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Transportation

**Federal Railroad
Administration**

# High Accuracy Global Positioning System Test: Phase II

Office of Research,
Development
and Technology
Washington, DC 20590

DOT/FRA/ORD-14/08

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13. ABSTRACT (Maximum 200 words)

The High Accuracy Nationwide Differential Global Positioning System (HA-NDGPS) is a prototype position location service that uses carrier phase and code measurement data to obtain precise geolocation information. This project was established to assess the feasibility of improving upon the accuracy of the NDGPS service using existing infrastructure to meet the requirements of additional applications without decreasing its availability and integrity, while still meeting the needs of existing users.

The Transportation Technology Center developed this project to independently test the ability of the high accuracy portion of the HA-NDGPS system to achieve sub decimeter positional accuracy with only relatively minor modifications to an existing NDGPS site. This high accuracy capability may provide a low-cost positioning solution for railroad systems, such as Positive Train Control (PTC), which require precise tracking of trains in real time to ensure operational safety. Another railroad-related benefit may be the more efficient collection of track feature information needed for generating and maintaining track databases that support PTC operations. Other transportation applications include Federal Highway Administration applications such as those defined by the Vehicle Infrastructure Integration project of the Intelligent Transportation Systems initiative.

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# METRIC/ENGLISH CONVERSION FACTORS

## ENGLISH TO METRIC

### LENGTH (APPROXIMATE)

| | | |
|---|---|---|
| 1 inch (in) | = | 2.5 centimeters (cm) |
| 1 foot (ft) | = | 30 centimeters (cm) |
| 1 yard (yd) | = | 0.9 meter (m) |
| 1 mile (mi) | = | 1.6 kilometers (km) |

### AREA (APPROXIMATE)

| | | |
|---|---|---|
| 1 square inch (sq in, $in^2$) | = | 6.5 square centimeters ($cm^2$) |
| 1 square foot (sq ft, $ft^2$) | = | 0.09 square meter ($m^2$) |
| 1 square yard (sq yd, $yd^2$) | = | 0.8 square meter ($m^2$) |
| 1 square mile (sq mi, $mi^2$) | = | 2.6 square kilometers ($km^2$) |
| 1 acre = 0.4 hectare (he) | = | 4,000 square meters ($m^2$) |

### MASS - WEIGHT (APPROXIMATE)

| | | |
|---|---|---|
| 1 ounce (oz) | = | 28 grams (gm) |
| 1 pound (lb) | = | 0.45 kilogram (kg) |
| 1 short ton = 2,000 pounds (lb) | = | 0.9 tonne (t) |

### VOLUME (APPROXIMATE)

| | | |
|---|---|---|
| 1 teaspoon (tsp) | = | 5 milliliters (ml) |
| 1 tablespoon (tbsp) | = | 15 milliliters (ml) |
| 1 fluid ounce (fl oz) | = | 30 milliliters (ml) |
| 1 cup (c) | = | 0.24 liter (l) |
| 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 yard (cu yd, $yd^3$) | = | 0.76 cubic meter ($m^3$) |

### TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

## METRIC TO ENGLISH

### LENGTH (APPROXIMATE)

| | | |
|---|---|---|
| 1 millimeter (mm) | = | 0.04 inch (in) |
| 1 centimeter (cm) | = | 0.4 inch (in) |
| 1 meter (m) | = | 3.3 feet (ft) |
| 1 meter (m) | = | 1.1 yards (yd) |
| 1 kilometer (km) | = | 0.6 mile (mi) |

### AREA (APPROXIMATE)

| | | |
|---|---|---|
| 1 square centimeter ($cm^2$) | = | 0.16 square inch (sq in, $in^2$) |
| 1 square meter ($m^2$) | = | 1.2 square yards (sq yd, $yd^2$) |
| 1 square kilometer ($km^2$) | = | 0.4 square mile (sq mi, $mi^2$) |
| 10,000 square meters ($m^2$) | = | 1 hectare (ha) = 2.5 acres |

### MASS - WEIGHT (APPROXIMATE)

| | | |
|---|---|---|
| 1 gram (gm) | = | 0.036 ounce (oz) |
| 1 kilogram (kg) | = | 2.2 pounds (lb) |
| 1 tonne (t) | = | 1,000 kilograms (kg) |
| | = | 1.1 short tons |

