeatability in GNSS denied areas

Repeatability in GNSS denied areas is assessed by collecting dynamic SLAM positioning data over the same path in a forested area. Sections of the post-processed track plots where the system was known to have been operated over the same path to within ±15cm are reviewed, and distances between the two outer tracks at random locations is measured.

3. SITE DESCRIPTION

Two areas were used for this assessment: the parking lot of the USAECSH offices at 475 Quality Circle in Huntsville, AL, and Monte Sano State Park in Huntsville, AL. The former is referred herein as the Parking Lot Assessment. The latter is referred to as the Forest Assessment.

The Parking Lot Assessment compares SLAM system accuracies to RTK DGPS data. The Parking Lot Assessment area has full view of the sky allowing RTK DGPS to operate at centimeter-level accuracies. This area is approximately 50 meters east from high tension power transmission lines and approximately 150 meters southeast from a power sub-station. Figure 3-1 shows the Parking Lot Assessment area.

Figure 3-1. Parking Lot assessment area.

Portions of a paved access road and several hiking trails in Monte Sano State Park were used for the Forest Area assessment. This work was performed in August 2019; full and well established tree canopies existed along the entire length of the road and sections of trails navigated during this assessment. Tree canopy height ranged between forty and eighty feet above the ground the surfaces that were traversed during this effort. Figure 3-2 shows the Forest Assessment area.

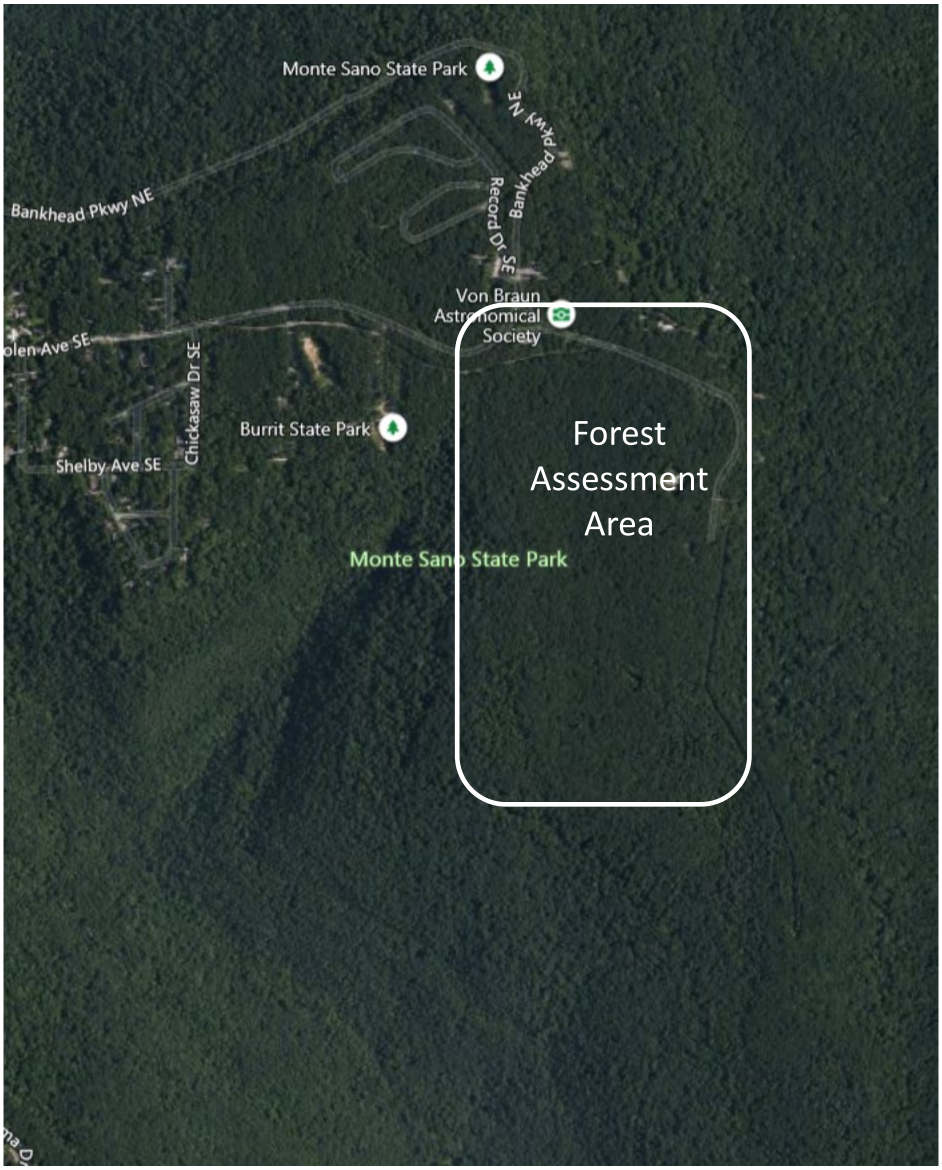


Figure 3-2. General location for Forest Area assessment.

4. ASSESSMENT'S CONCEPTUAL DESIGN

The concept for this assessment was to compare the SLAM system's positioning data to high-precision RTK DGPS positioning data, and to assess the SLAM system's repeatability over the same track in a GNSS denied area. The former is a true assessment of the SLAM system's performance, albeit in an area where RTK DGPS is viable. The latter provides a low-cost, easy to implement, initial indication of system performance in areas for which it is desired for MMRP geophysical operations.

The manner in which the Stencil was used for the first of the two Parking Lot Assessment sorties mimics a GNSS denied test because the RTK DGPS was disconnected from the Stencil--the RTK DGPS data stream was recorded on an independent computer. All of the SLAM positions were generated using only LiDAR and IMU data streams, none were produced using the benefit of a GNSS data stream.

4.2 SITE PREPARATION

Site preparation for the Parking Lot assessment consisted of erecting eight tripods throughout a sixty by twenty meter area. The intent, not knowing at the time of the assessment how the Kaarta Engine works, was for the tripods to act as surrogates for trees that the Kaarta Engine could use for its real-time location algorithm. No other preparations were made.

No site preparations were performed for the Forest Area assessment.

4.4 CALIBRATION ACTIVITIES

No calibration activities are required.

4.5 DATA COLLECTION

Data was collected in several modes:

1. RTK DGPS data was recorded independent of the Stencil in Parking Lot area assessment
2. RTK DGPS data was recorded using the Stencil in Parking Lot Assessment area (note: these data were not used in the Stencil post-processing algorithm)
3. GNSS data, including RTK DGPS when fix quality=4, was recorded using the Stencil in Forest Area.

All SLAM positioning data was recorded at 5 Hertz.

Four datasets were collected and analyzed in this assessment, as described in Table 4.1.

Table 4.1
Summary of Assessment Datasets Collected

Survey Area	Purpose	Sortie/Dataset ID
Parking Lot	SLAM independent of GNSS input	Parking Lot #1
Parking Lot	SLAM with GNSS input	Parking Lot #2
Forest Area	Long Duration Base Map	Forest #1
Forest Area	Repeatability assessment	Forest #2

For all sorties, the form factor used to collect SLAM and GNSS data is shown in Figure 4-1. For all sorties, the SLAM system was started and stopped at the same location and in the same orientation to facilitate post processing. This is not a requirement for system operation, but was adopted for this assessment to simplify the learning curve.

