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| 16. ABSTRACT This report documents implementation and training for the Mountain Pass Road Opening (MPRO) Driver Assistance System, including deployment of eight systems to four California Department of Transportation (Caltrans) yards. Caltrans has eight mountain passes that are closed each fall and reopened each spring. Opening these passes is a difficult job with few visual indicators or landmarks to guide experienced snowplow operators. Existing techniques, such as probing the snowpack with poles, path staking, and active embedded cable systems, have associated drawbacks. The MPRO system uses an infrastructure-free approach that uses the Global Navigation Satellite System to provide a real-time in-cab mountain pass road opening system for rotary plow driver assistance. The system was developed in previous research to be portable, easy to install, and sharable across multiple vehicles. Field-testing indicated the system is ready for widespread use within Caltrans Winter Maintenance Operations. Results indicate promising benefits for deployment on a wider basis for other functional types of Caltrans vehicles. In the current research, the MPRO system was updated to the latest hardware, and the MPRO software was updated for these hardware changes and implemented on the Android operating system to further enhance portability and ease of installation. Caltrans personnel were trained on the updated system in April 2021. | | 13. TYPE OF REPORT AND PERIOD COVERED Final Report August 2018 – November 2021 |
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Mountain Pass Road Opening (MPRO) Implementation and Training

Kin Yen, Stephen Donecker, Travis Swanston, &
Ty Lasky: Principal Investigator

Report Number: CA22-3255
AHMCT Research Report: UCD-ARR-21-11-30-01
Final Report of Contract: 65A0749 Task 3255

November 17, 2021

California Department of Transportation

Division of Research, Innovation and System Information

Executive Summary

Problem and Need

Due to limited usage and difficulties maintaining pass roadways, the California Department of Transportation (Caltrans) closes eight mountain passes over each winter season. In the spring or early summer, Caltrans Maintenance must re-open these passes for the traveling public. In heavy snowfall winters, closed mountain pass highways can build up 30 to 40 feet of snow over a season, making it extremely difficult and hazardous to locate and clear the road.

The Advanced Highway Maintenance and Construction Technology Research Center (AHMCT) previously developed, tested, and successfully demonstrated a field-ready and deployable Global Navigation Satellite System-based Mountain Pass Road Opening (MPRO) Driver Assistance System (DAS). This system was tested over several seasons on both State Route (SR) 108 (Sonora Pass) and SR 120 (Tioga Pass). In the most recent testing in spring 2017, which followed a higher than normal snow season, operator feedback was extremely positive. There is now a demand for this beneficial system at four Caltrans sites. Through this current implementation effort, Caltrans now has a modernized MPRO design and can exploit the demonstrated benefits at four of its pass closure locations.

The AHMCT Research Center developed a field-ready and deployable GPS-based mountain pass road-opening rotary plow DAS to guide rotary plow operators to drive and stay over the roadway during road opening operations. Primary system objectives are increased safety and snow-removal efficiency with minimal capital investment and decreased environmental impact and costs associated with infrastructure repair. The system was developed to be portable and easily installed with a small number of units sharable across statewide mountain pass opening operations.

The primary goal of the current research project was to address porting of the MPRO design and implementation to SR 108, SR 4, and SR 120 and evaluate the system's performance in these new environments. The key task in porting the system, in addition to the physical installation of the hardware, was the development of a base map to support the GNSS-based location of the vehicle. In the current project, a new approach was developed based on Mobile Terrestrial Laser Scanning (MTLS).

Overview of the Work and Methodology

At the request of Caltrans Maintenance as well as the Division of Research, Innovation and System Information, AHMCT revised the MPRO system for full Caltrans deployment. This included system redesign to current commercial off-the-shelf (COTS) technology, modifications to enhance system portability, and any needed software revisions for compatibility with an appropriate up-to-date operating system.

AHMCT produced two of the updated systems for each of the four sites identified by Caltrans. These sites are District 9, SR 108, Sonora Pass eastern slope; District 9, SR 120, Tioga Pass; and District 10, SR 4, Alpine (two sites, each with its own crew). The effort produced eight systems in total. Additionally, AHMCT provided training to selected Caltrans staff for ongoing usage, support, and maintenance of the systems.

The high-level research tasks were:

1. System redesign, build, and validation
2. Porting existing Windows code to the Android platform
3. Training
4. Site testing and evaluation
5. Document and manage project

Major Results and Recommendations

The research results included:

- Development of base maps for three additional Caltrans road opening sites
- Complete redesign of the MPRO system for increased portability, functionality, and ease of installation
- Complete update of the MPRO hardware to current state-of-the-art off-the-shelf components
- Full redesign and reimplement of the MPRO software to support the modified hardware, including implementation on the Android operating system

AHMCT recommends on-going use of the eight MPRO systems at the four Caltrans road opening sites. In addition, AHMCT recommends Caltrans evaluate whether the MPRO system would be useful for its remaining winter closure sites. Finally, the general MPRO concept should be assessed for application in other highway maintenance and construction operations.

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List of Acronyms and Abbreviations

| Acronym | Definition |
|----------------|--|
| 3D | Three-Dimensional |
| AHMCT | Advanced Highway Maintenance and Construction Technology Research Center |
| API | Application Programming Interface |
| bps | bits per second |
| Caltrans | California Department of Transportation |
| CAD | Computer-Aided Design |
| COTS | Commercial Off-The-Shelf |
| CSV | Comma-Separated-Value |
| DAS | Driver Assistance System |
| DC | Direct Current |
| DOE | Division of Equipment |
| DRISI | Division of Research, Innovation and System Information |
| FTDI | Future Technology Devices International |
| GIS | Geographic Information System |
| GLONASS | Globalnaya Navigatsionnaya Sputnikovaya Sistema |
| GNSS | Global Navigation Satellite System |
| GPS | Global Positioning System |
| HMI | Human-Machine Interface |
| LCD | Liquid Crystal Display |
| LR | Local Request |

| Acronym | Definition |
|----------------|--|
| META | Maintenance Equipment Training Academy |
| MPRO | Mountain Pass Road Opening |
| MTLS | Mobile Terrestrial Laser Scanning |
| NDGPS | Nationwide Differential GPS |
| OLED | Organic Light-Emitting Diode |
| OS | Operating System |
| PM | Postmile |
| RTK | Real-Time Kinematic |
| SBAS | Satellite-Based Augmentation System |
| SR | State Route |
| UI | User Interface |
| USB | Universal Serial Bus |
| UTC | Coordinated Universal Time |
| WAAS | Wide Area Augmentation System |

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Chapter 1: Introduction

Problem

Due to limited usage (i.e., low traffic volume) and difficulties maintaining pass roadways, the California Department of Transportation (Caltrans) allows several mountain passes to close each winter season. In the spring or early summer, Caltrans Maintenance must re-open these passes for the traveling public. In heavy snowfall winters, closed mountain pass highways can build up 30 to 40 feet of snow, making it extremely difficult and hazardous to locate and clear the road.

The Advanced Highway Maintenance and Construction Technology Research Center (AHMCT) previously developed, tested, and successfully demonstrated a field-ready and deployable Global Positioning System (GPS)-based Mountain Pass Road Opening (MPRO) Driver Assistance System (DAS). This system was tested over several seasons on both State Route (SR) 108 (Sonora Pass) and SR 120 (Tioga Pass). In the most recent testing in spring 2017, which followed a higher than normal snow season, operator feedback was extremely positive.

Objectives

There is now a demand for this beneficial system at four Caltrans sites. Through this implementation effort, Caltrans now has a modernized MPRO design with a better GPS receiver and tablet display and can exploit the demonstrated benefits for four of its pass closure locations.

Scope

At the request of Caltrans Maintenance, as well as the Division of Research, Innovation and System Information (DRISI), AHMCT revised the MPRO system for full Caltrans deployment. This included system redesign to current state of the art commercial off-the-shelf (COTS) technology, modifications to enhance system portability, and any needed software revisions for compatibility with an appropriate up-to-date operating system (OS).

AHMCT produced two of the updated systems for each of the four sites identified by Caltrans. These sites are District 9, SR 108, Sonora Pass eastern slope; District 9, SR 120, Tioga Pass; and District 10, SR 4, Alpine (two sites, each with its own crew). The effort produced eight systems in total. Additionally,

AHMCT provided training to selected Caltrans staff for ongoing usage, support, and maintenance of the systems.

Research Methodology

The high level research tasks were:

1. System redesign, build, and validation
2. Update existing Windows code to new platform
3. User training
4. Site testing and evaluation
5. Document and manage project

Overview of Research Results and Benefits

The research results included:

- Base maps for three additional Caltrans road opening sites
- Complete redesign of the MPRO system for increased portability, functionality, and ease of installation
- Complete update of the MPRO hardware to current state-of-the-art off-the-shelf components
- Full redesign and re-implementation of the MPRO software to support the modified hardware, including implementation on Android OS

The primary benefit of the system is enhanced safety. By providing enhanced situational awareness and specific locations over the roadway, the system allows the operator to safely clear the snow from significant heights, without concern of plummeting into a nearby ravine. In addition, by providing indication of position relative to roadside hardware, such as signs, the system prevents collision with these obstacles, eliminating added damages to the roadside hardware and the rotary plow.

The key deliverables of this project include:

- Eight MPRO systems based on the new design
- Documentation of the updated system design
- MPRO system software
- Documentation of software issues requiring revision
- Maintenance Equipment Training Academy (META) training material

Chapter 2:

MPRO System Overview

Background

Caltrans has eight mountain passes that it closes each winter season due to large snow precipitation and opens each spring: Ebbetts Pass (SR 4), Monitor Pass (SR 89), Lassen Loop (SR 89), Sonora Pass (SR 108), Tioga Pass (SR 120), June Lake Loop (SR 158), Mammoth Lakes (SR 203), and Lake Sabrina to Aspendell (SR 168).¹ Opening these passes in the spring is challenging when there is large snow accumulation over the winter season, which occurs in wet years. In some areas, there are few visual indicators (e.g., terrain, snow stakes, or trees) of road location. Generally, experienced operators lead the road-opening effort and identify the first cut paths in the snow build-up based on their experience and local terrain features and landmarks. For inexperienced operators, it can be difficult to determine the roadway location. If the rotary plow were steered off course, the vehicle could slide off a steep slope, sink into a creek bed, or damage the blower mechanism due to ingestion of rocks or running into rocks hidden in the snow along the roadside. Existing techniques to guide rotary plow operators include probing the snow pack with poles, path staking, and active embedded cable systems.

These annual road opening operations are essential for mobility and tourism. In conjunction with Caltrans DRISL and the Caltrans winter maintenance group, the AHMCT Research Center developed the GPS-based MPRO rotary plow DAS under previous research.² The user feedback in that effort was positive, and the experience was valuable for system improvement.

The first generation MPRO DAS system had some drawbacks:

- It used two GPS receivers. One GPS receiver provided the positioning solution, and one GPS receiver provided the heading solution.
- The MPRO software ran on Microsoft Windows XP and was not compatible with Windows 10.

¹ For information on Caltrans winter pass closures see [Mountain Pass Closures \(https://dot.ca.gov/travel/winter-driving-tips\)](https://dot.ca.gov/travel/winter-driving-tips)

² Kin Yen, Bahram Ravani, and Ty A. Lasky, [Evaluation of GPS-based Mountain Pass Road Opening for Tioga Pass \(http://ahmct.ucdavis.edu/pdf/UCD-ARR-15-07-31-01.pdf\)](http://ahmct.ucdavis.edu/pdf/UCD-ARR-15-07-31-01.pdf), AHMCT Research Report UCD-ARR-15-07-31-01, July 2015

- The Intel X86-based computer and power supply system was complex to assemble and could not be easily duplicated.
- All the COTS components are now obsolete and no longer available.
- The new generation of computers or tablets could be used to reduce power consumption and size of the hardware, resulting in increased ease of installation and portability.
- An Android app with touch screen user interface may be easier to use.
- There have also been new advances in subscription Satellite-Based Augmentation System (SBAS) services. New SBAS services support Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS) and European Galileo Global Navigation Satellite System (GNSS). By using GPS, GLONASS, and Galileo, the GNSS positional and heading solution will be more robust and reliable in GNSS-challenged areas, such as canyons and near tall trees. However, a new, state-of-the-art GNSS receiver will be required to utilize these new SBAS advances.³
- The remaining area of improvement is the GPS positional accuracy and robustness. This presents a significant challenge due to signal blockage by tall trees and terrain. The original MPRO system used a GPS-only receiver. Due to the mountainous terrain, GPS systems typically can only receive signal from four to six GPS satellites compared to seven to nine satellites in areas with open sky. The reduced number of satellite signals degrades positional accuracy and availability. As a result, the user can occasionally observe a discrepancy between the vehicle position relative to the road as shown by the system vs. what they can detect with their own eyes. The positional solution availability will improve as overall GNSS systems are modernized and deployed and as more satellites and signal frequencies are added.