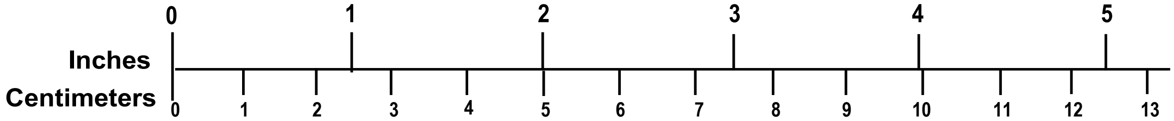
### VOLUME (APPROXIMATE)

| | | |
|---|---|---|
| 1 milliliter (ml) | = | 0.03 fluid ounce (fl oz) |
| 1 liter (l) | = | 2.1 pints (pt) |
| 1 liter (l) | = | 1.06 quarts (qt) |
| 1 liter (l) | = | 0.26 gallon (gal) |
| 1 cubic meter ($m^3$) | = | 36 cubic feet (cu ft, $ft^3$) |
| 1 cubic meter ($m^3$) | = | 1.3 cubic yards (cu yd, $yd^3$) |

### TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

## QUICK INCH - CENTIMETER LENGTH CONVERSION




## QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

| °F | -40° | -22° | -4° | 14° | 32° | 50° | 68° | 86° | 104° | 122° | 140° | 158° | 176° | 194° | 212° |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | -40° | -30° | -20° | -10° | 0° | 10° | 20° | 30° | 40° | 50° | 60° | 70° | 80° | 90° | 100° |

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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# Executive Summary

The High Accuracy Nationwide Differential Global Positioning System (HA-NDGPS) is a prototype position location service that uses carrier phase and code measurement data to obtain precise location information. This project was initiated to assess the feasibility of further improving upon the accuracy of the NDGPS service using its existing infrastructure to meet the requirements of additional applications without degrading or diminishing its availability and functional integrity, while still meeting the needs of existing users.

The Transportation Technology Center (TTC) developed the High Accuracy GPS (HA-GPS) project to independently test the ability of the high accuracy portion of the system to achieve sub decimeter (0.1 m) positional accuracy with only relatively minor modifications to an existing NDGPS site. This high accuracy capability may provide a low-cost positioning solution for railroad systems, such as Positive Train Control (PTC) technology, which require high accuracy tracking of trains in real time to enhance and ensure operational safety. Another railroad-related benefit may be the more efficient collection of track feature information needed for generating and maintaining track databases that support PTC operations. Other transportation applications include Federal Highway Administration (FHWA) applications such as those defined by the Vehicle Infrastructure Integration project of the Intelligent Transportation Systems initiative.

First, this project upgraded legacy equipment provided by FHWA and calibrated it to the TTC survey control network. This provided the TTC HA-GPS system with modern, highly sophisticated survey capabilities.

Second, the reliability and validity of the high accuracy broadcast was tested at various distances from the HA-GPS base station at the TTC. There was a clear relationship between baseline distance and the accuracy of the measurement: The closer one is to the base station broadcasting the corrections, the more accurate the positional solution values. So, in order for HA-GPS to meet the needs of its users nationwide, hundreds of base stations with overlapping broadcasts would be required to provide sub decimeter positional accuracies across the entire country.

Third, the TTC track mapping capabilities were upgraded by procuring a track survey trolley and modifying it to receive the HA-GPS broadcast. This modification enables a very accurate track centerline, top of rail measurement that is calculated easily and eliminates the need to conduct a track survey of both rails in order to compute track superelevation and centerline values.

Fourth, the centerline of as much track as possible was mapped by the TTC with an HA-GPS equipped track survey system. This trolley-equipment configuration proved to be an effective method for collecting track features.

Finally, a locomotive was instrumented with HA-GPS equipment and a series of laps around the 13.5-mile Railroad Test Track (RTT) was conducted to evaluate the effects of interference from an energized overhead catenary system. Electromagnetic interference was a factor in the disruption of the broadcast at times, but it did not affect the accuracy of the measurements when the signal was received. The HA-GPS system did, however, fail to perform to the level of survey grade Global Navigation Satellite System (GNSS) and real-time kinematic (RTK) GPS equipment. The RTK GPS system reliably calculated a position on 99.99 percent of the track during both the energized and de-energized states, but the HA-GPS system only successfully calculated a position, over a number of data runs, which varied from 76.14 to 95.84 percent of the track.

