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13. ABSTRACT (Maximum 200 words)
The overall goal of the Positive Train Location (PTL) project is to develop a system capable of providing the onboard PTC system with timely and accurate position reports of the head-of -train (HOT) and the end-of-train (EOT) for determining track discrimination and train length without the use of a track database or wayside infrastructure. To accomplish this, an onboard Global Navigation Satellite System (GNSS) receiver and auxiliary sensors should reach a position accuracy of < 18.55cm (1 σ). The PTL Phase II project builds on the successes of the proof of concept demonstrated during the Phase I portion of the project. Phase II took the commercial off-the-shelf (COTS) manufacturer development kits from Phase I, incorporated them into the proper locomotive form factor, and integrated them with the onboard PTC system.

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1 pint (pt)	=	0.47 liter (l)			
1 quart (qt)	=	0.96 liter (l)			
1 gallon (gal)	=	3.8 liters (l)			
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)	1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)	1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)
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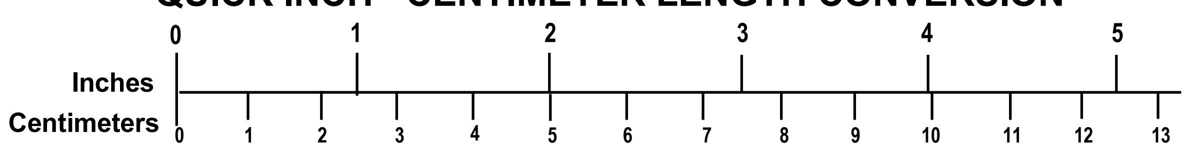

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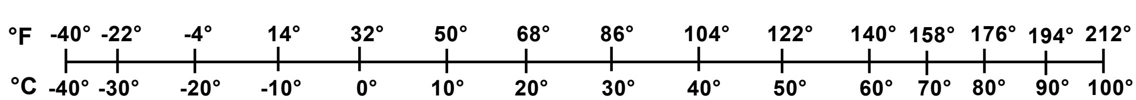

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Executive Summary

The Federal Railroad Administration (FRA) sponsored a research and development program executed by Transportation Technology Center, Inc. (TTCI) to develop the requirements for Positive Train Location (PTL) and to develop such a system. This report describes the efforts and findings from Phase II of this program, performed May 2012 through January 2017.

The goal of the Positive Train Location (PTL) project was to develop a system that can accurately determine the position of the front of the train and the rear of the train to an accuracy of less than 1.2 m, at a confidence level of 99.999999997% (10 nines), in order to define train length and track discrimination. The PTL system uses an onboard Global Navigation Satellite System (GNSS) receiver and auxiliary sensors to support positioning when GNSS satellite visibility (including GPS) is degraded or not available. Phase I sought to develop a Proof-of-Concept (POC) prototype PTL system. Under Phase II, the POC prototype was integrated and tested with an Interoperable Train Control (ITC) compliant PTC onboard system.

The following are key results from the PTL project:

- Phase I - Locomotive head-of-train (HOT) position accuracy with a track database was 0.15 m (1 σ) across-track and 0.18 m (1 σ) along-track, enabling the PTL system to achieve confidence levels of 12 nines and 10 nines, respectively. End-of-train (EOT) position accuracy was 0.11 m (1 σ) across-track and 0.27 m (1 σ) along-track, allowing for confidence levels of 15-plus nines in across-track and 5 nines in along-track performance.
- Phase IIa.1 –HOT position accuracy without a track database was 0.18 m (1 σ) across-track and 0.24 m (1 σ) along-track, enabling the PTL system to achieve confidence levels of 10 nines and 5 nines, respectively.
- Phase IIa.2 –EOT position accuracy without a track database was 0.396 m (1 σ) across-track and 0.461 m (1 σ) along-track.
- PTL's communication link – As anticipated, the 900 MHz band exhibited significant bit error rate (BER) at distances greater than 0.8 mi (1,287.5 m). Near-zero BER was observed for 220 and 450 MHz at 4.5 mi (7,242 m).

PTL Phase IIa.1 testing demonstrated an increase of measurement standard deviation for both across-track and along-track positioning metrics as compared to Phase I. This position performance degradation was attributed to a combination of change of wheel speed sensor (WSS) device in addition to the new constraint of restricted track database application. Even subject to these constraints, Phase II HOT across-track error standard deviation was observed to remain consistent with PTL level of confidence requirements. Phase II along-track standard deviation was observed to have degraded from 17 cm to 24 cm (in the absence of a track database), with marginal improvement of 22 cm with a track database. In response, the railroad advisory group indicated that a 6 cm increase of along-track error was acceptable and would not impact track discrimination confidence or siding position margin relative to main track clearance.

Phase IIa.2 EOT positioning performance in the absence of a track database demonstrated across-track and along-track error standard deviations of 40 cm and 46 cm, respectively. However, application of a track database significantly reduced across-track and along-track error

standard deviation to 11 cm and 27 cm, respectively. Consequently, application of a track database to at least EOT positioning is strongly encouraged to appreciably reduce position error.

Finally, use of a 900 MHz center frequency for EOT-to-HOT communications was demonstrated to be insufficient to accommodate PTL range requirements subjected to end-of-train device (ETD) rear car masking. As testing at the lower 160, 220, and 450 MHz frequencies demonstrated, extended range performance is feasible. As a consequence of PTL operational track testing during Phases IIb and IIc, an alternative radio communication data link leveraging multiple low frequency bands is presently in progress and is anticipated to enhance this challenging communication link.

1. Introduction

Train location is a key input for Positive Train Control (PTC) systems to effectively track against authority limits and speed restrictions along the train route, and to enforce those limits and restrictions when necessary. While Global Positioning System (GPS) data is typically used to collect this information in most PTC systems, under some conditions the PTC system could benefit from higher accuracy location determination. The Federal Railroad Administration (FRA) funded a research and development program executed by Transportation Technology Center, Inc. (TTCI) to develop the requirements for Positive Train Location (PTL) and to develop a system that meets these requirements. This report describes the efforts and findings from Phase II of this program.

1.1 Background

PTC is a technology designed to automatically stop a train before certain types of accidents occur. PTC is intended to keep a train within authorized limits on a track and under its speed limit. To accomplish this, movement authorities and speed limits are electronically transmitted to the train, which follows its position relative to these limits and employs predictive braking enforcement algorithms to automatically bring the train to a safe stop before violating a limit. PTC is designed to prevent train-to-train collisions, over-speed derailments, unauthorized incursions into established work zones, and movement of a train through a main line switch in the wrong position. The Rail Safety Improvement Act of 2008 [1] mandates installation of interoperable PTC on all main lines with regularly scheduled intercity passenger or commuter service, and on all main lines over which poisonous or toxic-by-inhalation hazardous materials are transported.

Most PTC systems rely on GPS to identify the location of the controlling locomotive of a train. The location of the rear of the train is then derived from the location of the locomotive using the train length typically provided by the railroad's management information systems (MIS) and confirmed or updated by the locomotive engineer. The MIS train length is an approximation and is not considered to be reliable enough by itself to determine the actual length of the train. Train length is critical data that needs to be dependable, as operating performance and safety can be affected when truncating or releasing movement authorities behind a train, especially in dark (unsignaled) territory. In addition, the GPS-based location used by PTC systems does not provide a sufficient level of accuracy to perform track level discrimination under all conditions.

Improved accuracy of location determination will provide more reliable location data to the PTC onboard system for dependable track discrimination, especially important during initialization in multiple-track territory. The ability to locate the locomotive and the rear end of a train with greater accuracy, in conjunction with other enhancements, will permit the railroads to explore several options to improve the operational reliability of the PTC system. These options could potentially include:

- Automatic truncation and release of train authorities in dark territory
- Automatic determination of train clearing a grade crossing
- Automatic determination of train clearing a power-operated switch with no track circuit (for future use)
- Less degradation in capacity

- Determination of train integrity (train split or intact)
- Moving block operations
- Possible inference of train weight accuracy

This project has been identified by the FRA and the Association of American Railroads (AAR) committees as critical to the successful long-term implementation of PTC, from both operational effectiveness and safety perspective. It is the intent that, once developed, these capabilities may be incorporated as interoperable train control (ITC) standards, which specify standards for interoperable PTC systems in use and being deployed by U.S. Class I and many commuter and short line rail carriers.

1.2 Objectives

The overall objective of the PTL program was to develop a system to determine and report the position of both the controlling locomotive head-of-train (HOT) and end-of-train (EOT) with along-track and across-track accuracy of < 1.2 m, at a confidence level of 99.999999997%. To accomplish this, the PTL system must be capable of providing position measurements to an accuracy of < 18.55 cm (1 σ) along- and across-track standard deviation.

The primary objective of Phase II was to expand the development of the POC PTL system developed under Phase I for integration with an ITC-compliant PTC onboard system and with an end-of-train device (ETD) and testing on revenue-service territory:

- Phase IIa.1 objectives were to demonstrate up to three PTL HOT units using locomotives equipped with an ITC-compliant onboard PTC system on track at the Transportation Technology Center (TTC).
- Phase IIa.2 objectives were to demonstrate up to three pairs of PTL systems (PTL HOT and PTL EOT) units using locomotives equipped with an ITC-compliant onboard PTC system on track at TTC.
- Phase IIb objectives were to demonstrate up to four PTL HOT units and three PTL EOT units during two weeks of unattended testing on host railroad pilot territory.
- Phase IIc objectives were to demonstrate up to four PTL HOT units and three PTL EOT units on a larger scale (three weeks) of unattended testing on host railroad pilot territory.

Additional objectives included in Phase II efforts were to:

- Finalize PTL locomotive interface control document (ICD)
- Define requirements for the PTL HOT-EOT radio link, implement in hardware and perform a radio test evaluation
- Develop an integration specification for integrating PTL EOT with an ETD
- Develop, implement, and test an algorithm to detect and report pull-aparts within a train consist
- Perform environmental testing on PTL HOT and PTL EOT components

1.3 Overall Approach

This project was conducted by TTCI and Leidos in close cooperation with an advisory group with representation from:

- CSX Transportation (CSX)
- Norfolk Southern Railway (NS)
- BNSF Railway Company (BNSF)
- Union Pacific Railroad (UP)
- FRA

Phase II integrated the PTL system with the ITC PTC system in the proper form factor (HOT auxiliary card cage [ACC] Card and ETD), followed by field testing at TTC and on revenue service railroads. Position measurements from PTL testing were compared to a "truth" reference real time kinetic (RTK) system at TTC and to survey data in the case of revenue service testing.

1.4 Scope

Phase II consisted of:

- Prototyping the POC and verifying that the system was a commercially-viable technology
- Testing the prototype system using locomotives equipped with an ITC-compliant PTC onboard system, on dedicated test track at TTC and on revenue-service tracks
- Evaluating the 900 MHz radio data link performance as it applies to PTL operational scenarios
- Integrating the PTL system into the correct locomotive form factor

The project scope was expanded to refine certain PTL functions and explore future PTL uses in the following areas:

- Enhanced statistical analysis of Phase II data
- PTL locomotive interface control document development
- Wrong-side failure (WSF) analysis support
- PTL production radio implementation
- PTL EOT/ ETD integration specification development
- PTL decoupling (pull apart) detection schema development
- Environmental testing report

1.5 Organization of the Report

This report is organized into the following sections:

- Section 1 provides background information on the project
- Section 2 provides overviews of the PTL system
- Section 3 provides testing the PTL's positioning performance
- Section 4 provides testing the PTL's communication link
- Section 5 presents design challenges
- Section 6 discusses next steps
- Section 7 contains project conclusions

2. PTL Overview

The main objective of the PTL system is to provide the PTC system with accurate and timely HOT and EOT positions, from which enhanced train length can be derived (compared to the manual input). PTL requirements prescribe the level of positioning accuracy to ensure track discrimination to > 10 nines (0.99999999990); i.e., position error < 1.2 m with probability = 0.99999999990. To accomplish this, the PTL system must be capable of providing position measurements to an accuracy of < 18.55 cm (1 σ) along-track and across-track standard deviation. In addition to track discrimination capability as determined by across-track accuracy, along-track accuracy is critical to ensure that both HOT and EOT are safely secured within a siding to avoid fouling main track. Finally, this level of accuracy must be accomplished without aid of external infrastructure. This implies that deployment of fixed RTK base stations or subscription services are not allowed. Consequently, positioning must be accomplished solely by an onboard Global Navigation Satellite System (GNSS) receiver and auxiliary sensors to support positioning when GNSS satellite visibility (including GPS) is degraded or not available.

Generally available low-cost GPS receivers can only provide measurements with accuracy on the order of 200 cm (1 σ). Consequently, a high performance GNSS receiver is required to improve measurement confidence. Even the most capable GNSS receivers without aid of external reference or satellite subscription service can only provide 30 cm standalone position accuracy. Additional sensors and sophisticated measurement filtering are necessary to reduce position error to within the 18cm objective. These additional sensors include onboard locomotive devices such as a wheel speed sensor (WSS) and gear selection signal to determine direction of travel or stoppage. Auxiliary sensors also include a 3-axis accelerometer, gyros and altimeter. These sensors are optimally integrated through a process of sensor fusion that leverages Leidos' Embedded Data-fusion Geospatial Engine (EDGE). EDGE consists of a library of sensor fusion and filtering algorithms that may be generally applied to any set of sensors capable of providing position, velocity, or heading (PVH) information. Comprehensive simulations were performed to identify a suite of sensors that yielded a level of performance sufficient to provide PTL accuracy requirements at minimal cost. Once the appropriate sensors had been selected and rigorously tested on test and operational track, the resulting integrated hardware/software solution evolved to become the PTL system.

2.1 What is PTL Designed to Do?

Highly dependable automatic determination of which track a train occupies (i.e., track discrimination) is needed, in particular for cases where a PTC-equipped train must initialize in multiple-track territory. PTL has been designed to provide accurate PVH measurements for HOT and EOT positions, along with the relative range between HOT and EOT. What makes PTL unique is the 18 cm (1 σ) accuracy that enables PTC to perform locomotive track discrimination with a confidence level exceeding 99.99999999% (10 nines).