System Overview

The MPRO system consists of six major components:

1. GNSS receiver that provides the vehicle position and heading
2. SBAS service subscription
3. High-accuracy and detailed digital base map
4. Android tablet with high-brightness display

³ For the remainder of this report, GNSS will be used generically to mean any combination of GPS, GGLONASS, and Galileo.

5. Tablet power and Universal Serial Bus (USB) hub interface
6. USB-to-RS232 adapter: data interface to the GNSS receiver

Design Considerations

The MPRO DAS system Human-Machine Interface (HMI), shown in Figure 2.1, provides a bird's eye view of the roadway and any obstacles, such as road signs, postmile markers, and buildings, along with the vehicle location, heading, and vehicle outline clearly illustrated. Additional information, e.g. postmile location, is provided to help operators have a context for their location along the route.

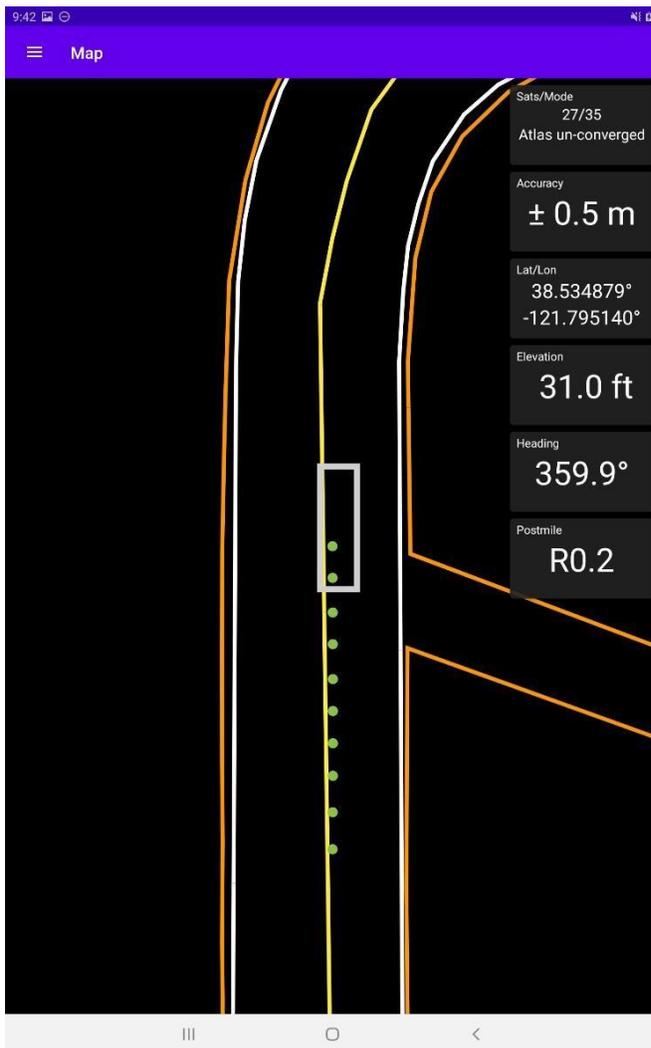


Figure 2.1: MPRO DAS HMI

The MPRO system design criteria are:

1. Compact, portable, easy field installation and configuration, and simple to remove. As such, the system is sharable among multiple vehicles in

case of equipment breakdown or relocation. The small equipment size will allow it to fit in a rental compact dozer or a snow cat.

2. Easy to duplicate by extensive use of COTS parts and minimized part count. In addition, the mounting hardware must be designed to accommodate various vehicle configurations and types.
3. Uses a single integrated GNSS receiver to provide accurate vehicle location (~10 cm) and heading (~0.2 degree).
4. Lower the annual cost of SBAS subscription services.
5. Provide location of above-ground roadside assets, such as sign, guard rail, and building outline, so that the operator can better avoid damaging the roadside assets buried in snow. This will also reduce rotary plow damage.
6. Simple to use. There may be new personnel in this annual road opening operation. An operator must be able to learn to use the MPRO system quickly.
7. The display must be bright and sunlight-readable (500 nits⁴ or higher). White snow is often very bright on sunny days. A sunlight-readable display enables the operator to read the screen while wearing sunglasses.

GNSS Technologies

The GNSS-based approach for vehicle positioning and heading determination does not require any added reference infrastructure in the pavement or on the guardrails, such as energized buried cable. An infrastructure-free approach provides a significant advantage in terms of maintainability and portability. This section overviews the required support MPRO systems: GNSS receiver, base maps for position reference, and SBAS service.

GNSS receiver

The GNSS receiver is a vital sensor in the MPRO system. The new generation of GNSS receivers support the GPS, GLONASS, and European Galileo GNSS as well as the Chinese BeiDou GNSS in some cases. GNSS receivers require a direct line-of-sight to the satellites in order to obtain a signal representative of the true distance from the satellite to the receiver. Therefore, any object in the path of the weak GPS signal has the potential to interfere with its reception. Objects that can block a weak GPS signal include tree canopies, buildings, and terrain features. In some instances, operating under a heavy and wet forest canopy can degrade the ability of a GNSS receiver to track satellites. With the addition

⁴ 1 nit = 1 candela / square meter (cd/m²)

of GLONASS and Galileo GNSS satellites, the number of satellites available for positional solution significantly increases, which improves the GNSS positional availability and robustness. Multi-GNSS constellation support is crucial since the GNSS receiver will be employed in mountainous terrain with tall trees.

A GNSS-based compass was selected to determine vehicle heading. The large steel vehicle body generates large interference to a magnetic compass. However, the GNSS system has been augmented to include a dual-antenna vector GPS unit that directly provides accurate heading data that is not subject to magnetic interference.

Satellite-Based Augmentation System Services

To safely find the road center and keep the vehicle over the road, sub-meter accuracy is crucial. Real-time kinematic (RTK) GNSS receivers can provide centimeter-level (or even sub-centimeter level) accuracy. However, RTK GNSS requires a fixed base station and some form of radio communication for real-time differential corrections. Rural mountain passes do not have cellular communications coverage in most area. Setting up reliable communication infrastructure to cover an entire mountain's terrain would be challenging and prohibitively expensive.

The Wide Area Augmentation System (WAAS) and the Nationwide Differential GPS (NDGPS) are two free differential GPS services available in the United States. Both systems provide improved GPS accuracy (0.5 to 3 meter) and integrity monitoring services. However, WAAS and NDGPS accuracy do not meet the MPRO accuracy requirement.

An alternative approach, SBAS, a Space-Based commercial solution, can provide quite high-accuracy (~10 cm) positional solutions without the need for a fixed base station, using the real-time data link provided via a satellite-based system. SBAS subscription services are available from a number of commercial vendors, and SBAS-enabled receivers available from multiple manufacturers. Areas that would typically need such a road opening system are generally well-suited for SBAS DGPS. They are in high passes, often above the tree line (hence the need for additional guidance) so that satellite signals typically have high availability. In addition, SBAS has the strong advantage of removing the need for a fixed or temporary base station, maximizes system portability, and minimizes site requirements. The previous MPRO system proved that SBAS works well for this application. However, the system does require an SBAS subscription service fee, and Caltrans must maintain an annual SBAS subscription for each MPRO system it operates.

Accurate As-Built Roadway Digital Base Map

The three-dimensional (3D) digital roadway base map provides the positioning reference for the GNSS-based guidance system. This digital base map must be generated for each system installation site. The base map would need update for any significant change of the roadway. In the special case of vehicle guidance, a centimeter-level accuracy digital map is required. The 3D digital map contains the roadway and roadside elements: lane lines, fog lines, edge of pavement and shoulder, outline of all buildings, signs, light poles, guardrails, snow poles, and rest stop facilities.

Caltrans has been using Mobile Terrestrial Laser Scanning (MTLS) for mapping for more than eight years. MTLS provides the most suitable survey solution for the mapping application. Data is collected at approximately highway speed and provides the level of accuracy needed. As shown in Figures 2.2 and 2.3, the dense geo-referenced 3D point clouds capture all features of the roadway area accurately and rapidly; thus, a surveyor can go back to the point clouds and perform virtual survey of any point and survey of any dimension that was not conceived before the physical survey from the safety of an office.

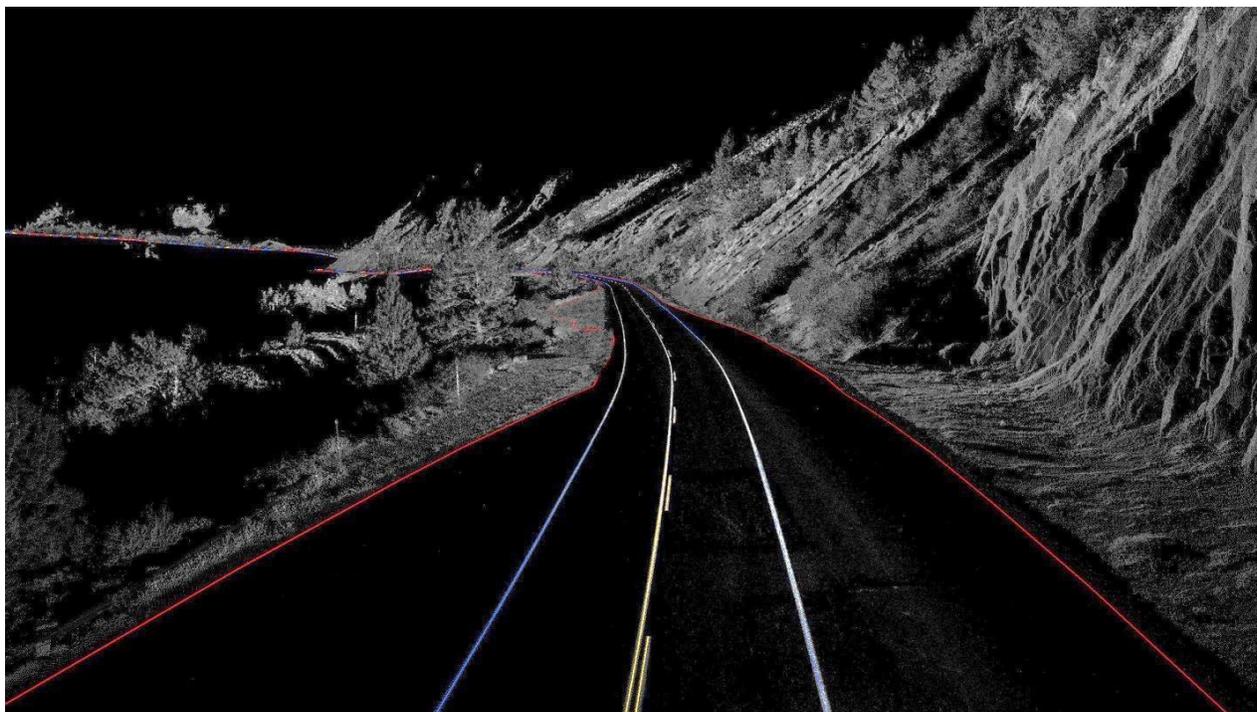


Figure 2.2: Example 3D laser scan point cloud with extracted base map overlay

A Caltrans Survey Request was submitted to Caltrans District Survey. As a result, District 6 Survey carried out the MTLS survey in 2018 with support from local district surveyors for setting up control and GNSS base stations. District 6 Survey also performed the MTLS data post-processing and subsequent feature

extraction. The 3D digital maps were provided in MicroStation Design (dgn) format. The digital maps are in the California State Plane (Zone 2 and Zone 3) coordinate system. Postmile (PM) information was added to the digital map by an AHMCT researcher. The 3D digital maps cover Mono County SR 108 PM 0 to PM 14.2, Alpine County SR 4 PM 3.2 to PM 31.67, and Mono County SR 120 PM 1 to PM 12 as well as the maintenance yard at Woodfords, Camp Connell, and Lee Vining. Map coverage in maintenance yards is essential to support operator training.