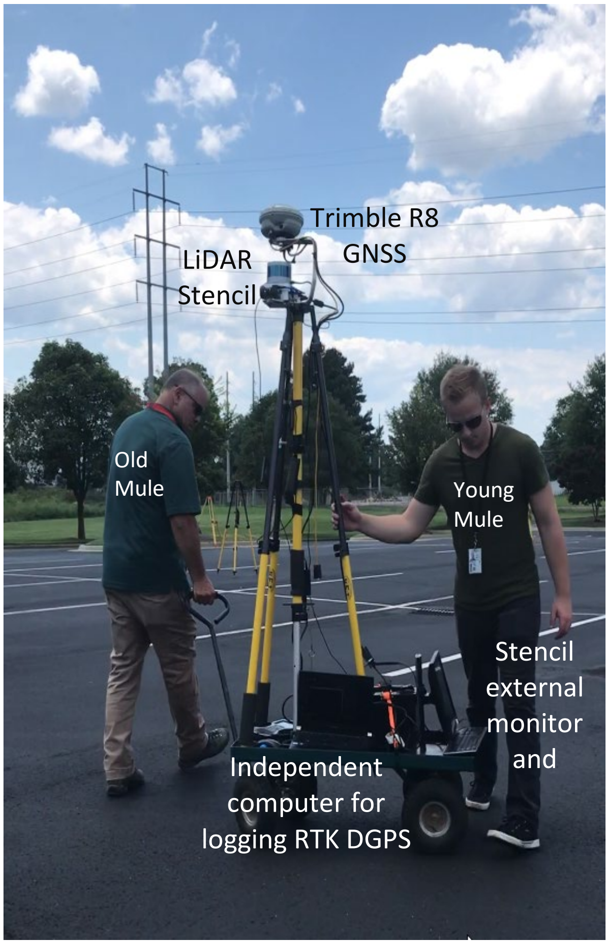


Figure 4-1. Form factor used to collect data for this assessment

4.5.1 Narrative for Parking Lot #1 Dataset

The SLAM data was acquired using default acquisition parameters recommended in the Stencil User's Guide. RTK DGPS data was not fed in to the Stencil, rather, RTK DGPS data was recorded on an independent computer at 5 Hertz. Multiple "drop-outs" were noted in the Stencil track plot, which upon discussion with the manufacturer is attributed to the nearby high tension power transmission lines (the manufacturer suggested adding shielding around Stencil to remedy the problem). Data was collected in a manner that mimics a typical digital geophysical survey with ~60cm line spacing. Data acquisition took approximately 50 minutes.

4.5.2 Narrative for Parking Lot #2 Dataset

The SLAM data was acquired using default acquisition parameters recommended in the Stencil User's Guide. RTK DGPS data was fed in to the Stencil at 1 Hertz was recorded on the Stencil computer (using the Stencil SLAM mapping software). Drop outs were noted as described above. Data was collected in a manner that mimics a typical digital geophysical survey with ~60cm line spacing. Data acquisition took approximately 50 minutes

4.5.3 Narrative for Forest #1 Dataset

The SLAM data was acquired using default acquisition parameters recommended in the Stencil User's Guide. RTK DGPS data was fed in to the Stencil at 1 Hertz and recorded on the Stencil computer (using the Stencil SLAM mapping software) for possible use in rotating and translating the SLAM track plot in to UTM Zone 16N coordinates during post processing. Very few RTK DGPS data had a fix quality of 4 (RTK fixed integers); most fix qualities were either 2 (DGPS fix) and some were 5 (float integers). Zero SLAM system drop outs were noted. Data was collected in a manner that mimics a typical digital geophysical VSP transect survey, which consisted of navigating various trails within the forested survey area. Data acquisition took approximately 70 minutes. Approximately four line-kilometers of data were acquired. Figure 4-2 shows examples of the environment within which data were acquired. In preparation for the repeatability assessment with the Forest #2 dataset, the center of the road was navigated, and the first half-kilometer of the trail was navigated and boot scuffs were made in the dirt every five steps (~4m). Figure 4-3 shows an example of the path walked along the road and the marked trail (the photos are from Forest #2 Dataset).

Figure 4-2. Example of trails typical of the Forest #1 sortie.

Figure 4-3. Example of path navigated along painted road centerline (left) and center of trail (right) in preparation for Forest #2 dataset. Boot scuffs made during initial pass (Forest #1 acquisition) are circled in red (photos are from the Forest #2 sortie).

4.5.4 Narrative for Forest #2 Dataset

The SLAM data was acquired using default acquisition parameters recommended in the Stencil User's Guide. RTK DGPS data was fed in to the Stencil at 1 Hertz and recorded on the Stencil computer (using the Stencil SLAM mapping software). Zero drop outs were noted. Data was collected over the same track as the Forest #1 dataset, to within ±10cm typical (visual estimate from operator), with deviations of up to ±15cm typical (visual estimate from operator). Data was recorded continually. Acquisition took approximately 70 minutes. The actual path navigated during this survey is as follows (refer to Figure 4-4):

1. Begin at Point A at start of painted centerline on road
2. Navigate painted road centerline to beginning of trail at Point B (Section 1)
3. Navigate center of trail in a southerly direction to Turn Point C (Section 2)
4. Return along center of trail in a northerly direction to Turn Point D (Section 3)
5. Return along center of trail in southerly direction to Turn Point E (Section 4)
6. Return along center of trail in a northerly direction to trailhead (Section 5)
7. Return along painted road centerline to starting point A (Section 6)

The operator erred in which hand was used to tow the system for Section #3 (from C to D). The data from that track is noticeably shifted to the right (operator used right hand) whereas the left foot was tracking the scuff marks along the trail. This section of the data was not used in the analysis reported in Chapter 6 below.

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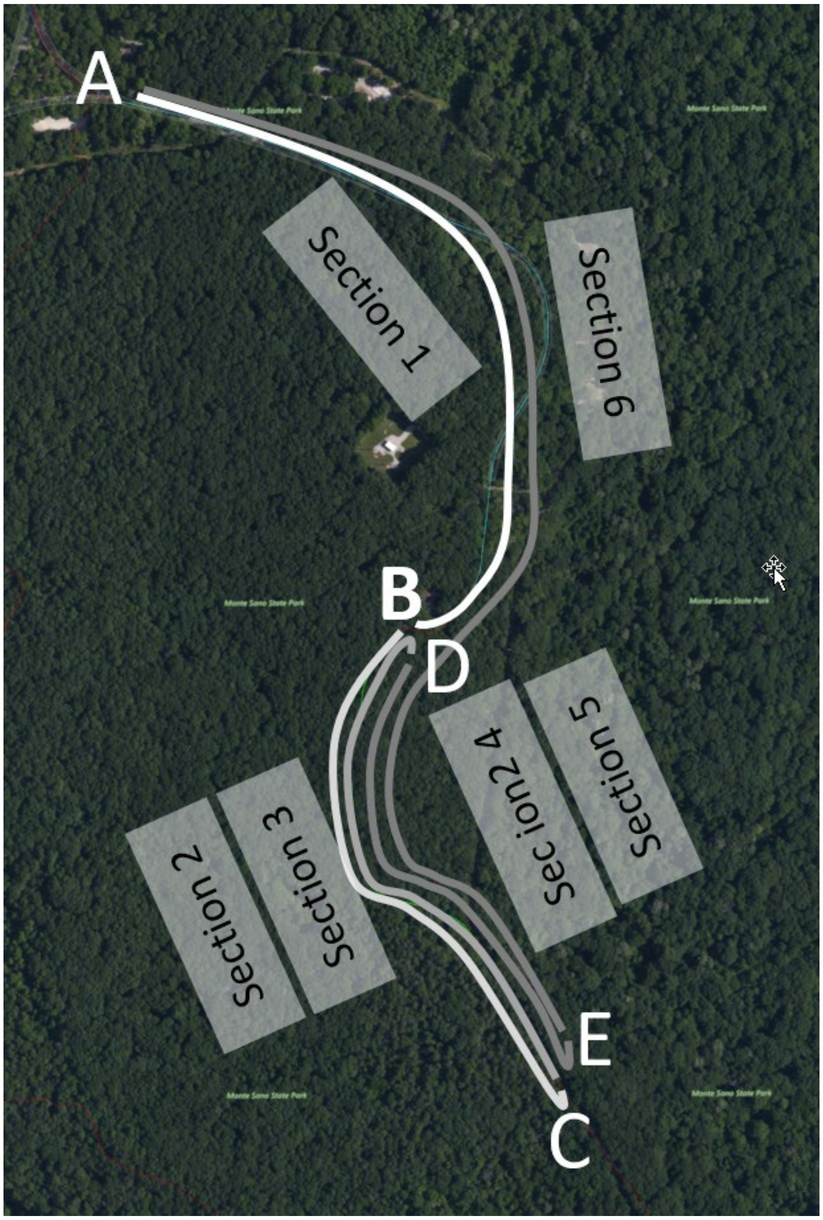

