U.S. Department of
Transportation

**Federal Railroad
Administration**

# High Accuracy Global Positioning System Tests: Phase I

Office of Research,
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Washington, DC 20590

DOT/FRA/ORD-21/19

Final Report
May 2021

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| 1 square foot (sq ft, ft$^2$) | = | 0.09 square meter (m$^2$) | 1 square meter (m$^2$) | = | 1.2 square yards (sq yd, yd$^2$) |
| 1 square yard (sq yd, yd$^2$) | = | 0.8 square meter (m$^2$) | 1 square kilometer (km$^2$) | = | 0.4 square mile (sq mi, mi$^2$) |
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| 1 short ton = 2,000 pounds (lb) | = | 0.9 tonne (t) | 1 tonne (t) | = | 1,000 kilograms (kg) |
| | | | | = | 1.1 short tons |
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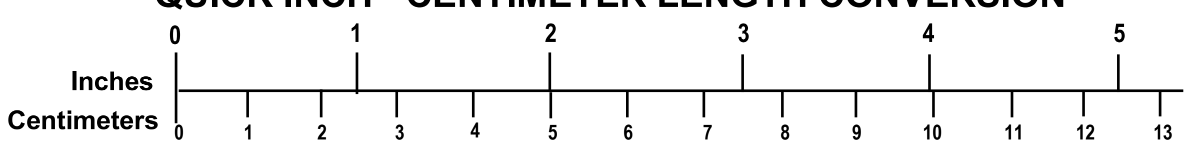


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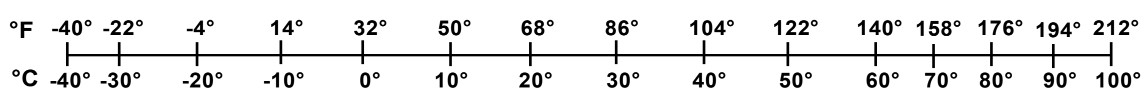


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## Executive Summary

The High Accuracy Nationwide Differential Global Positioning System (HA-NDGPS) is a prototype service that uses carrier phase and code measurement data to obtain precise location information. It has been in development for several years and is slated for possible deployment within the next several years. The importance of this project was to assess the implementation feasibility for improving the accuracy of the Nationwide Differential Global Positioning System (NDGPS) service, using the existing infrastructure, to meet the requirements of additional applications without decreasing availability and integrity while meeting the needs of existing users.

In April 2011, the Federal Railroad Administration (FRA) contracted Transportation Technology Center, Inc. to develop the High Accuracy Global Positioning System (HA-GPS) at the Transportation Technology Center (TTC) to independently test feasibility of the high accuracy portion of the HA-NDGPS system's ability to achieve sub decimeter positional accuracy without the need to modify an existing NDGPS site. This ability may provide a low cost positioning solution for railroad systems such as Positive Train Control (PTC), which requires high accuracy tracking of trains to enhance operational safety. Another railroad related benefit may be the more timely and efficient collection of track feature information needed for generating and maintaining track databases that support PTC operations. Other transportation applications of HA-NDGPS have been defined by the Vehicle Infrastructure Integration project of the Intelligent Transportation Systems initiative.

Researchers constructed a prototype HA-GPS base station at the TTC to broadcast carrier code and phase measurement data at 1 kilowatt and 458 kilohertz (kHz) to remote users to obtain sub decimeter real time kinematic (RTK) GPS positional solutions within a 200-nautical mile radius. Testing of the operation and accuracy of the solution obtained via HA-GPS was under a variety of conditions related to railroad operations.

During the validation phase, researchers tested the accuracy of the HA-GPS broadcast statically against National Geodetic Survey (NGS) monuments. The use of three NGS survey monuments near the TTC could validate the operation of the HA-GPS base station. Two of the monuments were Level 1 horizontal (+/- 1 [cm), while the third monument was Level 2 Horizontal (+/- 2 cm). The comparison of the HA-GPS solutions to the NGS datasheets showed relative accuracies of 1.1, 4.4, and 11.9 cm, respectively.

The next phase of testing statically and dynamically validated the accuracy of the HA-GPS broadcast with a slow speed GPS cart to minimize electromagnetic interference (EMI). This motorized cart was driven around the Railroad Test Track (RTT) at the TTC and collected static and dynamic position information. The average root mean square error (RMSE) accuracies of the dynamic test were 0.1655, 0.329, and 0.494 m at confidence levels of 68 percent (root mean square [RMS]), 95 percent (2 dRMS), and 99.7 percent (3 dRMS), respectively.

The third phase of this test measured statically and dynamically the accuracy of HA-GPS on an unpowered locomotive under tow by another locomotive. The research team performed this test as a baseline test with the EMI of the locomotive systems minimized. The average RMSE accuracies of the dynamic test were 0.189, 0.379, and 0.568 m at confidence levels of 68, 95, and 99.7 percent, respectively.

Finally, the fourth phase of this test measured statically and dynamically the accuracy of HA-GPS on a locomotive with all systems energized. The performance of this test occurred so that a comparison could be made with the unpowered locomotive test to evaluate the effect of the EMI of the locomotive systems. The average RMSE accuracies of the dynamic test were 0.2083, 0.4167, and 0.6249 m at confidence levels of 68, 95, and 99.7 percent, respectively. The locomotive systems affected HA-GPS, but the accuracies still offer improved performance over NDGPS for PTC applications.

FRA's specifications for PTC applications required a 2 dRMS accuracy of 1.0 m (95% confidence) [1]. In all cases, the accuracies are within the FRA specifications for PTC applications at 2 dRMS. With a few exceptions, HA-GPS achieved this accuracy even at the 3 dRMS level (99.7%). Test results indicated that this technology can support PTC applications, but there is a need for more testing.

The testing performed at the TTC only showed the potential to support PTC under basic conditions. Future testing may include the influence of the charged overhead catenary on the RTT. Also, a remote positioning test from a back office location would be enlightening to evaluate the ability to track a train's location in real time and the latency involved in making a determination as to what course of action should be taken when a train exceeds its authority.

The communications range of the HA-GPS system at the TTC is currently unverified. A coverage map of the broadcast would help evaluate the number of high accuracy equipped sites required to provide adequate coverage for PTC applications. Additionally, upgrading the equipment used would reduce the systematic error and increase the positional accuracies. Eventually, this would lead to a specific definition of the system requirements for railroad applications and could possibly reduce the cost to railroad agencies.

# 1. Introduction

The High Accuracy Nationwide Differential Global Positioning System (HA-NDGPS) service has been in development for several years. Researchers established the project to assess the implementation feasibility for improving the accuracy of the Nationwide Differential Global Positioning System (NDGPS) service, while using the existing infrastructure to meet the requirements of additional applications without decreasing availability and integrity while meeting the needs of existing users.

## 1.1 Background

The HA-NDGPS system offers 10 to 20 cm resolutions to HA-NDGPS applications and users, while continuing to provide support to existing NDGPS users. This improvement in resolution may provide a low-cost positioning solution for railroad systems such as Positive Train Control (PTC), which requires high accuracy tracking of trains to enhance operational safety. Another railroad related benefit may be the more timely and efficient collection of track feature information needed for generating and maintaining track databases that support PTC operations. Other transportation applications have been defined by the Vehicle Infrastructure Integration project of the Intelligent Transportation Systems initiative.

PTC applications, such as Vital Positive Train Control (VPTC), require information on the position of a locomotive or train sufficient to resolve which track the locomotive or train occupies with a probability of success greater than 0.999999. Conventional Global Positioning Systems (GPS) offer an average position accuracy of 15 m. Differential Global Positioning Systems (DGPS) offer an average accuracy of 3 to 5 m with 95 percent confidence. These systems alone do not offer the resolution required to resolve track occupancy (i.e., what track is occupied in multiple track territory) with the necessary confidence for fail-safe train control applications.

The HA-NDGPS is a prototype service that researchers established to assess the feasibility of adding a new signal to the existing NDGPS service, which would significantly improve the accuracy and integrity of the system for demanding applications like PTC, Track Defect Location (TDL), and Automated Asset Mapping (AAM). The goal of the HA-NDGPS program is to add a new signal to the existing NDGPS infrastructure without degrading the original NDGPS service.

GPS accuracy is approximately 10 m and the time to alarm for integrity issues can be up to 2 hours. Basic NDGPS accuracy is 1–2 m and the time to alarm integrity is 6 seconds. The research team anticipated that HA-NDGPS will have an accuracy of better the 10 cm and a time to alarm integrity of 1 second. Thus, it appears that HA-NDGPS could be useful in meeting positioning, navigation, and timing requirements for the PTC, TDL, and AAM applications as Table 1 indicates.

**Table 1. FRA Requirements for GPS and Augmentation System Development**

| REQUIREMENTS | MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS | | | | | |
|---|---|---|---|---|---|---|
| | ACCURACY (meters, 2dRMS) | AVAILABILITY | CONTINUITY | INTEGRITY | TIME TO FIRST FIX | COVERAGE |
| Positive Train Control (PTC) | **1.0** | 99.9% | N/A | 6 Seconds Time to Alarm Integrity | 1 Minute | Contiguous 48 states and Alaska Railroad |
| Track Defect Location (TDL) | 0.3 | 99.9% | N/A | 30 Seconds Time to Alarm Integrity | 15 Minutes | Contiguous 48 states and Alaska Railroad |
| Automated Asset Mapping (AAM) | 0.1 | 99.9% | N/A | 30 Seconds Time to Alarm Integrity | 15 Minutes | Contiguous 48 states and Alaska Railroad |
| Surveying | 0.01 | 99.7% | N/A | 30 Seconds Time to Alarm Integrity | 15 Minutes | Contiguous 48 states and Alaska Railroad |
| Bridge and Tectonic Monitoring for Bridge Safety | 0.001 | 99.7% | N/A | 30 Seconds Time to Alarm Integrity | 1 Day | Fault Lines and Specific Bridges |
| Telecommunications Timing | 340 nsec | 99.7% | N/A | 30 Seconds Time to Alarm Integrity | 1 Minute | Contiguous 48 states and Alaska Railroad |
| Weather Forecasting | Improved short term weather forecasts of severe weather such as: tornados, winter storms, thunder storms, and hurricanes. | | | | | Contiguous 48 states and Alaska Railroad |

## 1.2 Objectives

Researchers constructed a prototype HA-GPS base station at the Transportation Technology Center (TTC) to broadcast carrier code and phase measurement data at 1 kilowatt and 458 kHz to remote users to obtain sub decimeter real time kinematic (RTK) GPS positional solutions within a 200-nautical mile radius. Testing of the operation and accuracy of the solution obtained via HA-GPS took place under a variety of conditions related to railroad operations.

## 1.3 Overall Approach

This project consisted of three primary tasks. Task 1 was the preparation of the TTC site for the installation of the HA-GPS base station. Task 2 was to conduct the installation, checkout, and validation of the HA-GPS site at the TTC. Task 3 was to demonstrate potential benefits of using HA-GPS data as a functional equivalent of HA-NDGPS data for train control applications by conducting the testing described in the original Task Order 234.

## 1.4 Scope

Static surveys took place at local National Geodetic Survey (NGS) monuments to verify the site's calibration. Also, baseline tests took place using a slow-speed frame cart with GPS and HA-GPS receivers installed. Researchers installed two receivers of each type on the cart, one of each on the front and on the rear of the cart. The size of the cart allowed a minimum of 40 feet of separation between the front and rear GPS/HA-GPS receivers. Using a cart for this test provided an environment with minimal conducting planes near the receivers' antennas and minimal electromagnetic interference (EMI).

A set of test runs occurred with this test configuration. The test runs included static position measurement, slow-speed runs around the Railroad Test Track (RTT), and runs through turnouts aligned normal and reverse. For each test run, researchers recorded the discrete GPS data received by each receiver, along with the discrete HA-GPS data.

The research team conducted locomotive positioning tests with GPS and HA-GPS receivers installed on a GP-40 locomotive (Association of American Railroads [AAR] 2000 or Transportation Technology Center, Inc. [TTCI] 2001). For this work an installation of two GPS and two HA-GPS receivers took place on the locomotive; i.e., one of each in the front and in the rear of the locomotive. The distance between the front and back GPS and HA-GPS receivers was the same as in the baseline tests.

Two sets of test runs took place. The first set of tests occurred with the GPS equipped locomotive being towed, with all systems shut down. The first test set provided an environment with horizontal conducting planes near the receivers' antennas, as would be found in a typical locomotive installation, and with minimal EMI from locomotive systems.

The second set of tests occurred with the same GPS-equipped locomotive with all systems powered up and moving under its own power. The second test set provided an environment with horizontal conducting planes near the receivers' antennas, as would be found in a typical locomotive installation, as well as exposing the equipment to EMI from locomotive systems.

Each set of locomotive positioning tests included the following test runs:

- Static position measurement
- Runs around the RTT at multiple different speeds (i.e., 10, 20, 40, 60, 80, and 100 mph)

For each test run, the following data was collected:

- Discrete data received from each satellite
- Discrete data received from the HA-GPS systems

In addition to the instrumentation installed as described in the locomotive position tests, researchers conducted end of train (EOT) positioning tests with GPS and HA-GPS receivers installed on the rear of the locomotive in a mock-up of an EOT case. This was used to evaluate the performance of the GPS and HA-GPS systems when placement of their antennas was near a vertical conducting plane.