Figure 2.3: Example 3D laser scan point cloud with extracted base map overlay

HMI

The HMI is an essential element in the MPRO system. The HMI design is based on the previous MPRO HMI with some modifications. The HMI is based on a bird's eye view of the roadway.

Major HMI requirements are:

- If GNSS position solution is unavailable, the system will alert the operator to resume operation without the aid of the DAS.
- The display must be compact and easily integrated into a variety of snow-blower cabs without interference with equipment operation or the operator's visibility.

- White snow and sunlight create a bright background that can produce significant glare on a Liquid Crystal Display (LCD). A high-brightness, sunlight-readable display is required in such challenging conditions.
- The primary HMI function is display of the vehicle position and heading relative to the roadway, obstacles such as signs and guard rails, and postmile location.

Chapter 3:

MPRO Hardware Design

System Hardware Overview

The MPRO hardware is responsible for providing GNSS receiver position and heading data to software applications, executing MPRO software applications, and displaying DAS information for the operator. The wiring diagram is provided in Figure 3.1. The MPRO hardware includes the system box and display installed inside the rotary plow cab (Figure 3.3) and the GNSS receiver. The tablet, power supplies, and GNSS receiver for position and heading are packaged together into a single integrated unit. Hardware model numbers are shown in Table 3.1. The only cabling connection between the vehicle and the DAS is for the 12-volt Direct Current (DC) power supply. The MPRO system consists of a GNSS receiver, Android tablet, power/data junction box, and associated hardware mounts and cables. System current draw is 2.5-3 A at 12 v.

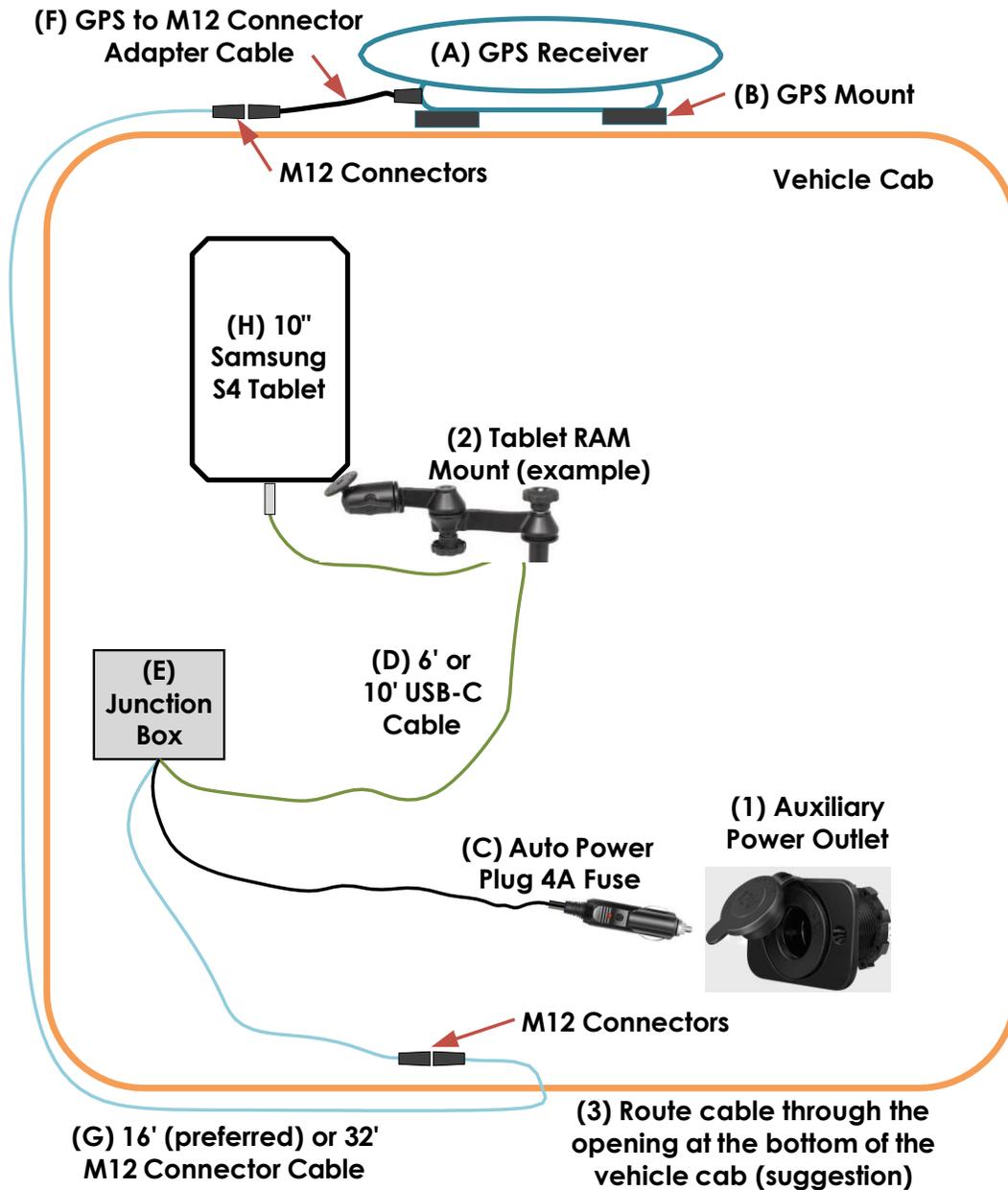


Figure 3.1: MPRO system wiring diagram

Table 3.1: MPRO system component descriptions

| Part | Descriptions |
|----------|--|
| A | Hemisphere V500 GNSS Smart Antenna |
| B | <p>GPS mounts:</p> <ul style="list-style-type: none"> • Magnetic mount for flat roof (see GPSwFlatRoofMagMount.pdf and GPSFlatRoofMagMount.SLDASM) • Magnetic mount for curved roof (see GPSwCurveRoofMagMount.pdf and GPSwCurveRoofMagMount.SLDASM) • GPS mount for loader (see GPS_loader_mount.pdf and GPS_loader_mount.SLDASM) <p>These GPS mounts have been fabricated and provided.</p> |
| C | Auto power plug (4 A fused) |
| D | 6' USB-C cable tied to the junction box (E) |
| E | Power/data junction box |
| F | GPS-to-M12-connector adapter cable |
| G | 5-meter (L-com.com TRG884-C6G-5M) (preferred) or 10-meter (L-com TRG884-C6G-10M) M12 connector cable to be installed from vehicle roof to inside vehicle cab |
| H | Samsung Tab S4 10" Android tablet |
| 1 | Automobile auxiliary power outlet if it is not already available inside the vehicle cabin. The outlet is to be controlled by the vehicle ignition switch (outlet power on when the ignition switch is on, and outlet power off when the ignition switch is off). |
| 2 | RAM mount (1.5" ball). This mount must be capable of supporting a 10"-diagonal Samsung Galaxy tablet inside the vehicle cabin. The tablet must be within the operator's field of view but not block any vehicle instrument panels, switches, other controls, or the field of view when looking out of the vehicle. The tablet requires very little operator interaction. The tablet should also be within the reach of the operator. |
| 3 | Install one 8-conductor 5-m (preferred) or 10-m-long cable from the center console or anywhere accessible inside the vehicle cab to the left or right corner of the vehicle cab roof. The installer should select the proper required cable length. The provided 5-m and 10-m cables have nylon loom protection. The cable end labeled "Roof" should be located on the roof, and the cable end labeled "Inside Cab" should be located inside the vehicle cab. All excess cable length can be left inside the vehicle cab towards the RAM mount location but out of way of normal operations. |

Hemisphere Vector V500 GNSS Smart Antenna

The Hemisphere Vector V500 GNSS Smart Antenna (see Figure 3.2) was chosen for the MPRO system GNSS receiver that provides vehicle position and heading. The V500 Smart Antenna has two GNSS antennas and two GNSS receivers integrated into a single robust waterproof housing designed for marine applications. This integrated unit reduces mount and cabling complexity. The user can configure the V500 via a simple to use web-based user interface (WebUI) through WiFi. Table 3.2 show some of the desirable V500 features.

Table 3.2: Desirable Hemisphere Vector V500 GNSS Smart Antenna features for MPRO application

| Item | Specifications |
|----------------------------------|---|
| Operating temperature range | -40° F to +158° F |
| Size | 68.6 cm L x 22.0 cm W x 12.3 cm H |
| Weight | 3.7 kg (8.2 lb) |
| Input voltage | 9 - 32 VDC with reverse polarity operation |
| Power consumption | 7.5 watts |
| Position and heading update rate | 20 Hz or lower |
| GNSS supported | GPS, GLONASS, BeiDou, Galileo, QZSS, IRNSS, and Atlas |
| SBAS services support | Atlas H10, Atlas H30, Atlas Basic |
| Heading accuracy | < 0.2 degree |
| Configuration tool | WebUI via WiFi |
| Other built-in sensors | Gyro and tilt sensors |

The V500 Smart Antenna outputs proprietary binary data stream containing Coordinated Universal Time (UTC) date and time, latitude, longitude, heading, altitude, geoidal separation, number of visible satellites, speed, heading, estimated positional accuracy, and solution status through its RS232 serial port at a baud rate of 115,200 bits per second (bps). The V500 RS232 serial port is connected to a USB-to-RS232 serial converter connected to the Android tablet.



Figure 3.2: Hemisphere Vector V500 GNSS Smart Antenna with M12 connector extension cable

Atlas H10 SBAS service

The Hemisphere Vector V500 GNSS Smart Antenna supports Hemisphere GNSS' proprietary Atlas H10 Land/Coastal coverage SBAS service for decimeter-level corrections. The Atlas SBAS services has a few options (Atlas H10, Atlas H30, and Atlas Basic) for different position accuracy requirements. The Atlas H10 Land/Coastal coverage SBAS subscription is available in monthly, quarterly, annual, and three year subscriptions. The quarterly option was chosen for the 2021 deployment and testing. However, the monthly option may be viable for a dry year.

To activate the Atlas H10 Land/Coastal coverage SBAS subscription, the user sends an email activation code request to contact person at [mail to ag at Subsea Technologies \(mailto:ag@subseatechnologies.com\)](mailto:ag@subseatechnologies.com) including the Vector V500 GNSS Smart Antenna serial number (printed on the bottom of the V500 or available from the WebUI). The user can pay for the subscription using a credit card. Upon receiving the Atlas H10 subscription activation code, the user can provide the code to the receiver unit by copy/paste to the WebUI. Detailed activation instructions are provided in the MPRO training documentation.

V500 Mounting

The V500 Smart Antenna is mounted on the roof of the snow removing vehicle, such as snow blower, snow cat, small dozer, or front-end loader with a

snow blower attachment (see Figures 3.3, 3.4, and 3.5). For vehicles with a steel metal roof, a magnetic mount (four 3"-diameter magnets) was used to secure the V500. Two magnetic mount versions were designed and fabricated. One version was intended for flat steel roof, and the other version was designed for curved surface roof. A majority of the current snow blowers and front-end loaders have a flat steel roof. The magnetic mount Smart Antenna was easy to install and remove. In the current research, there was one Caterpillar 950 front-end loader (see Figure 3.9) with a fiberglass roof as shown in Figure 3.3. Working with Caltrans Division of Equipment (DOE), a custom mounting plate was designed and fabricated.