2.2 What Benefits is PTL Intended to Provide?

PTL provides an enabling technology for PTC to identify locomotive and last railcar operational track (track discrimination) through the provision of highly accurate PVH information for both HOT and EOT hosts. This reduces the potential for error in selecting the wrong track when the PTC system is initialized and must determine which track the train is occupying. Simultaneous

HOT and EOT position determination is also useful to PTC for verifying train length. PTL further provides this level of accuracy without dependency on external infrastructure including subscription services, wayside assets or track databases. PTL also provides improved dead reckoning (lower error growth rate) when GPS signals are not available. Accurate knowledge of HOT and EOT further ensures secure railcar positioning on sidings without delay.

2.3 High-level Architecture of the PTL System

Figure 1 depicts the PTL high-level hardware architecture consisting of the Catalyst TC processor module, Septentrio AsteRx-M GNSS receiver, Analog Devices ADIS16448 Inertial Measurement Unit (IMU) and Intuicom C1000µ 900 MHz radio.

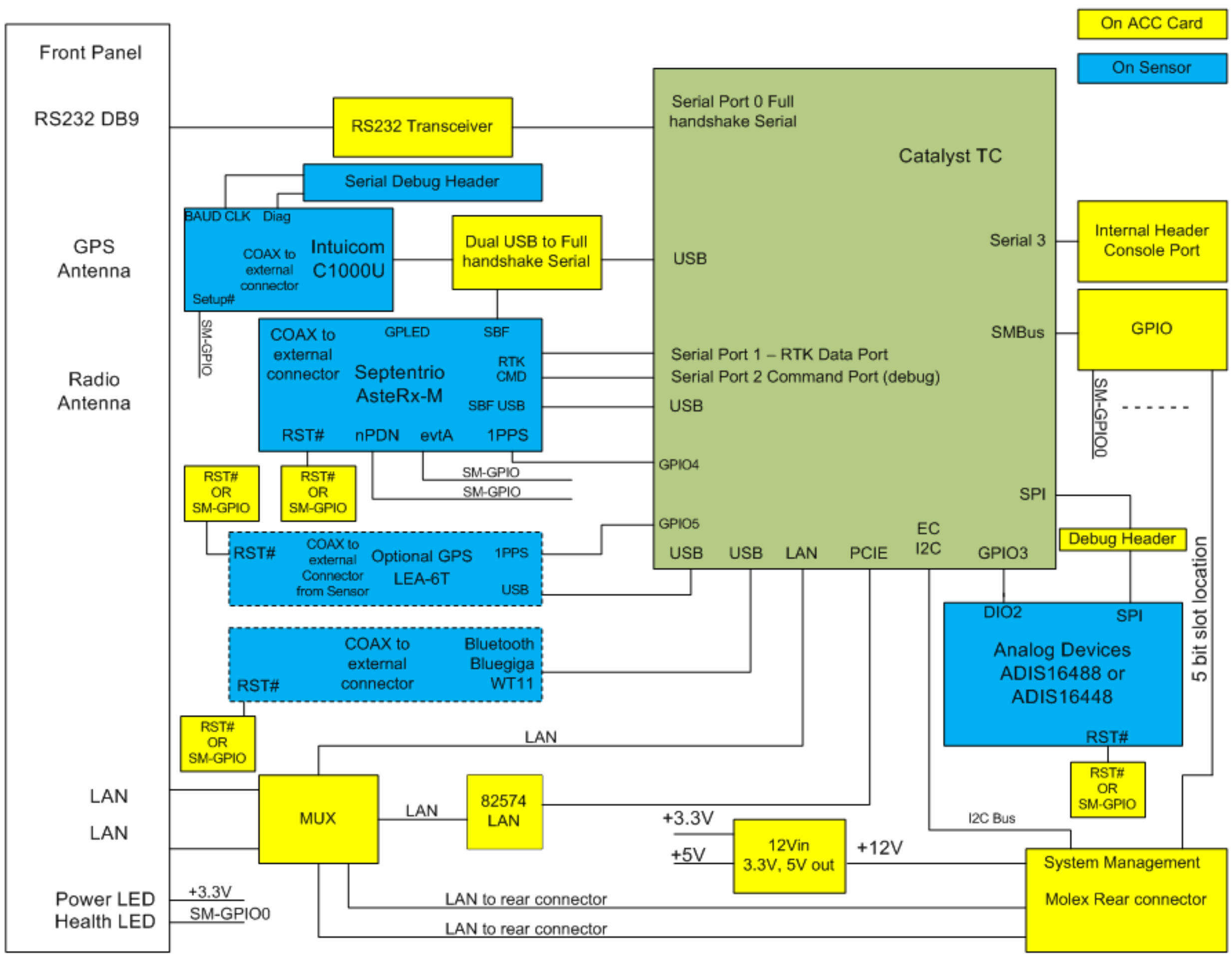


Figure 1. PTL High Level Architecture

2.4 The PTL HOT Unit

Figure 2 depicts the PTL HOT unit consisting of an ACC compliant circuit board. The PTL ACC card is operational in any ACC card slot and may be communicated with via the front panel Ethernet, backplane Ethernet or RS232 front panel serial port. Front panel interfaces accommodate up to two M12-terminated Ethernet cables, one GNSS antenna cable (N-Male), and one 900 MHz antenna cable (RP TNC). Front panel LED lights indicate device operational state and health status.

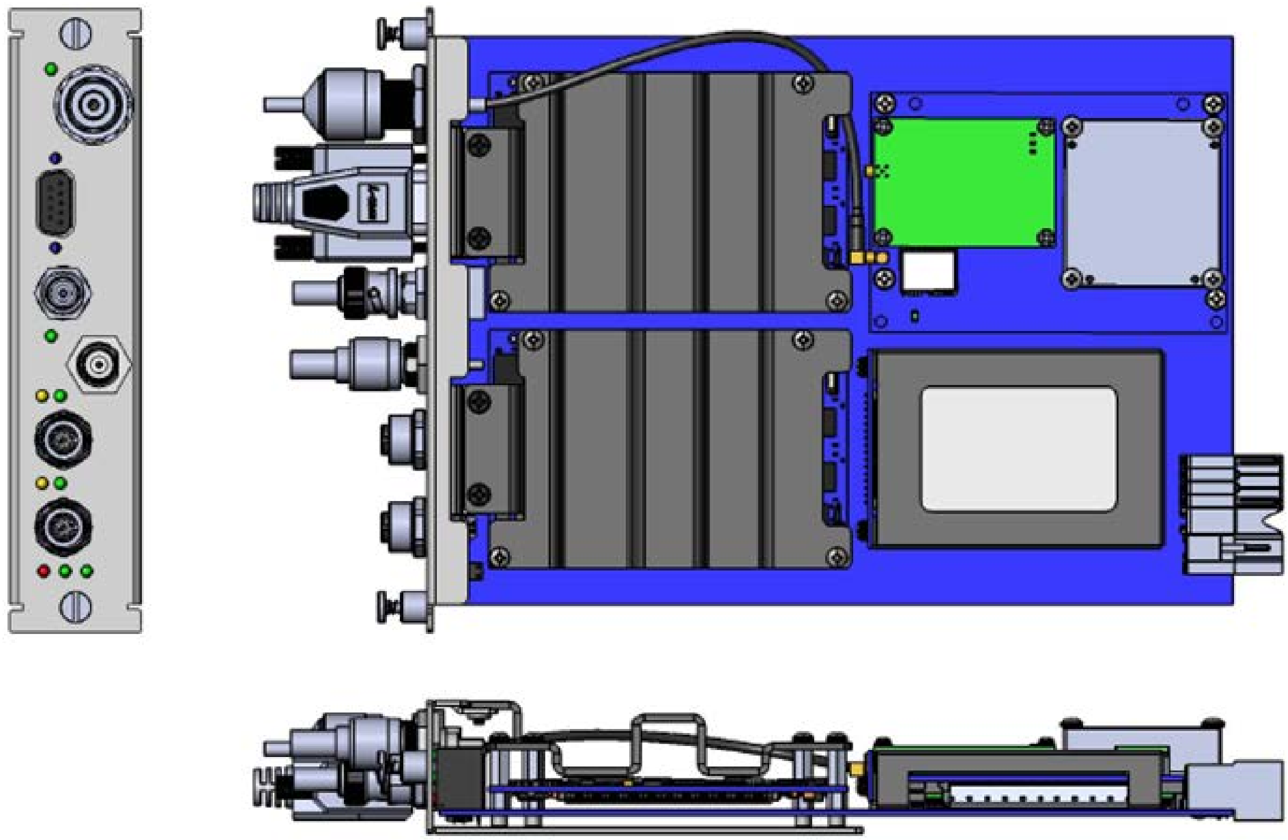


Figure 2. HOT ACC PTL Card

2.4.1 Hardware Description

As indicated in Figure 1, the PTL ACC card hosts two GbE ports that are controlled by the primary Catalyst TC CPU. By default, the CPU onboard LAN is connected to the front panel M12-1 connector and rear Molex connector as a 1000BaseT connection. Under software configuration, backplane Ethernet may be switched to the front panel M12-2 connector. Front panel Ethernet ports support both 100BaseT and 1000BaseT. The front panel provides an N type connector for GPS and a TNC Reversed Polarity connector for the Radio. The front panel further provides a full handshake EIA-232 serial port using a male DE-9 connector. The port is optically isolated. As indicated in Figure 2, nine LEDs are further provided on the front panel to provide visual indication of system operational status.

Table 1 depicts the PTL hardware components, dimensions, weight, power, and connector interface requirements.

Table 1. Hardware Description

Component	Weight	Dimensions (mm)	Power	Mating Connector
Analog Devices ADIS16488	48 g	44.3 x 47.3 x 14.3	3.3V @ 840mW	SAMTEC CLM-112-02
Analog Devices ADIS16448 (optional)	TBD	37.7 x 24.2 x 11	3.3V @ 343mW	SAMTEC CLM-110-02
Septentrio AsteRx-m_OEM	47 g	70 x 47.5 x 7.56	3.3V @ 600mW	**RF Connectors:** U.FL **I/O Connector:** Hirose DF40C-30DP-0.4V(51)
Ublox NEO-6T	1.6 g	16.6 x 12.3 x 2.6	2.7 – 3.6V 3.3V @ 221mW	Surface Mount
Intuicom's OEM C1000µ	18 g	36 x 50.8 x 9.6	3–5.25V @ 2W	**Data Port:** Samtec CLM series 14 pin 2mm **Antenna:** MMCX Connector
Eurotech Catalyst TC Module	43 g	67 x 100 x 6.3	3.3 and 5V @ 3-7W	**Docking Connector: Data** Tyco Electronics 3-1827253-6, 5mm stacking height Tyco Electronics 3-6318491-6, 8mm stacking height **Docking Connector: Power** Samtec MW-07-03-G-D-095-085, 5mm stacking height Samtec MW-07-03-G-D-226-065, 8mm stacking height
ACC Application Card	TBD	158.75 x 223.75 x 2.41	12 V Max 30 W	**Molex GBXI-Trac** Molex P/N 76020-3004 (primary connector) Molex P/N 78229-1002 (12 VDC power connector)

2.4.2 ACC Card Design

The ACC card assembly has been designed to comply with environmental requirements as defined in the *AAR Manual of Standards and Recommended Practices*, Section K-V, Standard S-9401.V1.0 (formerly MSRP Standard S-5702), "Railroad Electronics Environmental Requirements," Revised 2009 [2]. Temperatures are measured at any physical boundary of the mechanical envelope of the ACC card assembly. The temperature requirements are from -40ºC to +70ºC.

2.5 The PTL EOT Unit

While the PTL EOT unit maintains the same functionality as the PTL HOT, it employs a more compact form factor to accommodate ETD integration as depicted in Figure 3. Functionally, the only distinction between HOT and EOT is device configuration, whereby the EOT is configured as a slave with respect to the HOT master. Consequently, the EOT employs its integrated 900 MHz radio to transmit its position information and RTK data to the HOT. The HOT then refines EOT position information by application of its stored past position history, a process termed Backward Propagation. The resulting HOT and EOT PVH data is then communicated to the Train Management Computer (TMC) interface for PTC processing.

Figure 3. PTL EOT Unit

2.5.1 Hardware Description

Figure 4 depicts the PTL EOT high-level hardware architecture. As observed, the EOT hardware employs identical sensors as the HOT to enable equivalent navigation functionality. However, in comparison with Figure 1, it is observed that the EOT does not require the additional interface hardware to accommodate ACC chassis implementation. Consequently, only one Ethernet interface is used, and there is no provision for an ACC system management interface. While similar circuitry is employed, the EOT circuit board is further designed to accommodate a more compact form factor suitable for ETD integration.

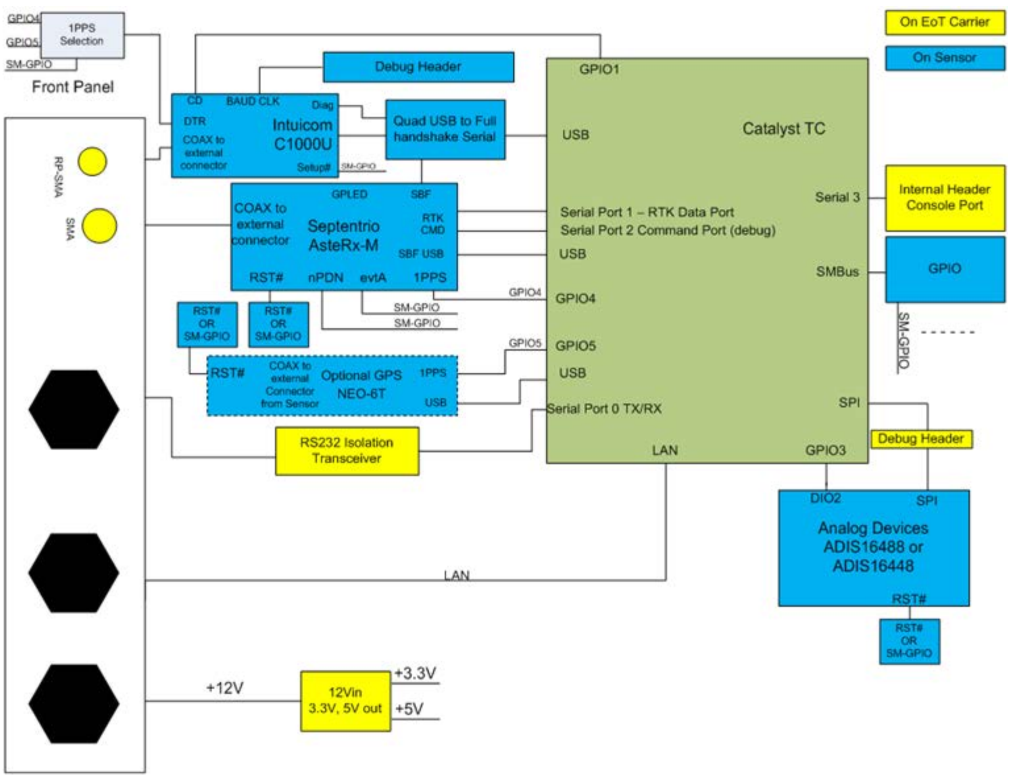


Figure 4. PTL EOT High Level Architecture

Since the PTL EOT obtains power from the ETD air turbine and its internal battery, EOT power consumption is critical. Thus, to accommodate the ETD power source, the EOT operates over an input voltage range from 10.8 to 13.2 volts and maximum power draw of 30 watts, with approximately 10 watts as typical.