Figure 4-4. Notional depiction of the series of repeated passes over the road center and trail center. The color scale indicates the order of events: white was the first, the darkest gray was the last. The actual path walked can be seen intermittently as the cyan (road) and green (trail) lines. Figure 5.5 shows the actual paths.

5.0 DATA ANALYSIS & RESULTS

5.1 DATA ANALYSIS

Initial post-acquisition data analysis consisted of running the Kaarta Loop Closure tool on the acquired point cloud and track plot data. That tool does two things: it integrates any geodetic data available (e.g. from RTK DGPS) to locate the point cloud and Stencil track plots in to a projected UTM coordinate system; and second, it minimizes drift to enhance point cloud and track plot precision. One of the real-time acquisition parameters, relating to the age of point cloud data, was not properly set. The resulting initial loop closure track-plots were of insufficient quality to be used. This error was easily corrected by completely replaying the raw LiDAR and IMU data back through the Stencil's acquisition software with the correct settings.

For the Parking Lot assessment, no prior map was used. For the Forest Area, the Forest #1 dataset was used as the base map for localizing Forest #2 track plots. The overall process adopted for the parking Lot assessment is shown in Figure 5-1. The overall process for the Forest Area assessment is shown in Figure 5-2.

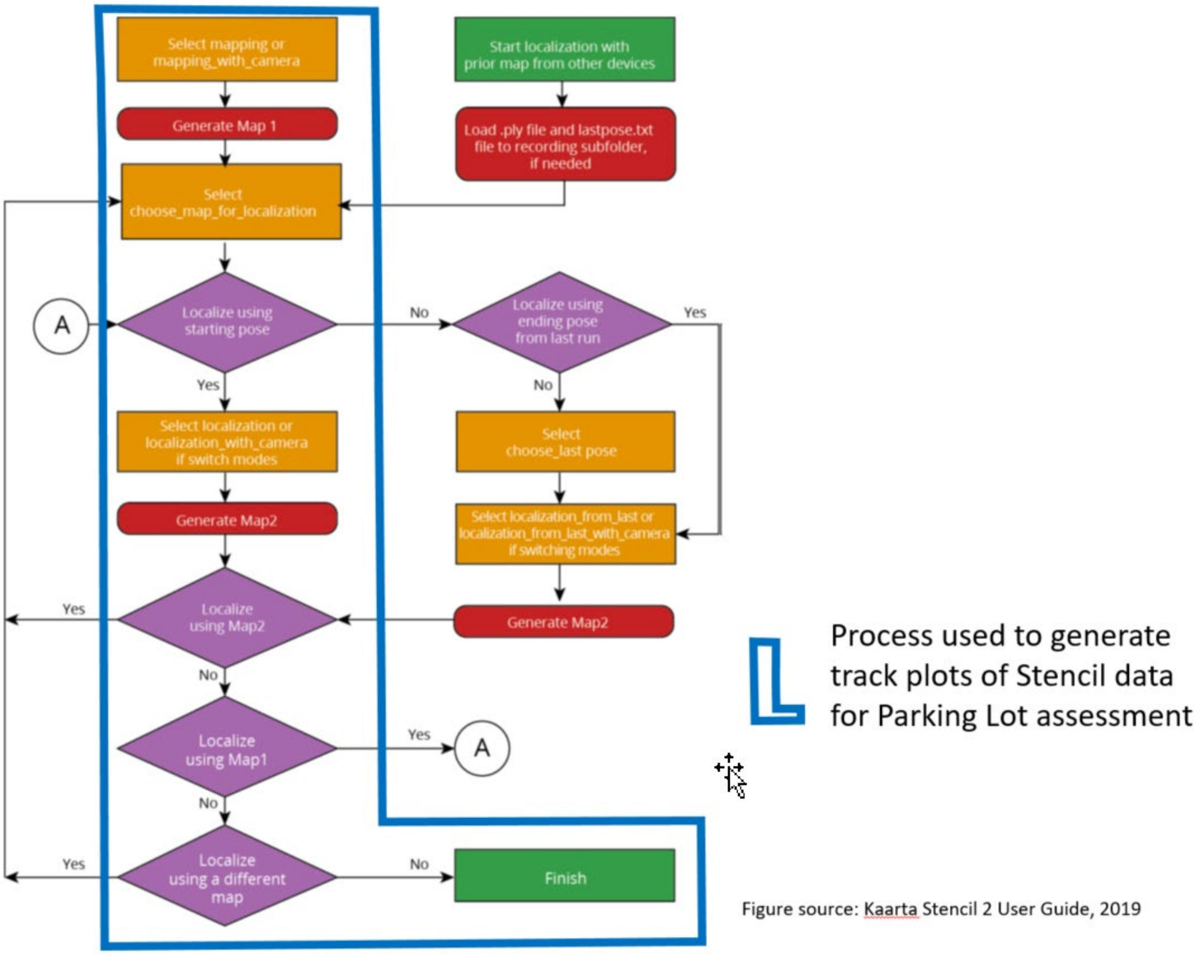

Figure source: Kaarta Stencil 2 User Guide, 2019

Figure 5-1. Process used to generate Stencil track plots for Parking Lot assessment.