Figure 3.3: Vector V500 GNSS Smart Antenna custom-mounted on a Caterpillar 950 front-end loader with fiber glass roof



Figure 3.4: Vector V500 GNSS Smart Antenna mounted on a flat steel roof of a front-end loader using magnetic mount



Figure 3.5: Vector V500 GNSS Smart Antenna mount on a flat steel roof of a snow blower using magnetic mount

Samsung Tablet

A few tablet solutions were evaluated. The main selection criteria was display sunlight-readability. The minimum display brightness was 500 nits. Organic Light-Emitting Diode (OLED) display performs better than LCDs. The Samsung Tab S4 Android tablet was selected for the HMI computer. It features a 10.5" OLED display. A larger display would not fit well inside the vehicle without obstructing the operator's field of view. Android tablets with 7" to 8" sunlight-readable displays are not commonly available. The Samsung S4 tablet is enclosed in a Supcase Unicorn Beetle Pro protective case. Newer versions of the Samsung S series tablet, such as Tab S7 and S6, were recently made available. Some new lower cost S-series Android tablets use LCD, which may not perform as well in a bright sunlight environment.

Tablet Mounting

The tablet Supcase Unicorn Beetle Pro protective case is mounted on a 3/8" black ultra-high molecular weight polyethylene plastic plate with several threaded mounting holes for a RAM Mount (1.5" ball) RAM-2461U. This mount

safely secures the Samsung Galaxy tablet in the high-vibration environment inside the snow removal vehicle cabin. The tablet is mounted within the operator's field of view while not blocking any vehicle instrument panels, switches, other controls, or the field of view looking out of the vehicle. The tablet requires very little operator interaction. However, the tablet should be within the reach of the operator.

FTDI USB to RS232 Serial Adapter

A Future Technology Devices International, Ltd. (FTDI) USB-RS232-WE-1800-BT-0.0 cable converts the RS232 communication data from the V500 to USB protocol. The USB-RS232-WE-1800-BT-0.0 USB connector contains a small circuit board featuring the FTDI FT232RQ serial interface integrated circuit to handle all the USB signaling and protocols. It was chosen because there is an open source driver available for the Android OS. The USB-RS232-WE-1800-BT-0.0 cable was shortened and connected to the LAVASynC 1U-OEM board USB-A connector as shown in Figure 3.6. The entire MPRO electronics is housed inside a waterproof plastic junction box.

Power Interface Junction Box

The LAVASynC 1U-OEM⁵ (see Figure 3.6) is designed specifically for USB-C-type mobile phones and tablets. This adapter simultaneously charges and supports USB peripherals while they are connected to a mobile phone or tablet via a USB-C interface. In addition, it automatically detects connection to an Android device. It has two USB-C ports and one USB-A port for USB peripherals (FTDI USB-to-RS232 adapter for the MPRO application). One USB-C port is connected to the 5-volt DC power source, and the other USB-C port is connected to the Android tablet via a 6' USB-C-to-USB-C cable. When power is disconnected, the LAVASynC 1U-OEM will disconnect power to the peripheral (FTDI USB-to-RS232 adapter) connected to the USB-A port. Thus, it prevents power drain from the tablet to USB peripherals in the event of power loss. It works out-of-the-box without any modification to the Android devices such as "rooting" the tablets.

⁵ [LAVASynC 1U-OEM SimulCharge USB-C adapters \(https://lavasimulcharge.com/products/lavasync-usb-c-mobile-adapters/lavasync-usb-c-adapters-hubs/lavasync-1u-oem/\)](https://lavasimulcharge.com/products/lavasync-usb-c-mobile-adapters/lavasync-usb-c-adapters-hubs/lavasync-1u-oem/)

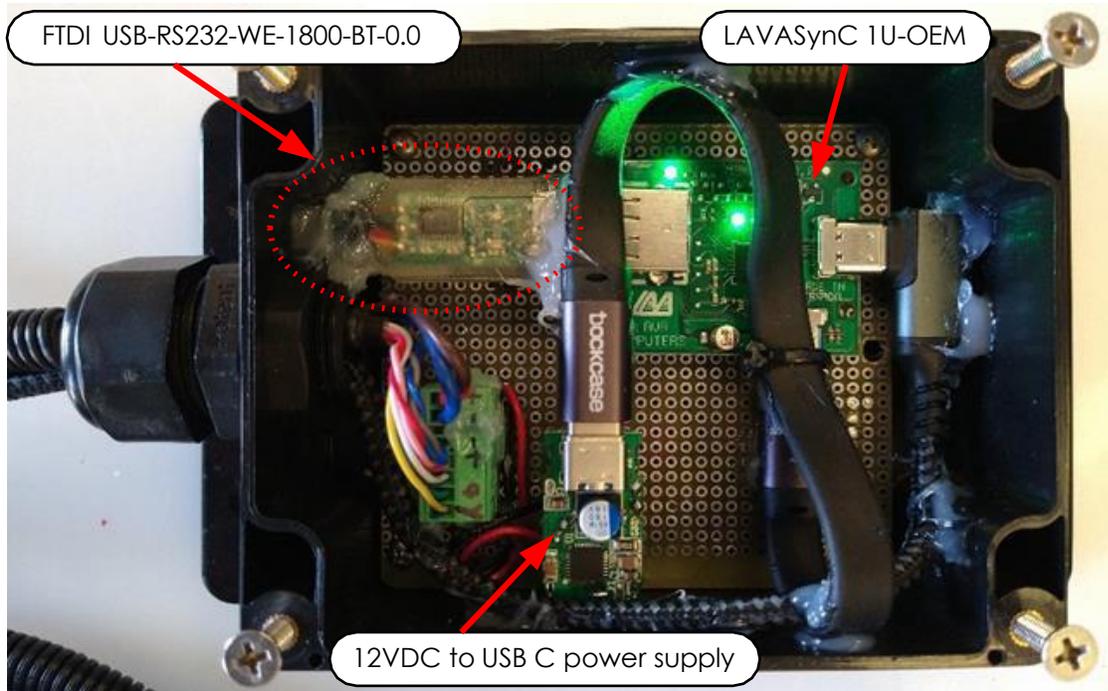


Figure 3.6: MPRO system power and data junction box inside view

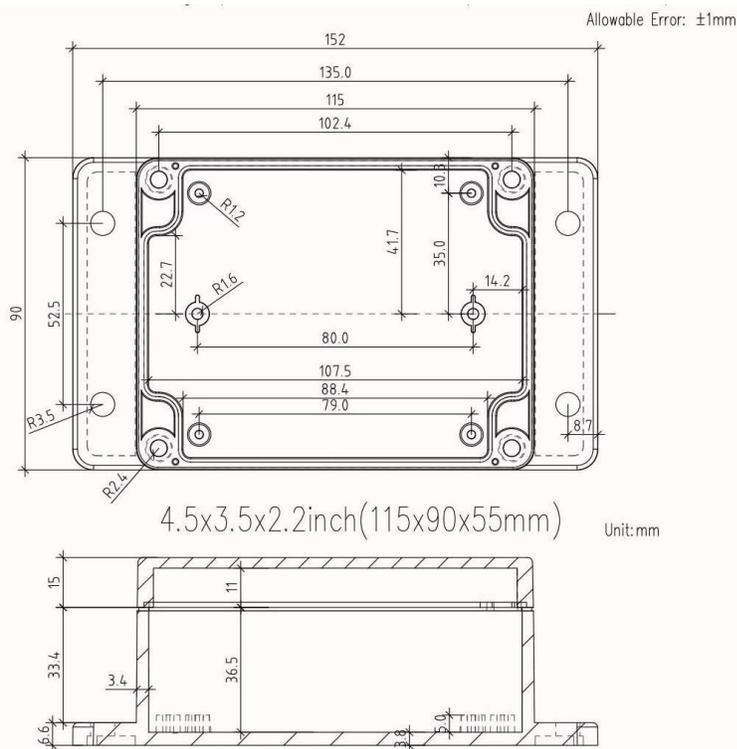


Figure 3.7: Part E Power/data junction box size and dimensions (not to scale)

Cabling and Mounting

Local Requests (LRs) were made to Caltrans DOE to modify eight snow removal vehicles. An ignition switch-controlled automobile auxiliary power outlet (see Figure 3.8) was added to each of eight snow removal vehicles if it was not already available inside the vehicle cabin. The outlet is controlled by the vehicle ignition switch (outlet power is on when the ignition switch is on, and outlet power is off when the ignition switch is off). A 1.5" ball RAM-202U RAM Mount (see Figure 3.8) was also mounted inside the cab. A RAM-201U RAM Mount attached to the RAM-201U and the Samsung tablet's RAM-2461U. A custom 90-degree aluminum bracket (SolidWorks Computer-Aided Design [CAD] design file available) was designed and fabricated to attach the 12-volt power outlet and the RAM-202U to the snow blowers and front-end loaders. In some cases, the RAM-202U was directly attached to the snow blower center console.

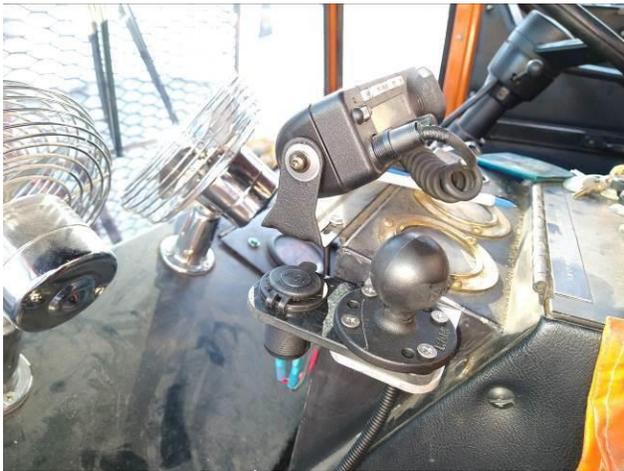


Figure 3.8: Example of a 12-volt power outlet and Ram Mount 1.5" ball added to a snow blower interior

In addition, a single 5-meter (L-com.com TRG884-C6G-5M) or 10-meter (L-com TRG884-C6G-10M) M12 connector cable was installed from the vehicle roof to inside the vehicle cab center console or anywhere accessible inside the vehicle cab to the left or right corner of the vehicle cab roof. The cable length depended on the vehicle size and practical cable routing. In most cases, the 5-meter-long cable was used. The 5M and 10M cables were provided with nylon loom protection. The cable end labeled "Roof" should be located on the roof, and the cable end labeled "Cab" should be located inside the vehicle cab. All excess cable length was left inside the vehicle cab towards the RAM mount location. The M12 connector cable is connected to the V500 Smart Antenna and provides the V500 power and RS232 data link to the junction box.



Figure 3.9: Example MPRO system installation inside a snow blower cab



Figure 3.10: Example MPRO system installation inside a front-end loader cab



Figure 3.11: Caltrans Equipment #41870 2016 Caterpillar 950 front-end loader MPRO system installation

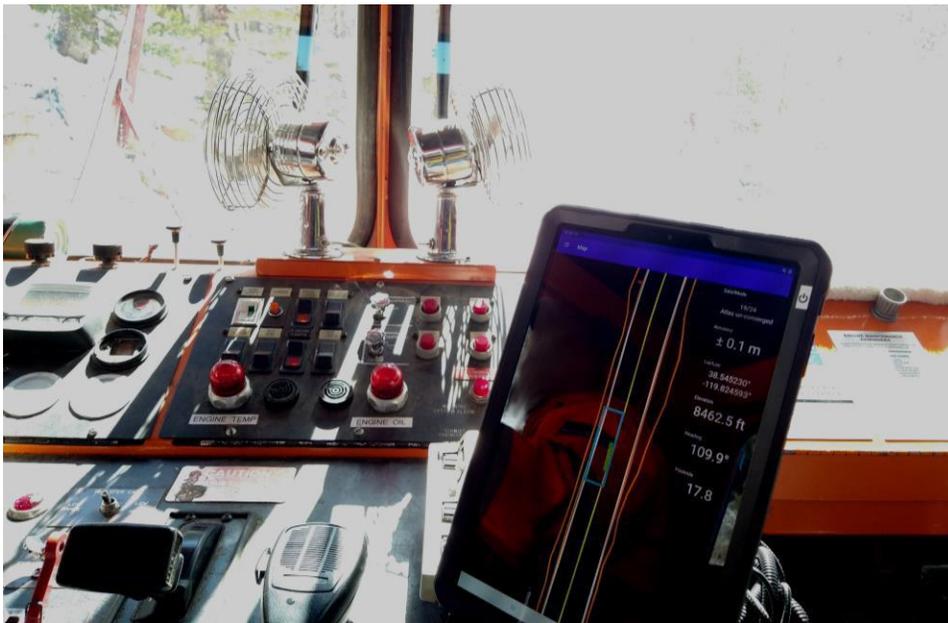


Figure 3.12: MPRO system with active HMI inside the snow blower. The operator's face was intentionally blurred out.