2.5.2 Prototype integrated with ETD

Figure 5 shows a photograph and the profile mechanical drawings (back, left, right, front) of the prototype ETD fabricated by DPS Electronics (DPS). DPS rapidly made a prototype PTL EOT ETD using an existing DPS design. To facilitate fabrication, an AeroAntenna GNSS antenna and 900 MHz radio antenna were top mounted without a radome cover. Internal design remains the same as the mechanical drawings. As indicated in Figure 6, the PTL EOT unit is shock mounted within the DPS ETD to mitigate vibration impact on the IMU. Access to EOT serial and Ethernet connectors are found beneath a weather proof cover plate and are generally used for diagnostic purposes only. During typical operation, the EOT transmits its PTL state and RTK data to the HOT unit for PTC dissemination.

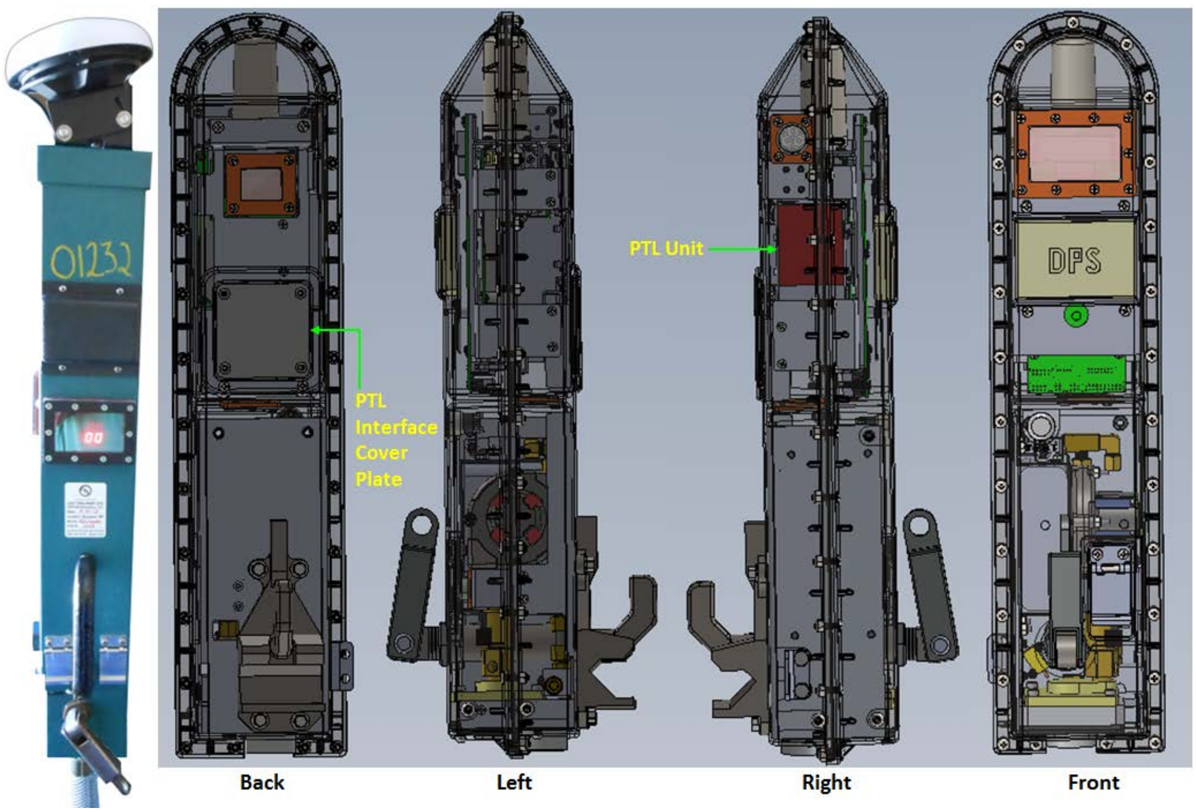


Figure 5. PTL EOT Integrated within DPS ETD

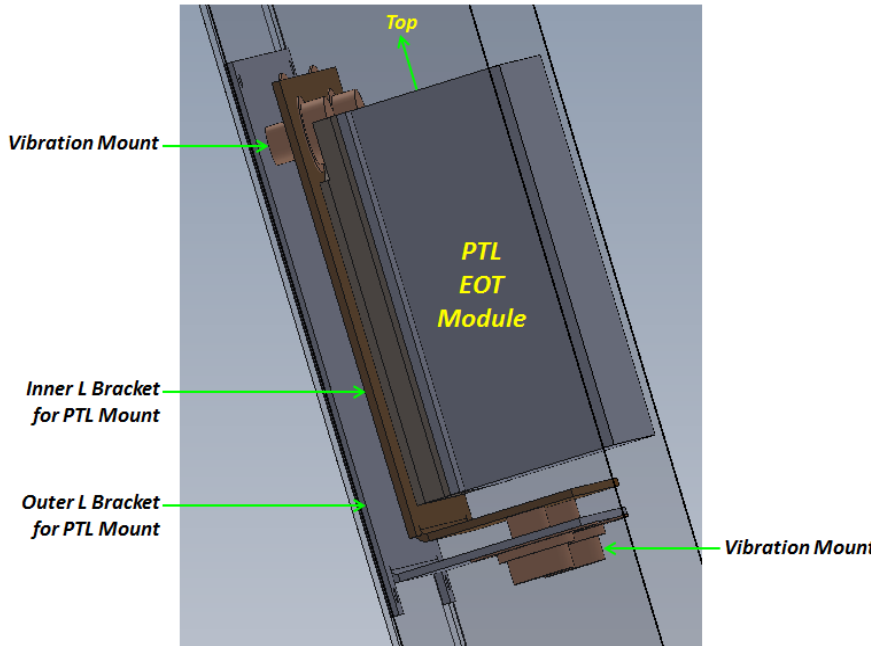


Figure 6. PTL EOT Shock Mounting

2.6 Integration of PTL with Existing Onboard Systems

While resident within an operational ETD, the PTL EOT unit does not interface with any ETD functions and only uses the ETD as a power source. At the HOT, the PTL HOT unit interfaces with a Wabtec WSS and locomotive gear selector through the Wabtec PTC TMC interface. PTL HOT input messages are sourced from the Wabtec Interoperable Electronic Train Management System (IETMS®) Locomotive 3000 series message Data Distribution. Table 2 lists the subsets of the 3000 series messages used by the PTL System. For purposes of radio pairing, PTL will further support ETD ID input from an auxiliary message source once the corresponding message interface has been defined.

Table 2. Onboard System Input Message

Byte	Field Name or Value	Number of Bytes	Type	Description
33	Throttle Notch	1	uint8	4 msb's = Throttle Notch 4 lsb's = Reverser
44,45	Speed	2	uint16F	Wheel Tach Speed, ft/sec

PTL HOT/EOT ITC output messages are provided within two National Marine Electronics Association (NMEA) output strings. For each of the two message strings, there are both HOT and EOT versions, providing a total of four NMEA message groups

3. Testing of PTL's Positioning Performance

The PTL system has evolved over two project phases. During the Phase I effort, Leidos integrated commercial off-the-shelf (COTS) manufacturer development kits to demonstrate system potential accuracy capability. From the successful demonstration of Phase I system performance, Phase II was awarded and a compact, ruggedized PTL design was developed. Throughout Phase I and Phase II, a succession of tests were conducted to refine and demonstrate PTL performance on test track at TTC and on railroad operational track. The following summarizes these test events.

3.1 Testing at TTC

3.1.1 Phase I (PTL HOT and PTL EOT)

Phase I testing conducted at TTC addressed the impact of environment phenomenology (GPS multipath and radio communication loss) and operational parameters (direction of motion, speed and availability of surveyed track) on PTL system performance. Nine test categories and 24 distinct test procedures were designed by TTCI to assess PTL response to a variety of anticipated conditions, and they are summarized in Table 3. Data from these test procedures was used to address PTL response to a variety of external influences.

Table 3. Phase I Test Procedure Summary

No.	Category	ID	Description
1	Location Performance	1A	On the RTT in clockwise (CW) direction at constant speed (10 and 50 mph) and variable speed)
1	Location Performance	1B	On the RTT in counterclockwise (CCW) direction at constant speed (10 and 70 mph) and variable speed
1	Location Performance	1C	Transitions between surveyed and unsurveyed track and at switches and when traveling at 1 mph and at switch speed
1	Location Performance	1D	Balloon Loop to turn the train in CW and CCW directions
1	Location Performance	1E	RTT and TTT tracks and siding in CW direction at constant speed 40 mph
2	Train Stopped	2A	Train is stopped
3	Track Discrimination	3A	Locomotive PTL system powers up
3	Track Discrimination	3B	PTL system powers up in proximity of unsurveyed track
3	Track Discrimination	3C	Portion of the train is on unsurveyed track
4	Switching Moves	4A	Under switching moves
5	Radio Failures	5A	Under radio communication failures
6	GPS Multipath	6A	Under GPS multipath and when the rear of train PTL System's view of the sky is blocked by other cars
7	Train Dynamics Scenarios	7A	Under specific train dynamics scenarios
		7B	Under specific train braking scenarios
8	Speed Measurement	8A	Moving at high speed, and under acceleration and deceleration
9	Signals Unavailable	9A	External inputs unavailable for 1 hour and the train is moving without stopping
9	Signals Unavailable	9B	External inputs unavailable for 1 hour; train is moving, stopping, reversing direction
9	Signals Unavailable	9C	Externals inputs unavailable for 50 miles and train is moving without stopping
9	Signals Unavailable	9D	External inputs unavailable for 50 miles; train is moving, stopping, reversing direction
9	Signals Unavailable	9E	Compare Science Applications International Corporation's (SAIC) post-processing results after processing to same input data without GPS
9	Signals Unavailable	9F	Compare SAIC's post-processing results after processing to same input data without GPS
9	Signals Unavailable	9G	Train operates through a tunnel
9	Signals Unavailable	9H	Train operates through a tunnel
9	Signals Unavailable	9I	Train operates through a tunnel

As indicated in Figure 7, TTCI provided a Trimble SPS852 RTK reference receiver system employing a surveyed fixed base station as test instrumentation enabling reference position measurement on the order of 2cm horizontal position error standard deviation. Dual across-track antennas further enabled reference heading determination to an accuracy of 0.09 degree root mean square (RMS).

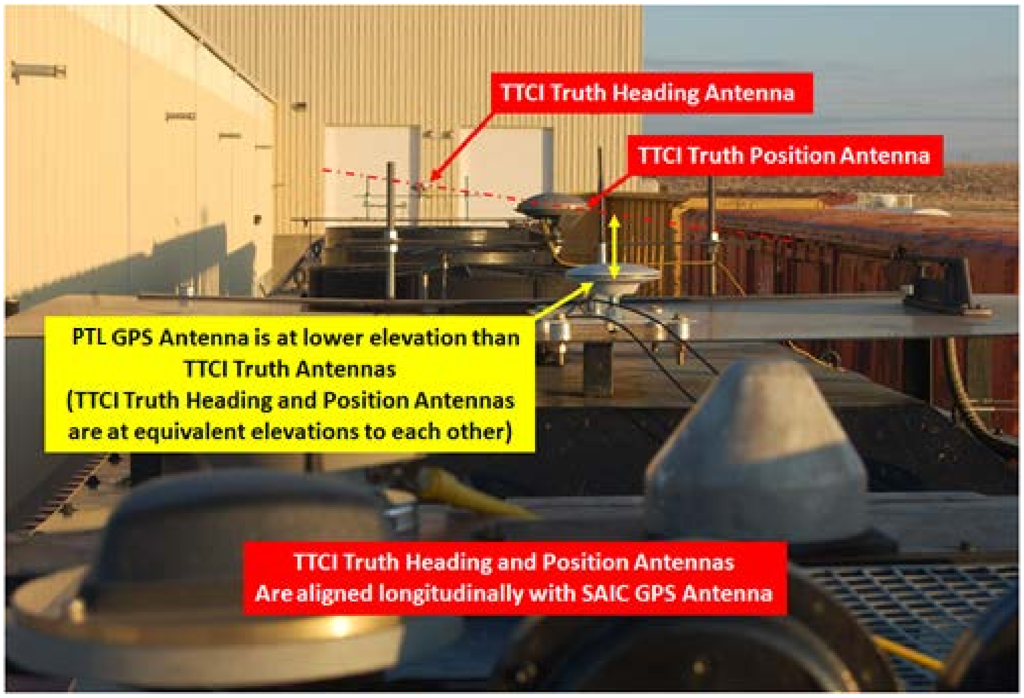


Figure 7. TTCI Reference System Antenna Configuration

Across-track and along-track positioning performance was assessed over aggregated test results for all in-motion test procedures with all sensors available (including GPS, IMU, and WSS) and a high-resolution track database. The resulting test results are summarized in Table 4.