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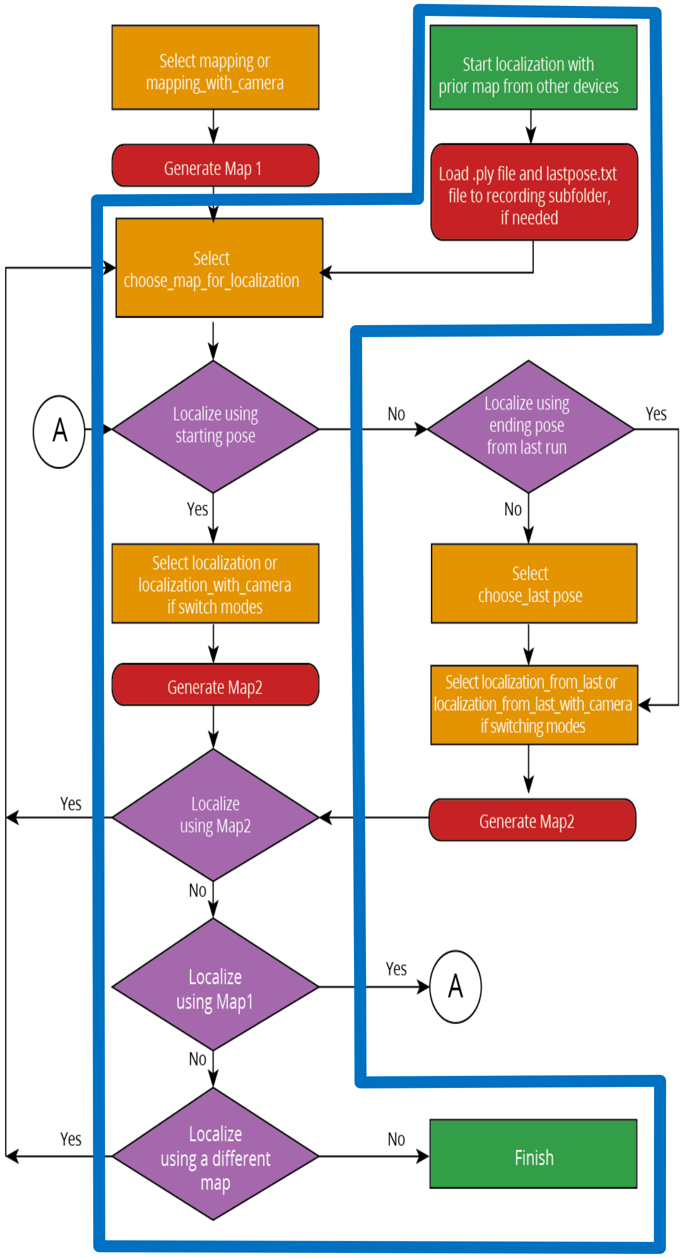

Process used to generate track plots of Stencil data for Forest Area assessment

Figure source: Kaarta Stencil 2 User Guide, 2019

Figure 5-2. Process used to generate Stencil track plots for Forest Area assessment.

A further processing step was performed to apply a warp correction in the SLAM data (using Geosoft Oasis Montaj software) for the Parking Lot assessment, ranging from zero to eighteen centimeters. This was performed to remove some drift from the SLAM data and improve the match between the SLAM and RTK DGPS track plots.

5.2 RESULTS

The results of the Parking Lot #1 and Parking Lot #2 sorties are shown in Figures 5-3 and 5-4, respectively. Figure 5-5 shows the results of the repeatability assessment performed in the forest. Figures 5-6 and 5-7 show examples of zoomed-in repeatability assessment results.

5.2.1. Parking Lot Assessment

A total of 26,504 SLAM location measurements were analyzed for Parking Lot #1, and a total of 17,177 in Parking Lot #2. Those numbers exclude turn-around locations and areas near SLAM drop-outs where the SLAM track plot clearly showed interference effects—there were zig-zags in the path that could not exist in the actual path. These points would normally be rejected during geophysical data processing.

To estimate SLAM precision, additional points were interpolated along the RTK DGPS track until an RTK DGPS-based location existed along the RTK path approximately every 1 to 2cm. The distance between SLAM positions and the RTK path were estimated by finding the nearest RTK DGPS point to each SLAM point. The summary statistics for the entire dataset for both Parking Lot #1 and Parking Lot #2 is shown in Table 5.1.

Table 5.1
Summary Results for Parking Lot Assessment

	Total Number of SLAM Data Points	Number of SLAM Points within 5cm of RTK path	Number of SLAM Points within 5 to 10cm of RTK path	Number of SLAM Points within 10 to 15cm of RTK path	Average Polar Distance	Standard Deviation
Parking Lot #1	26,504	23,390	3,013	101	2.7cm	1.9cm
Parking Lot #2	17,177	12,303	4,775	99	3.7cm	2.3cm

5.2.2. Forest Area Assessment

Approximately 3.5 line-kilometers of data were collected along the same walking path. There is no RTK DGPS data to compare the SLAM data against. Repeatability was assessed by measuring the greatest width between any two passes at randomly selected locations along the track plots. Table 5.2 summarizes the results of this analysis.

Table 5.2 Summary Results for Forest Area Assessment					
	Total Number of Measurements	Mean of Distances Measured	Minimum of Distances Measured	Maximum of Distances Measured	Standard Deviation
Road	35	49cm	0cm	115cm	33cm
Trail	50	30cm	0cm	130cm	27cm

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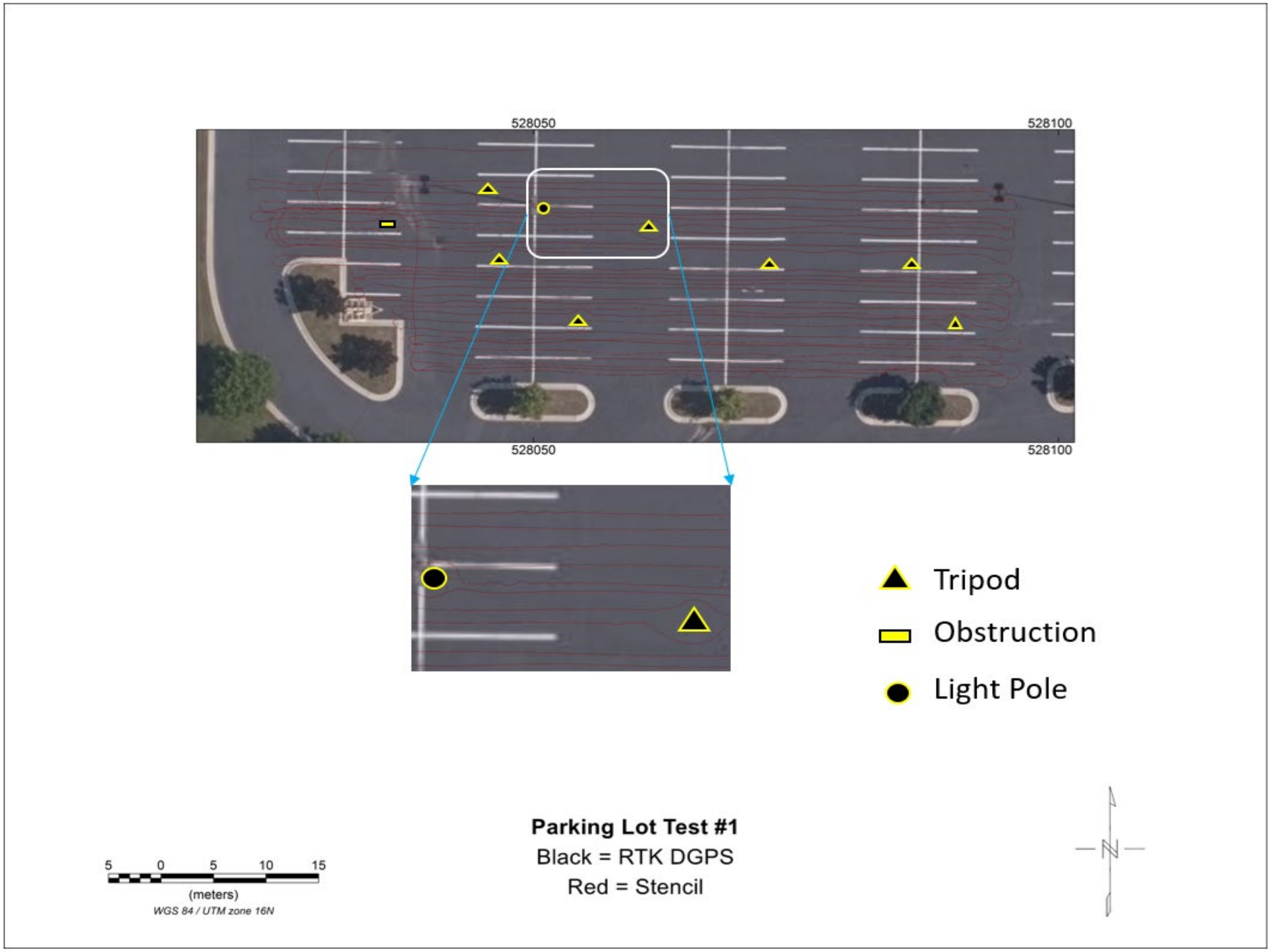