Currently, HA-GPS only utilizes the Navigation Signal Timing and Ranging Global Positioning System (NAVSTAR GPS) constellation of satellites. Modern survey equipment can use all or most of the GNSS satellites, which include the Russian GLONASS constellation of satellites. This could account for some of the differences between RTK GPS and HA-GPS system performance.

# 1. Introduction

The High Accuracy Nationwide Differential Global Positioning System (HA-NDGPS) is a prototype position location service that uses carrier phase and code measurement data to obtain precise location information. This project was established to assess the feasibility of improving the accuracy of the Nationwide Differential Global Positioning System (NDGPS) service using its existing infrastructure to meet the requirements of additional applications without decreasing its availability and integrity, and still meeting the needs of existing users [1].

## 1.1 Background

The High Accuracy GPS (HA-GPS) project at the Transportation Technology Center (TTC) near Pueblo, CO, was developed to independently test the high accuracy portion of the HA-NDGPS system's ability to achieve sub decimeter positional accuracy with only relatively minor modifications to an existing NDGPS site [2]. This high accuracy capability may provide a low-cost positioning solution for railroad systems, such as Positive Train Control (PTC), which require high accuracy tracking of trains to enhance operational safety. Another railroad-related benefit may be a more efficient collection of track feature information needed for generating and maintaining track databases that support PTC operations. Other transportation applications include Federal Highway Administration (FHWA) applications such as those defined by the Vehicle Infrastructure Integration project of the Intelligent Transportation Systems initiative.

This project is Phase II of Federal Railroad Administration (FRA) Task Order 234. A prototype HA-GPS base station was constructed at the TTC to broadcast carrier code and phase measurement data (at 1 kilowatt and 458 kilohertz (kHz)) to remote users in order for them to obtain sub decimeter real-time kinematic (RTK) GPS position solutions within a 200-nautical mile radius of the base station. The operation and accuracy of the solution obtained via HA-GPS was tested under a variety of conditions related to railroad operations [3]. Figure 1 and Figure 2 show the TTC base station and a functional diagram of the HA-GPS system.

The HA-GPS system works by first collecting Navigation Signal Timing and Ranging (NAVSTAR) GPS measurement data from the constellation of satellites in view. This data is compressed by a software program, GPS Receiver Interface Module (GRIM), and then modulated onto a 458 kHz carrier wave that is then transmitted to the user. On the user end, a beacon receiver receives the broadcast data and the data is decompressed by GRIM, converted to Radio Technical Commission for Maritime Services (RTCM) messages 18/19, and input into the user's GPS receiver where it is combined and processed to obtain a precise (decimeter level) RTK GPS solution.