Table 4. Phase I Across-Track and Along-Track Performance Summary

Key Performance Parameter	Requirement Value	PTL HOT x (Across)	PTL HOT y (Along)	PTL EOT x (Across)	PTL EOT y (Along)
Position Mean		0.09m	0.03m	0.23m	0.04m
Position Standard Deviation		0.15m	0.17m	0.11m	0.27m
Confidence at 1.2m	99.999999990% (10 nines)	99.99999999998% (12 nines)	99.9999999993% (11 nines)	99.999999999+% (15 nines)	99.998% (5 nines)
Velocity Mean (mph)		0.01 mph	0.01 mph	-0.01 mph	-0.01 mph
Velocity Standard Deviation (mph)		0.09 mph	0.09 mph	0.12 mph	0.12 mph
Confidence at 0.1 mph	99.99%	NA*	NA*	NA*	NA*
Heading Mean (degree)		0.05 deg	0.05 deg	0.14 deg	0.14 deg
Heading Standard Deviation (degree)		0.25 deg	0.25 deg	0.41 deg	0.41 deg
Confidence at 1 degree	95%	99.98%	99.98%	96.5%	96.5%

*Note: Reference system accurate to only 0.07 mph, invalidating statistics

Position error performance was observed to be excellent when all primary signals were available. Locomotive HOT position accuracy was 0.15 m (1 σ) across-track and 0.17 m (1 σ) along-track, enabling the PTL system to achieve confidence level of twelve nines and eleven nines, respectively. Rear of train EOT position accuracy was 0.11 m (1 σ) across-track and 0.27 m (1 σ) along-track, allowing for fifteen-plus nines in across-track and nearly five nines in along-track performance. Velocity and heading performance met requirements to the accuracy levels capable of being measured by the reference system.

As indicated in Figure 8, multipath can contribute significant impact on GPS receiver performance. Here, application of EDGE filtering is demonstrated to minimize system position error by using statistical measurement weighting to reject outlier GPS fixes resulting from multipath.

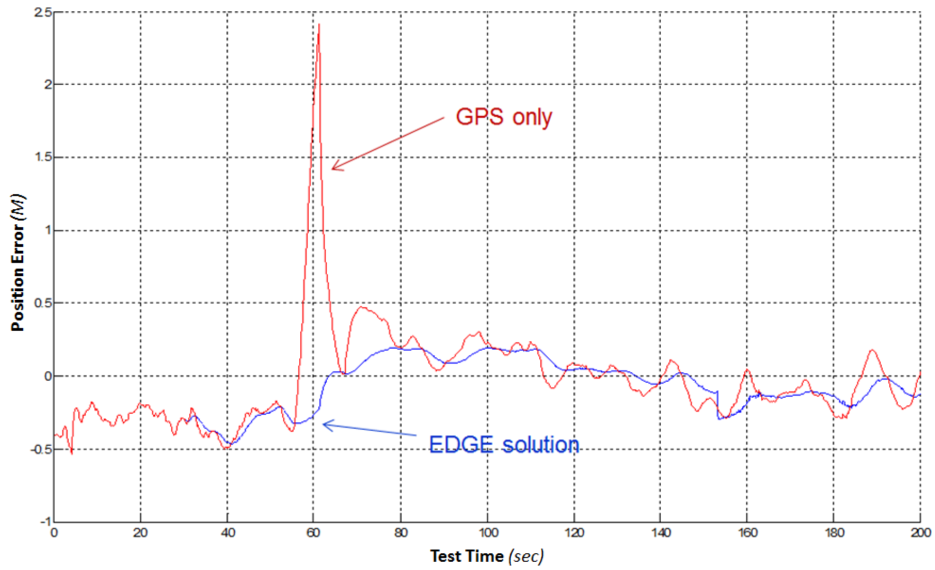


Figure 8. Phase I Along-Track Error in the Presence of Multipath

3.1.2 Phase IIa.1 (PTL HOT)

Phase IIa.1 HOT PTL testing was conducted at TTC during May 2013. The objective of this test was to demonstrate the PTL HOT unit installed on a locomotive equipped with an ITC-compliant onboard PTC system. Regression testing as well as validation of new functionality was also performed. As for all testing conducted at TTC, tests were performed as specified by the associated TTCI PTL test procedures. Table 5 summarizes aggregate PTL system performance (including wide area augmentation system (WAAS) GPS, stationary and motion conditions, and with track database available) as observed during Phase IIa.1 testing and demonstrated during Phase I testing for GPS unconstrained operations. The same methodology was employed for both Phase I and Phase IIa.1 test analysis. Specifically, data was collected at TTC and run through the EDGE filter in post-processing with a single unified set of filter parameters for all test scenarios. No custom-tuning was performed for any individual test procedure to ensure consistency and validity of results. As indicated, Phase IIa.1 testing yielded an increase of measurement standard deviation for both across-track and along-track positioning metrics as compared to Phase I. However, across-track error standard deviations for both Phase I and Phase II are observed to be below the 18 cm PTL threshold requirement. This capability ensures track discrimination capability with a level of confidence exceeding PTL requirements. Along-track Phase II standard deviation is observed to have degraded from 17 cm to 22 cm. The railroad advisory group has indicated that a 5 cm increase of along-track error would not impact track discrimination confidence or siding position margin relative to main track clearance. Accounting for fundamental differences between the Phase IIa.1 and Phase I test configurations, it is believed that this degradation results from (1) Phase II WSS message interface delay in contrast to the Phase I direct WSS device output and (2) increased PTL chassis mount vibration associated with Locomotive System Integration (LSI) rack installation versus Phase I chassis floor mount.

Table 5. Phase IIa.1 versus Phase I Performance Comparison (with Track Database)

Key Performance Parameter	Objective	PTL HOT Phase II.A.1 (with Track Database) x (Across)	PTL HOT Phase II.A.1 (with Track Database) y (Along)	PTL HOT Phase I (Optimized with Track Database) x (Across)	PTL HOT Phase I (Optimized with Track Database) y (Along)
Position Mean		-0.15m	0.04m	0.09m	0.09m
Position Standard Deviation (meter)	0.18m	0.15m	0.22m	0.15m	0.17m
Confidence Interval (fraction)	0.99999999997	0.9999999999994	0.99999995	0.99999999999993	0.99999999997
Confidence Interval (#nines)	10	12	7	13	10

Recognizing that a reference track database would not always be available during operational deployment, Phase IIa.1 performance results were further determined for the case of no reference track database, and summary results are captured in Table 6. As observed, across-track discrimination remained PTL compliant at 18 cm while along-track error increased by 2 cm.

Table 6. Phase IIa.1 Performance (without Track Database)

Key Performance Parameter	Objective	PTL HOT Phase II.A.1 (without Track Database) x (Across)	PTL HOT Phase II.A.1 (without Track Database) y (Along)
Position Mean		0.00m	0.10m
Position Standard Deviation (meter)	0.18m	0.18m	0.24m
Confidence Interval (fraction)	0.99999999997	0.99999999996	0.999997
Confidence Interval (#nines)	10	10	5

Phase IIa.1 HOT testing further investigated PTL positioning performance while operating within tunnels of various lengths. While database availability significantly reduces positioning error, operation without aid of a database is presented in Table 7 as being more representative of desired mode of operation. In the absence of a reference database, and without an accurate and "real time" WSS, no effective absolute positioning reference is available. Consequently, all positioning is dependent on unaided IMU capability and consequent drift. Even subject to these adverse conditions, good PTL performance is realized with a confidence = 0.999999990 (8 nines) with the absence of a database. Hence, for shorter duration intervals < 500ft of GPS denial, excellent positioning performance remains enabled. Due to the increased distance and time duration introduced by the long tunnel, increased error drift is observed in the absence of

GPS or effective WSS so that track discrimination confidence becomes unusable without aid of a reference track database.

Table 7. Phase IIa.1 HOT Performance in a Tunnel (without Track Database)

Category	Length (feet)	Across Track σ (meter)	Along Track σ (meter)
Short	500	0.18	6.68
Long	40,000	58.41	64.35

Along-track and across-track performance at the time of initialization and subject to GPS availability with at least 4 satellites was further assessed during Phase IIa.1 testing. Results with use of a reference track database are summarized in Table 8a, and performance results without database use are summarized in Table 8b. In both cases (i.e., with and without aid of a track database), it was observed that an appreciable bias results at the time of initialization when reported at 60 seconds after start-up. This was attributed to the time required for the GPS receiver to select the optimum available constellation of satellites for use in its solution. However, due to the prolonged integration time enabled by static initialization, significantly reduced across-track error standard deviations of 6 cm and 9 cm, respectively were observed; i.e., notably better than the 18 cm PTL threshold specification.

Table 8. Phase IIa.1 Initialization Accuracy

Parameter (status)	Position Difference x (Across)	Position Difference x (Across)
N (count of samples)	9560	9560
Mean (μ) (m)	-0.18	0.63
Standard Deviation (σ) (m)	0.06	0.16

(a) Location Accuracy: initialization with >4 satellites with track database

Parameter	Position Difference x (Across)	Position Difference x (Across)
N (count of samples)	9560	9560
Mean (μ) (m)	-0.26	0.65
Standard Deviation (σ) (m)	0.09	0.21

(b) Location Accuracy: initialization with >4 satellites without track database

Initialization testing further highlighted a significant characteristic of GPS positioning error noise. Specifically, what had previously been reported as standard deviation actually reflects the contributions of bias induced by the instantaneous constellation configuration. As the orientation of the GPS receiver antenna relative to the constellation changes with motion, the resulting bias changes, which artificially inflates standard deviation calculation. The results of Table 8 more accurately characterize actual PTL error behavior (in the presence of GPS).

3.1.3 Phase IIa.2 (PTL HOT and PTL EOT)

PTL Phase IIa.2 testing was conducted at TTC during September 2013. Phase IIa.2 testing focused on PTL EOT performance with supplemental acquisition of HOT data to demonstrate repeatability of Phase IIa.1 PTL HOT test results. All test procedures compared PTL system position measurements with the TTCI Trimble reference RTK GPS receiver.

Table 9 compares Phase IIa.2 against IIa.1 HOT positioning results. Since IIa.2 and IIa.1 tests were identical, results are expected to be statistically equivalent. As indicated, Phase IIa.2 HOT test results are indeed consistent with Phase IIa.1 HOT test results to within a 3.8 percent and 7.3 percent variation of across-track and along-track performance respectively.

Table 9. Phase IIa.2 vs. IIa.1 HOT Accuracy

Performance Parameter	Objective	PTL HOT Phase IIa.2 (without Track Database) (Across)	PTL HOT Phase IIa.2 (without Track Database) (Along)	PTL HOT Phase IIa.1 (without Track Database) (Across)	PTL HOT Phase IIa.1 (without Track Database) (Along)
Position Mean (cm)		2.8	6.8	-1.6	5.6
Position Standard Deviation (cm)	18	18.2	22.6	18.9	24.4
Confidence Interval (fraction)	0.99999999997	0.99999999996	0.9999999	0.9999999998	0.9999991
Confidence Interval (#nines)	10	10	7	9	6

Phase IIa.2 testing further introduced the notion of statistical polling whereby the binomial distribution was proposed to evaluate a succession of PTL samples to verify whether the across-track error criteria of 1.2 µ had been exceeded. Recognizing that such an approach is only valid when GPS receiver position samples are independent and uncorrelated, receiver sample correlation was further evaluated for cases of Satellite-based Augmentation System (SBAS) aiding and degraded GPS. As indicated in Figure 9 (a), very high correlation was observed when SBAS is available so that sample correlation persists in excess of 2 minutes. As indicated in Figure 9 (b), sample correlation diminishes significantly along with receiver sample quality for the case of no SBAS and reduced number of visible satellites. However, even in this case sample independence does not become applicable until over ½ minute has elapsed. Consequently, statistical confidence enhancement through sample aggregation is regarded as not practical.

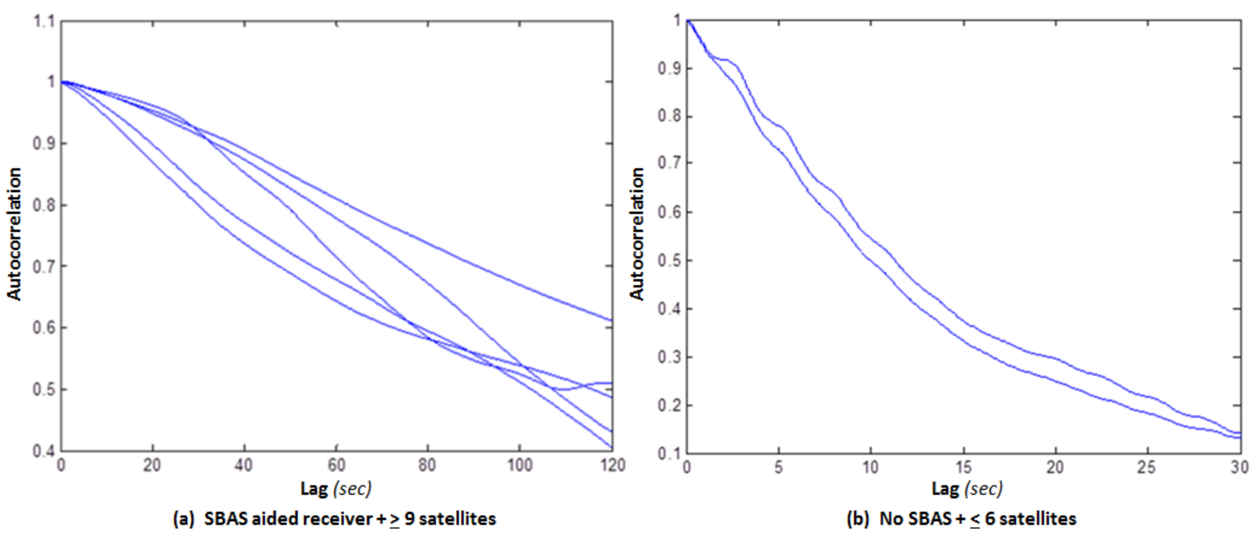


Figure 9. Receiver position sample correlation (ensemble trials)

PTL Phase IIa.2 EOT performance for the case of GPS availability is summarized in Table 10 and compared against EOT performance observed during Phase I when pre-surveyed track databases were used to aid the solution. In contrast to HOT performance gains, EOT availability of a reference track database is observed to contribute a significant improvement of 61 percent and 46 percent position error reduction relative to Phase IIa.2 results without aid of a track database. The reason for this improvement is that the EOT unit experiences more constrained GPS visibility due to the low height and close proximity to the rear car. Therefore, it relies on sensor fusion of HOT and EOT information as well as a high-accuracy pre-surveyed track reference database in order to achieve the improved performance levels demonstrated in Phase I.

Table 10. PTL Phase IIa.2 versus Phase I EOT Performance

Performance Parameter	Objective	PTL HOT Phase IIa.2 (without Track Database) (Across)	PTL HOT Phase IIa.2 (without Track Database) (Along)	PTL HOT Phase I (with Track Database) (Across)	PTL HOT Phase I (without Track Database) (Along)
Position Mean (cm)		59.3	7.4	23.0	4.0
Position Standard Deviation (cm)	18	39.6	46.1	11.0	27.0

Phase IIa.2 further comprehensively addressed PTL positioning performance while operating within tunnels of varying length and maneuver complexity. Across-track and along-track test results are summarized in Table 11.