The EOT positioning tests included the following test runs:

- Static position measurements taken at multiple locations so that position data was collected for each of the following cases:
  - With the rear of the car such that the GPS systems' antennas were exposed to the TTC HA-GPS site
  - With the body of the rail car between the GPS systems' antennas and the TTC HA-GPS site
  - With the body of the rail car partially blocking the GPS systems' antennas from the TTC HA-GPS site
- Test runs went around the RTT at multiple different speeds (i.e., 10, 20, 40, 60, 80, and 100 mph)

In addition to the data collected as defined for the locomotive position tests, EOT position tests collected the following data for each test run:

- Discrete data received from each satellite
- Discrete differential correction signals received for the HA-GPS systems

Data collected in the test runs were post processed using commercially available analysis tools and analysis tools provided as Government Furnished Equipment (GFE) (e.g., GPS Receiver Interface Module [GRIM]). The post processing evaluated the comparative accuracy of the GPS versus the Online Positioning User Service (OPUS) provided by NGS versus HA-GPS and the relative performance of various railroad applications with each type of positioning system tested.

Data processing included, but was not limited to the following:

- Static Performance Evaluation: Researchers processed data to show the relative accuracy of GPS, OPUS, and HA-GPS for each of the following cases:
  - Static position measurement accuracy, and confidence for each positioning system (i.e., GPS and HA-GPS) as a function of the number of samples used in the measurement for each receiver for low EMI, locomotive EMI, and EOT environments.
  - Static position measurement accuracy, variance, and confidence for each positioning system as a function of the number of satellites visible (i.e., data from individual satellites to be removed during post processing) for each receiver for low EMI, locomotive EMI, and EOT environments

- Dynamic Location Monitoring: Researchers processed data to show the relative accuracy of GPS and HA-GPS for each of the following cases:
  - Dynamic position measurement accuracy, variance, and confidence for each positioning system (i.e., GPS and HA-GPS) as a function of the number of samples used in the measurement for each receiver for low EMI, locomotive EMI, and EOT environments
  - Dynamic position measurement accuracy, variance, and confidence for each positioning system as a function of the number of satellites visible (i.e., data from individual satellites to be removed during post processing) for each receiver for low EMI, locomotive EMI, and EOT environments
  - Relative dynamic locomotive position measurement accuracy, variance, and confidence for each positioning system as a function of using a single receiver or two receivers
  - Dynamic locomotive position measurement offset resulting from time averaging of multiple samples and processing delays

## 1.5 Organization of the Report

The report is organized in the following sections: site construction and site operation in Section 2; site calibration, static testing (survey monuments) and results, baseline testing and results, and support from Stanford University on Pikes Peak in Section 3; locomotive and EOT testing and results, signal strength and signal-to-noise ratio plots for all test runs in Section 4; and Section 5 offers conclusions and recommendations of continuous work.

## 2. Site Development

The Federal Highway Administration (FHWA) provided the following equipment to TTCI as GFE for this project:

| **Hardware** | **Software** |
|---|---|
| One Nautel 3-kilowatt transmitter | GRIM |
| One Nautel RF coupler | High Accuracy Control Program (HACP) |
| Three HA-GPS rover receivers | HA-RTCM.EXE program |
| One HA-GPS mother-daughter modulator card | DynaPos post-processing software |

### 2.1 Site Selection and Requirements

The TTC has 52 square miles of property. However, due to the nature of Medium Frequency (MF) transmissions, the location of the facility is of the utmost importance. MF waves use the positively charged top of the antenna to excite the ionosphere and the negatively charged ground plane (i.e., conductive grid placed 6 inches underground) to propagate a wave that follows the curvature of the earth, which allows the signal to travel a long distance even when there is no line-of-sight between the user and the broadcast antenna. As a result, the site cannot be located within 1 wavelength (i.e., 2,144 feet for 458 kHz transmission) from any tall structures, such as buildings. It also cannot be within 1 wavelength from overhead power lines, because they can reradiate the signal and cause interference. Any high voltage sources greater than 100 kilovolts can also cause interference if within a 1/2 mile radius. Additionally, people should be kept a safe distance away from the site, because the output of TTCI's broadcast is 1 kilowatt of radiated power.

MF transmissions also require tall towers, some on the order of 300 feet tall. A hybrid antenna was used that can be shorter due to its T-shaped design. The design required the construction of two medium height towers (e.g., the TTC's are 60 feet tall) with a 270-foot long, two-cable radiator strung between the tops of the towers. Even with this shorter design, 60-foot tall towers still needed to be securely anchored to the ground. This requires good soil or engineering to accomplish.

The base station also required a single phase, 208-volt power source. Much of the TTC's property is unpowered, and trenching/running cable over long distances is very expensive. So, choosing a site with easy access to power is a plus. Site preparation can also be costly. A site that requires little or no heavy equipment to clear, level, and grade puts less stress on the budget.

The TTC's HA-GPS base station required a significant amount of electronic equipment, a shelter to house that equipment, two 60-foot tall towers, a grounding well to which everything was grounded, some minor excavation, and a lot of electrical work to provide power. For this project, TTCI purchased one Trimble NetRs GPS receiver, two Dell PowerEdge servers to store and process data, one Dell rack mounted monitor, two equipment racks, two data radios to transmit data 2 miles from the site to the core area, a GPS splitter, an Ethernet switch, and two "smart" uninterruptable power supplies. TTCI contracted with Nautel, Inc. for the purchase and installation of the antenna towers and antenna tuning unit (ATU), and they provided a Nautel RF coupler and 3-kilowatt transmitter as GFE equipment. FHWA loaned TTCI three proto-type HA-GPS receivers.

Researchers designed a shelter to house all this equipment. It had to be large enough to house all the equipment and personnel comfortably, be shielded from MF energy, and be climate controlled. Figure 1 shows the layout TTCI developed, which was built by Sermi Products, Inc. in Atlanta, GA.

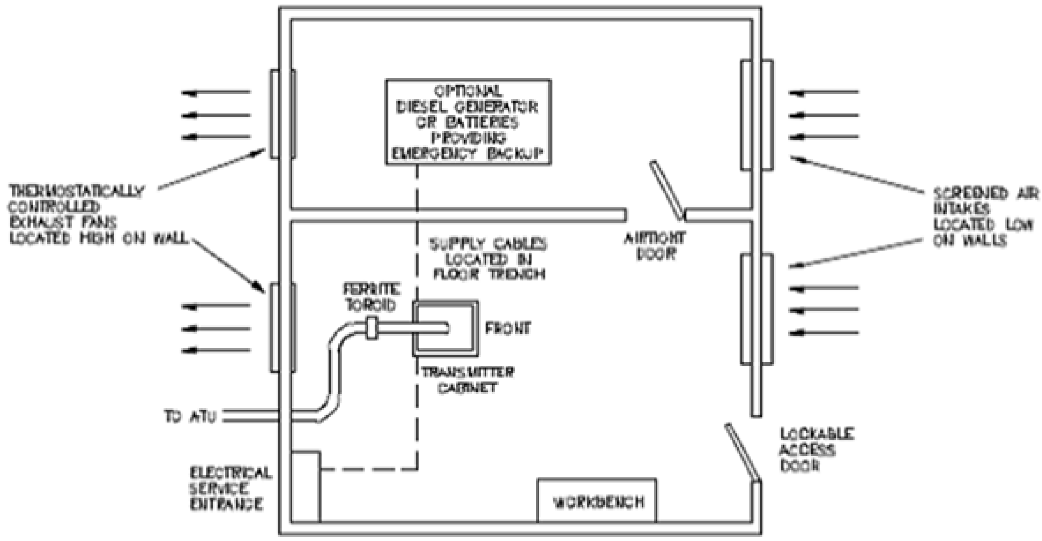



**Figure 1. HA-GPS Base Station Building Layout**

The only site at the TTC that met the criteria was the Simulated Resonance Electromagnetic Pulse (SREMP) site. The SREMP site was used in the '70s to test the effects of electromagnetic pulses on train technology. Thus, a 480-volt transformer and several distribution panels were available to use for the power requirements of the HA-GPS equipment, as well as water and a septic system (see map in Figure 2).


**Figure 2. Map of the TTC SREMP Circled in Red**

## 2.2 Site Layout

In addition to the building layout, TTCI designed a site layout for the contractors that installed the antenna. TTCI took measurements from all existing landmarks, mapped all underground cables, and planned the shelter location, ground well, ground plane, antenna towers, ATU, and security fence. Figure 3 shows the site layout, which researchers created using AutoCad and submitted to antenna installation contractors.

The yellow star-like formation in the center of the site layout drawing is the ground plane that the research team installed 6 inches underground. To ground the entire site, researchers drilled a 60-foot-deep hole and inserted a ground rod. Drilling another 60-foot-deep hole and pouring a concrete pillar occurred to create a sturdy foundation for the GPS receiving antenna. In June 2010, TTCI completed the HA-GPS site at the TTC and deemed it fully operational, as Figure 4 shows.

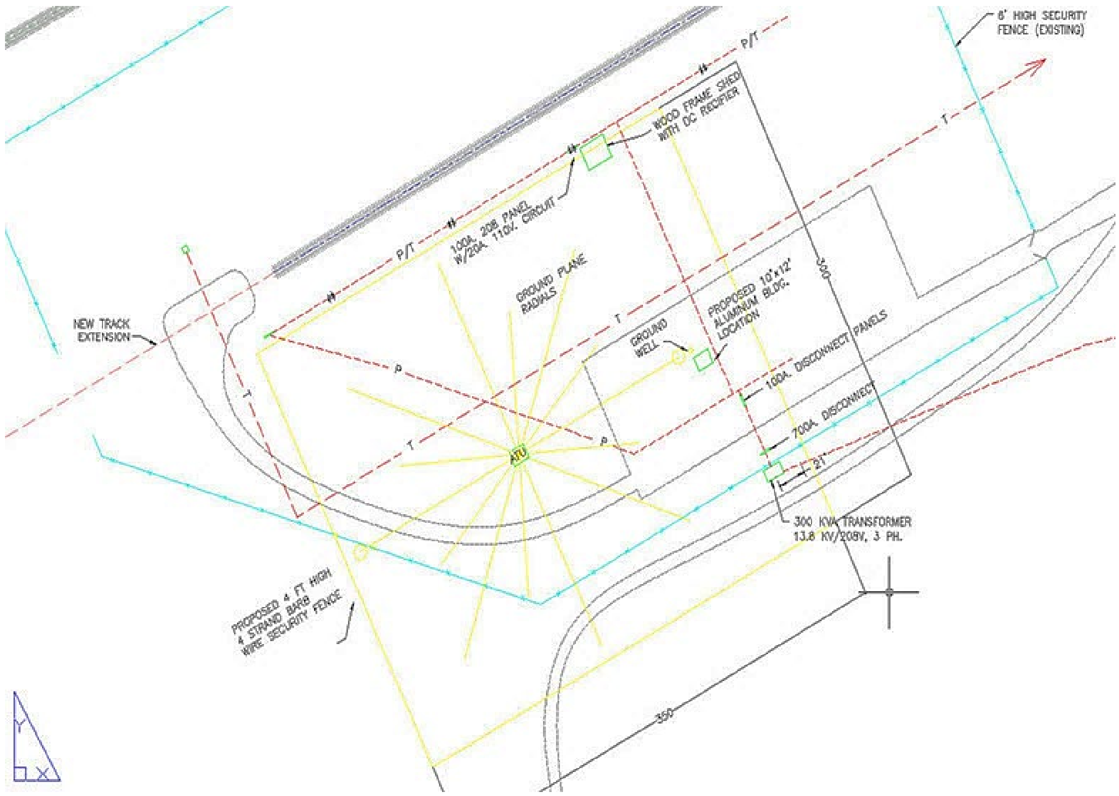



**Figure 3. Site Layout**

**Figure 4. HA-GPS Site**

## 3. Installation, Checkout, and Validation of HA-GPS Site

Figure 5 shows how the HA-GPS system works. First, it collects GPS measurement data from the constellation of satellites in view. Then, GRIM compressed this data and modulated it onto a 458-kHz carrier wave transmitted to the user. On the user end, a beacon receiver receives the broadcast that GRIM decompressed and converted to Radio Technical Commission (RTCM) 18/19 and input into the user's GPS receiver where it is combined and processed to obtain a precise RTK solution.

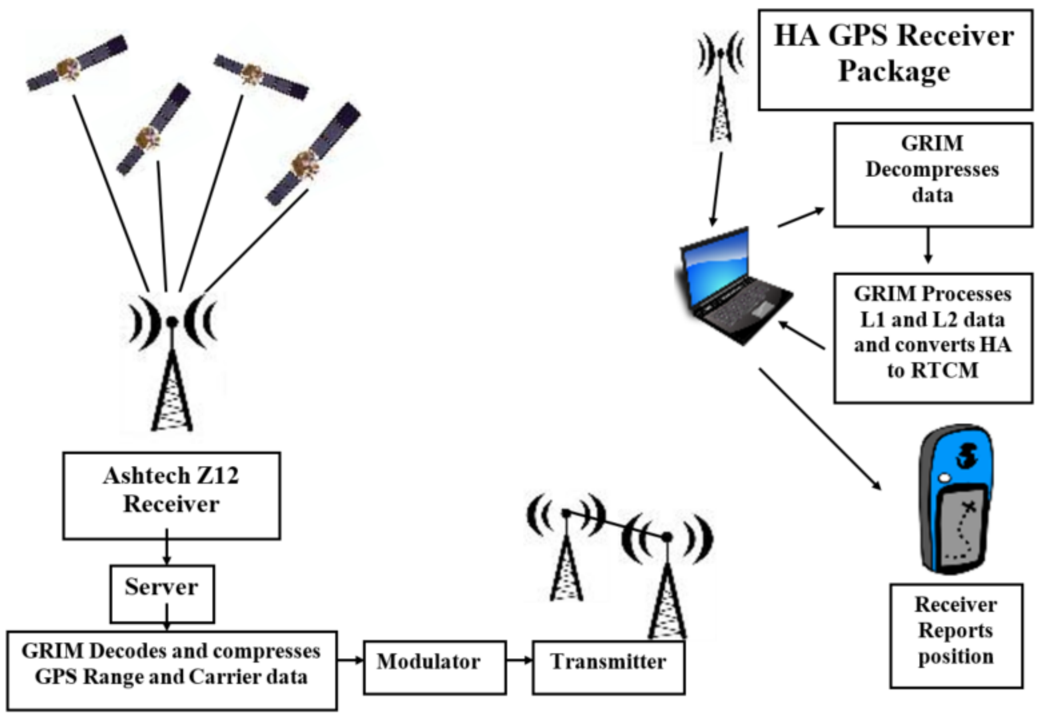



**Figure 5. The HA-GPS System**

### 3.1 Site Calibration

To obtain precise GPS coordinates for the location of the base station from which all measurements would reference, researchers collected 24 hours of data and submitted it to OPUS. OPUS returned a solution in the NAD 83 datum, which was then transformed to WGS 84 to remain consistent with the datum used by the other equipment. Once the base station computer had these coordinates, validation of the HA-GPS site was necessary before performing further testing. This was accomplished by recording data during a 20–30-minute occupation at three NGS survey monuments (control points). The TTC site has two NGS Level 1 and one NGS Level 2 control points (Figure 6). Figure 7 shows the best NGS Level 1 control point, which researchers referred to as Southeast 2. The other two control points are referred to as South 2 (NGS Level 1) and Southeast (NGS Level 2). Figure 8 and Figure 9 show GPS data from the Southeast and South2 control points.