Figure 3.13: MPRO system with active HMI inside the front-end loader

Chapter 4: MPRO Software

The previous MPRO software was developed for an X86 computer running Microsoft Windows XP and is not compatible with Windows 10. Based on system requirements and review of the Windows MPRO code, AHMCT decided to port the MPRO software to the Android OS.

Software Architecture

The MPRO software architecture is based on Clean Architecture as defined by Robert C. Martin.⁶ A key component of Clean Architecture is that outer, or lower level, layers depend on inner, or higher level, layers, but not the other way around. This is known as the dependency inversion rule. This allows inner layers to be developed and depend only on an interface and thus allow for outer layer details to be substituted without changing the inner layers.

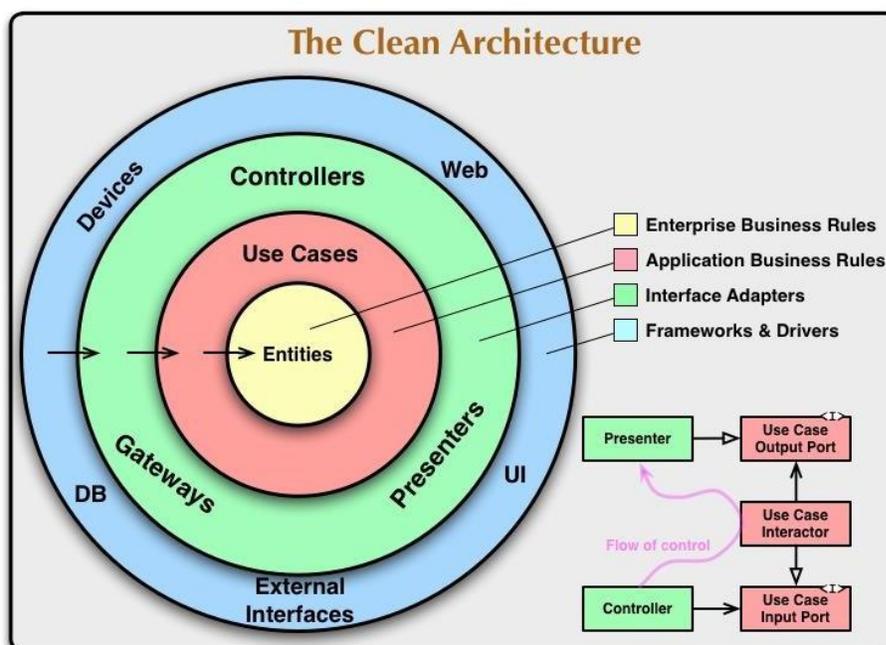


Figure 4.1: Clean Architecture concept⁷

⁶ Robert Martin, Clean Architecture: A Craftsman's Guide to Software Structure and Design, Pearson, 432 pp., 2017

⁷ Figure from [The Clean Code Blog \(https://blog.cleancoder.com/uncle-bob/2012/08/13/the-clean-architecture.html\)](https://blog.cleancoder.com/uncle-bob/2012/08/13/the-clean-architecture.html) courtesy of and © [Robert Martin \(http://www.cleancoder.com\)](http://www.cleancoder.com).

The application has been divided into the primary presentation, application, domain, and data modules. The presentation module is composed of the user interface (UI), models, dependency injection, mappers, and view models. The UI includes providers, fragments, listeners, activities, and preferences. The application module is composed of use cases, executors, and repository/gateway interfaces. The domain module contains the domain models, and the data module is composed of the repository and gateway implementations, models, mappers, and data sources. The data sources include the GNSS device drivers, the data stores (i.e., polyline, postmile, setting, and coordinate), and logging.

In general, a task in the executor is periodically executed which requests the current location from the GNSS gateway. The GNSS gateway and associated device implementation supports opening/closing the GNSS device and polling the current location. The resultant gateway data is mapped to the domain model and passed through to the presentation layer. The current location is used to query the map polylines based on the current location and the screen zoom level. The polyline repository and associated data store implementation supports opening/closing a specific mountain pass (i.e., Ebbetts, Sonora, or Tioga) and executing queries that typically request all polylines contained in a specified radius surrounding the current GNSS location. The resultant data from the repository is mapped to the domain model and passed through to the presentation layer for updating the UI map fragment. The polyline repository is only queried when necessary based on the distance traveled since the last polyline update.

GPS Gateway Driver

hemignss software library

The hemignss library facilitates the use of Hemisphere GNSS devices. It processes incoming data from a GNSS device, generating corresponding message objects that are then published to subscribing clients. Clients may subscribe to messages of a specific type or to messages of all types. The library also allows for the generation of byte sequences for various GNSS commands, which can then be transmitted to a device.

hemignss Android interface components

The MPRO Android application interfaces with the hemignss library through the following internal MPRO components:

- **HemiManager:** HemiManager simplifies the use of the hemignss library with a USB serial port adaptor under Android. It makes use of the Android USB host Application Programming Interfaces (APIs), as well as the usbserial library, to manage the USB serial port adaptor. It also provides

convenience interfaces to the hemignss library for use by the MPRO application.

- SerialIoManager: Used by HemiManager, SerialIoManager manages the reading and writing of serial data via the usbserial library.

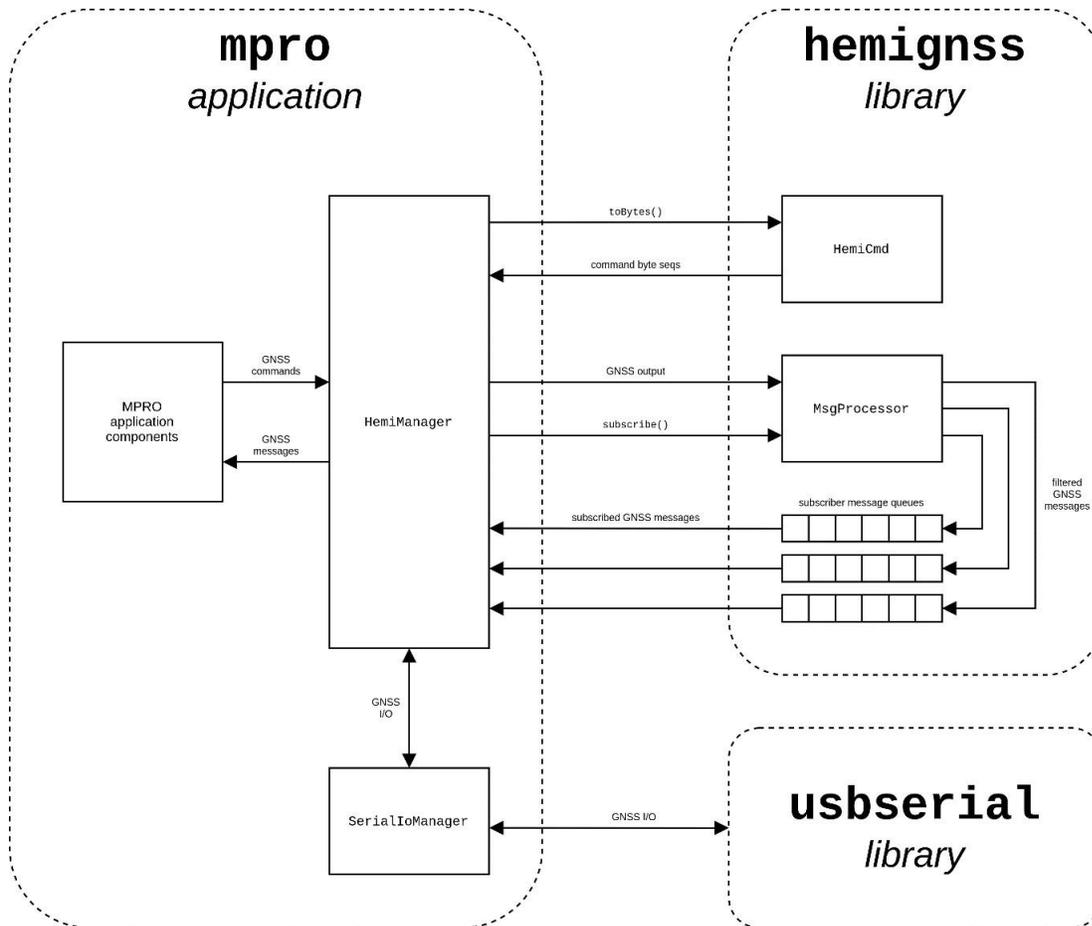


Figure 4.2: Simplified MPRO GNSS data flow

usb-serial-for-android

The USB-serial-for-android library (referred to as usbserial by MPRO) is a third-party Android driver library for various USB serial UART devices, including chips from FTDI and Prolific. The library is available under an open-source license at: [USB-serial-for-android \(https://github.com/mik3y/usb-serial-for-android\)](https://github.com/mik3y/usb-serial-for-android)

Auto-launch

The software is designed so that the application will auto-launch without user intervention or permission approvals under all typical use cases. However, there exists a known case where if the tablet is rebooted without power cycling the vehicle, the application will not auto-start.

User Interface

The primary user interfaces of the MPRO application are comprised of detailed settings and map interfaces. The navigation drawer, shown in Figure 4.3, is used to navigate between the settings, map, and log UI fragments. The drawer can be accessed by either clicking on the upper left three-line icon or swiping from the left edge of the screen to the right.

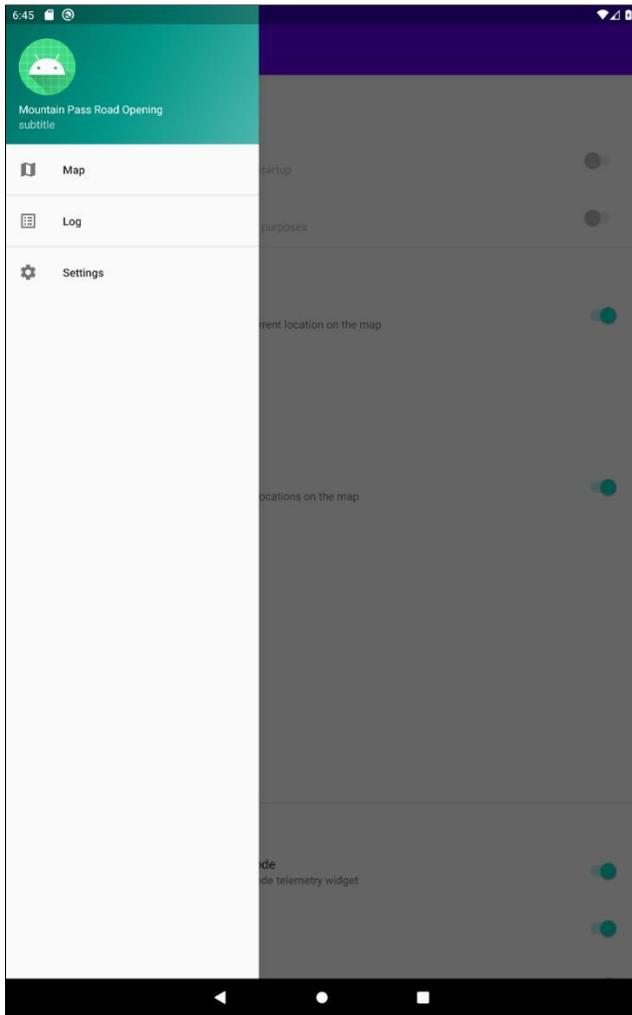


Figure 4.3: The navigation drawer

MPRO Software Settings

The application settings are accessed by clicking on the settings icon in the navigation drawer. The main settings view, shown in Figure 4.4, include the vehicle and GNSS offset dimensions, USB serial, map, and log configurations. The dimension configuration must be configured and contains the vehicle width, length, GNSS x-axis offset, and GNSS y-axis offset in feet. It is important to note that the offsets are relative to the center of the vehicle following the ISO 8855

convention for direction. The USB serial configuration includes the serial baud rate, data bits, parity, and stop bits between the MPRO serial adapter and the GNSS. The recommended default configuration is rate 115,200 bps, 8 data bits, parity none, and 1 stop bit. The log configuration allows for filtering the log output based on the log severity levels of error, warn, info, debug, and trace. The map settings are accessed by clicking on the map configuration.