As indicated in Table 11 and Figure 10, positioning error is observed to rapidly increase nonlinearly with tunnel length. In the absence of a reference database, and without an accurate and lag-free WSS, no effective absolute positioning reference is available. Consequently, all positioning is dependent on unaided IMU capability and consequent drift that rapidly grows over time and with maneuver complexity. For brief intervals of GPS denial within shorter tunnels, PTL-compliant EOT positioning is possible. However, as tunnel length increases, aid of a reference database or alternative absolute reference markers becomes requisite. Given that such protracted length locations are well defined, dedicated application of such approaches may be considered in order to maintain PTL-level accuracy in such environments.

Table 11. EOT Location Accuracy for Train operation through tunnels of various lengths

Category	Length (ft)	Across Track σ (m)	Along Track σ (m)
Short	500	0.33	0.66
Medium	6,000	0.85	3.04
Long	40,000	45.08	54.335

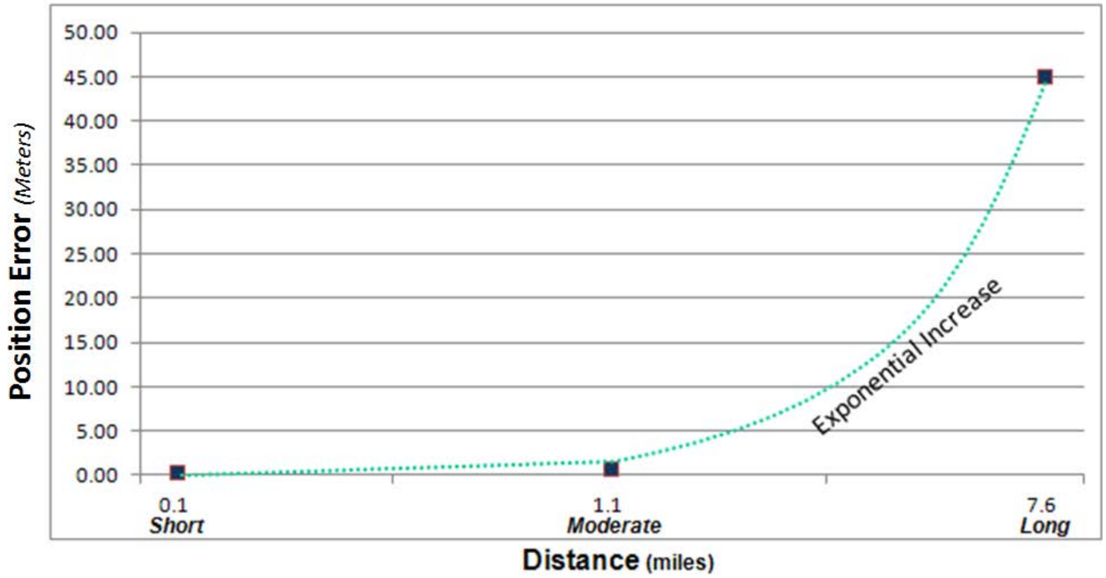


Figure 10. EOT Positioning performance within tunnels

3.2 Testing on Class I Freight Railroads

3.2.1 Phase IIb

Phase IIb PTL testing was conducted on operational track from November 7, 2013 through January 17, 2014. While successful PTL operation had been demonstrated on test track at TTC, testing on operational track was essential to introduce the effects of operational environments not observed on the test track. Consequently, the objective of Phase IIb testing was to demonstrate PTL HOT and EOT capability to reliably operate on operational track for prolonged durations and exhibit a level of performance consistent with TTC test results. Moreover, when unanticipated system behavior was observed during Phase IIb testing, appropriate measures to update the PTL system were enabled to be performed before Phase IIc performance evaluation.

Phase IIb testing was performed on BNSF and NS operational track affording extensive terrain diversity. To enable PTL positioning performance evaluation, each railroad provided track centerline reference data with survey error standard deviation of no more than 1 meter. However, over the range of available operational test track, BNSF reference track centerline database error standard deviation was expected to vary between 30 cm to 90 cm. Similarly, a 43 cm level of accuracy was expected with NS reference track centerline data. Under assumption that the PTL system maintains the 18 cm across-track performance demonstrated at TTC, a BNSF composite standard deviation would be expected to be observed during operational track test:

$$\sigma_{Composite} = \sqrt{{\sigma_{PTL}}^2 + {\sigma_{Ref}}^2} = \sqrt{18^2 + {\sigma_{Ref}}^2} \qquad (1)$$

So that

$$35 = \sqrt{18^2 + 30^2} \leq \sigma_{Composite} \leq \sqrt{18^2 + 90^2} = 92 \qquad (2)$$

Table 12 summarizes BNSF and NS observed and expected success criteria. As indicated, the measured error standard deviation resulting from comparison with the respective track centerline references was better than the expected best case performance criteria. This was likely due to both good PTL system performance as well as track centerline information that was more accurate than expected for these locations. Consequently, PTL HOT performance was observed to operate reliably and with sufficient performance to warrant transition to next step Phase IIc testing.

Table 12. Phase IIb PTL HOT Performance Assessment Summary

Railroad	Number of Samples	% of Total Samples	Best Case Reference σ (cm)	Worst Case Reference σ (cm)	Expected Reference σ (cm)	Observed Composite σ (cm)	Phase IIb σ Success Criteria	Pass?
BNSF	8,261,527	76.2	30	90		25.7	<35 best case <92 worst case	Yes
NS	2,574,337	23.8			43	31.9	<47	Yes
Total	10,835,864	100.0						

As indicated in Table 13, test routes for each railroad were selected to provide a variety of terrains, data samples and route repeats. Summary statistics were determined from the PTL position samples acquired while in motion and stationary.

Table 13. Railroad Test Routes

Railroad	Environment	Number of Repeats	Number of Samples	% of Total Samples	PTL IIb Composite σ (cm)
BNSF	City	4	1,008,567	12.4%	33.9
BNSF	Mountain	4	4,532,251	55.9%	24.1
BNSF	Plains	4	2,568,193	31.7%	25.1
NS	Hot – Varied	12	2,699,103	83.3%	31.9

As indicated in Figure 11, Phase IIb testing on BNSF track consisted of two distinct loops: (1) between Texas and California and (2) between Missouri and Texas. BNSF Phase IIb testing commenced November 7, 2013 and was completed November 20, 2013, which provided two weeks and over 6,000 miles of track coverage.

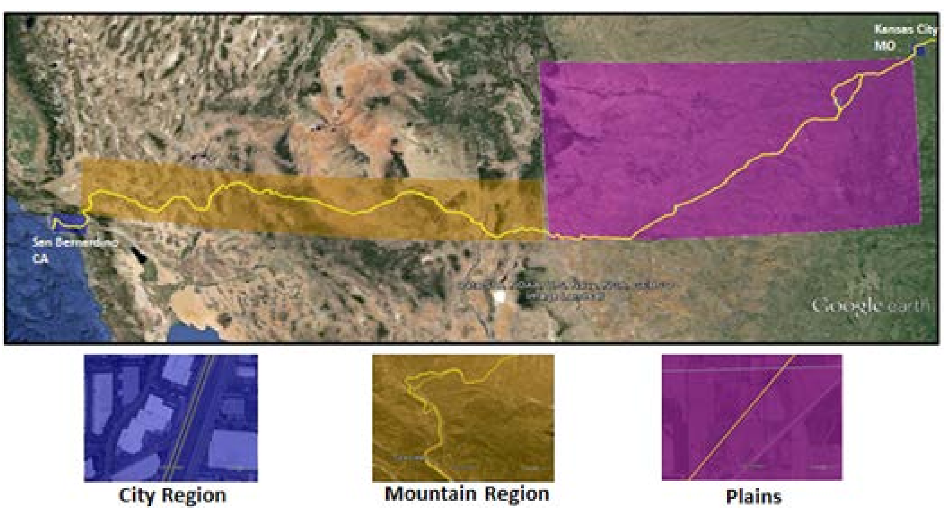


Figure 11. BNSF Phase IIb Route Map

As indicated in Figure 11 and Table 14, the BNSF test route was composed of city, mountain, and plains territory. As expected, city regions presented the most challenging scenarios due to presence of urban canyons and increased presence of overpasses and tunnels.

Table 14. BNSF Phase IIb Operating Environment

Environment	Number of Samples	% of Total Samples	PTL IIb σ Observed (cm)	Phase IIb σ Success Criteria	Pass?
City	1,008,567	12.4	33.9	<35 (optimistic)	Yes
Mountain	4,532,251	55.9	24.1	<35 (optimistic)	Yes
Plains	2,568,193	31.7	25.1	<35 (optimistic)	Yes

Positioning performance for mountains and plains was observed to be comparable and notably better than that observed for city regions. However, geopositional performance for all scenarios exceeded even the most stringent success criteria for all scenarios.

NS testing was performed on the 105-mile Roanoke-to-Belews Creek route depicted in Figure 12. The terrain was characterized predominately by forest and hills. The comparatively short route enabled data capture of multiple repeated runs with 12 HOT repeated runs available for analysis. Due to ETD setup and monitoring demands to accommodate the EOT system, ETD installation required additional coordination and resources so that only three EOT runs were accomplished.

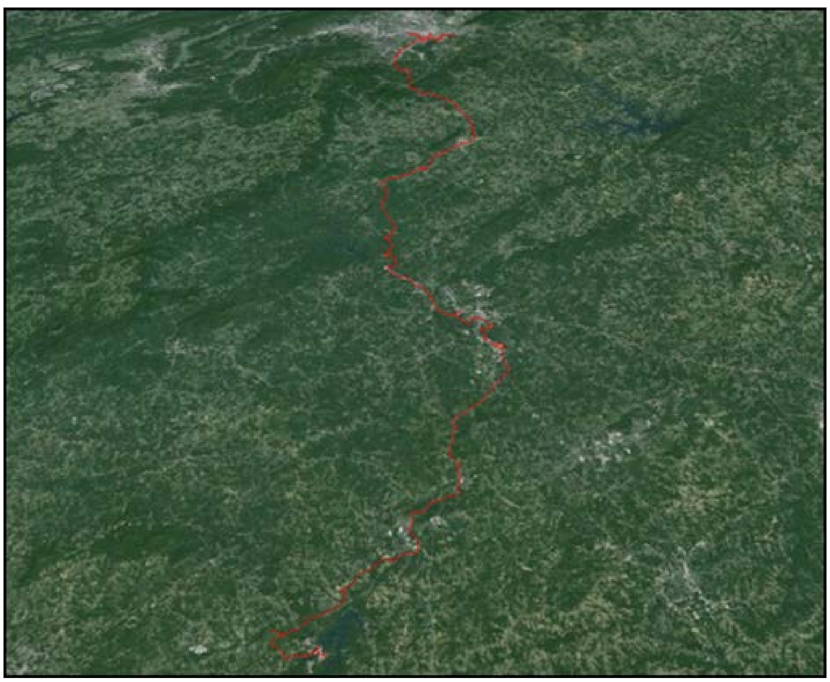


Figure 12. NS Phase IIb Route Map

As indicated in Table 15 and in contrast to the 44 percent city and plains terrain variation observed for the BNSF test route, the NS route was predominately comprised of forest and hills. HOT positioning performance was moderately reduced from that observed for BNSF with variation resulting from either reduced accuracy track centerline data or more obscured satellite visibility. However, PTL geopositional performance continued to exceed the most stringent HOT success criteria.

Table 15. NS Phase IIb Operating Environment

Number of Samples	Number of Repeats	Application	PTL IIb σ Observed (cm)	PTL IIb σ Success Criteria	Pass?
2,699,103	15	HOT	31.9	<47	Yes

EOT performance was further investigated on NS operational track. Fundamental EOT antenna geometry as well as the selected NS test route made for a challenging communication environment. As expected, the 900 MHz PTL radio struggled to maintain communication during NS EOT testing and exhibited <10 percent connectivity. Limited radio connectivity further limited opportunity to evaluate EOT accuracy so that the longest available interval of continuous connectivity was only ~5 minutes. During this time, an EOT position standard deviation of 0.63m was observed. Such behavior exhibited by the 900 MHz radio prompted subsequent investigations of 160, 220, and 450 MHz frequencies and application of the Leidos wideband software-defined radio (WSDR).

Analysis of BNSF and NS data acquired during Phase IIb operational track testing indicated a level of performance consistent with results observed during TTC testing. While a limited number of inconsistencies between PTL and track centerline data were observed, the sources of these deviations were addressed by either compensation updates to the PTL EDGE sensor fusion software or updates to GPS receiver firmware. Subsequent to update, the resulting PTL configuration demonstrated robust, accurate positioning consistent with TTC Phase IIa tests results per Phase IIb test objectives. Consequently, transition to Phase IIc testing was demonstrated as appropriate.

3.2.2 Phase IIc

Phase IIc PTL testing was conducted on BNSF, NS, and UP operational track from January 20, 2014 through March 5, 2014. Phase IIb testing demonstrated PTL HOT and EOT capability to reliably operate on operational track for prolonged durations and exhibit a level of performance consistent with Phase IIa TTC test results. As expected when testing in a new environment, some unanticipated system behavior was observed early in Phase IIb testing, and several software updates were made before Phase IIc testing to further enhance system performance on operational track.

The core Phase IIc test objective was to gather sufficient PTL system measurements to statistically validate system compliance with PTL requirements. To this end, track centerline data was provided by the host railroads to enable statistical assessment of across-track performance. An RTK reference system was further provided by UP to enable both across-track and along-track position comparison. However, the RTK accuracy was observed to vary significantly according to terrain and base station-to-receiver range and was thus appreciably degraded relative to what was available during TTC testing. Assessment of RTK-referenced results consequently had to be strategic in application whereby only select stable regions of higher-confidence RTK measurements were applied. In contrast to TTC testing, no viable reference was available to assess heading and speed performance. Since no truth reference was available to assess speed and heading, a statistical analysis method was used on the basis of derivations from differential position test results.

Given the diversity of test territory terrain, extensive track mileage, availability of track centerline and RTK reference data and large number of route repeats, sufficient data was available to accomplish statistical assessment of PTL performance compliance with PTL specifications. Specific attention was directed to extracting PTL position measurement standard deviation from measurements compared to a much less accurate reference.