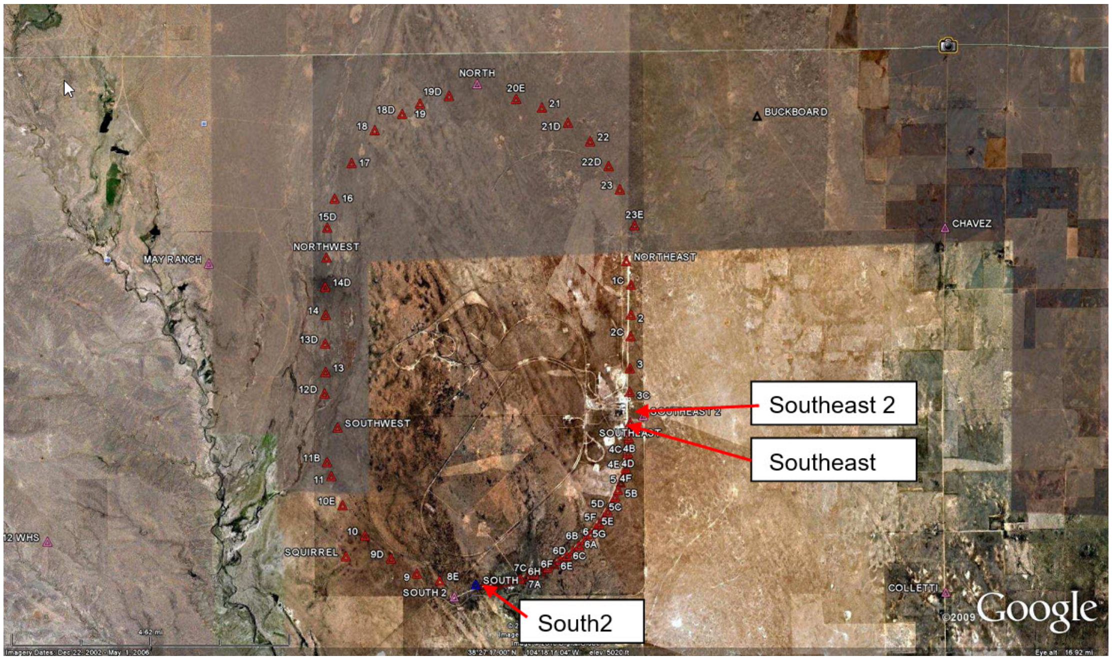



**Figure 6. Control Points from Left to Right, South2, Southeast, and Southeast 2**

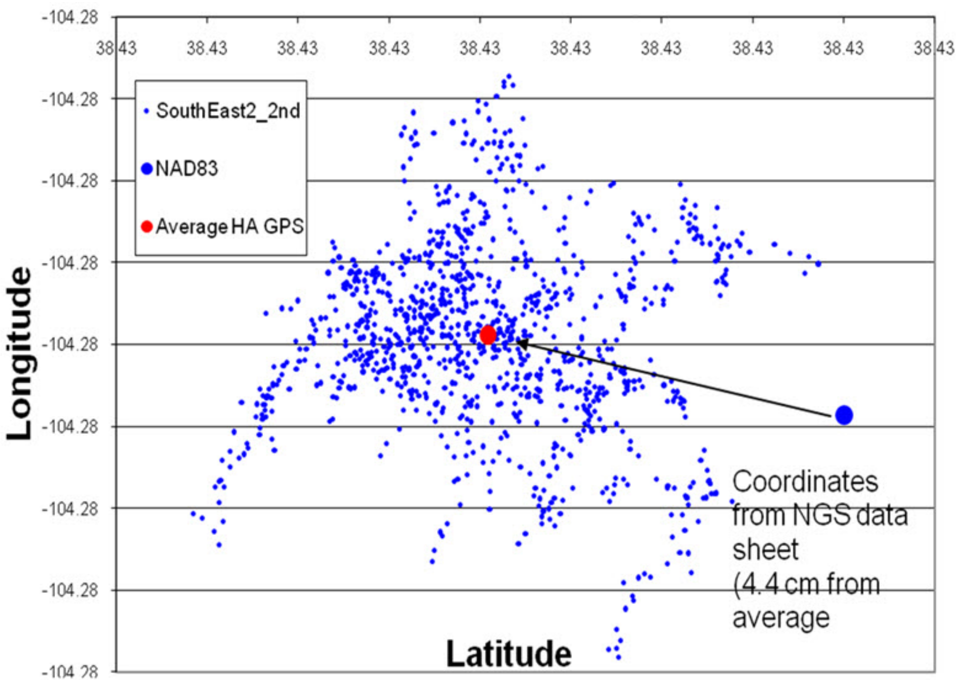



**Figure 7. NGS Level 1 Southeast2 Control Point**

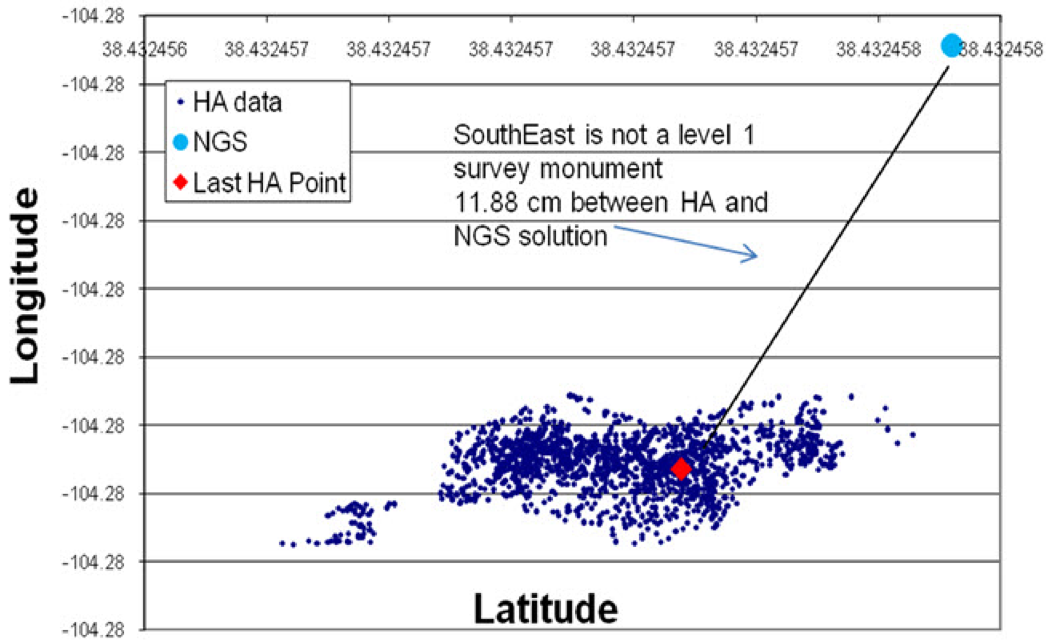



**Figure 8. NGS Level 2 Southeast Control Point**

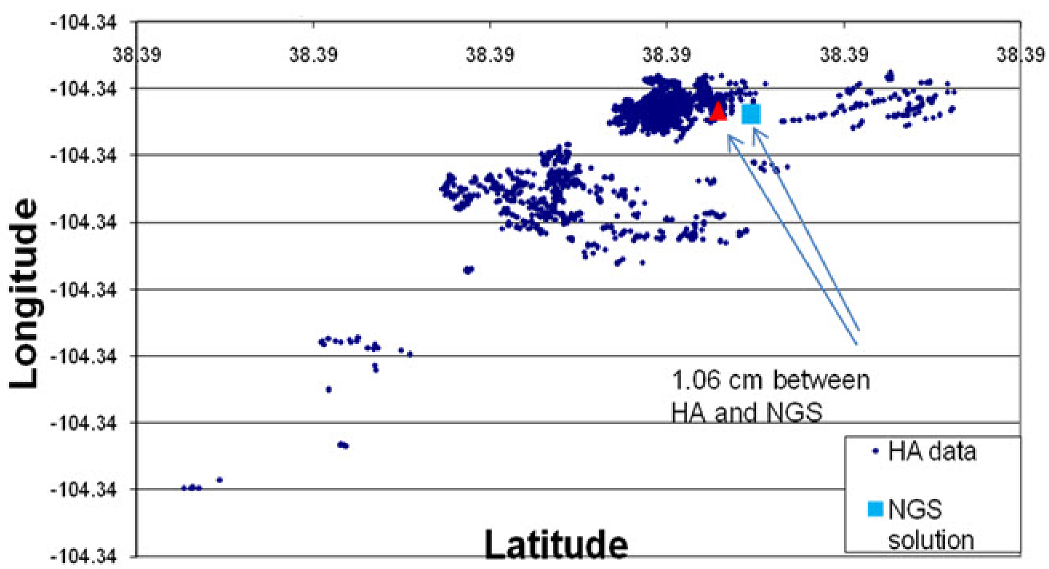



**Figure 9. NGS Level 1 South2 Control Point**

Table 2 shows differences between OPUS and HA-GPS data at three NGS control points at the TTC locations: Southeast 2, Southeast, and South 2.

**Table 2. Differences Between OPUS and HA-GPS Data**

| | Horizontal Difference | | Vertical Difference | |
|---|---|---|---|---|
| **TTC Location** | **cm** | **ft** | **cm** | **ft** |
| Southeast | 11.88 | 0.39 | 19.3 | 0.63 |
| Southeast 2 | 4.44 | 0.14 | 7.6 | 0.25 |
| South 2 | 1.06 | .035 | 7.2 | 0.24 |

## 3.2 Baseline Validation Testing

Researchers conducted baseline tests using a slow speed frame cart system (Figure 10) with GPS and HA-GPS receivers installed on it. The cart held two of each type of receiver, one each in the front and in the rear of the cart. The size of the cart allowed a minimum of 40 feet of separation between the front and back GPS and HA-GPS receivers. Using a cart for this test provided an environment with minimal conducting planes near the receivers' antennas and minimal EMI.

The following is a list of test equipment used for baseline testing:

- GPS Receiver (2)
- HA-GPS Receiver (2)
- GPS Track Cart (Figure 10)
- Data Acquisition Equipment
- Remote Control Equipment

All measurement equipment had valid calibration certifications.

**Figure 10. Slow Speed GPS Cart**

The positioning of each end of the slow speed frame cart system was at four previously mapped points on the RTT. The discrete data received by each receiver was recorded, as well as the associated HA-GPS data. Figure 11 shows the previously mapped points on the RTT that were used to compare the GPS measurements.

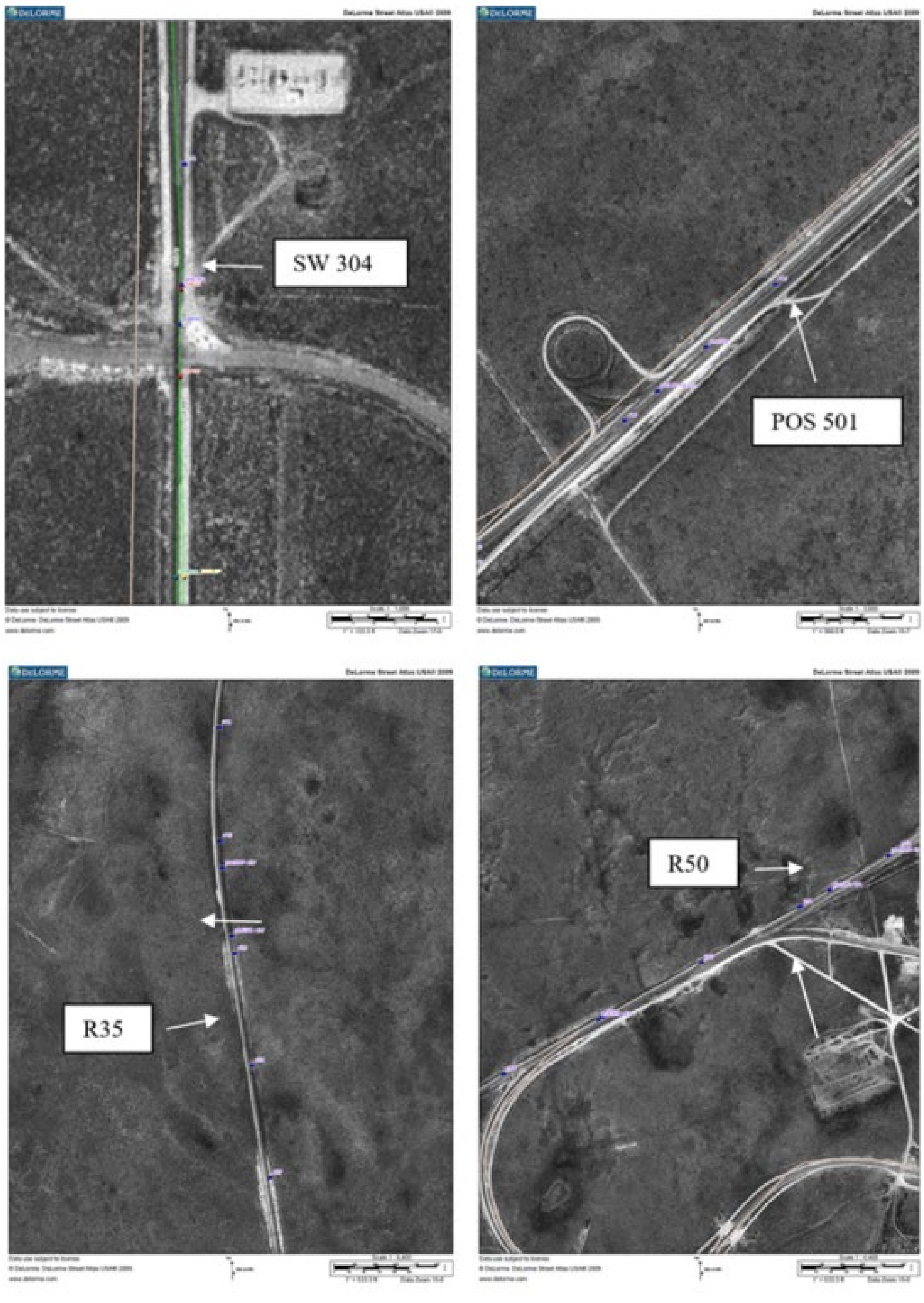



**Figure 11. Aerial of RTT Mapped Location Points: SW 304, R35, POS 501, and R50**

The test procedure using the slow speed GPS cart followed these steps:

1. Researchers placed one end of the GPS cart at location point SW304 POS and 15 minutes of data was recorded.

2. Placement of the other end of the cart was at location point SW304 POS and 15 minutes of data was recorded.
3. Steps 1 and 2 were repeated at location points R50, R35, and 501 POS.
4. The data was post processed and compared to the known positions for all the location points.

Figure 12 shows the dynamic slow-speed measurements taken around the RTT.

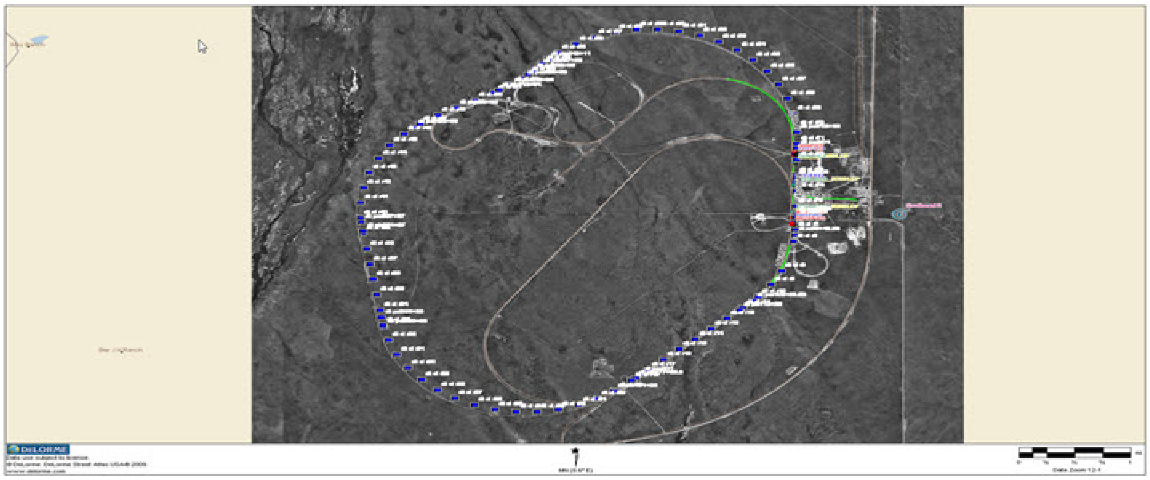


**Figure 12. Dynamic Slow Speed GPS Measurements Taken Around the RTT**

The dynamic measurements were taken using the following procedure:

1. A test run was conducted around the RTT through turnouts aligned normal.
2. Recorded data took place for each test run the discrete data received by each receiver and associated HA-GPS data.
3. The HA-GPS data was compared with the HA-GPS site data to verify that the data compared all the way around the RTT.
4. Processing of the raw data took place with the NDGPS data.
5. Processing of the raw data occurred with the HA-GPS data.
6. The results from the two sources were compared to the known positions around the RTT loop.

### 3.2.1 *Methodology for Computing Static Accuracies*

See the following procedure that allowed researchers to compute the difference between the measured position of each location and the OPUS provided solution:

$$D_{HorizontalPosition} = \sqrt{\left(\frac{(Lat_{opus} - Lat_{measured}) * meters}{\text{Latitude degree}}\right)^2 + \left(\frac{(Long_{opus} - Long_{measured}) * meters}{\text{Longitude degree}}\right)^2}$$

$$D_{VerticalPosition} = Vertical_{OPUS} - Vertical_{Measured}$$

Table 3 shows a summary of the differences between the HA-GPS measured data and the OPUS provided known solutions for the horizontal and vertical positions around the RTT loop.

**Table 3. Static Accuracy Summary**

| **Static** | **Difference between OPUS and HA-GPS** | | | |
|---|---|---|---|---|
| | **Horizontal** | | **Vertical** | |
| Site | Meter | Foot | Meter | Foot |
| R50 Front | 0.130 | 0.428 | 0.134 | 0.440 |
| R35 Front | 0.080 | 0.263 | 0.178 | 0.584 |
| SW 304 Front | 0.244 | 0.801 | 0.061 | 0.200 |
| POS 501 Front | 0.163 | 0.863 | 0.117 | 0.384 |
| R50 Rear | 0.124 | 0.407 | 0.102 | 0.335 |
| R35 Rear | 0.069 | 0.226 | 0.156 | 0.512 |
| SW 304 Rear | 0.296 | 0.971 | 0.070 | 0.230 |
| POS 501 Rear | 0.141 | 0.463 | 0.081 | 0.266 |

### *3.2.2 Methodology for Computing Dynamic Accuracies*

When a data set from a theoretical prediction and another data set from an actual measurement of some physical variable are compared, the RMS of the differences of the two data sets can serve as a measure of how far (on average) the error is from 0. This is referred to as the RMSE. The mean of the differences does not measure the variability of the difference, and the variability as indicated by the standard deviation is around the mean instead of 0. Therefore, the RMSE of the differences is a meaningful measure of the error. The RMSE is the standard adopted by the National Forest Service as it pertains to GPS data accuracy [2].

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(x_{1,i} - x_{2,i})^2}{n}}.$$

where $x_{1,i}$ = truth coordinate

$x_{2,i}$ = measured coordinate

n = number of observations

RMSE is shown at three levels of confidence:

- RMS 68% confidence
- Two dRMS 95% confidence
- Three dRMS 99.7% confidence[4]

Table 4 shows a summary of the dynamic RMSE results taken at the two ends of the slow speed GPS cart.

**Table 4. Dynamic RMSE Results**

| Dynamic RMSE | 68% confidence | | 95% confidence | | 99.7% confidence | |
|---|---|---|---|---|---|---|
| | **Meter** | **Foot** | **Meter** | **Foot** | **Meter** | **Foot** |
| Front | 0.182 | 0.596 | 0.364 | 0.711 | 0.546 | 1.787 |
| Rear | 0.147 | 0.481 | 0.294 | 0.965 | 0.441 | 1.345 |

### *3.2.3 Stanford University and Pikes Peak Support*

During the HA-GPS testing at the TTC, Stanford University expressed interest in using the TTC's signal as a navigation source for their unmanned Audi TT's (Figure 13) ascent of Pikes Peak.

**Figure 13. Audi TT Provided by Stanford University Team**

The design of the HA-GPS receivers and the HA-RTCM.exe program allows any manufacturer's version of a GPS receiver that can accept an RTCM input to use the HA-GPS broadcast. Figure 14 shows the Audi TT with the TTC laptop and Raven Beacon installed on it.

**Figure 14. The TTC Laptop and Raven Beacon Receiver Installed on Audi TT**

The navigation system in the car could receive TTC's RTCM 18/19 signal and use it to achieve a carrier phase based solution of approximately 6 cm RMS. Figure 15 and Figure 16 show north and east positioning errors during the Audi TT's ascent of Pikes Peak.

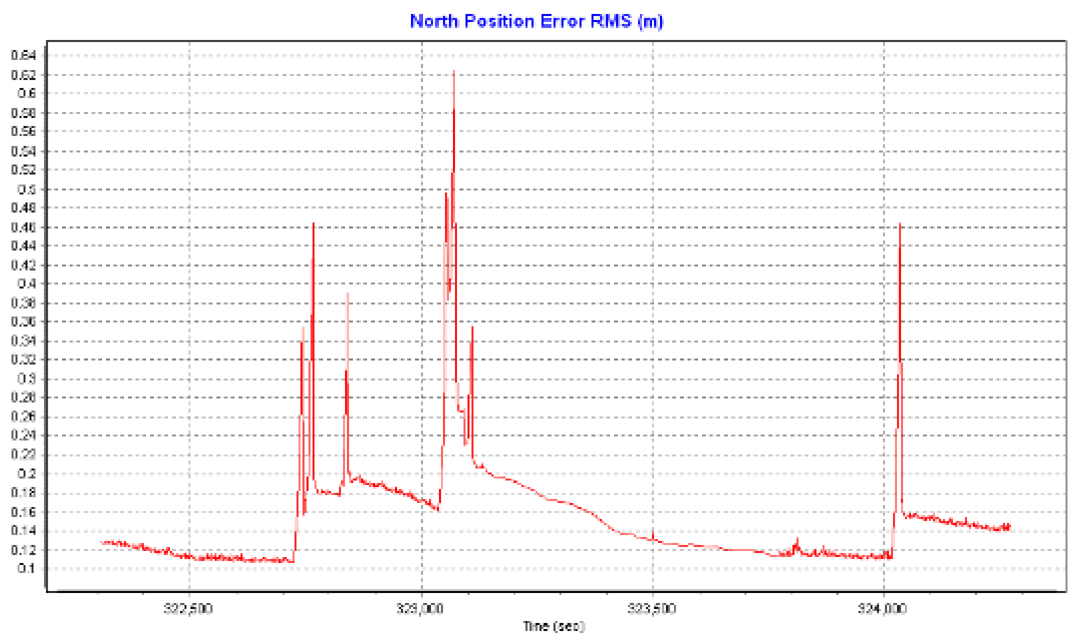



**Figure 15. North Positioning Error Provided by Stanford University Team**

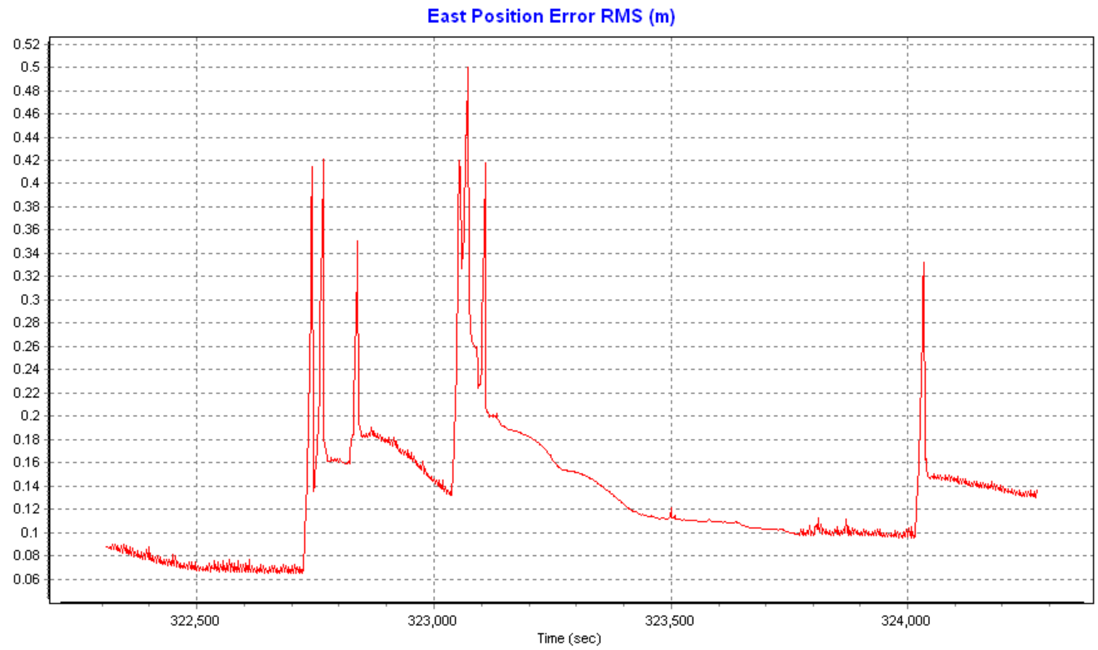



**Figure 16. East Positioning Error Provided by Stanford University Team**

Although the TTC site was not able to provide 100 percent coverage of the mountain due to the terrain, it could provide HA-GPS coverage over much of the race course. Unfortunately, the four “dark” (not covered) portions of the course were stretches of several hundred feet. This prevented the Stanford team from autonomously navigating the 13-mile course with the HA-GPS signal broadcast from the TTC. In the future, TTCI hopes to extend its coverage area and eliminate the need to use a conventional RTK system (Figure 17). Figure 18 shows an aerial for the piloted ascent up Pikes Peak by the Stanford University team.