Figure 5-3. All precision assessment data collected during Parking Lot #1 sortie

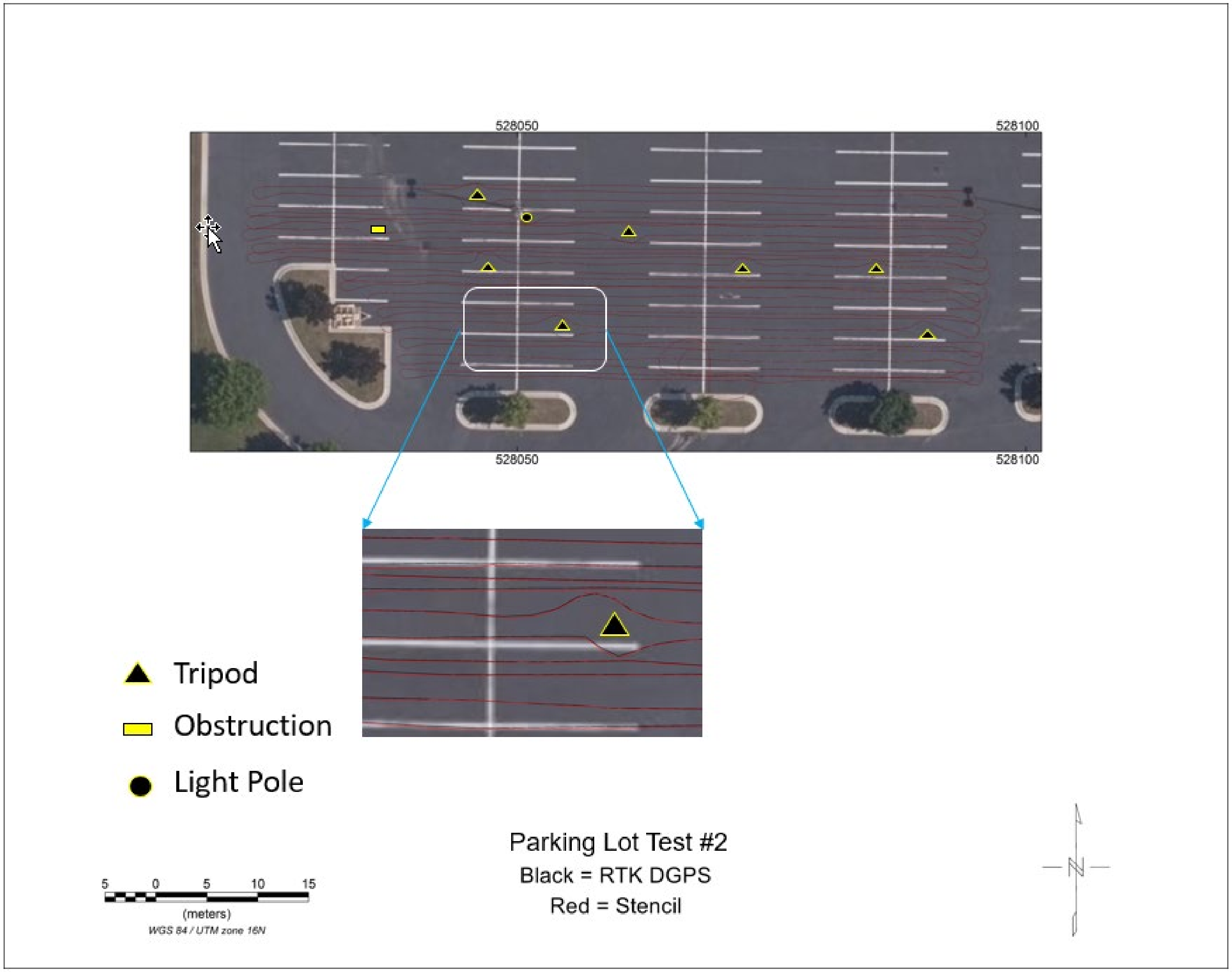
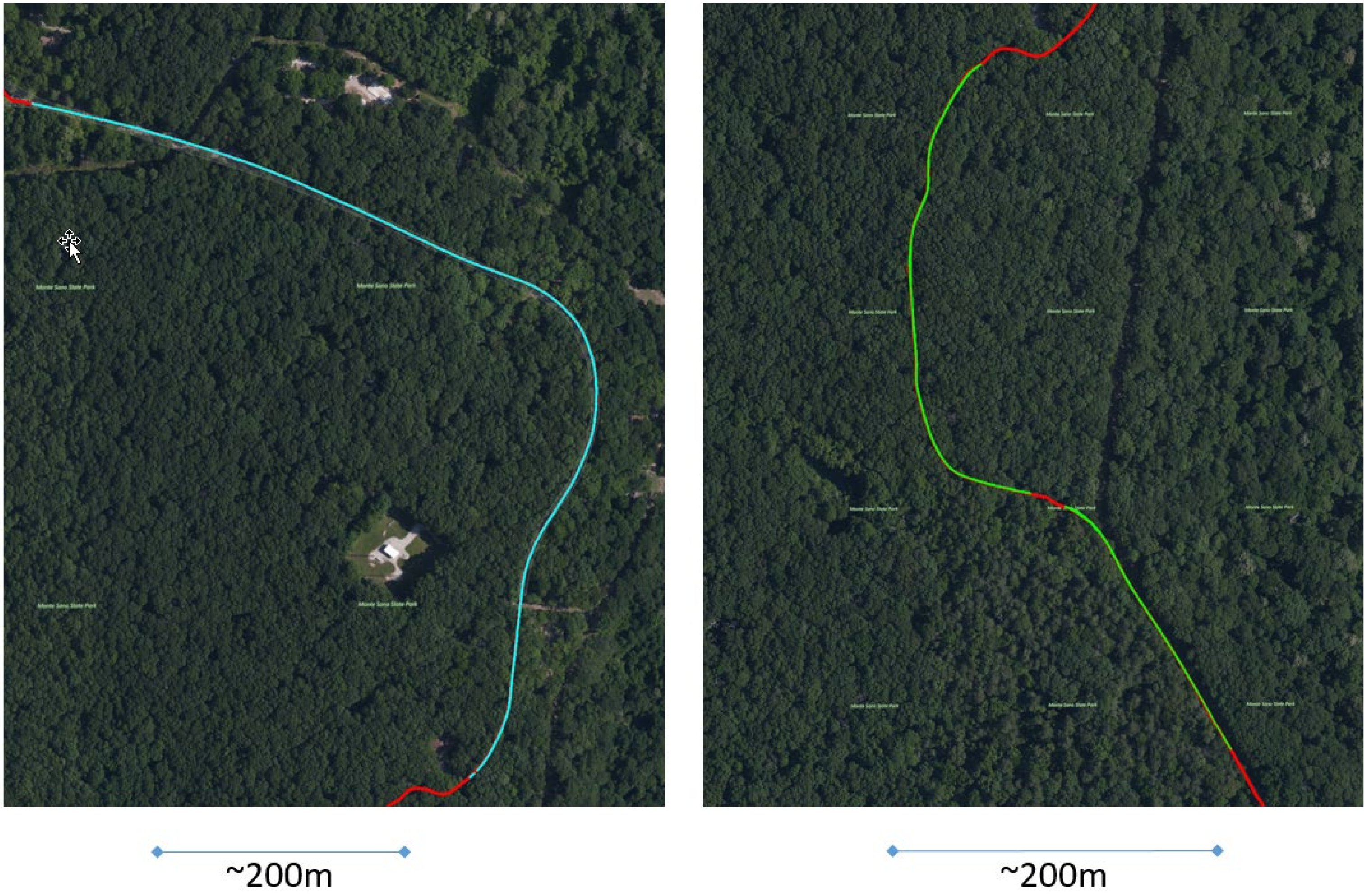