Analysis was accomplished by two distinct strategies. First, the method of Chi Squared Statistical Consistency test used the respective railroad track centerline data accuracies for analysis. As observed in Table 16, PTL HOT positioning performance met or exceeded the PTL objective requirement of 18cm for all scenarios.

Table 16. Phase IIC HOT Performance Results (Statistical Consistency)

Railroad	Number of Samples	Track Centerline σ_{ref}	$\sqrt{\sigma_{PTL}^2 + \sigma_{REF}^2}$	Observed Standard Deviation s_{EFF}	x^2 $\frac{(N-1)\,s_{EFF}^2}{\sigma_{PTL}^2 + \sigma_{REF}^2}$	Critical Value	Pass $x^2 < CV$?
BNSF	8,261,527	30.0	35	25.7	4,458,052	8,270,986	Yes
NS	2,574,337	43.0	47	33.6	1,337,470	2,579,619	Yes
UP	2,935,170	90.0	92	39.1	532,682	2,940,809	Yes
Composite	13,771,034	45.2	49	30.0	5,243,801	13,783,246	Yes

Second, to provide further insight into PTL HOT positioning performance, estimates of PTL positioning standard deviation were derived for the respective railroads. A minimum of 2,500,000 samples were required to determine PTL standard deviation to a fraction of a centimeter accuracy with 99.99% confidence. Table 17 summarizes the resulting estimated PTL HOT standard deviation for each railroad scenario. Using these analysis assumptions, PTL HOT positioning performance is inferred to meet or exceed the PTL objective requirement of 18cm for all scenarios.

Table 17. Phase IIC PTL HOT standard deviation per Railroad Scenario

Railroad	Number of Samples	% of Total Samples	Reference σ (cm)	PTL Observed σ (cm)	Success Criteria σ (cm)	PTL σ (cm)
BNSF	8,261,527	60	30.0	25.7	35	Yes
NS	2,574,337	19	43.0	33.6	47	Yes
UP	2,935,170	21	90.0	39.1	92	Yes
Composite	13,771,034	100	45.2	30.1	49	Yes

As observed during Phase IIb testing, poor 900 MHz radio connectivity was inherent during Phase IIc test. Consequently, the 0.63m EOT position standard deviation performance observed during Phase IIb testing characterizes EOT position performance when radio reception is available.

In addition to performance assessment, PTL HOT positioning performance within GPS-denied tunnel environments was investigated, and it demonstrated system position estimates to exponentially drift with distance, d, traveled, similar to results observed at TTC during Phase IIa testing.

$$Across - Track\ Position\ Error(d) = 0.6784\ e^{.0028\,d} \quad (3)$$

Table 18 summarizes PTL HOT and EOT requirement compliance applicable to all phases of PTL testing. In general, the method of functional requirement verification is inspection. It is noted that the scope of the current PTL effort addressed only Phase I and II requirements, and Phase III represents future unit production objectives. As indicated in Table 18, 100 percent of

PTL HOT PTL Phases I and II requirements were demonstrated to be fully PTL-compliant. Moreover, 2 out of 7 Phase III functional production requirements were accomplished early. Similarly, 100 percent of EOT functional requirements for Phases I and II were realized, and 2 out of 15 Phase III production requirements satisfied. It is noted that the 1.2m EOT positioning requirement had fallen moderately short and the 900 MHz radio did not accommodate freight and passenger train length requirements. This observation motivated Leidos' application of its WSDR to PTL EOT-to-HOT applications to provide increased operational range at lower frequencies and increased bandwidth through concurrent use of multiple bands.

Table 18. PTL HOT and EOT Requirement Compliance with 2 of the PTL Requirements

Unit	Category	Phase I	Phase II	Phase III
HOT	Functional	18/18	7/7	2/7
HOT	Performance	6/6	2/2	
EOT	Functional	5/5	5/5	2/15
EOT	Performance	1/4	2/2	

As indicated in Table 19, track centerline reference databases varied between the railroads. For BNSF and NS, 1m point spacing enabled accurate PTL-to-reference comparison over all scenarios including large track curvature. By contrast, UP track centerline spaced at 30m intervals introduced artificially inflated reference comparison error under operation over curved track. Consequently, it can be inferred that PTL across-track position error standard deviation was <18cm across all railroads.

Table 19. Track Centerline Reference Characteristics

Railroad	Point Spacing (m)	Best Case Accuracy (cm)	Worst Case σ Composite (cm)	PTL σ (cm)
BNSF	1	30	33.9	15.8
NS	1	30	33.6	15.1
UP	30	35	39.1	17.4

For purposes of EOT testing, the NS-hosted ETD unit was mounted at the end of an approximately 100-car consist of approximately 1-mile length. Fundamental EOT antenna geometry as well as the selected NS test route made for a challenging communication environment. As expected, the 900 MHz PTL radio struggled to maintain connectivity during testing and demonstrated <10 percent connectivity. The limited connectivity resulted in limited opportunity to evaluate EOT accuracy. The longest available interval of HOT-to-EOT connectivity was ~5 minutes. However, an apparent ACC chassis physical reboot (not PTL-initiated) occurred before the brief interval of connectivity. The PTL unit consequently was required to perform a dynamic reboot. Ordinarily, stationary system initialization uniquely determines direction of travel based on the sign of the value of the IMU along-track accelerometer.

However, when initializing during motion, accelerometer sign values can become ambiguous, depending on whether the locomotive is accelerating or decelerating. To resolve this ambiguity, dynamic initialization requires the gear indicator signal from WSS onboard PTC unit. While WSS values were available during NS testing, gear indicator signal was not. Given the absence of sufficient data to accomplish PTL decision logic, unknown direction of travel prevented use of dynamic track database capability (backward propagation). Thus, without EOT position augmentation via HOT-hosted dynamic database 12 capability, EOT position reporting was essentially equivalent to standalone GPS. Consequently, the EOT position standard deviation observed during the longest continuous interval of radio connectivity was 0.63m; i.e., Septentrio GPS standalone performance.

Evaluation of PTL operation in GPS-denied environments was conducted for the case of tunnels observed during operation on BNSF track. Table 20 summarizes growth of across-track position error versus distance traveled within a tunnel. The observed behavior exhibits the same exponential growth with tunnel length as observed at TTC.

Table 20. Tunnel Error Growth versus Distance (BNSF)

Description	Tunnel Length (m)	Error σ	Estimate (m)
Large Connected Overpass	80	0.93	0.85
Large Connected Overpass	80	0.70	0.85
Tunnel/Subway-like Trench	650	4.91	4.19
Tunnel/Subway-like Trench	1,250	19.53	22.47

Figure 13 shows the curve obtained by performing an exponential curve fit to the observed data, using estimated values from Table 20.

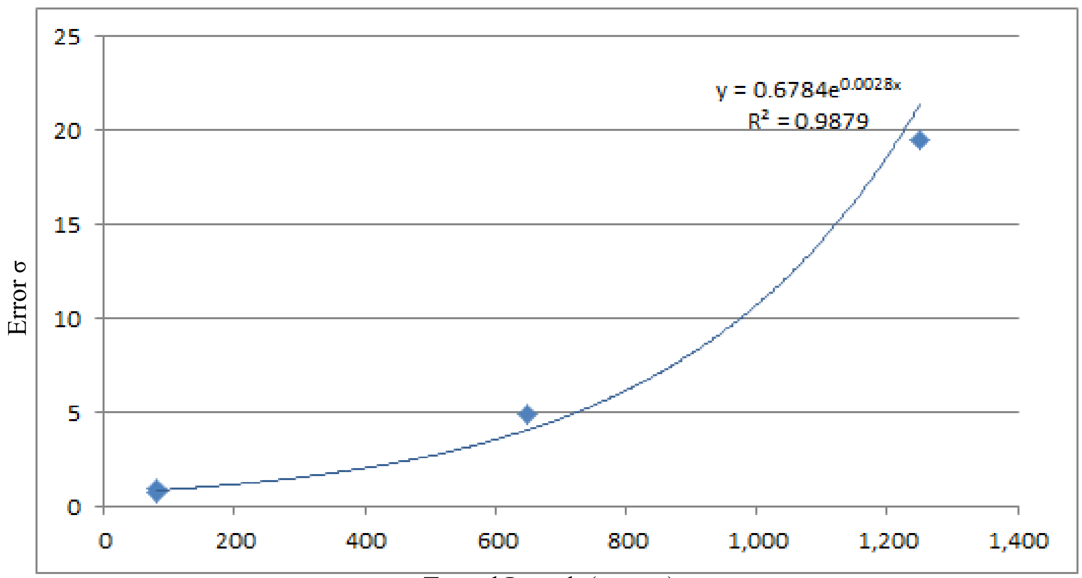


Figure 13. Curve Fit to BNSF Tunnel Data

As indicated in Figure 13, position error standard deviation, Error σ, grows exponentially with distance, D, traveled within the tunnel where units are in meters.

$$\sigma_{Error} = 0.6784\, e^{.0028\, D} \qquad (4)$$

Table 21 summarizes repeated passes through the 152 m NS tunnel MP R6.8. As indicated, six runs were conducted southbound with six runs northbound. A similar average offset error of 5 meters is observed for both directions as well as similar results variation.

Table 21. End of Tunnel Offset Error Growth (NS)

Direction	Description	Error 1σ (cm)	Mean μ	Standard Deviation
Southbound	Roanoke to Belews Creek	3.13		
Southbound	Roanoke to Belews Creek	1.85		
Southbound	Roanoke to Belews Creek	6.75		
Southbound	Roanoke to Belews Creek	0.26		
Southbound	Roanoke to Belews Creek	6.81		
Southbound	Roanoke to Belews Creek	12.04	5.1	3.9
Northbound	Belews Creek to Roanoke	1.62		
Northbound	Belews Creek to Roanoke	3.49		
Northbound	Belews Creek to Roanoke	5.04		
Northbound	Belews Creek to Roanoke	3.04		
Northbound	Belews Creek to Roanoke	1.45		
Northbound	Belews Creek to Roanoke	10.37	5.3	3.0

When NS tunnel error growth is compared against BNSF-based prediction, an approximate 4-meter increase of NS drift error is observed.

$$Predicted\ NS\ \sigma_{Error} = 0.6784\ e^{.0028\ x\ 152} = \ 1.04\mu\ <\ 5.1\mu \qquad (5)$$

This additional drift is attributed to an earlier and more pronounced loss of GPS satellites attributed to steep track embankment as the locomotive approached the NS tunnel entrance in contrast to the unobscured BNSF tunnel entrance. Degraded GPS velocity in turn results in degraded initial filter heading on tunnel entrance, since a GPS-velocity derived heading is used as a measurement in the filter. As little as a 2 degree error can result in the observed 5 m offset by tunnel end.

$$Across\ Track\ Offset\ =\ 152\ sin\left(\frac{\pi}{180}\ 2\right) = \ 5.3\ \mu \qquad (6)$$

Testing on operational track provided valuable insight into this phenomenon. Previous testing at TTC simulated tunnels by disconnecting the GPS antenna. This method failed to capture the changing observable GPS constellation as the locomotive enters tunnels. Leidos has subsequently developed a software change to improve GPS-denied performance when entering tunnels. This software change was applied to the Table 21 data sets and the results are shown in Table 22. It shows that the software modification significantly improved performance and across-track error standard deviation drops dramatically.

Table 22. Corrected End of Tunnel Offset Error Growth for NS Repeatability Test

Direction	Description	Error 1σ (cm)	Mean μ	Standard Deviation
Southbound	Roanoke to Belews Creek	0.45		
Southbound	Roanoke to Belews Creek	0.57		
Southbound	Roanoke to Belews Creek	0.61		
Southbound	Roanoke to Belews Creek	0.65		
Southbound	Roanoke to Belews Creek	0.08		
Southbound	Roanoke to Belews Creek	0.07	0.4	0.3
Northbound	Belews Creek to Roanoke	0.14		
Northbound	Belews Creek to Roanoke	0.07		
Northbound	Belews Creek to Roanoke	0.17		
Northbound	Belews Creek to Roanoke	0.30		
Northbound	Belews Creek to Roanoke	0.42		
Northbound	Belews Creek to Roanoke	0.07	0.2	0.1

4. Testing of PTL's Communications Link

In order to accommodate potential extended train lengths to 5mi as identified in the PTL Requirements Document, a new approach to EOT-to-HOT communications was required. In response to this need, Leidos proposed a software-defined radio (SDR) with multiple-band capabilities. This capability will enable future radios to (1) incorporate proposed next generation waveform designs as well as support legacy waveforms and (2) automatically adapt to environmental conditions to enable maximum received signal power at the HOT for transmissions originated at the EOT. Conversely, the SDR would in turn maximize received signal power at the EOT for transmissions originated from the HOT. As addressed in the following sections, testing was conducted at TTC to evaluate radio response to controlled environmental conditions as well as to identify and correct radio communication challenges before testing on operational track.

4.1 Testing at TTC

Testing at TTC assessed two candidate SDRs: (1) XetaWave 450 MHz and (2) Leidos WSDR. Both Leidos and XetaWave provided radio test kits in support of the evaluation. The primary purpose of testing at TTC was to investigate fundamental radio attributes as they impact sustained and reliable operational radio range performance. Table 23 describes five test procedures that were conducted to evaluate radio configuration impact on radio capability.

Table 23. Radio Tests Conducted at TTC

Test Procedure	Description
1	HOT-to-EOT Relative Range Measurement Accuracy versus Radio Configuration
2	EDGE EOT Position Measurement Accuracy versus Radio Configuration
3	Received Signal Strength Profile versus Radio Design and Frequency
4	Maximum Range Determination versus Radio Design and Frequency: No test procedures are required (Frequency refers to the three fundamental radio frequencies inherent in the radio under test: 900, 450, 220 MHz. This is intrinsic to the radio implementation; e.g., the current PTL radio operates ~900 MHz, XetaWave operates exclusively ~450 MHz, and Leidos WSDR operates ~450 and 220 MHz)
5	Interference with Other Radios versus Radio Design and Frequency

Data for PTL EOT relative range and positioning performance was accumulated under a range of radio parameters. Radio received signal strength (RSS) measurements along the length of railcars in addition to RSS and bit error rate (BER) at the locomotive were accumulated to evaluate radio performance. Maximum operable range was further determined for each candidate radio along with assessment of radio interference on and by near proximity legacy radios. The TTC Trimble RTK GPS receiver system was used as a truth position and relative range reference.