**Figure 17. Conventional RTK System Used by the Stanford University Team**

**Figure 18. Google Earth Map of Piloted Ascent of Pikes Peak (Datum Shift Present)**

# 4. Locomotive and EOT Testing

## 4.1 Powered and Unpowered Locomotive Test Procedure

Researchers conducted two sets of locomotive positioning tests. Figure 19 shows the GPS equipped locomotive, which had all systems shut down, and towed (Figure 20). This test set provided an environment with horizontal conducting planes near the receivers' antennas, as would be found in a typical locomotive installation, and with minimal EMI from locomotive systems.

These tests used the following test equipment (Figure 19 through Figure 23):

- Three GPS receivers (i.e., mounted directly over the centerline of the track on the front and rear of the locomotive) and on the rear coupler (i.e., to represent an EOT device)
- Three HA-GPS receivers (i.e., mounted near corresponding GPS receiver)
- One GP-40 locomotive
- Towing locomotive
- Mock-up of EOT case
- Data acquisition equipment

All measurement equipment had valid calibration certifications.


**Figure 19. AAR 2000 Locomotive**


**Figure 20. Unpowered Towing Configuration**

**Figure 21. Front of Locomotive**

**Figure 22. Rear of Locomotive (Near Exhaust Fan)**

**Figure 23. A Mock-up of an EOT Case Constructed to Mount the Antennas**

The positioning of each end of the locomotive was at four previously mapped points on the RTT. There was a recording of discrete data received by each receiver, as well as the associated HA-GPS data. The test procedure for the powered and unpowered locomotive tests followed these steps:

1. Placement of one end of the locomotive was at the RTT mapped point SW304 and a 15-minute recording of data occurred.

2. Placement of the other end of the locomotive was location point SW304 and a 15-minute recording of data occurred.
3. Placement of the EOT was at location point SW304 and a 15-minute recording of data occurred. This evaluated the performance of the positioning systems when their antennas were placed near a vertical conducting plane.
4. Researchers repeated steps 1–3 at locations R50 ALD, R35 ALD, and 501 POS.
5. Processing the raw data took place on site with the HA-GPS data.
6. A comparison ensued with the results from the two sources to the actual positions.
7. A comparison occurred of the HA-GPS data to the data recorded at the HA-GPS site to verify that the recorded data was the same.

Figure 24 shows the dynamic measurements around the RTT.

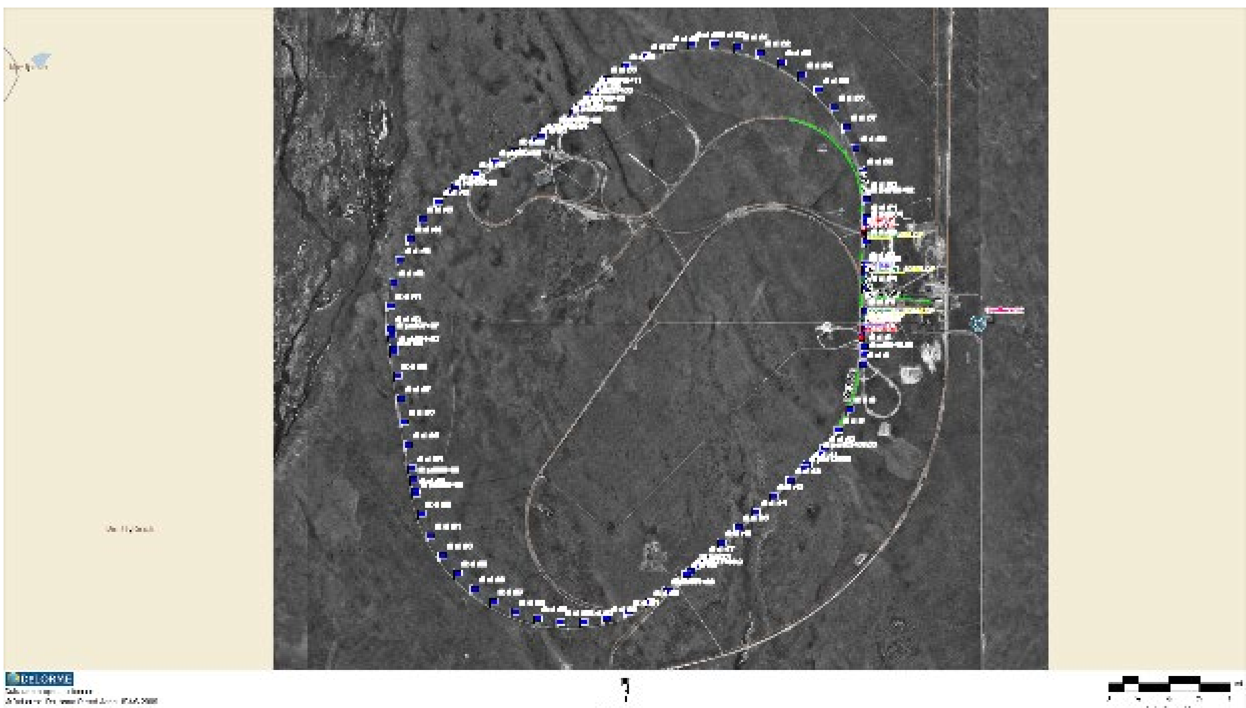


**Figure 24. Dynamic Measurements Around the RTT to Verify HA-GPS Data**

Researchers conducted test runs around the RTT through turnouts aligned normal at speeds of 10, 20, 40, 60, 80, and 100 mph. The test proceeded according to the following steps:

1. Test runs were made through the new siding in the core area with the turnouts aligned for diverging into the siding.
2. For each test run, the discrete data received by each receiver was recorded, as well as the associated HA-GPS data.
3. A comparison of the HA-GPS data took place with the HA-GPS site data to verify that the data compared all the way around the RTT.

4. Processing the raw data occurred with the HA-GPS data.
5. A comparison of the results from the two sources ensued to the known positions around the loop.
6. Researchers repeated steps 1–5 with all locomotive systems energized and the locomotive moving under its own power. This test set provided an environment with horizontal conducting planes near the receivers' antennas, as would be found in a typical locomotive installation, as well as exposing the equipment to EMI from locomotive systems [3].

## 4.2 Work Instruction and Test Matrix

The research team performed the locomotive and EOT testing simultaneously to reduce the amount of track time needed by completely instrumenting the locomotive with two of each type of receiver and the EOT with one type of each receiver. The locomotive systems powered all GPS packages.

The first 12 tests were static measurements taken at locations SW304, POS, R50, R35, and 501 POS. Runs 13–18 were loops around the RTT at various speeds. Runs 19–26 were static measurements with the towing locomotive removed and the instrumented locomotive running under its own power. Runs 27–32 were loops around the RTT at various speeds with the instrumented locomotive running under its own power. Table 5 shows the test matrix.

**Table 5. Text Matrix for Locomotive Powered/Unpowered and EOT Test Runs**

| Run | Location | Position | Powered/Unpowered |
|---|---|---|---|
| 1 | SW304 | Front Loco | Unpowered |
| 2 | SW304 | Rear Loco | Unpowered |
| 3 | SW304 | EOT | Unpowered |
| 4 | R50 ALD | Front Loco | Unpowered |
| 5 | R50 ALD | Rear Loco | Unpowered |
| 6 | R50 ALD | EOT | Unpowered |
| 7 | R35 ALD | Front Loco | Unpowered |
| 8 | R35 ALD | Rear Loco | Unpowered |
| 9 | R35 ALD | EOT | Unpowered |
| 10 | 501 POS | Front Loco | Unpowered |
| 11 | 501 POS | Rear Loco | Unpowered |
| 12 | 501 POS | EOT | Unpowered |
| 13 | 10 mph | | Unpowered |
| 14 | 20 mph | | Unpowered |
| 15 | 40 mph | | Unpowered |
| 16 | 60 mph | | Unpowered |
| 17 | 80 mph | | Unpowered |
| 18 | 100 mph | | Unpowered |
| 19 | SW304 | Front Loco | Powered |
| 20 | SW304 | Rear Loco | Powered |
| 21 | R50 ALD | Front Loco | Powered |
| 22 | R50 ALD | Rear Loco | Powered |
| 23 | R35 ALD | Front Loco | Powered |

| Run | Location | Position | Powered/Unpowered |
|---|---|---|---|
| 24 | R35 ALD | Rear Loco | Powered |
| 25 | 501 POS | Front Loco | Powered |
| 26 | 501 POS | Rear Loco | Powered |
| 27 | 10 mph | | Powered |
| 28 | 20 mph | | Powered |
| 29 | 40 mph | | Powered |
| 30 | 60 mph | | Powered |
| 31 | 80 mph | | Powered |
| 32 | 100 mph | | Powered |

Figure 25 illustrates how the Front Locomotive position was measured.

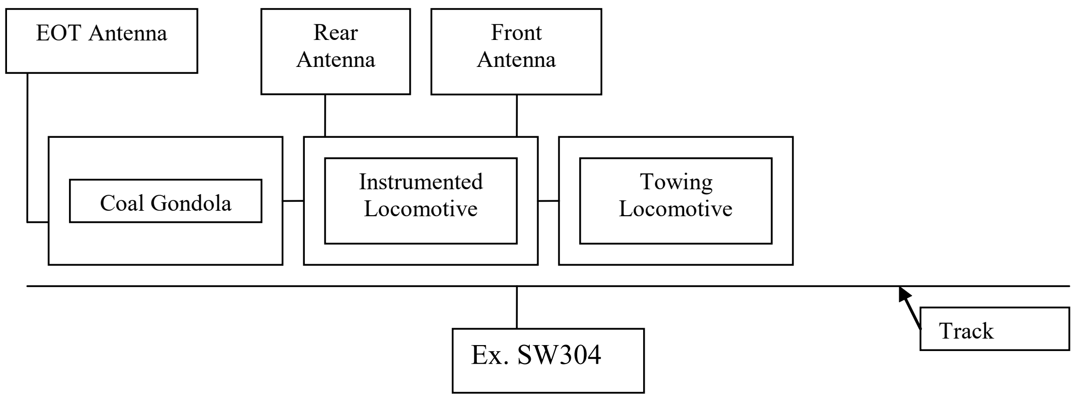



**Figure 25. Front Locomotive Antenna is Aligned with SW304**

Figure 26 illustrates how the Rear Locomotive position was measured.

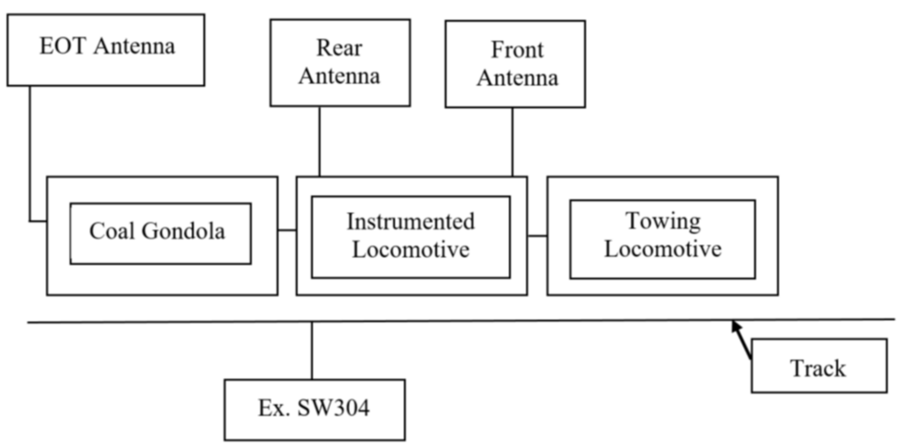



**Figure 26. Rear Locomotive Antenna is Aligned with SW304**

Figure 27 illustrates how the EOT position was measured.

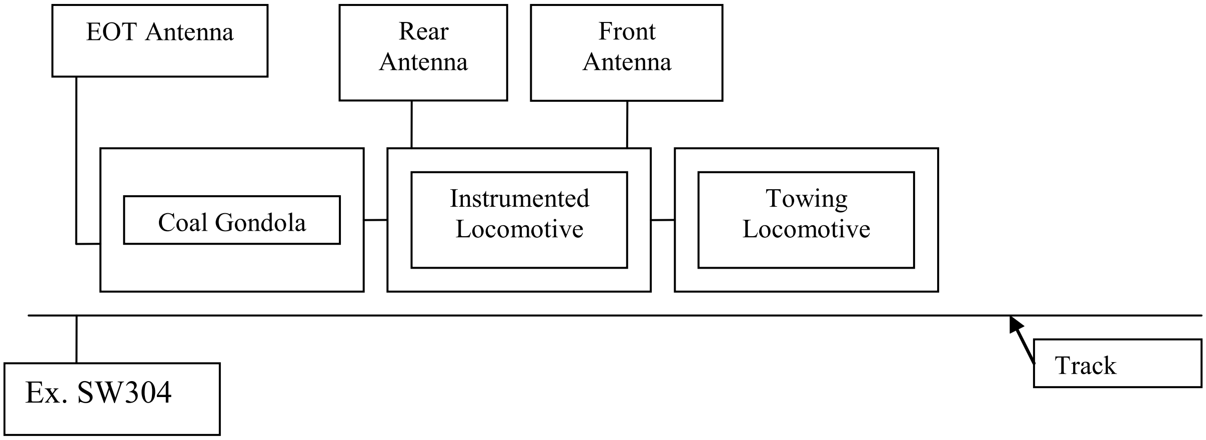



**Figure 27. EOT Antenna Aligned with SW304**

## 4.3 Locomotive and EOT Static Results

The static and dynamic rear of locomotive and EOT test results also serve as train length data, because they were compared to the post-processed solutions of the front locomotive data. This was done because that there was no autonomous (i.e., receiver independent exchange [RINEX]) formatted data available for post processing the RTCM input method.