Figure 5-4. All precision assessment data collected during Parking Lot #2 sortie



Red Track = Initial Pass (Forest #1 Dataset)
Cyan track = Repeat Passes Road (2 each)
Green Track = Repeat Passes Trail (4 each)

Figure 5-5. All repeatability assessment data collected.

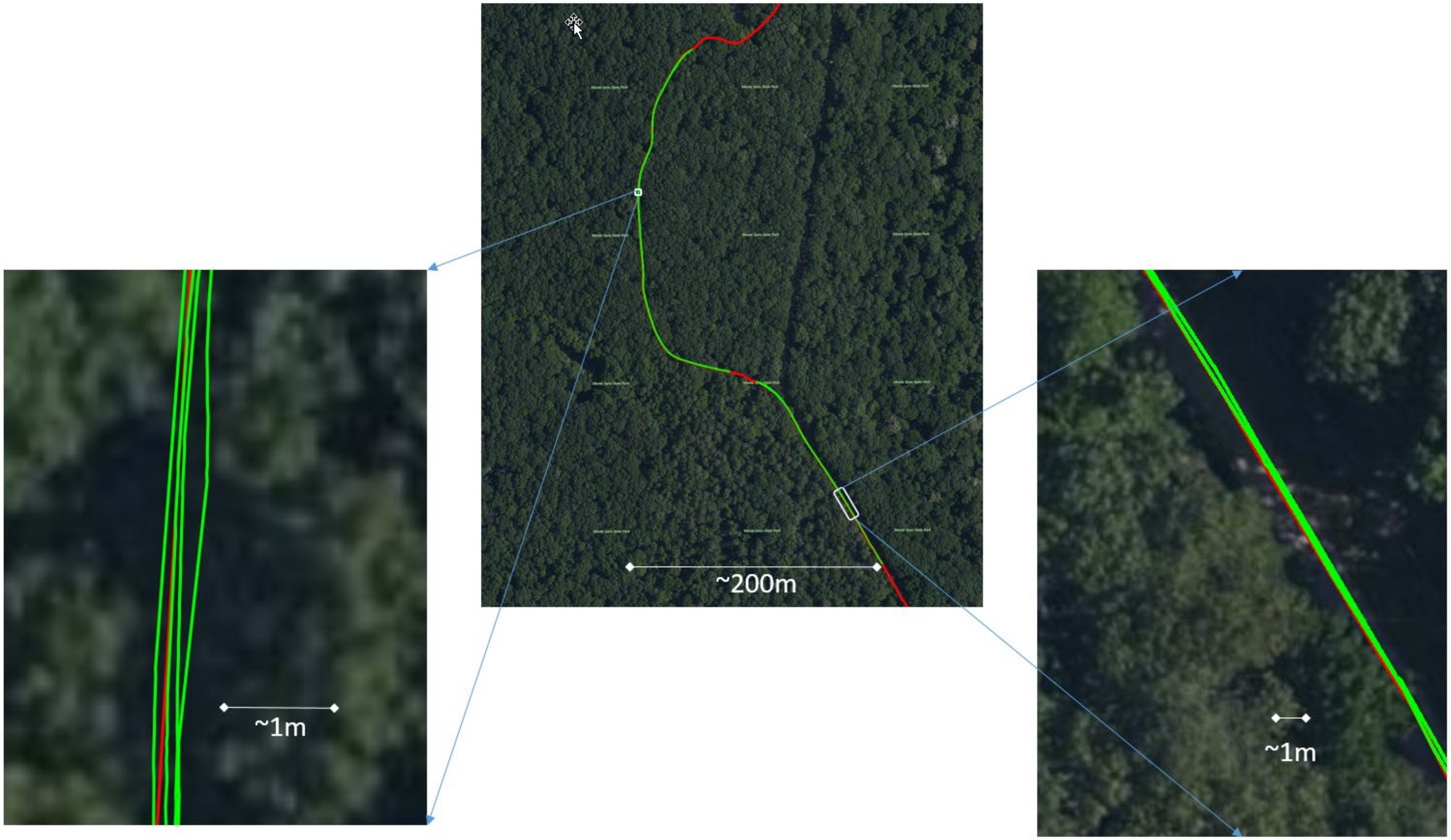


Figure 5-6. Detail examples of repeatability assessments for sections along the trails. Red track plot is the path recorded during the initial mapping effort. The green track plots are the repeat surveys (Sections B-C, C-D, D-E, E-D in Figure 5-5).