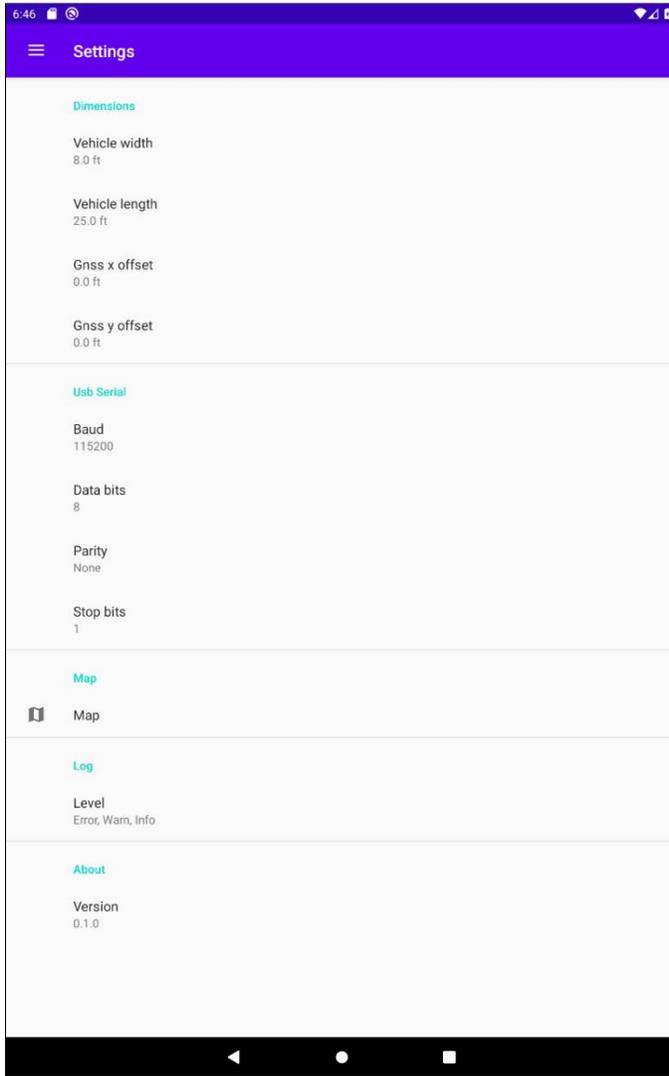


Figure 4.4: The main settings

The map settings view, shown in Figure 4.5, include the operational area, vehicle, telemetry, and layer configurations. The operational area must be selected (i.e., Ebbetts Pass, Sonora Pass, Tioga Pass, etc.) in order to display the associated map. The vehicle configuration includes the ability to display the vehicle outline and trail as a map overlay and specify the vehicle overlay outline color and stroke width as well as the vehicle trail overlay interval, expiration, color, stroke width, and radius. The telemetry configuration includes

the ability to individually display the satellites and navigation mode, accuracy, latitude and longitude, elevation, course, heading, roll, pitch, and postmile telemetry widgets. Additionally, the telemetry widget cluster screen bias location can be specified. The map layer color and stroke width settings are accessed by clicking on the layer color and stroke width configurations.

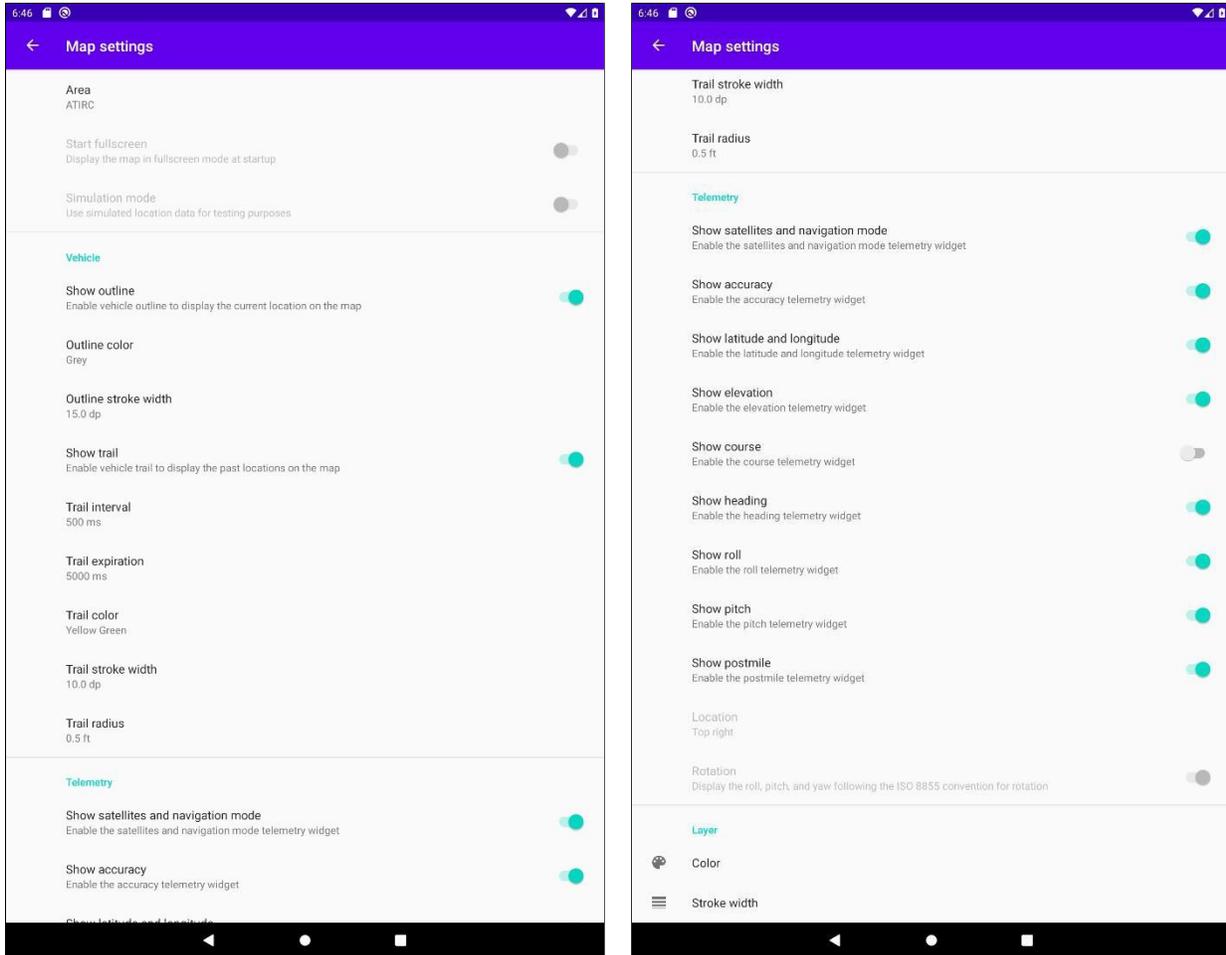


Figure 4.5: The map settings

The map layer color settings view, shown in Figure 4.6, includes the ability to configure the color for each layer in the map.

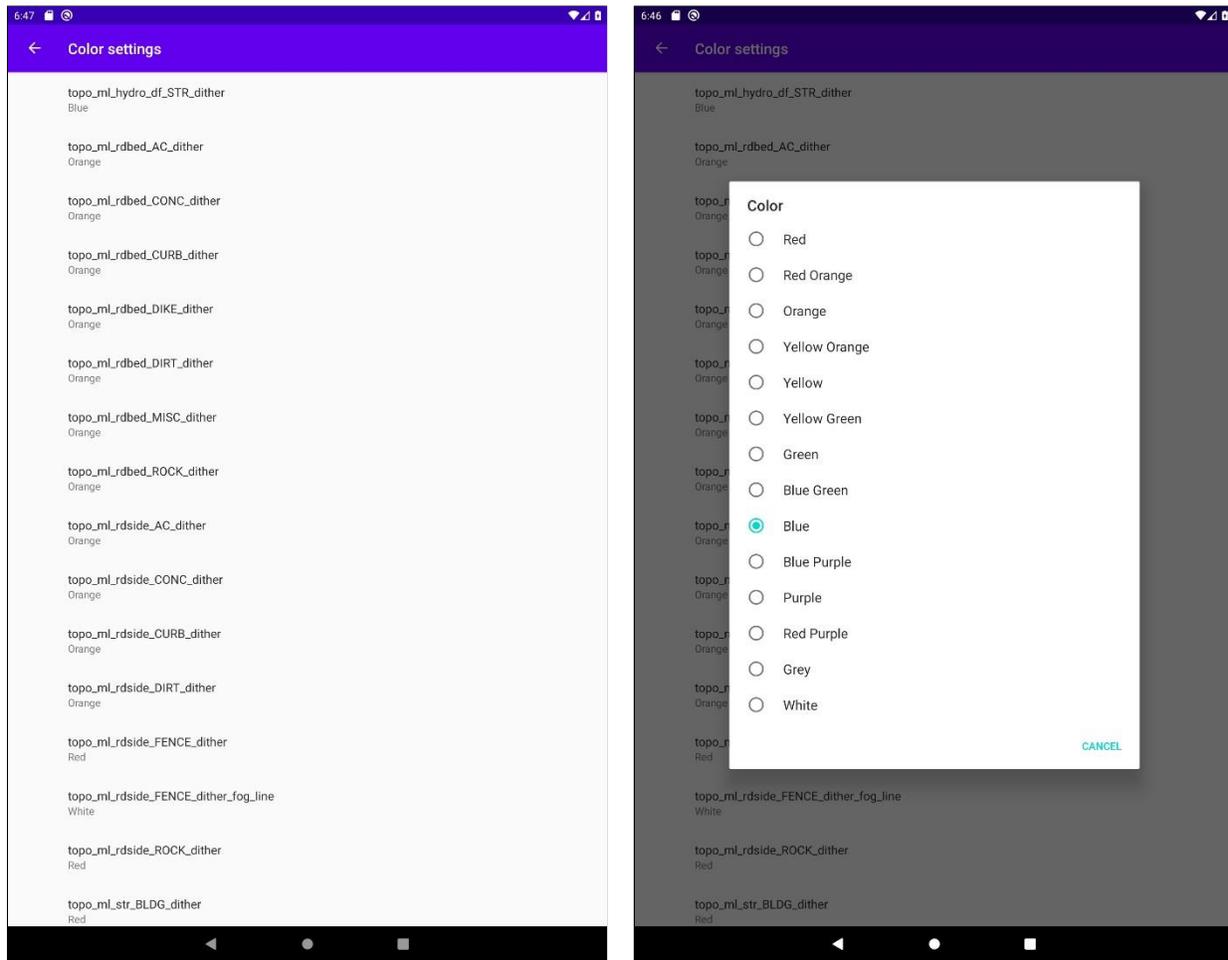


Figure 4.6: The map layer color settings

The map layer stroke width settings view, shown in Figure 4.7, includes the ability to configure the stroke width for each layer in the map. The map layer configuration names are derived directly from Caltrans map layer definitions.