Figure 28 through Figure 33 are scatter plots of measurements taken at location R35 with front and rear locomotive powered and unpowered conditions.

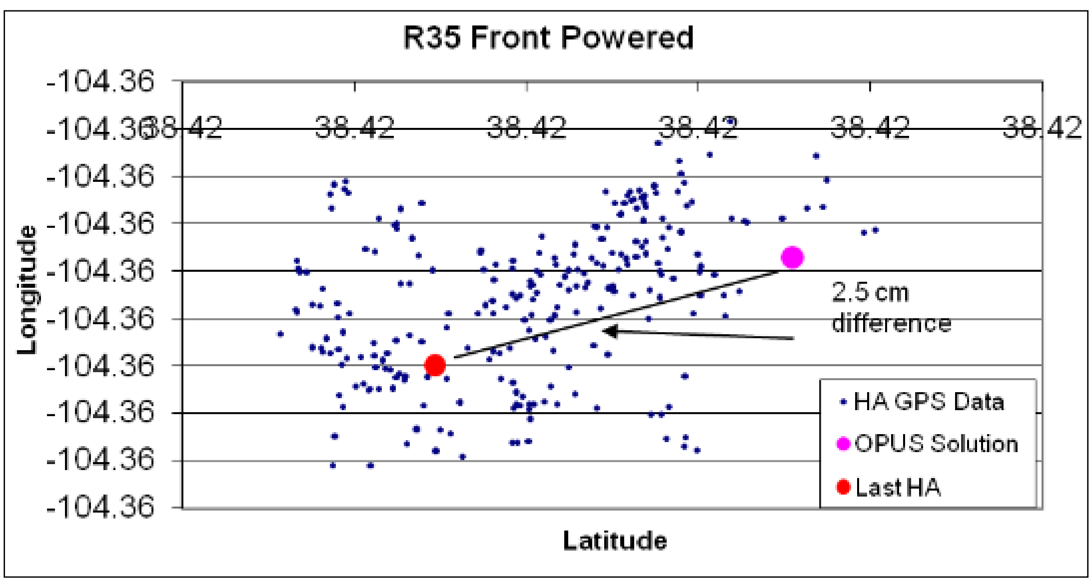



**Figure 28. Scatter Plots of Measurements Taken at Location R35 with Front Powered Locomotive**

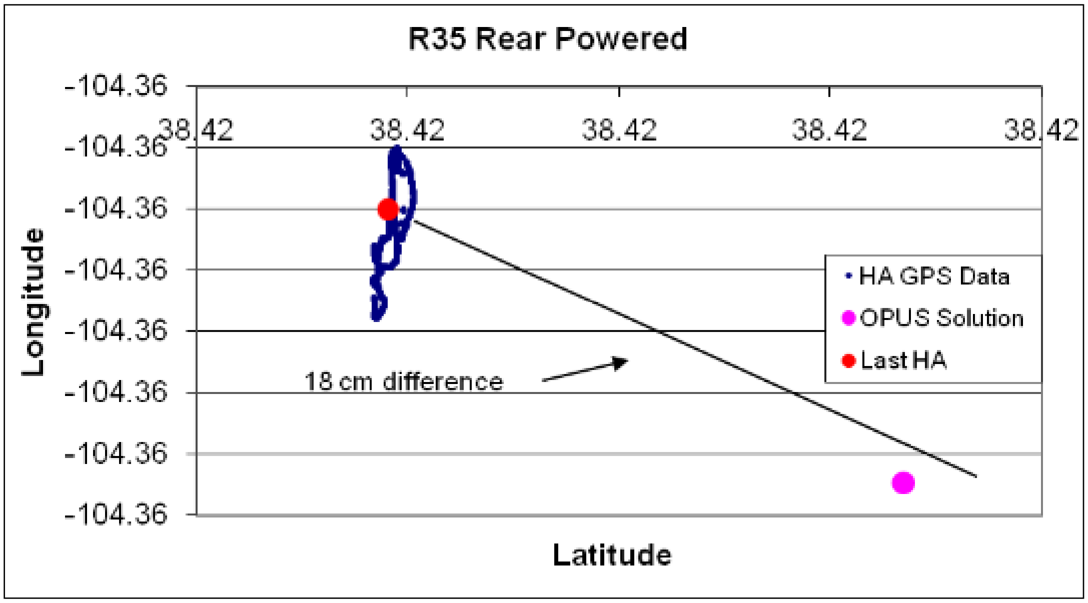



**Figure 29. Scatter Plots of Measurements Taken at Location R35 with Rear Powered Locomotive**

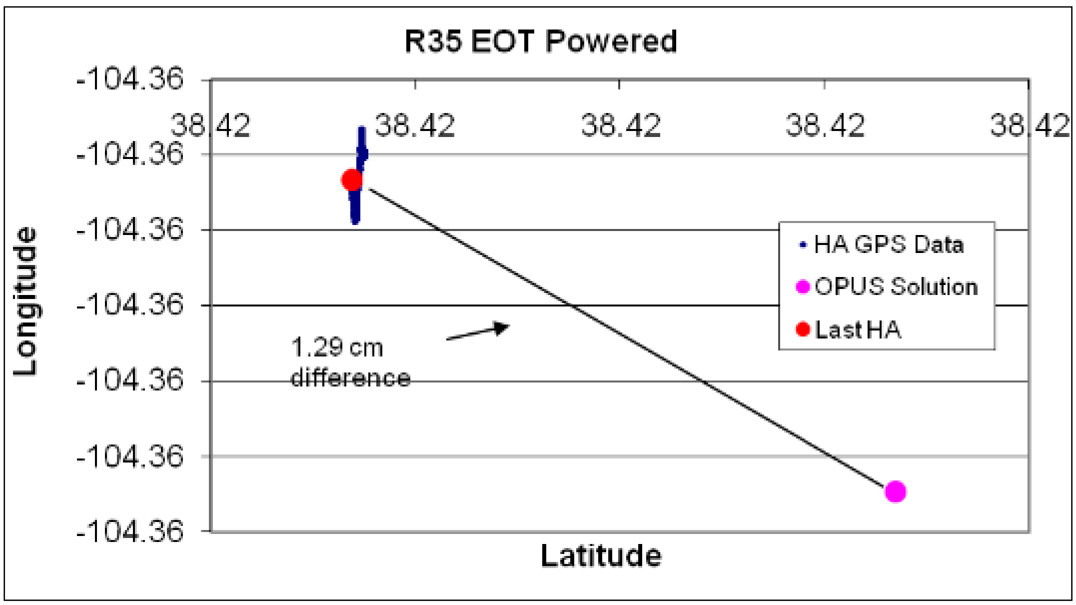



**Figure 30. Scatter Plots of Measurements Taken at Location R35 with EOT Powered Locomotive**

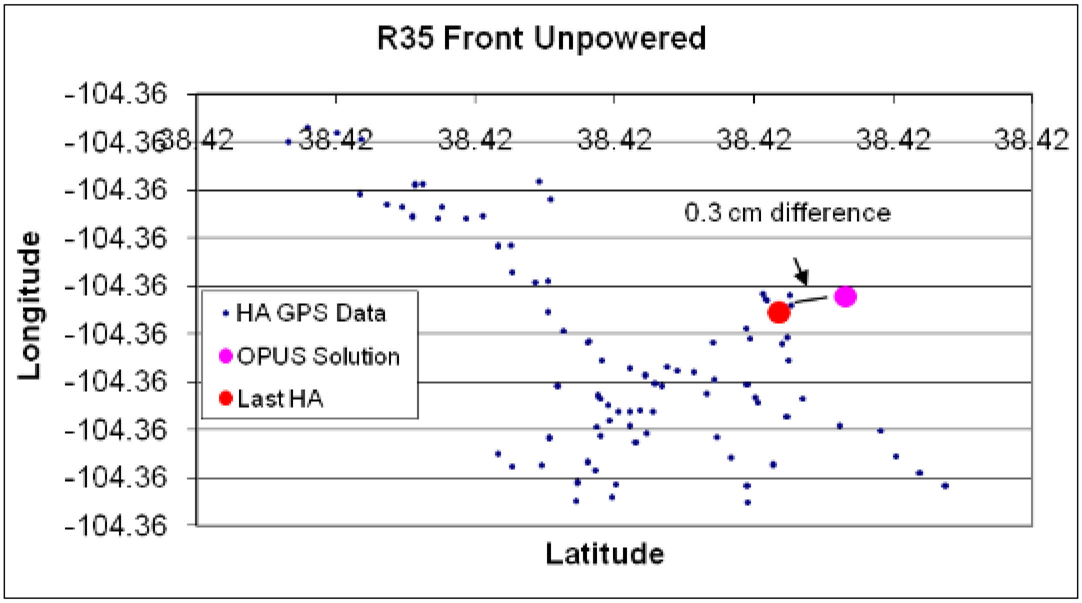



**Figure 31. Scatter Plots of Measurements Taken at Location R35 with Front Unpowered Locomotive**

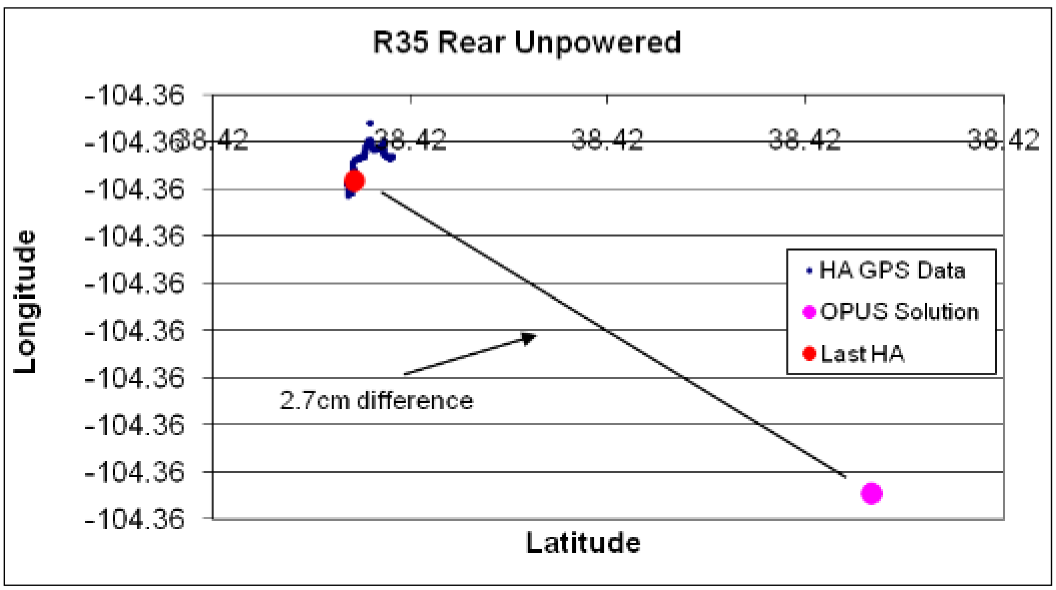



**Figure 32. Scatter Plots of Measurements Taken at Location R35 with Rear Unpowered Locomotive**

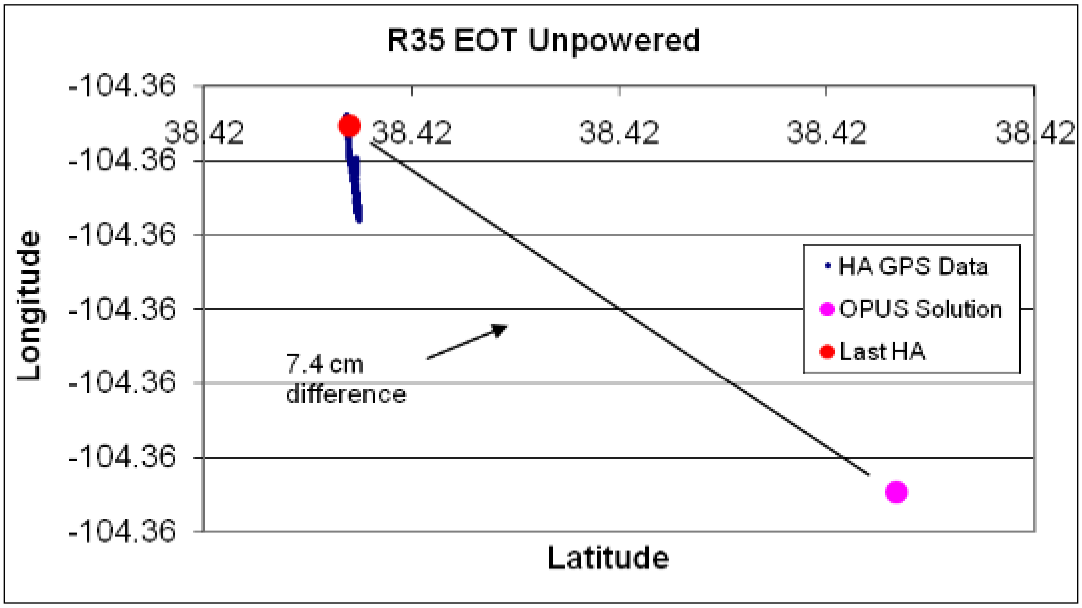



**Figure 33. Scatter Plots of Measurements Taken at Location R35 with EOT Unpowered Locomotive**

Table 6 shows the accuracies of the HA-GPS data results as compared to the OPUS solutions of the four static locations measured at the three locomotive positions: front locomotive, rear locomotive, and EOT. The results show that sub decimeter accuracies are achievable using HA-GPS technology.