4.1.1 Data Rate versus EOT Position Accuracy

To use radio bandwidth most efficiently, it is desirable to reduce radio EOT-to-HOT data rate. Thus, as long as track geometry does not significantly change during successive EOT updates, accurate EOT positioning may be maintained by method of back propagation performed at the HOT. From the back propagation method of simulation and analysis, Table 24 lists EOT position accuracy resulting from unknown coupler slack between radio updates for a variety of terrain grades and train lengths. The yellow color in the table indicates, $< 1\mu$ along-track error may be maintained for a variety of train lengths and track geometries if EOT-to-HOT message rate is once every 10 seconds. Moreover, by using the PTL IMU to sense track curvature or grade, much slower data rates may be applied for more benign cases.

Table 24. EOT Positioning versus Radio Rate versus Terrain

Number of Rail Cars	Average Car Length (ft)	Train Length (mi)	Grade (%)	Time to Δ Slack of 30 μ (seconds)	Time to Δ Slack of 20 μ (seconds)	Time to Δ Slack of 15 μ (seconds)	Time to Δ Slack of 10 μ (seconds)	Time to Δ Slack of 5 μ (seconds)	Time to Δ Slack of 1 μ (seconds)
100	53	1.0	3.50			24.4	21.3	16.8	9.9
150	53	1.5	3.50		26.8	24.4	21.3	16.8	9.9
200	53	2.0	3.50	30.8	26.8	24.4	21.3	16.8	9.9
200	53	2.0	2.00	44.4	38.8	35.2	30.7	24.4	14.2
200	53	2.0	1.00	70.3	61.5	55.7	48.7	38.7	23.2
200	53	2.0	0.25	176.1	154.2	140.2	122.1	96.9	58.0

4.1.2 Radio Range Testing

Test procedures 3 through 5, from Table 24, were conducted on the Perturbation Test Track (PTT) at TTC as depicted in Figure 14. Here the XetaWave and Leidos WSDR radio range performances were evaluated from ½ to 5mi EOT-to-HOT distances. To accomplish this, the EOT was coupled to one stationary box car preceded by five coach cars. To vary radio communication distances, the HOT plus five towed coach cars moved at 10 mph to a total along-track distance of 6 miles (~5mi line-of-sight (LOS) distance).

Figure 14. PTT Track Radio Testing

For this range testing, the Leidos WSDR operated at 160, 220, 450, and 900 MHz while the XetaWave operated at 450 MHz. During this test, a near-zero BER was observed with the Leidos WSDR for 220 and 450 MHz at 4.5mi (actual track length = 5.0mi). Continued operation to 5mi LOS distance (actual track length = 5.5mi) resulted in moderate degradation of 2 percent to 7 percent message loss for 220 MHz and 450 MHz. As the locomotive approached 5.5mi LOS (actual track length = 6mi), useable to marginal communications were observed. As anticipated, the 900 MHz band exhibited significant fall off > 0.8mi. The 160 MHz band should have exhibited the best range performance, but it exhibited erratic behavior throughout all testing. Later it was determined it had a degraded connector. The 450 MHz XetaWave radio was tested separately with appreciable range detection observed at 2 miles.

4.1.3 Multipath Behavior

Figure 15 shows a photograph of train operation between adjacent cars for multipath testing. This dynamic testing was conducted to determine multipath impact, and it involved moving a locomotive towing five coach cars between four combinations of adjacent track railcars: (1) No cars on adjacent tracks, (2) 20 coal cars on west track, (3) 20 coal cars on east track, (4) 20 coal cars on west and east tracks.

Figure 15. Multipath testing with operation between adjacent cars

To facilitate radio performance analysis, the Leidos WSDR was used as a measurement instrument to characterize radio propagation path characteristics with results applicable to all radios. WSDR baseband signal magnitude is displayed in Figure 16 for cases of stationary and moving locomotive. For the case of a stationary locomotive (Figure 16 a), baseband signal magnitude was observed to be stable and reasonably flat, reflecting ~+3 dB magnitude variation over time. However, as soon as motion was initiated (Figure 16 b to d), slow, deep 20 dB signal fades were observed to increase with frequency and increased speed.

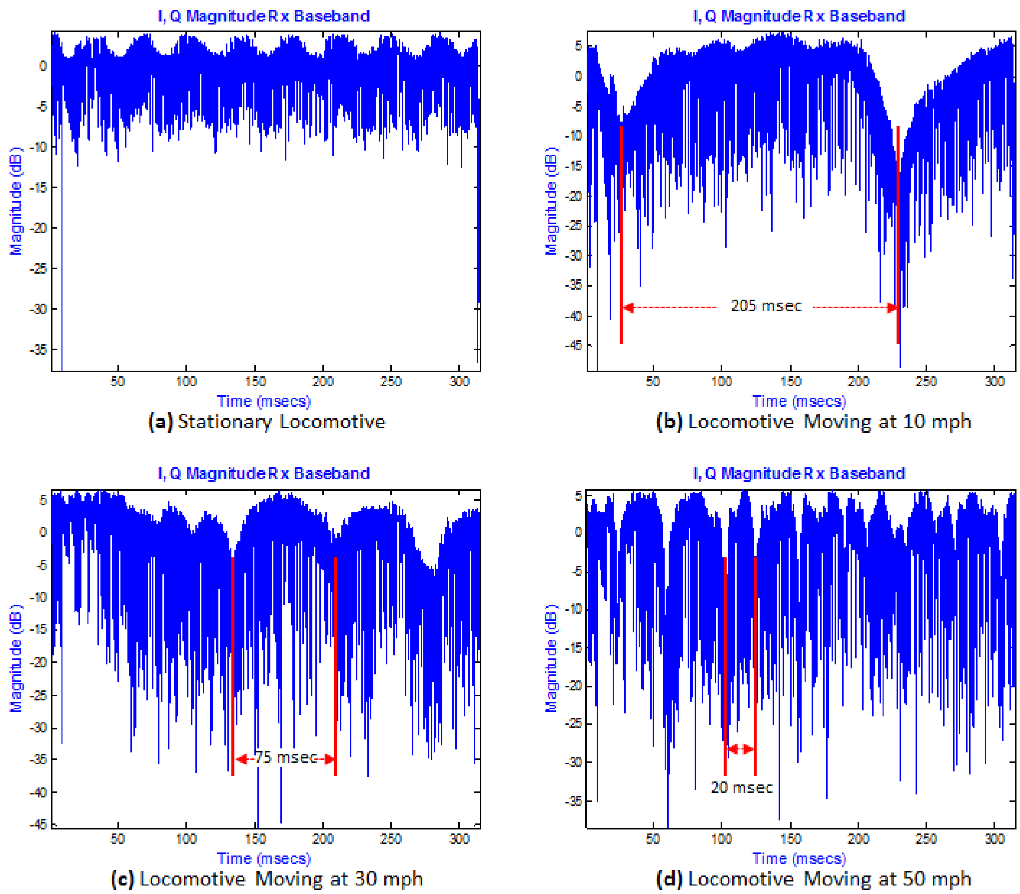


Figure 16. Baseband Signal Magnitude for Stationary and Dynamic Cases

This behavior was further observed for the reference case of no adjacent cars. Consequently, for the case of non-LOS communication between the EOT and HOT, RSS behavior is highly dependent on the intervening instantaneous consist geometry. This interaction results in temporal amplitude and phase modulation induced upon the received signal with distinct RSS null positions determined by locomotive speed and operational band (160, 220, 450, 900 MHz). In order to compensate for this phenomenon, Leidos modified its radio implementation to incorporate antenna diversity combining and adaptive equalization.

Diversity combining is a technique applied to combine signals received from multiple antennas into a single improved signal. The Leidos WSDR is presently programmed to provide equal-gain combining where the signals received from two "along-track" antennas separated by either 0.75λ or 1.25λ are coherently summed to provide a composite signal. Switched combining provides an alternative approach whereby the receiver switches to another signal when the currently selected signal drops below a predefined threshold. Equal-gain combining is preferred over switched combining to mitigate the significant impact of signal discontinuity induced by frequent switching at high locomotive speeds.

Adaptive equalization is the process by which a signal history is adaptively combined to automatically adjust to the time-varying properties of the communication channel. The WSDR digital implementation is depicted in Figure 17. In this implementation, a least mean squares algorithm is used to find the filter coefficients corresponding to the least mean squares of the error signal (difference between the desired and the actual signal). This application further assists in minimizing the amplitude modulation induced on the received wave form as attributed to dynamics induced multipath.

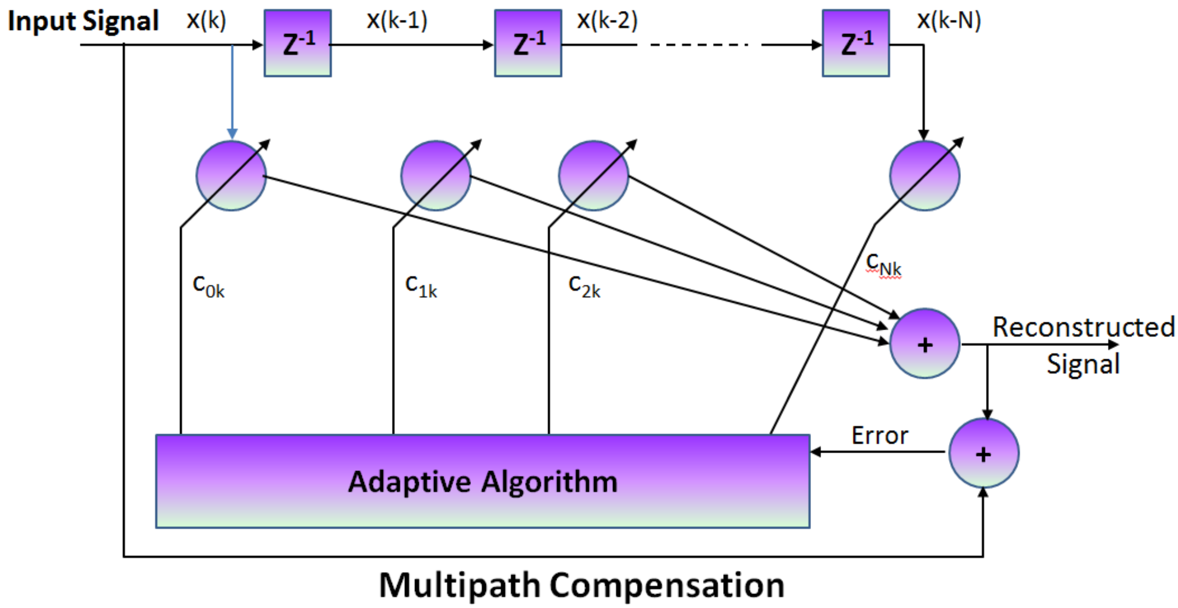


Figure 17. Adaptive Equalization

Once Leidos completed diversity combining and adaptive equalization upgrades to the WSDR, final testing was conducted at TTC to verify implementation functionality. This radio validation test was completed February 2016, and it demonstrated significant reduction of channel fading and more stable RSS over a range of diverse operational scenarios. Consequently, transition to NS operational track for field testing was recommended.

4.2 Testing on Class I Freight Railroads

While limited radio testing was conducted during PTL Phase IIb and IIc system tests, these configurations employed the 900 MHz radio, which was already recognized to provide insufficient operational range. Consequently, dedicated radio testing on Class I freight railroad track was accomplished during June 2016 on NS revenue service track. The principal objective of the radio investigation was to extend the previous February 2016 TTC test cases to actual operational conditions. The objective was to assess 160, 220, and 450 MHz radio performance while subject to challenging operational territory. Consequently, the NS coal train route from Roanoke to Belews Creek was selected due to its diverse environmental conditions including near track forest and high track curvature. To minimize impact to NS revenue operations, a small antenna footprint was required along with minimal installation time. This consequently motivated use of only the 450 MHz antenna (due to comparatively small size) and understanding that 450 MHz results could analytically infer performance assessment at 160 and 220 MHz frequencies. While provision was made for antenna magnetic side mount, the test locomotive (#1172) was equipped with 450 MHz antennas, as indicated in Figure 18. These antennas were consequently employed for test to minimize equipment setup. As further noted, antenna along-track spacing is 2λ in contrast to the desired ½λ antenna separation of the bracket assembly. As a consequence of 2λ antenna spacing, the percent of power above receiver operational threshold is no better than a single antenna. Hence, the benefit of antenna diversity combining was lost.

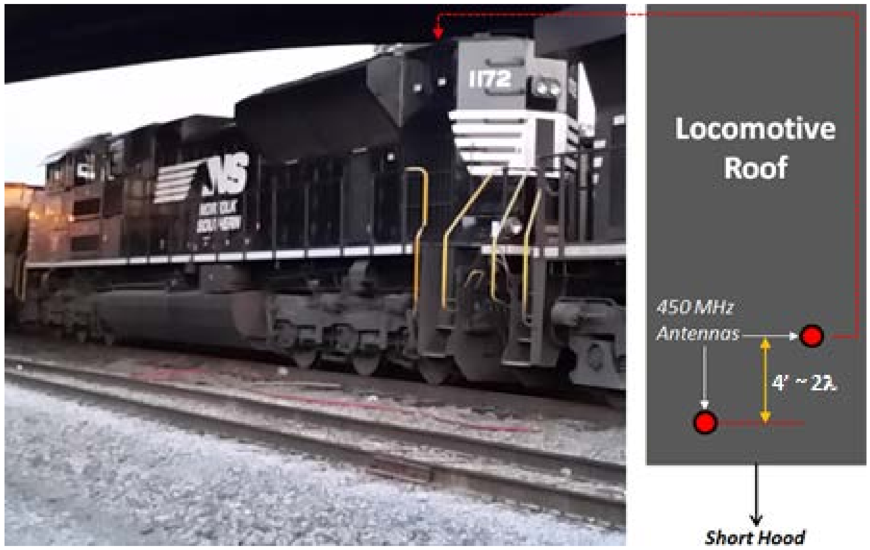
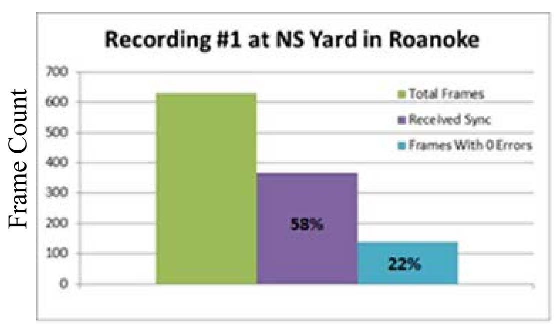
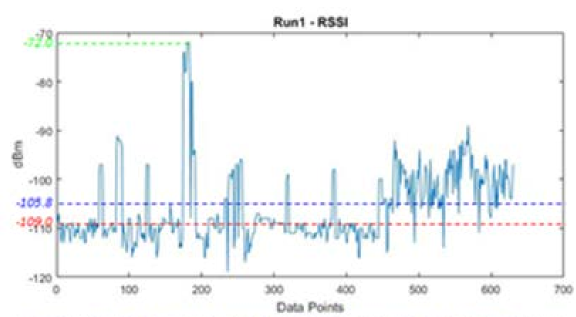


Figure 18. HOT Locomotive Antenna Mount during NS Radio Test

In preparation for NS Radio testing, a link budget analysis was performed to assess anticipated radio operation as determined by expected RSS. From testing conducted at TTC and at a range of 1mi (NS train length), the RSS was anticipated to be on the order of -85 dBm as compared to the radio's operational threshold of -113 dBm for a 28 dB margin. However, the mean received signal level was observed to be -106 dBm to yield only a 7 dBm. Motion-induced channel fade results in signal levels below receiver operational threshold and hence loss of signal synchronization. Figure 19 shows the first 10.5 minutes when the train progressed forward very slowly. As indicated in the chart and table, of the received and synchronized frames, 22 percent were recovered without error. As further shown, the LOS propagation path was approximately 0.92mi, with the EOT position causing transmission blockage.