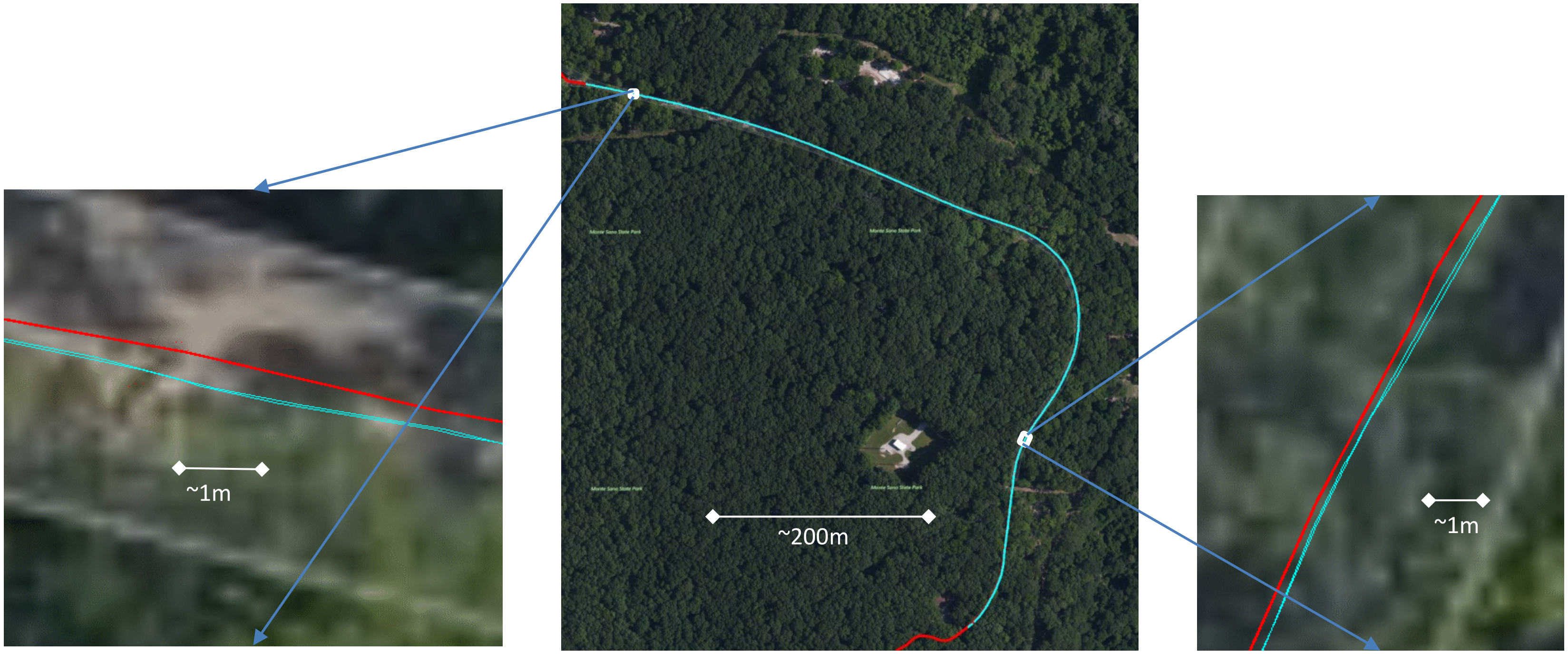


Figure 5-7. Detail examples of repeatability assessments for sections along the road. Red track plot is the path recorded during the initial mapping effort. The cyan track plots are the repeat surveys (Sections A-B and D-A in Figure 5-5

6.0 PERFORMANCE ASSESSMENT

The SLAM system assessment demonstrates the technology is viable for munitions response geophysical operations in GNSS denied areas. System precision can achieve that of RTK DGPS when acquisition procedures are tailored to maximize the SLAM system's performance (see lessons learned below).

The Parking Lot assessment shows the SLAM track plot being almost indistinguishable from that of the RTK DGPS when factored for RTK DGPS precision and the fact data was acquired dynamically on cart that was not engineered to mitigate platform tilt; the RTK antenna was 2cm lateral and 30cm vertical from the SLAM system, which was approximately 2m off the ground surface.

The Forest Area assessment shows SLAM system repeatability is very high when operated over long distances and long periods of time between control points. The repeated track plots of the repeat survey itself show very high repeatability (see enlarged areas in Figures 5-6 and 5-7); the observed repeatability is within the ±15cm estimated by the operator during the sortie. Repeatability between the initial mapping survey and the repeat sortie was good, in the range of 30 to 50 centimeters average, though significantly better results should be expected when the rotation and translation procedure for the base map is improved from that used for this assessment (see lessons learned below).

7.0 LESSONS LEARNED

The SLAM system assessed herein (the KAARTA Stencil) is designed to work with all input modes available: LiDAR, IMU, GNSS and visual imagery. The system is designed to operate either within a self-produced point cloud environment (acquired during the first thirty seconds of data acquisition) or within a previously collected point cloud. There are no known SLAM systems designed explicitly to provide positioning data for geophysical investigations, but in order for a SLAM system to produce high-accuracy point clouds, it must know where the unit is located within the environment it is being navigated through. The lessons learned from this assessment are:

1. Disable Point Cloud age-out parameter
2. Do not rotate and tilt the system while stationary
3. Enable the visual imagery (odometry) feature
4. Force the loop closure routine to only use fix quality 4 (fixed integer)
5. Plan the survey so that rubber sheeting can be applied as linearly as possible
6. Generate an initial map against-which 100% coverage mapping can be registered to.
7. Try not to 'hop' the survey platform over a curb (or large rock or felled tree)
8. Get training on the system for the various survey options and parameter options available within the system's package that are offered by the manufacturer.
9. Plan the survey to maximize SLAM precisions

Each of these lessons learned is discussed in further detail below.

7.1. Disable Point Cloud age-out parameter

This parameter is intended for uses other than as a positioning system for geophysical surveys. Disabling this parameter prevents the Kaarta Engine from 'forgetting' (i.e. deleting from memory) point cloud points based on distance travelled. The result is that all positioning data is continually referenced within the same environment identified by the LiDAR data stream.

7.2. Do not rotate and tilt the system while stationary or during tight turns

The User's Guide warns against this action, though there were instances where the operators forgot to pay attention to this detail. An SOP is required to require re-starting the survey from the last known point, or perhaps from the last pose, to improve post-processing accuracies and precisions. Effects from this action are evident when viewing the z-values (viewing the data in the x- or y-plane), see figure 7-1. This problem was exacerbated by having the wrong point cloud age-out parameter setting.

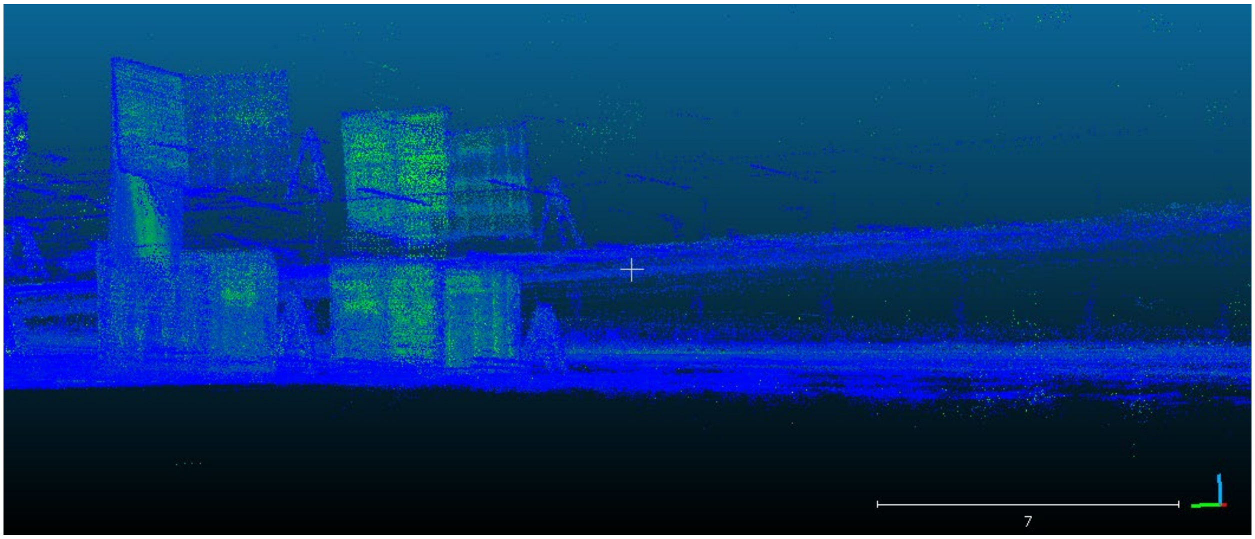


Figure 7-1. Example of tilt induced by tight turns. This effect is also a function of the improper point cloud age-out parameter.

7.3. Enable the visual imagery (odometry) feature

This assessment did not use the visual imagery because the operator's guide suggested it was not necessary for wooded areas. Operator inexperience with the unit resulted in the visual imagery function being turned off in an effort to reduce the size of the data files. After consulting with the manufacturer, and after learning the file sizes do not present a storage issue during surveys, this function should be enabled at all times.