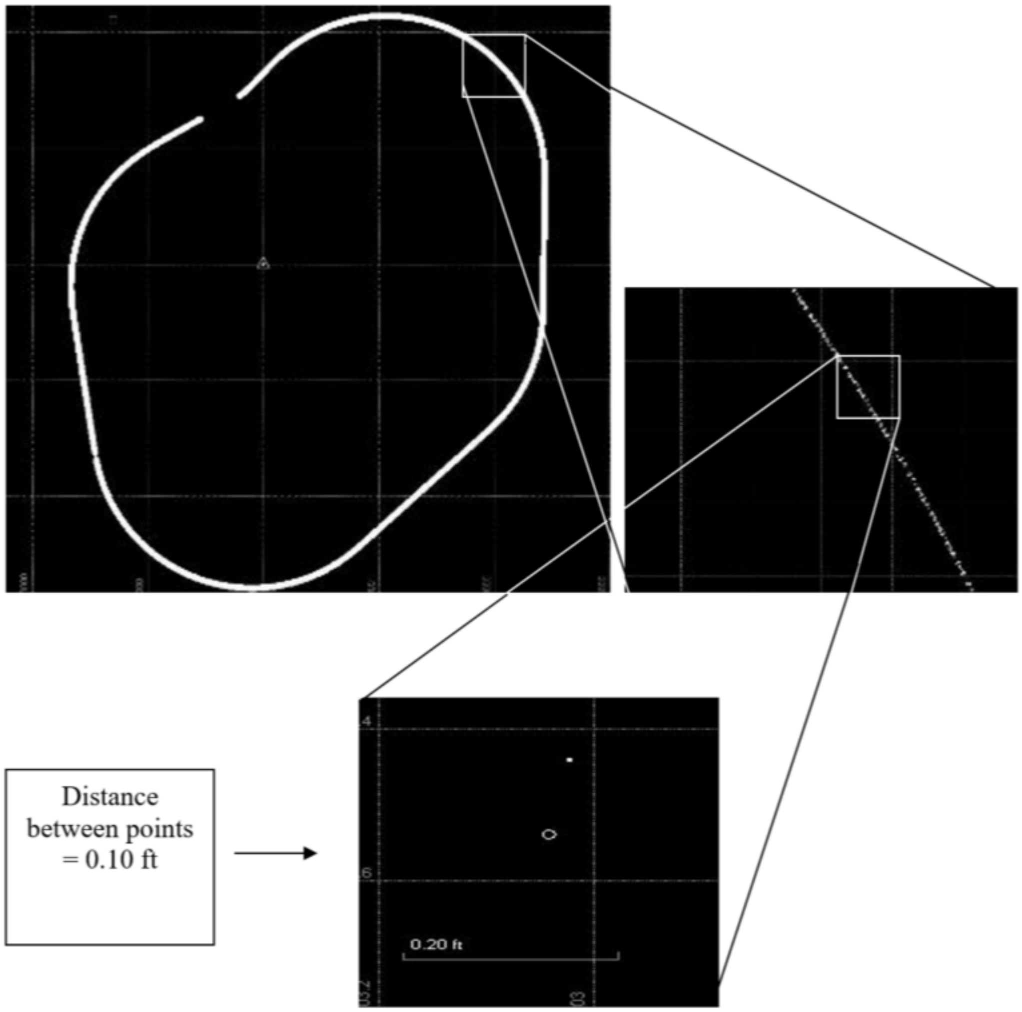
**Table 6. HA-GPS Data Compared to OPUS Solutions at Four Static Locations**

| Location, State | Difference (m) | Difference (ft) | Diff Elev (m) |
|---|---|---|---|
| **Front Locomotive** | | | |
| CSB Unpowered | 0.065 | 0.214 | 0.184 |
| CSB Powered | 0.120 | 0.394 | 0.268 |
| 304 Unpowered | 0.016 | 0.054 | 0.102 |
| 304 Powered | 0.104 | 0.343 | 0.214 |
| R50 powered | 0.103 | 0.337 | 0.212 |
| R50 Unpowered | 0.133 | 0.436 | 0.531 |
| R35 Unpowered | 0.003 | 0.010 | 0.206 |
| R35 Powered | 0.025 | 0.082 | 0.025 |
| POS501 Unpowered | 0.010 | 0.034 | 0.225 |
| | | | |
| **Rear Locomotive** | | | |
| CSB Unpowered | 0.553 | 1.815 | 0.556 |
| CSB Powered | No OPUS solution | No OPUS solution | No OPUS solution |
| 304 Unpowered | 0.213 | 0.700 | 0.2219 |
| 304 Powered | 0.531 | 1.743 | 1.925 |
| R50 Powered | 0.190 | 0.624 | 1.520 |
| R50 Unpowered | 0.185 | 0.624 | 1.201 |
| R35 Unpowered | 0.028 | 0.091 | 0.597 |
| R35 Powered | 0.182 | 0.595 | 1.132 |

| Location, State | Difference (m) | Difference (ft) | Diff Elev (m) |
|---|---|---|---|
| POS501 Unpowered | 0.150 | 0.493 | 0.151 |
| | | | |
| **EOT** | | | |
| CSB Unpowered | 0.101 | 0.330 | 1.313 |
| CSB Powered | No OPUS solution | No OPUS solution | No OPUS solution |
| 304 Unpowered | 0.259 | 0.850 | 2.0371 |
| 304 Powered | 0.559 | 1.833 | 0.212 |
| R50 Powered | 0.316 | 1.038 | 0.052 |
| R50 Unpowered | 0.253 | 0.829 | 0.371 |
| R35 Unpowered | 0.075 | 0.246 | 0.087 |
| R35 Powered | 0.013 | 0.043 | 0.326 |
| POS501 Unpowered | 0.082 | 0.269 | 0.165 |

## 4.4 Locomotive and EOT Dynamic Results

Dynamic testing was done with the train operating over the area shown in Figure 34 at speeds of 10, 20, 40, 60, 80, and 100 mph. Figure 34 shows a screen shot from Trimble Business center of the data collected during a 10-mph run with the locomotive under its own power.




Screen shots from Trimble Business Center

**Figure 34. Area for Testing at 10 mph with Powered Front Locomotive**

Table 7 through Table 9 show the results from the dynamic tests for three confidence levels of RMSE. In all cases, the accuracies are within the FRA specifications for PTC applications at 2 dRMS, and in most cases, the accuracies are within the FRA specifications at 3 dRMS.

## Table 7. Dynamic Test Results for 68% Confidence Level

| Velocity, State | Horizontal 68 % Confidence | | Vertical 68 % Confidence | |
|---|---|---|---|---|
| | RMSE (m) | RMSE (ft) | RMSE (m) | RMSE(ft) |
| 100 mph, FrontUnpowered | 0 .134 | 0.608 | 0.128 | 0.420 |
| 100 mph, FrontPowered | 0.266 | 1.205 | 0.063 | 0.207 |
| 80 mph, FrontUnpowered | 0.131 | 0.595 | 0.286 | 0.939 |
| 80 mph, FrontPowered | 0.454 | 1.490 | 0.871 | 2.857 |
| 60 mph, FrontUnpowered | 0.270 | 0.887 | 0.512 | 1.681 |
| 40 mph, FrontUnpowered | 0.076 | 0.250 | 0.082 | 0.270 |
| 40 mph, FrontPowered | 0.073 | 0.239 | 0.237 | 0.779 |
| 20 mph, FrontUnpowered | 0.120 | 0.395 | 0.163 | 0.536 |
| 20 mph, FrontPowered | 0.172 | 0.565 | 0.148 | 0.488 |
| 10 mph, FrontPowered | 0.035 | 0.117 | 0.236 | 0.775 |
| | | | | |
| 100 mph, RearUnpowered | 0.045 | 0.150 | 0.603 | 1.979 |
| 100 mph, RearPowered | 0.068 | 0.223 | 0.384 | 1.261 |
| 80 mph, RearUnpowered | 0.165 | 0.541 | 0.662 | 2.170 |
| 80 mph, RearPowered | 0.063 | 0.208 | 0.552 | 1.812 |
| 60 mph, RearUnpowered | 0.070 | 0.232 | 1.284 | 4.213 |
| 40 mph, RearUnpowered | 0.045 | 0.150 | 0.627 | 2.056 |
| 40 mph, RearPowered | 0.004 | 0.014 | 1.587 | 5.206 |
| 20 mph, RearUnpowered | 0.027 | 0.089 | 1.418 | 4.652 |
| 20 mph, RearPowered | 0.024 | 0.081 | 0.935 | 3.068 |
| 10 mph, RearPowered | 0.516 | 1.695 | 1.302 | 4.271 |
| | | | | |
| 100 mph, EOTUnpowered | 0.309 | 1.014 | 1.071 | 3.513 |
| 100 mph, EOTPowered | 0.497 | 1.633 | 5.048 | 16.562 |
| 80 mph, EOTUnpowered | 0.059 | 0.192 | 0.857 | 2.811 |
| 80 mph, EOTPowered | 0.465 | 1.527 | 1.375 | 4.512 |
| 60 mph, EOTUnpowered | 0.760 | 2.492 | 1.357 | 4.451 |
| 40 mph, EOTUnpowered | 0.056 | 0.184 | 0.206 | 0.677 |
| 40 mph, EOTPowered | 0.004 | 0.014 | 1.587 | 5.206 |
| 20 mph, EOTUnpowered | 0.569 | 1.866 | 2.688 | 8.820 |
| 20 mph, EOTPowered | 0.102 | 0.334 | 3.602 | 11.818 |
| 10 mph, EOTPowered | 0.376 | 1.233 | 2.901 | 9.519 |

## Table 8. Dynamic Rest Results for 95% Confidence Level

| Velocity, State | Horizontal 95% Confidence | | Vertical 95% Confidence | |
|---|---|---|---|---|
| | RMSE (m) | RMSE (ft) | RMSE (m) | RMSE(ft) |
| 100 mph, FrontUnpowered | 0.268 | 1.217 | 0.256 | 0.841 |
| 100 mph, FrontPowered | 0.533 | 2.411 | 0.127 | 0.415 |
| 80 mph, FrontUnpowered | 0.264 | 1.190 | 0.573 | 1.879 |
| 80 mph, FrontPowered | 0.909 | 2.982 | 1.742 | 5.716 |
| 60 mph, FrontUnpowered | 0.541 | 1.776 | 1.025 | 3.362 |
| 40 mph, FrontUnpowered | 0.153 | 0.501 | 0.165 | 0.541 |
| 40 mph, FrontPowered | 0.146 | 0.479 | 0.475 | 1.559 |
| 20 mph, FrontUnpowered | 0.241 | 0.792 | 0.327 | 1.073 |
| 20 mph, FrontPowered | 0.345 | 1.132 | 0.298 | 0.976 |
| 10 mph, FrontPowered | 0.072 | 0.235 | 0.473 | 1.551 |
| | | | | |
| 100 mph, RearUnpowered | 0.091 | 0.300 | 1.206 | 3.958 |
| 100 mph, RearPowered | 0.136 | 0.448 | 0.769 | 2.522 |
| 80 mph, RearUnpowered | 0.330 | 1.083 | 1.323 | 4.341 |
| 80 mph, RearPowered | 0.127 | 0.418 | 1.105 | 3.624 |
| 60 mph, RearUnpowered | 0.142 | 0.465 | 2.568 | 8.427 |
| 40 mph, RearUnpowered | 0.091 | 0.300 | 1.254 | 4.113 |
| 40 mph, RearPowered | 0.009 | 0.028 | 3.173 | 10.411 |
| 20 mph, RearUnpowered | 0.055 | 0.179 | 2.836 | 9.304 |
| 20 mph, RearPowered | 0.050 | 0.162 | 1.870 | 6.135 |
| 10 mph, RearPowered | 1.033 | 3.391 | 2.604 | 8.542 |
| | | | | |
| 100 mph, EOTUnpowered | 0.618 | 2.028 | 2.142 | 7.027 |
| 100 mph, EOTPowered | 0.995 | 3.265 | 10.096 | 33.124 |
| 80 mph, EOTUnpowered | 0.117 | 0.385 | 1.713 | 5.622 |
| 80 mph, EOTPowered | 0.931 | 3.054 | 2.751 | 9.025 |
| 60 mph, EOTUnpowered | 1.519 | 4.984 | 2.713 | 8.902 |
| 40 mph, EOTUnpowered | 0.112 | 0.367 | 0.413 | 1.353 |
| 40 mph, EOTPowered | 0.009 | 0.028 | 3.173 | 10.411 |
| 20 mph, EOTUnpowered | 1.138 | 3.732 | 5.376 | 17.639 |
| 20 mph, EOTPowered | 0.204 | 0.669 | 7.204 | 23.636 |
| 10 mph, EOTPowered | 0.752 | 2.466 | 5.803 | 19.037 |