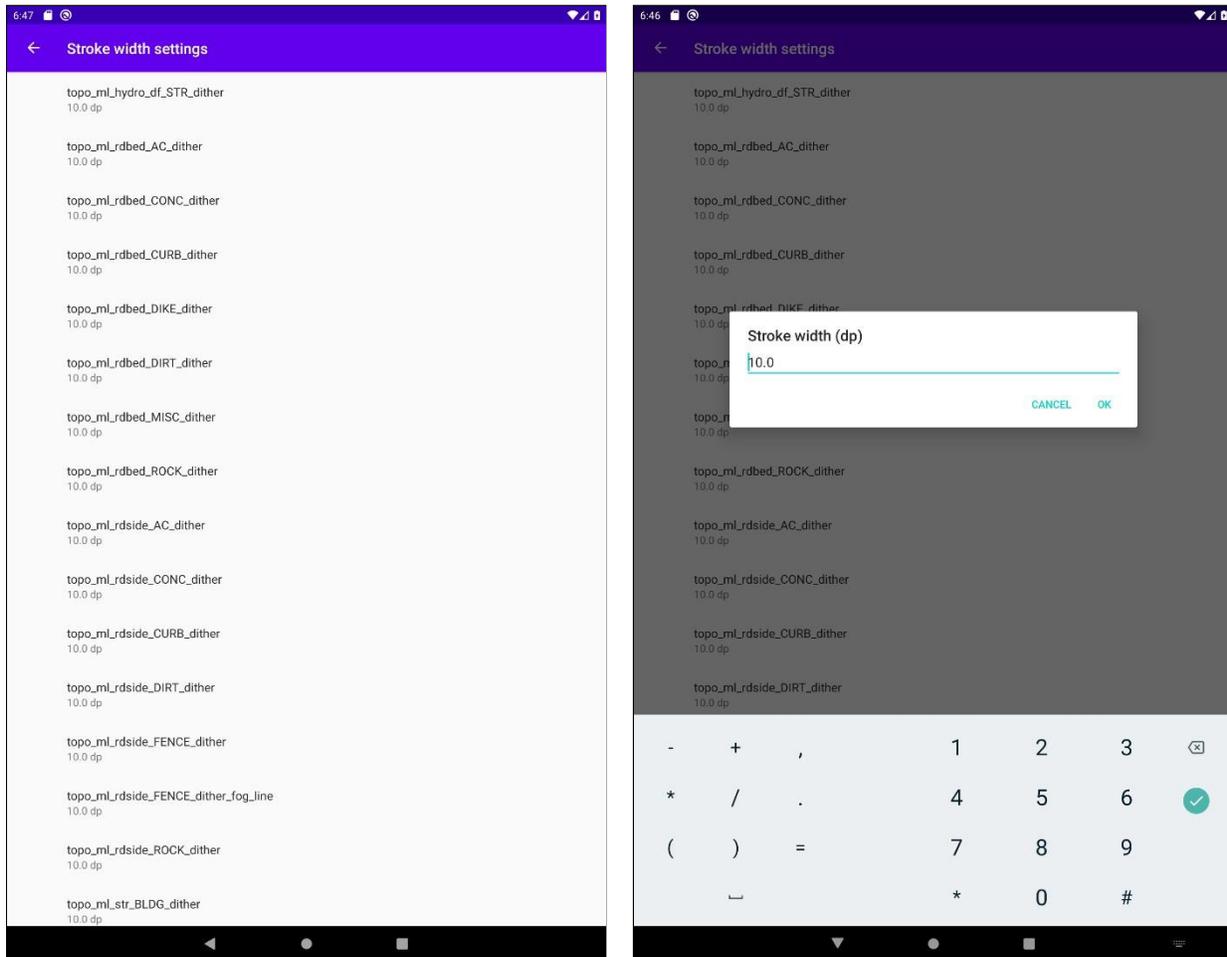


Figure 4.7: The map layer stroke width settings

Map

The primary application interface is the map view as shown in Figures 4.8 and 4.9. The map fragment includes the map, vehicle outline, and trail overlay and telemetry widgets. The map is centered at the vehicle location, rotated based on the vehicle's course and scaled based on the zoom level. The vehicle outline is always centered in the screen, and the map is rotated such that the vehicle forward direction is upwards. The vehicle trail represents the recent historical vehicle locations. The telemetry bar can be located to the left (see Figure 4.8), right, top, or bottom (see Figure 4.9) of the map view. Zoom is achieved using the pinch-to-zoom gesture common to modern mobile phones and tablets.

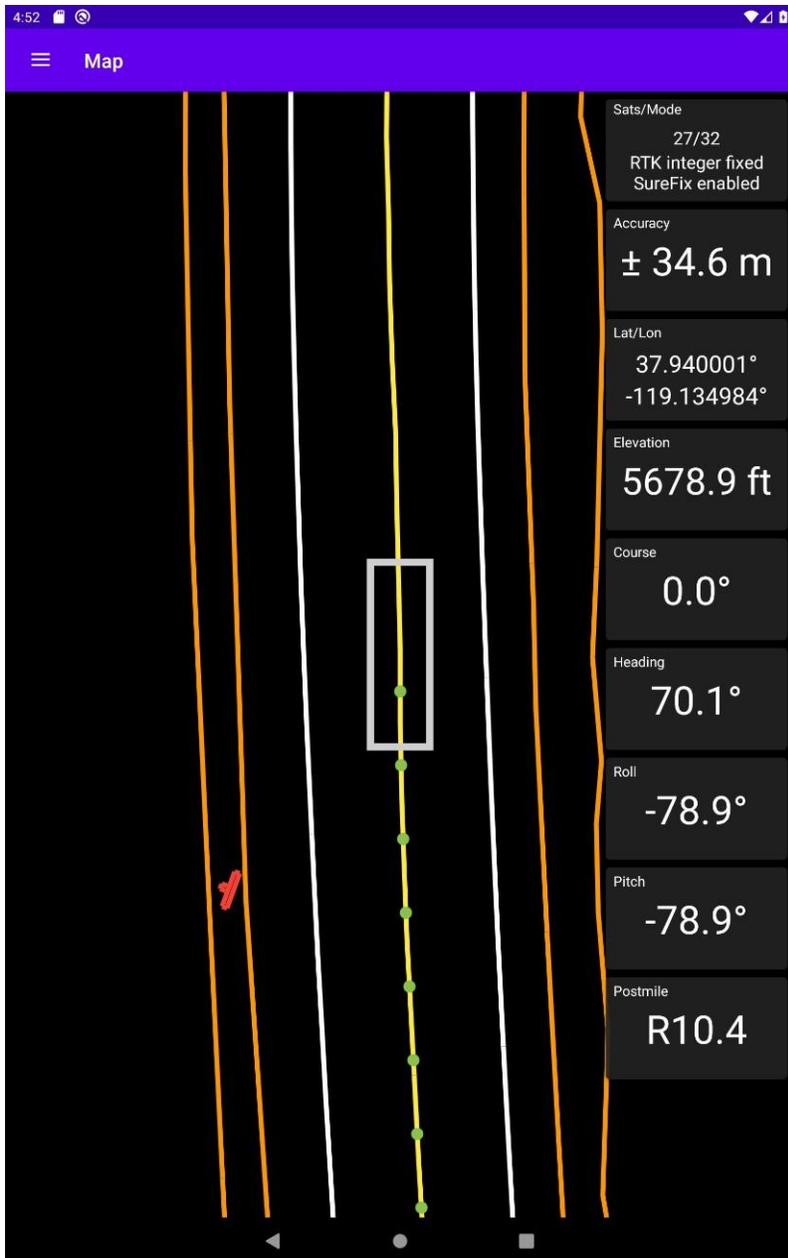


Figure 4.8: The map view with right located telemetry bar



Figure 4.9: The map view with bottom located telemetry bar

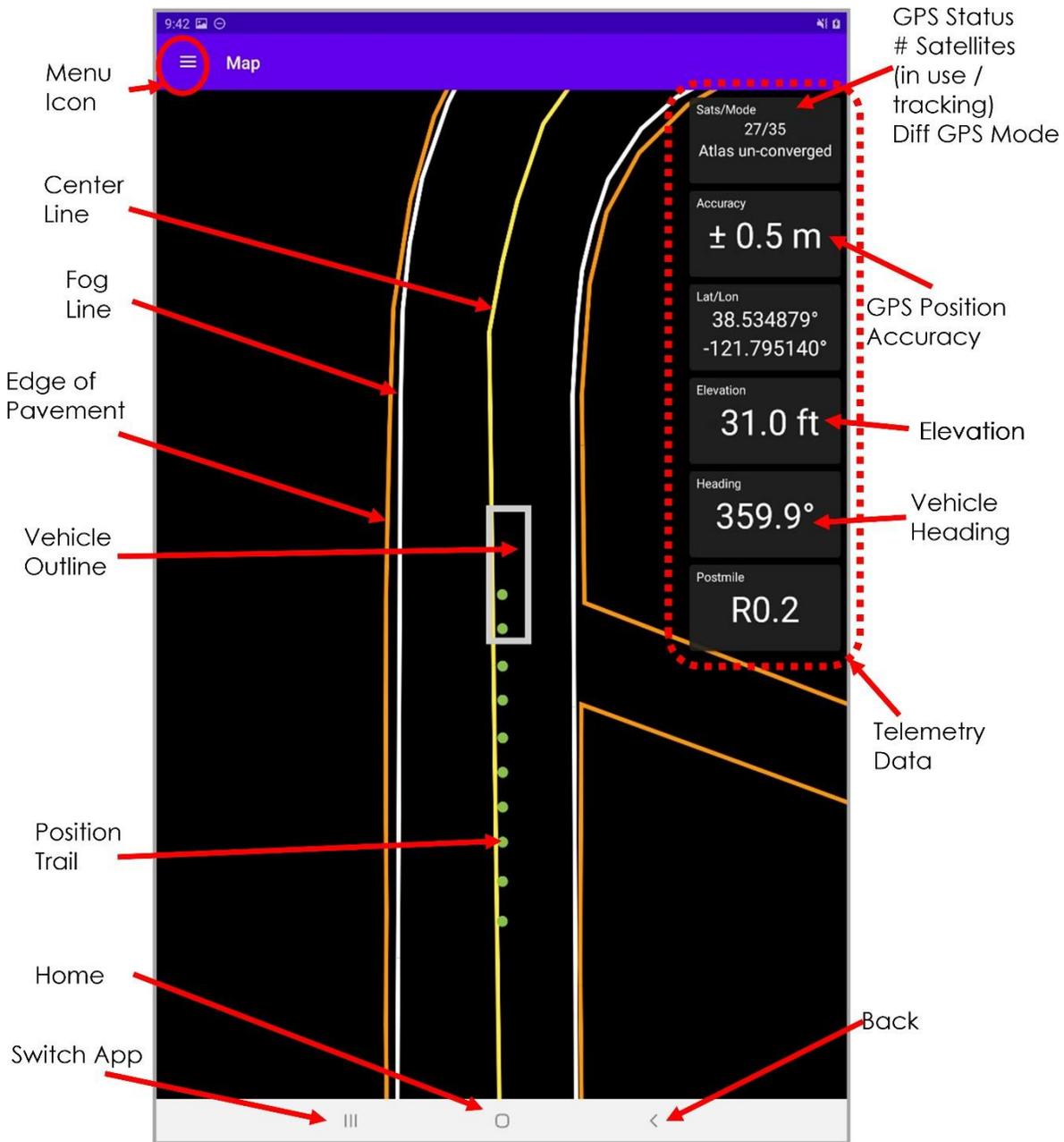


Figure 4.10: Mountain Pass Road Opening App Graphical User Interface

Map Provisioning

The primary source data, for the MPRO software effort, was provided by Caltrans District 6 Surveyors who surveyed Ebbetts Pass, Sonora Pass, and Tioga Pass and provided the resultant Geographic Information System (GIS) map data in a shapefile format. A major consideration, when designing the MPRO application, was an internal data storage methodology that would allow for fast retrieval of map data. Additionally, it was desired to store the map data in a

data structure that lends itself to non-proprietary provisioning using existing tool chains and workflows. It was decided that the map data would be stored in a SpatialLite data structure. SpatialLite is an open-source library intended to extend the SQLite core to support fully fledged Spatial SQL capabilities. Using QGIS open source tools, the map data in shapefile format was converted to a SpatialLite database.