7.4. Force the loop closure routine to only use fix quality 4 (fixed integer)

The User's Guide explains a minimum value can be set for using GNSS data, however, fix quality 5 (float integer) is less accurate than fix quality 4 (fixed integer), and fix quality 5 data is normally not adequate for munitions response geophysical operations.

7.5. Plan the survey so that rubber sheeting can be applied as linearly as possible

There is sometimes a small drift in the position solutions that the Loop Closure routine does not fully correct. This assessment planned for such a possibility and was easily corrected by collecting data that progressed in a constant direction, specifically, Parking Lot area survey lines were collected in east-west directions, and survey lines progressed from north to south. In this manner, system drift also ‘progressed’ in a north to south direction such that rubber sheeting applies a linear correction from south to north throughout the dataset. [Author’s note: after our field work, and prior to publishing this report, the manufacturer reported improvements to their Loop Closure routine that address this observation.]

7.6. Generate an initial map.

One of the survey methods available is to use a prior map (point cloud) to work within. This assessment was not designed to develop best practices, rather it sought only to assess whether SLAM is a viable option for munitions response geophysical operations in GNSS denied areas. As such, this survey option was not intended to be investigated, however, the Stencil system’s ability to replay all raw survey data enabled this feature to be used for the Forest Area assessment. After consulting with the manufacturer, using this feature is expected to greatly improve the flexibility for, and simplify operational procedures when, using the SLAM system for munitions response geophysical operations.

7.7. Try not to “hop” the survey platform over obstacles

The Stencil computer encountered some form of BIOS corruption error as the result of trying to jump a curb during a sortie. The source could have been from a) temporary power loss due to shock to the power supply connections, b) something moving/losing contact within the Stencil computer, c) the sudden vertical movement of the Stencil’s electronics package within the EMI field associated with the nearby high tension power transmission lines, or d) some other internal. Admittedly, the inadvertent “bump” of going over the curb was a pretty hard hit to the platform. The BIOS required a hard reboot be performed by the manufacturer as we used a rental unit. All data stored on the Stencil was recovered after the reboot.

7.8. Get training on the system.

This assessment was designed to answer a single question: is SLAM a viable option for munitions response geophysical operations in GNSS denied areas. As such, the User’s Guide was more than adequate for operating Stencil to produce data that affirmed SLAM is viable. To the Stencil manufacturer’s credit, the Stencil system is easy to use and the User’s Guide completely explains how to use it, which enabled quantitative assessments of the system’s accuracy and repeatability to be performed as described for the Parking Lot and Forest Area assessments.

7.9. Plan the survey to maximize SLAM precisions.

Simple efforts can be performed that will assist in post-processing the SLAM data to minimize precision errors and to the facilitate merging the SLAM data with geophysical measurements. Appendix B presents a notional standard operating procedure (SOP) that should maximize SLAM precisions for munitions response geophysical operations in GNSS denied areas, and facilitate merging SLAM and geophysical data when the two systems are not slaved to a common clock (e.g. GPS time), or cannot otherwise be easily synchronized.

8.0 REFERENCES

Kaarta Stencil 2 User’s Guide, 2019

APPENDICES

Appendix A. Points of Contact

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
Andrew Schwartz	USACE 475 Quality Circle, Huntsville, AL 35806	(256)895-1644 Andrew.b.schwartz@usace.army.mil	Project Lead
Rick Grabowski	USACE 475 Quality Circle, Huntsville, AL 35806		GNSS operations
Benton Williams	USACE 475 Quality Circle, Huntsville, AL 35806		Field Assistant

Appendix B. Notional Standard Operating Procedure for SLAM positioning of munitions response geophysical operations

1. Establish temporary control points at intervals convenient to the planned data acquisition production, e.g. every 50m. Actual distances between points does not have to be precise, within +/-10m of planned is fine.

2. To facilitate navigating through the area, remove as much vegetation as reasonably possible to the height of the SLAM LiDAR. One and a half to two meters is suggested as the LiDAR height above ground in order to provide as much forward (if towed) or rear (if pushed) view of the environment.

3. Erect distinct features (e.g. tripods) over the control points

4. Conduct a SLAM survey along the perimeter of the planned geophysical mapping area to produce a point cloud base map. Ensure the distinct features erected over the control points are observed in the point cloud in the vicinity of the four corners of the planned survey area. These can be used for rubber-sheeting during post processing. Check that the following SLAM acquisition parameters are set properly:
    a. LiDAR to GNSS Left: X.X (units are meters)
    b. LiDAR to GNSS Up: X.X (units are meters)
    c. LiDAR to GNSS Forward: X.X (units are meters)
    d. Blind Radius: X.X (units are meters)
    e. Force Decay: true; Force Decay Distance 0
    f. Log Sensor Path: true

5. Place a small metallic source in proximity to the four corners of the planned survey area. These will be referred to herein as the southwest, southeast, northwest and northeast temporary control points. Emplace these items in such an orientation so that they will produce a peak, monopole geophysical response directly over the source

6. The remainder of this notional SOP assumes: 1) geophysical mapping starts at the southwest corner; 2) survey lines are planned east-west; 3) the survey will progress from south to north in a back-and-forth (mowing the lawn) pattern; 4) the SLAM system is mounted above the center of the metal detector; and 5) no synchronization between SLAM computer and geophysical logging computer is performed. Some of the steps below can be omitted if synchronization is performed at the start and confirmed at the end of the sortie.

7. Facing due magnetic east, with the center of the mapping system located over the southwestern temporary control point, initiate data collection on the metal detector and initiate the SLAM system in the ‘use prior map’ localization mode. Use the base map from step 4 as the prior map. Ensure the system platform is stationary for the duration of the SLAM system initialization (thirty to sixty seconds)

8. Collect a waypoint over the temporary control point.

9. To establish a common time-reference point in both the SLAM and geophysical metal detector systems, collect a clover-leaf pattern over the southwestern temporary control point.

Navigate very slowly when one foot before and after the control point such that eight to ten measurements should be acquired on either side of the control point, in both the SLAM and geophysical data stream.

10. Perform the geophysical mapping survey (in this notional SOP, along east-west lines, lines progressing from south to north).

11. At the end of the sortie, or after approximately 60 minutes, whichever comes first, navigate the northeast temporary control point, collect a waypoint immediately above the control point, and then perform a clover leaf pattern in the same manner as Step 9.

12. Navigate to the northwest temporary control point, collect a waypoint immediately above the control point, and then perform a clover leaf pattern in the same manner as Step 9.

13. Return to the southwest control point, collect a waypoint immediately above the control point, and then perform a clover leaf pattern in the same manner as Step 9.

14. Stop all data recording.

15. If collecting more data, re-start process at Step 7, otherwise proceed to Step 16.

16. Run Loop Closure routine

17. Identify a common time-base using the time stamps in the SLAM data stream and the geophysical data stream from when the system was navigated immediately over the first temporary control point.

18. Confirm there is no slew in one clock (e.g. SLAM computer) with respect to the other (e.g. geophysical data logger) by performing the same routine as step 17 using either of the last two temporary control points surveyed in Steps 11 or 12.

19. Identify the SLAM coordinates for the center of four distinct features erected in Step 3.

20. Rubbersheet the SLAM data to the known coordinate of four control points

21. Merge the SLAM data to the geophysical data based on the common time-base.