## Table 9. Dynamic Test Results for 99.7% Confidence Level

| Velocity, State | Horizontal 99.7% Confidence | | Vertical 99.7% Confidence | |
|---|---|---|---|---|
| | RMSE (m) | RMSE (ft) | RMSE (m) | RMSE(ft) |
| 100 mph, FrontUnpowered | 0.401 | 1.825 | 0.385 | 1.262 |
| 100 mph, FrontPowered | 0.799 | 3.617 | 0.190 | 0.623 |
| 80 mph, FrontUnpowered | 0.396 | 1.786 | 0.859 | 2.819 |
| 80 mph, FrontPowered | 1.363 | 4.473 | 2.613 | 8.574 |
| 60 mph, FrontUnpowered | 0.812 | 2.664 | 1.537 | 5.044 |
| 40 mph, FrontUnpowered | 0.229 | 0.752 | 0.247 | 0.812 |
| 40 mph, FrontPowered | 0.219 | 0.719 | 0.713 | 2.338 |
| 20 mph, FrontUnpowered | 0.362 | 1.188 | 0.491 | 1.610 |
| 20 mph, FrontPowered | 0.518 | 1.698 | 0.446 | 1.465 |
| 10 mph, FrontPowered | 0.107 | 0.352 | 0.709 | 2.326 |
| | | | | |
| 100 mph, RearUnpowered | 0.137 | 0.450 | 1.809 | 5.936 |
| 100 mph, RearPowered | 0.205 | 0.671 | 1.153 | 3.783 |
| 80 mph, RearUnpowered | 0.495 | 1.624 | 1.985 | 6.511 |
| 80 mph, RearPowered | 0.191 | 0.626 | 1.657 | 5.437 |
| 60 mph, RearUnpowered | 0.212 | 0.697 | 3.853 | 12.640 |
| 40 mph, RearUnpowered | 0.137 | 0.450 | 1.880 | 6.169 |
| 40 mph, RearPowered | 0.013 | 0.042 | 4.760 | 15.617 |
| 20 mph, RearUnpowered | 0.082 | 0.268 | 4.254 | 13.956 |
| 20 mph, RearPowered | 0.074 | 0.244 | 2.805 | 9.203 |
| 10 mph, RearPowered | 1.550 | 5.086 | 3.905 | 12.813 |
| | | | | |
| 100 mph, EOTUnpowered | 0.927 | 3.041 | 3.213 | 10.540 |
| 100 mph, EOTPowered | 1.493 | 4.898 | 15.144 | 49.685 |
| 80 mph, EOTUnpowered | 0.176 | 0.577 | 2.570 | 8.432 |
| 80 mph, EOTPowered | 1.396 | 4.582 | 4.126 | 13.537 |
| 60 mph, EOTUnpowered | 2.279 | 7.475 | 4.070 | 13.354 |
| 40 mph, EOTUnpowered | 0.168 | 0.551 | 0.619 | 2.030 |
| 40 mph, EOTPowered | 0.013 | 0.042 | 4.760 | 15.617 |
| 20 mph, EOTUnpowered | 1.706 | 5.598 | 8.065 | 26.459 |
| 20 mph, EOTPowered | 0.306 | 1.003 | 10.806 | 35.453 |
| 10 mph, EOTPowered | 1.128 | 3.699 | 8.704 | 28.556 |

## 4.5 Signal Strength and Signal to Noise Ratio for Static and Dynamic Testing

Figure 35 shows the received signal strengths measured at the front receiver with the locomotive powered at various locations versus time. As expected, the signal strength data was very high since the testing occurred within a few miles of the 1 kW broadcast. However, this may also have negatively affected the signal to noise ratio [5], as seen in Figure 36.

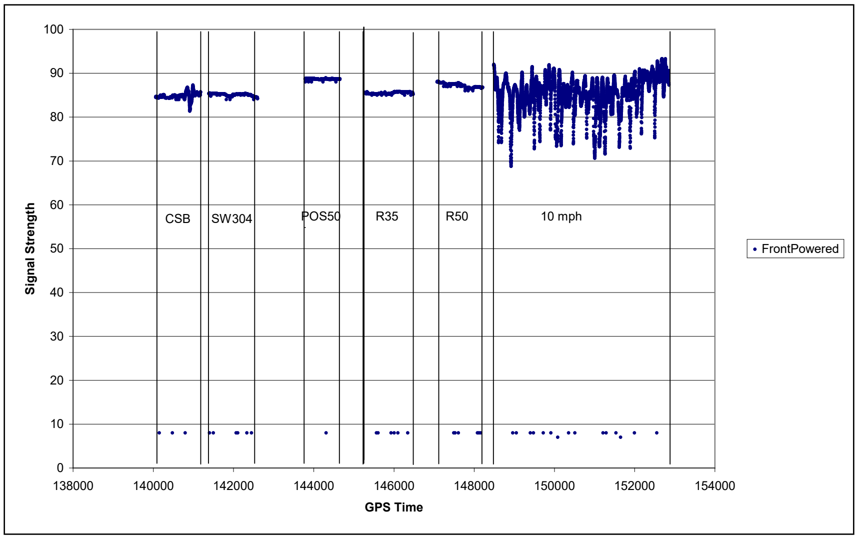



**Figure 35. Front Powered Locomotive Signal Strength in the Morning on December 27, 2010**

Figure 36 shows the signal-to-noise ratio measured at the front receiver with the locomotive powered at various locations versus time.

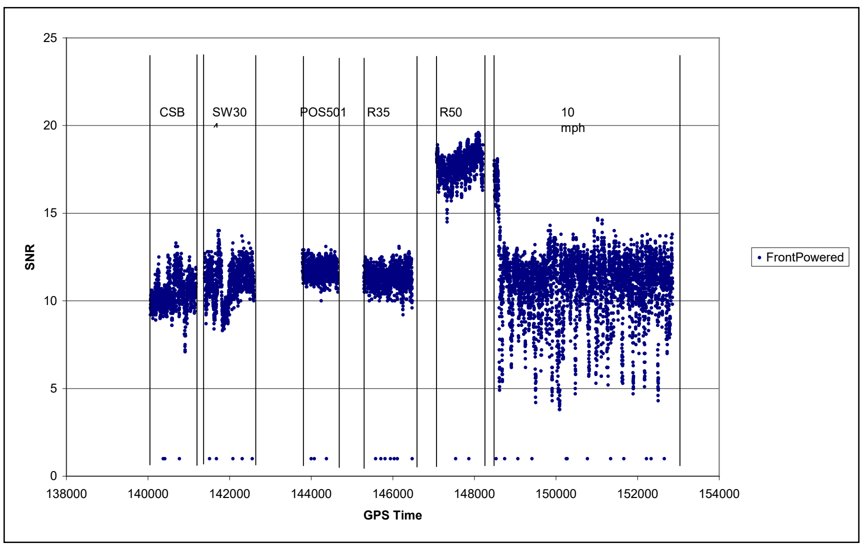



**Figure 36. Front Powered Locomotive Signal-to-Noise Ratio in the Morning on December 27, 2010**

Table 10 provides the average values of the received signal strength and signal-to-noise ratio measurements taken.

## Table 10. Averages of Signal Measurements

| Front Powered | | |
|---|---|---|
| **Run** | **Average Signal Strength** | **Average Signal-to-Noise Ratio** |
| **SW 304** | 84.687 | 10.960 |
| **POS 501** | 88.591 | 11.691 |
| **R35** | 85.069 | 11.251 |
| **R50** | 86.776 | 17.707 |
| **10 mph** | 84.962 | 10.949 |
| **20 mph** | 85.478 | 10.635 |
| **40 mph** | 85.523 | 9.991 |
| **60 mph** | 84.970 | 9.245 |
| **80 mph** | 85.610 | 9.991 |
| **100 mph** | 85.915 | 10.369 |
| **CSB** | 84.574 | 10.362 |
| **Rear Powered** | | |
| **Run** | **Average Signal Strength** | **Average Signal-to-Noise Ratio** |
| **SW 304** | 89.739 | 12.349 |
| **POS 501** | 94.625 | 19.899 |
| **R35** | 86.140 | 18.699 |
| **R50** | 95.736 | 19.589 |
| **10 mph** | 90.427 | 17.334 |
| **20 mph** | 90.561 | 13.503 |
| **40 mph** | 91.100 | 11.110 |
| **60 mph** | 90.399 | 11.110 |
| **80 mph** | 90.772 | 10.229 |
| **100 mph** | 91.360 | 10.568 |
| **CSB** | 90.945 | 16.821 |

| Front Unpowered | | |
|---|---|---|
| **Run** | **Average Signal Strength** | **Average Signal-to-Noise Ratio** |
| **SW 304** | 84.287 | 14.282 |
| **POS 501** | 88.786 | 11.565 |
| **R35** | 84.572 | 10.761 |
| **R50** | 86.783 | 11.593 |
| **10 mph** | 84.950 | 10.804 |
| **20 mph** | 85.363 | 10.702 |
| **40 mph** | 85.347 | 10.195 |
| **60 mph** | 85.091 | 9.152 |
| **80 mph** | 84.862 | 8.798 |
| **100 mph** | 84.418 | 9.670 |
| **CSB** | 86.051 | 11.815 |
| **Rear Unpowered** | | |
| **Run** | **Average Signal Strength** | **Average Signal-to-Noise Ratio** |
| **SW 304** | 89.478 | 12.003 |
| **POS 501** | 94.672 | 19.640 |
| **R35** | 85.337 | 18.538 |
| **R50** | 95.182 | 18.980 |
| **10 mph** | 90.858 | 16.339 |
| **20 mph** | 91.213 | 15.543 |
| **40 mph** | 91.530 | 12.886 |
| **60 mph** | 91.485 | 13.348 |
| **80 mph** | 91.124 | 10.332 |
| **100 mph** | 91.532 | 10.695 |
| **CSB** | 92.763 | 12.843 |

| EOT Powered | | |
|---|---|---|
| **Run** | **Average Signal Strength** | **Average Signal-to-Noise Ratio** |
| **SW 304** | 87.617 | 12.699 |
| **POS 501** | 93.913 | 12.848 |
| **R35** | 92.554 | 9.443 |
| **R50** | 96.127 | 9.725 |
| **10 mph** | 91.020 | 11.311 |
| **20 mph** | 91.034 | 10.250 |
| **40 mph** | 91.193 | 10.052 |
| **60 mph** | 91.092 | 9.027 |
| **80 mph** | 90.590 | 10.231 |
| **100 mph** | 91.125 | 9.327 |
| **CSB** | 94.158 | 10.637 |

| EOT Unpowered | | |
|---|---|---|
| **Run** | **Average Signal Strength** | **Average Signal-to-Noise Ratio** |
| **SW 304** | 88.024 | 9.331 |
| **POS 501** | 94.216 | 10.216 |
| **R35** | 91.870 | 13.420 |
| **R50** | 95.610 | 13.547 |
| **10 mph** | 91.497 | 11.927 |
| **20 mph** | 92.028 | 12.353 |
| **40 mph** | 92.584 | 9.575 |
| **60 mph** | 91.843 | 8.780 |
| **80 mph** | 91.962 | 10.239 |
| **100 mph** | 92.119 | 9.980 |
| **CSB** | 93.995 | 9.545 |

# 5. Conclusion and Recommendations

FRA specifications for PTC applications required a 2 dRMS accuracy of 1.0 meter (i.e., 95% confidence level) [1]. In all cases, the accuracies of the HA-GPS system are within the FRA specifications for PTC applications at 2 dRMS. With a few exceptions, HA-GPS achieved this accuracy even at the 3 dRMS level (99.7%). There is a clear EMI effect on HA-GPS accuracy by the locomotive systems, but the accuracies are still better than achievable with NDGPS.

The testing performed at the TTC showed the potential of the HA-GPS system to support PTC. Future testing is necessary to explore this potential under more rigorous and varied conditions. One such test may include the influence of the charged overhead of the RTT on the HA-GPS system. Also, a remote positioning test from a back office location while taking simultaneous measurements from HA-GPS and RTK would be enlightening to evaluate the ability to track a train's location in real time and the latency involved in making a determination as to what course of action should be taken when a train exceeds its authority.

The communications range of the HA-GPS system at the TTC is currently unverified. A coverage map of the broadcast would help evaluate the number of high accuracy equipped sites required to provide adequate coverage for PTC applications. Additionally, upgrading the equipment used would reduce the systematic error and increase the positional accuracies. Eventually, this would lead to a specific definition of the system requirements for railroad applications and could possibly reduce the cost to railroad agencies.

Overall, the HA-GPS system performed adequately despite the inhomogeneous selection of GPS receivers, as it was designed to do. This however, introduced untraceable errors. Future testing should include a homogenous selection of equipment that can be used both as HA-GPS and as RTK. This would place all receivers on a level field in which to evaluate their performance when placed in different locations on a train.

## 6. References


1. Boardman, J. H. *Nationwide Differential Global Positioning System (NDGPS) Program*, Memorandum from former FRA Administrator to the Administrator of the Research and Innovative Technology Administration: Washington, DC, 22 February 2008.
2. Chamberlain, K. "Proposal for a Forest Service GPS Data Accuracy Standard." PowerPoint Presentation. Forest Service 2003 Geospatial Conference: Oregon, 09 November 2010.
3. Bidwell, R. "Test Plans for HA-GPS Locomotive and EOT Testing." Transportation Technology Center, Inc.: Pueblo, CO, June 2010.
4. Conversations with Tim Smith, National Parks Service. January 2011.
5. Conversations with Chuck Hutchins, Vectors, Inc. January 2011.

## Abbreviations and Acronyms

| ACRONYMS | EXPLANATION |
|---|---|
| ATU | Antenna Tuning Unit |
| AAR | Association of American Railroads |
| AAM | Automatic Asset Mapping |
| DGPS | Differential Global Positioning Systems |
| EMI | Electromagnetic Interference |
| EOT | End of Train |
| FHWA | Federal Highway Administration |
| FRA | Federal Railroad Administration |
| GPS | Global Positioning System |
| GRIM | GPS Receiver Interface Module |
| GFE | Government Furnished Equipment |
| Hz | Hertz |
| HACP | High Accuracy Control Program |
| HA-GPS | High Accuracy Global Positioning System |
| HA-NDGPS | High Accuracy National Differential Global Positioning System |
| kHz | Kilohertz |
| MF | Medium Frequency |
| NDGPS | Nationwide Differential Global Positioning System |
| NGS | National Geodetic Survey |
| OPUS | Online Positioning User Service |
| PTC | Positive Train Control |
| RTC | Radio Technical Commission |
| RTT | Railroad Test Track |
| RTK | Real Time Kinematic |
| RINEX | Receiver Independent Exchange |
| RMSE | Root Mean Square Error |
| RMS | Root Mean Square |
| SREMP | Simulated Resonance Electromagnetic Pulse |
| TDL | Track Defect Location |

| ACRONYMS | EXPLANATION |
|---|---|
| TTC | Transportation Technology Center (the site) |
| TTCI | Transportation Technology Center (the company) |
| VII | Vehicle Infrastructure Integration |
| VPTC | Vital Positive Train Control |