Database Table Naming

The key mpro.sqlite tables are defined as:

- *ebbetts_pass_polyline*
- *ebbetts_pass_polygon*
- *ebbetts_pass_point*
- *ebbetts_pass_multipatch*
- *ebbetts_pass_annotation*
- *sonora_pass_...*
- *tioga_pass_...*

Main Steps in Creating the SpatialLite Map Database

1. Import shapefiles using QGIS
2. Set and verify layer projections
 - epsg 6420 - sonora_pass, tioga_pass
 - epsg 6418 - ebbetts_pass
3. Modify attributes
 - a. Layer labels
 - Center line: topo_ml_tcd_MARKING_dither_center_line
 - Lane line: topo_ml_tcd_MARKING_dither_lane_line
 - Fog line: topo_ml_tcd_MARKING_dither_fog_line
4. Split polylines by maximum length
5. SpatialLite database preconditions checks:
 - a. Double-check for importing all shapefiles
 - b. Check map projections
 - i. Geometry and coordinate reference system
 - ii. Set source coordinate reference system
 - iii. epsg 6420 - sonora_pass, tioga_pass

iv. espg 6418 - ebbetts_pass

6. Create/save the SpatialLite database

In addition, a postmile database was created in a similar fashion with the exception that the postmile data originated as a comma-separated-value (CSV) file.

Recommended Software Updates

The following is a list of software updates that are recommended but not included in the current software distribution.

- Support full screen mode option to maximize screen real estate and support increased font size for better operational usability and impact. The application has been deployed on various devices, some with display sizes, which would benefit from an increased usable area for map and telemetry ease of use.
- Add On Boot Completed state listener and associated handler to completely address auto-launch of application under all use cases. The goal of this update is to ensure the lowest operator burden possible.

Chapter 5:

Deployment and Implementation

MPRO System Installation

Due to the light snow accumulations in the 2020-2021 winter season, there was very little snow on all the mountain passes. For example, the Caltrans crew was able to clear snow on the SR 120 roadway in two days despite one equipment breakdown. Due to the lack of snow, the equipment was installed on only three of the eight Caltrans road opening snow removal equipment in the field in 2021. One MPRO system was installed on an AHMCT research vehicle (Ford F250 truck) for testing and evaluation of MPRO and V500 GNSS systems as well as for training and demonstration for larger group of potential users. The Atlas H10 SBAS three-month subscription service was purchased and activated for four V500 Smart antennas. The final system was usually installed in the field in one to two hours by a single person. The only field software configuration is to input the vehicle dimensions and antenna location relative to the vehicle. The majority of the time is spent on tying-up and securing cables and unpacking equipment from transportation protection boxes.

MPRO System Training

A laminated two-page double-sided MPRO user manual was also provided. AHMCT will train the META trainers so that Caltrans personnel are more independent using the MPRO user manual. The MPRO user manual contains:

1. MPRO Android App user guide
2. MPRO Android App setup and configuration instructions
3. V500 Smart Antenna setup and Atlas H10 SBAS subscription activation instructions

The operator training on the system was conducted after the system installation. In the case of SR 4 and SR 108, the AHMCT research vehicle was used to conduct the field user training since two to three operators can be trained at the same time. Thus, more user feedback was obtained. After that, an AHMCT researcher rode along with the snow removal vehicle operators to conduct more training as well as observe the MPRO system performance and the V500 GNSS Smart antenna's performance in GNSS-challenged conditions on the mountain passes. Moreover, the ride-along ensured MPRO systems were performing as expected. In addition, the new MPRO system was demonstrated to the local maintenance yard supervisors for input and feedback.



Figure 5.1: MPRO system field testing at SR 4 on a snow blower. GNSS-challenged condition with dense tall trees on both side of the roadway. The display was in the middle of refreshing the display.

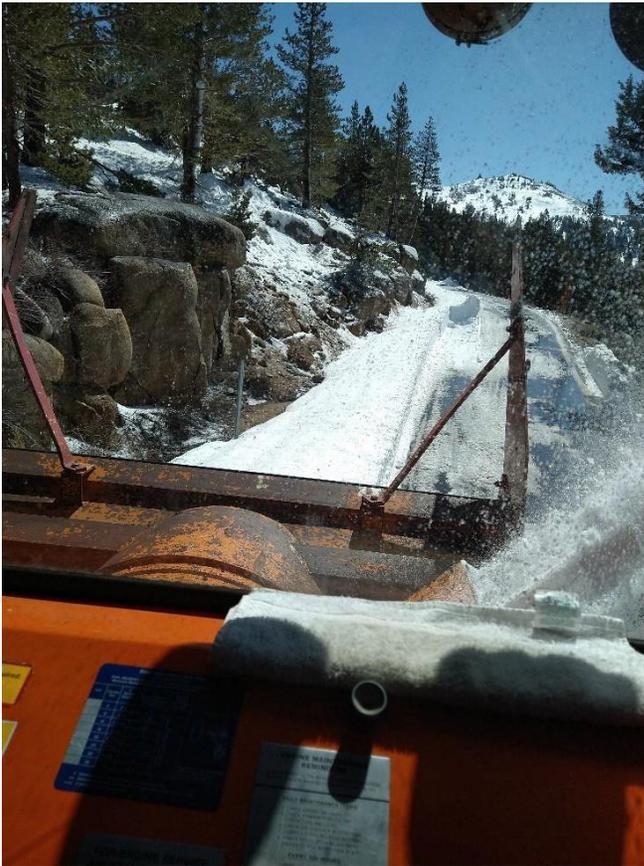


Figure 5.2: MPRO system field testing at SR 4 on a snow blower (passenger view)

Figure 5.2 shows only 2' to 3' of snow near the summit of Ebbetts Pass (SR 4). In wet years, there could be 10' to 12' of snow accumulation at this location. Moreover, there are sections that are a couple of hundred feet long that can have snow drift accumulation up to 80 ft. At SR 120, the snow blowers stayed on the pavement. A small dozer or snow cat is often used to get up on the snow to push snow down to the snow blower.

MPRO System Testing and Evaluation

The MPRO system was installed on a research vehicle and driven on all three mountain pass routes in 2021 to evaluate the MPRO system without hindering regular snow removal operations.

The test and evaluation objectives were:

1. Verify map accuracy and functionality. After loading the new base map onto the MPRO system, the map accuracy was checked visually as the vehicle was driven on mountain passes. The maps (X, Y, and elevation) matched well with the real-time GPS location data throughout the three passes. Snow posts and signs provided good reference points to the map accuracy. The MPRO system performed well as expected without any anomalies on both the test vehicle and snow removal vehicles.
2. Evaluate the V500 GNSS smart antenna field performance.
 - a. Examine the number of GNSS satellites used for position solutions particularly at GNSS-challenged locations. The majority of Ebbetts Pass (SR 4) has dense, tall trees along the narrow highway. Most of Ebbetts Pass does not have a center dividing line. It is the most GNSS-challenged area. The V500 smart antenna performs well on SR 4. The number of GNSS satellites used was often greater than nine. The position accuracy was within 1' which is sufficient for MPRO DAS.
 - b. Determine Atlas H10 SBAS service availability on all three mountain passes and locations where GNSS signal availability was limited due to terrain and/or vegetation (dense trees). Availability was good.
 - c. Evaluate V500 GNSS smart antenna's position and heading solution accuracy with Atlas H10 SBAS services. The position accuracy was within 1' at speeds below 5 mph. However, the position accuracy decreased as vehicle speed increased. At over 10 mph, the position accuracy degraded to about 2' to 4'. Since the snow removal operation vehicle speed is under 5 mph, the vehicle speed degrading of the position accuracy should not be detrimental to the MPRO system.

User feedback

1. Both the operators and AHMCT researcher are presently surprised and impressed with the V500 GNSS smart antenna position and heading accuracy even under dense trees.
2. Operators like having the map displaying above-ground obstacles, such as snow post, postmile markers, guardrails, road signs, and buildings (rest stop bathrooms) at visitor points. The displayed map helps them avoid damaging snow posts, postmile markers, and guard rails, which are often completely covered in snow. Any damaged snow posts, signs, and postmile markers would require repair or reinstallation after the snow removal operation before the road opens.

Operator and supervisor feedback were generally positive. Based on results and operator feedback, providing the MPRO system is effective in assisting in mountain pass opening. It is hopeful that there will be enough snow next year to more thoroughly test the system.

Problems and Issues that Affected Product Deployment

1. Atlas H10 SBAS service must be renewed annually followed by update of the receiver with authorization code. Funds are required for the SBAS service that is vital for the MPRO system operation.
2. MPRO system parts, such as the tablet, may require storage in off-season.
3. The 3D base map may require updates after several years or major changes on the highway. Caltrans Survey can perform new map survey using the MTLs system, which has proven to be an effective methodology for creating high-accuracy 3D digital maps.
4. The trained user base, as well as operator familiarity, can be disrupted if there are a few dry years and then a few wet years.
5. Battery maintenance of the tablet must be handled carefully. This will be essential when the system is in active use, but it is also important in the off season or in dry years.

Solutions to Noted Problems and Issues

- Continue training and support on MPRO system setup and usage
- Procure spare parts
- Work with local maintenance yard and DOE personnel to support future deployment

Issues Expected to Affect Full Implementation

AHMCT does not anticipate any major issues that will prevent the MPRO system from full implementation. However, there is some preparation work required to get the MPRO system working before each road opening season. A transition process would enable Caltrans to carry out these preparation tasks to activate the MPRO system each year.

Other Considerations for Reaching Full Product Deployment

Equipment Issues

The tablet battery will self-discharge after a few weeks even after a complete shutdown. The table may require recharging before use in the next road opening season.

Operational Issues

1. Purchase and activated Atlas H10 SBAS service yearly
2. Test the MPRO system after SBAS service activation to ensure the system is working properly
3. Training new operators to use the MPRO System

Policy Issues

Develop a policy to determine who, when, how, and funding sources for procuring the Atlas H10 SBAS service yearly for different snow removal equipment at different Districts.

Chapter 6:

Conclusions and Future Research

Conclusions and Recommendations

Key contributions of this research project included:

- Designed and built eight MPRO systems
- Demonstrated the portability of the MPRO system across vehicles and sites
- The current project demonstrated that MTLs works well for creating high-accuracy digital maps for vehicle guidance and driver assistance applications in a cost-effective manner. This approach allowed rapid generation of a highly-accurate base map for use in the MPRO system. Caltrans Survey can perform base map surveys in the future.
- Completed development of the MPRO software for Android OS
- Developed a V500 GNSS smart antenna test app and data logger for Android OS
- Developed a two-page, double-sided laminated training and configuration guide for the MPRO system and its components
- Conducted user training and system demonstration at SR 4, SR 108, and SR 120
- Integrated the current technological advances commercially available since the last MPRO system hardware design. The new GNSS system takes advantage of state-of-the-art GNSS technology and supports new GNSS constellations, resulting in major improvement in its performance in GNSS-challenged locations.
- Conducted field-testing of the MPRO system, and the results indicated the system is ready for widespread use within Caltrans road opening operations

Future work

- Add a robust data logging feature to the MPRO Android app to provide better statistical data for evaluating of the V500 GNSS smart antenna performance at different mountain passes
- Install and test MPRO system on a snow cat and/or small dozer, which are yearly rentals not available until March

Appendix A:

V500 Cable to L-com M12 to FTDI USB to RS232 Converter pin out

Table A.1: V500 cable to L-com M12 to FTDI USB to RS232 converter pin-out

| V500 Connector Pin # | Function | V500 Cable Color | L-com M12 cable Color | FTDI USB to RS232 Cable Color |
|----------------------|-----------------|--------------------|-----------------------|-------------------------------|
| 1 | Power + | Red | Red & Pink | |
| 11 | Port A RS232 RX | Pink | White | |
| 12 | Port A RS232 TX | Turquoise | Yellow | Orange |
| 13 | Signal Ground | Black-White Stripe | Green & Brown | Yellow |
| 21 | Power + | Brown | Red & Pink | Black |
| 22 | Power- | Black | Blue & Grey | |