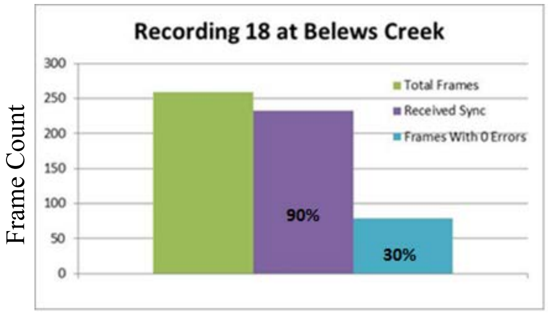


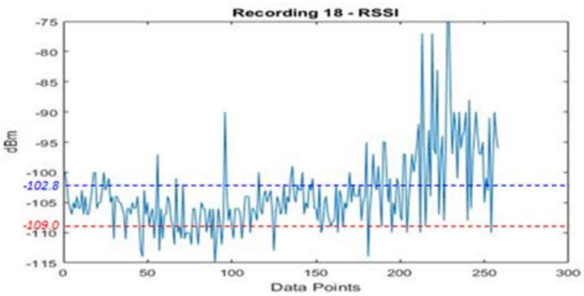


Roanoke Slow Departure		
Total Frames	631	
# Frames No Data Received	264	42%
# Received and Synchronized Frames	367	58%
# Received and Synchronized Frames **with** Errors	229	62%
# Received and Synchronized Frames **without** Errors	138	38%
# Frames attempted **without** Errors	138	22%

Figure 19. Roanoke Departure Scenario

Figure 20 shows the conditions as the train arrived at Belews Creek. The train orientation was on a slight curve with HOT positioned in a clearing next to the power plant with EOT positioned around the curve and engulfed among tall trees. As indicated on one chart, the average received signal power was -102dBm with some readings as low as -115dBm and some as high as -75 dBm, indicating the modulation induced by destructive and constructive multipath interference that would otherwise have been mitigated by ½λ antenna spacing. As indicated in another chart and table, of the received and synchronized frames, 30 percent were recovered without error.





Belews Creek Arrival		
Total Frames	259	
# Frames No Data Received	27	10%
# Received and Synchronized Frames	232	90%
# Received and Synchronized Frames **with** Errors	153	66%
# Received and Synchronized Frames **without** Errors	78	34%
# Frames attempted **without** Errors	78	30%

Figure 20. Belews Creek Arrival Scenario

Figure 21 shows signaling performance as the train transits between Roanoke to Belews Creek. During the slow initial and final positions, best performance is noted as previously described. During the route between Roanoke and Belews Creek, speed varied between 10 and 40 mph. EOT-to-HOT consist geometry and car-to-car orientation further varied appreciably throughout the transit. Terrain was characterized by many curves, wooded areas, and moderate elevation changes. Figure 21 indicates the percent of frames without error dropped appreciably in response to the increased signal strength modulation and operation near receiver operating threshold.

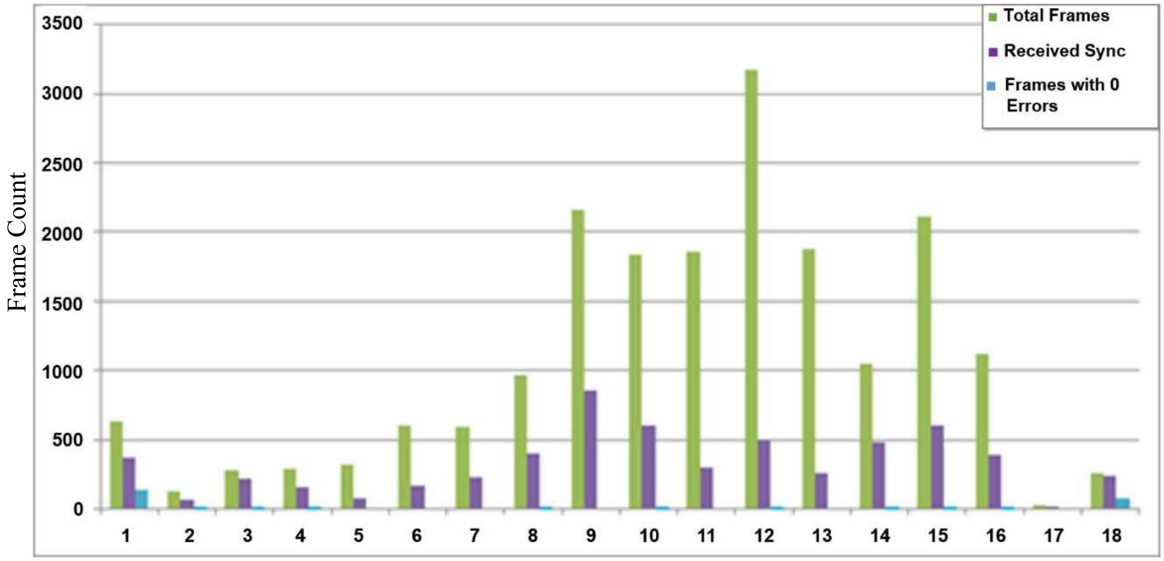


Figure 21. Summary Route Signaling Performance

Analysis of NS test results indicates favorable WSDR operational capability subject to proper installation and antenna configuration enabling proper antenna diversity combining. Unfortunately, the two fundamental assumptions were violated at system installation. However, analytical results are consistent with the system configuration characteristics. Consequently, there is no reason to believe that when properly configured, WSDR antenna diversity combining and accelerated Automatic Gain Control (AGC) would not sustain reliable operational performance over the NS or equivalent operational scenarios.

5. Design Challenges

The following subsections describe the design challenges of PTL development.

5.1 PTL EOT

The most significant design constraint encountered during PTL system development is EOT positioning directly behind the rear railcar, which blocks portions of GPS satellite constellations. Most PTL testing employed a 14-foot box car which acts as a near-field ground plane. This radio frequency obstruction first attenuates signal propagation on the order of 30 dB which significantly limits propagation range. The second component of EOT positioning is diminished constellation visibility. For unobstructed terrain, 12 GPS satellites may be expected to be observed at the EOT. However, EOT placement on average reduces the number of observable satellites to approximately six. Since RTK operation requires a minimum of 5 satellites, it becomes challenging to maintain sustained EOT-to-HOT RTK functionality even while operating in benign scenarios as observed during TTC testing.

5.2 Communication Link

The major challenge to communications is constrained bandwidth at lower operational frequencies. Early on in the PTL program it was realized that while 900 MHz operation accommodates large bandwidth, it supports only up to 0.8 mile train length, which is insufficient for practical operational train lengths. While lower frequencies better support extended range operation, they progressively accommodate reduced bandwidth capability with lower frequency. Fortunately, PTL investigations have demonstrated that reduced EOT-to-HOT update rates of <1 Hz are sufficient to maintain positioning performance and are readily accommodated by the bandwidths available from 160, 220, and 450 MHz radio operation.

6. Next Steps

The following subsections describe the recommended next steps of PTL development.

6.1 Larger-scale Testing on the Class I Freight Railroads

Building on the testing done under this project, the following future testing is recommended.

6.1.1 Large number of units (50–100 per railroad)

Leidos is presently in the final stages of contract negotiations with UP for the procurement of 50 units. It is anticipated that Leidos will be under contract to produce 50 units in 2017.

6.1.2 Longer duration (1 year)

Ideally, the objective of testing multiple PTL units over 1-year duration is to assess mean time between failure (MTBF). However, for the projected PTL MTBF of ~50,000 hours, statistically meaningful MTBF assessment would generally require a minimum of 10 observed failures within one year. On the order of 165 units would be required to test to observe this level of failure. Given a production quantity of 50 units, only three units would be observed to fail. Consequently, observation of on the order of three failures would be statistically consistent with the assertion of a MTBF of 50,000 hours. If significantly less units fail, it can be concluded that MTBF >> 50,000 hours, whereas if significantly more units fail, it would be concluded that MTBF << 50,000 hours.

6.2 Integration with Existing Railroad Operations

Successful deployment of PTL is dependent on integrations with other railroad systems.

6.2.1 PTC

PTL has been designed to be interoperable with PTC. To date, PTL has successfully operated with the Wabtec TMC PTC interface. UP has further employed PTL with the TMC interface for over 6 months. Leidos also developed software to enable PTL integration with the Meteorcomm Systems Management System (SMS) software framework. This functionality enables the railroads to remotely carry out actions such as file transfers, software updates, and health and status reporting. This capability was developed using the Meteorcomm provided SMS Test Harness. Leidos supported laboratory testing with UP from September 12–16, 2016, to ensure the SMS capability provided the needed functionality. Final software updates were made using the lessons learned from this testing. Leidos is coordinating with the railroads for further PTL-SMS testing on operational track.

6.2.2 Other systems

Beyond PTC positioning support, UP has employed PTL as a more reliable alternative to RTK. Specifically, during UP operations on its Pacific North track, the intermittent RTK radio links resulted in significantly degraded RTK positioning. However, by employing PTL as a position reference system and leveraging accumulative track position measurements with the PTL EDGE dead reckoning position solution, consistent and reliable positioning was provided.

6.2.3 ETD integration

PTL has been integrated within a prototype DPS ETD unit. The three custom devices have run without failure or issue for the past four years. However, since near term focus has been on HOT application by UP, further ETD integration has been deferred.

7. Conclusion

PTL Phase IIa.1 testing demonstrated an increase of measurement standard deviation for both across-track and along-track positioning metrics as compared to Phase I testing. This position performance degradation was attributed to a combination of change of WSS device with the new constraint of restricted track database application. Subject to these constraints, Phase II HOT across-track error standard deviation remained consistent with PTL level of confidence requirements. Phase II along-track standard deviation degraded from 17 cm to 24 cm (in the absence of a track database) with marginal improvement of 22 cm, with a track database. In response, the railroad advisory group indicated that a 6 cm increase of along-track error was acceptable and would not impact track discrimination confidence or siding position margin relative to main track clearance.

Phase IIa.2 EOT positioning performance in the absence of a track database demonstrated both across-track and along-track error standard deviations of 40 cm and 46 cm, respectively. However, application of a track database significantly reduced across-track and along-track error standard deviation to 11 cm and 27 cm, respectively. Consequently, application of a track database to at least EOT positioning is strongly encouraged to appreciably reduce position error.

Phase IIb data acquired during operational track testing indicated a level of performance consistent with results observed during testing at TTC, leading to further operational track testing conducted in Phase IIc.

Phase IIc testing encountered variances in track centerline data from individual host railroads that drove analysis to incorporate the Chi-squared method to meet or exceed the PTL objective requirement of 18 cm for all scenarios.

Finally, use of a 900 MHz center frequency for EOT-to-HOT communications was demonstrated to be insufficient to accommodate PTL range requirements subject to ETD rear car masking. As testing at the lower 160, 220, and 450 MHz frequencies has demonstrated, extended range performance is feasible. As a consequence of PTL operational track testing during Phase IIb and IIc, an alternative radio communication data link leveraging multiple low frequency bands is presently in progress and is anticipated to enhance this challenging communication link.

Abbreviations and Acronyms

ACC	auxiliary card cage
AGC	automatic gain control
BER	bit error rate
BNSF	BNSF Railway
COTS	commercial off-the-shelf
CSX	CSX Transportation
DPS	DPS Electronics
EDGE	embedded data-fusion geospatial engine
EOT	end-of-train
ETD	end-of-train device
FRA	Federal Railroad Administration
GbE	Gigabyte Ethernet
GNSS	global navigation satellite system
GPS	global positioning system
HOT	head-of-train
ICD	interface control document
IETMS®	Interoperable Electronic Train Management System
IMU	Inertial Measurement Unit
ITC	Interoperable Train Control
LOS	line-of-sight
LSI	Locomotive System Integration
MHz	megahertz
MIS	Management Information System
MTBF	mean time between failure
μ	statistical mean
NMEA	National Marine Electronics Association
NS	Norfolk Southern Railway
POC	Proof-of-Concept
PTC	Positive Train Control
PTL	Positive Train Location
PTT	Perturbation Test Track
PVH	position, velocity, and heading
RMS	root mean square

RSIA 08	Rail Safety Improvement Act of 2008
RSS	received signal strength
RTK	real time kinematic
SAIC	Science Applications International Corporation
SBAS	Satellite-based Augmentation System
σ	statistical standard deviation
SDR	software-defined radio
SMS	Systems Management System
TMC	Train Management Computer
TTC	Transportation Technology Center (the site)
TTCI	Transportation Technology Center, Inc. (the company)
UP	Union Pacific Railroad
WAAS	wide area augmentation system
WSDR	wideband software-defined radio
WSS	wheel speed sensor

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2. Association of American Railroads. *AAR Manual of Standards and Recommended Practices*, Section K-V, Standard S-9401.V1.0 (formerly MSRP Standard S-5702), "Railroad Electronics Environmental Requirements," Revised 2009, Washington, DC.