**Figure 1. HA-GPS TTC Base Station**

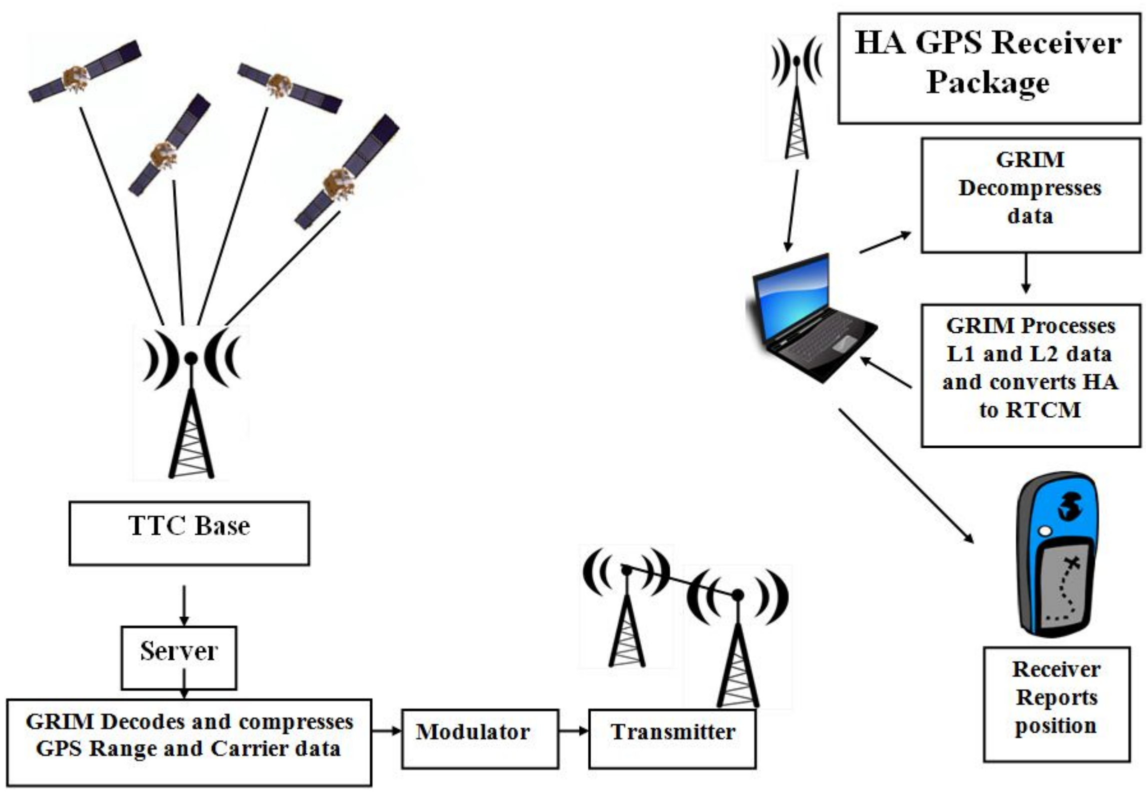


**Figure 2. HA-GPS Functional Diagram**

## 1.2 Objectives

The HA-GPS broadcasting base station at the TTC was used to assess the relationship between user distance from the base station (baseline) and user-derived positional accuracy. Additionally, researchers investigated the feasibility of using HA-GPS as a mapping solution and the effects of an energized overhead catenary on the performance of HA-GPS as a position determination system.

## 1.3 Overall Approach

The project consisted of five primary tasks. Task 1 involved upgrading legacy equipment provided by the FHWA and calibrating it to the TTC survey control network. Task 2 tested the accuracy of the high accuracy broadcast at various distances from the HA-GPS base station. Task 3 upgraded the TTC track-mapping capabilities by procuring a track survey trolley and modifying it to receive the HA-GPS broadcast. Task 4 consisted of mapping the centerline of as much track as possible at the TTC. Task 5 evaluated the potential benefits of using the combination of NDGPS data and HA-GPS data as a functional equivalent of HA-NDGPS data for train control applications by conducting the testing described in the original FRA Task Order 234 while determining the effects of interference from an energized overhead catenary system.

## 1.4 Scope

### *1.4.1 Equipment Upgrade*

For the equipment upgrade, a Trimble R8 Global Navigation Satellite System (GNSS) survey receiver and a Trimble S6 robotic total station were procured. Both the R8 and S6 are survey grade instruments. Additionally, a Trimble GEDO CE trolley system was purchased. This instrument works in conjunction with GPS or total station for positioning and uses a built-in gage sensor and inclinometer to calculate track centerline. Precise track measurements can be collected with the GEDO CE and then added to a track database.

### *1.4.2 Distance versus Accuracy*

The distance versus accuracy task consisted of testing the positional accuracy of the HA-GPS broadcast solution at various distances from the base station at the TTC. Control points were set up at distances of approximately 50, 100, 150, and 200 miles north, south, east, and west for a total of 16 measurements. These measurements were then compared with a post-processed solution using continuously operating reference station (CORS) sites that were in the vicinity of each measurement.

### *1.4.3 Track Mapping*

Track mapping was accomplished by using a commercially available track survey product (small trolley) called the Trimble GEDO CE. This equipment works with a total station (or GNSS) and measures gage and super-elevation, as well as the position of each rail.  With an R8 survey receiver, the trolley can utilize the signal broadcast by HA-GPS.

### *1.4.4 Effect of Energized Catenary on the Accuracy of HA-GPS*

To determine the effect of an energized catenary on the accuracy of HA-GPS, a locomotive was equipped with an R8 receiver and an HA-GPS receiver. Test runs around the Railroad Test Track (RTT) at the TTC were conducted at speeds of 20, 40, 60, 80, and 100 mph with the overhead catenary de-energized for the first set of test runs and then energized for the second set. Comparisons were made between the positions measured during the energized and de-energized states and the associated RTK GPS positions that were simultaneously recorded.

## 1.5 Organization of the Report

The report is organized in the following manner: Section 2 regarding equipment upgrade, Section 3 for distance versus accuracy test and results, track mapping with HA-GPS in Section 4, locomotive testing with energized and de-energized overhead catenary in Section 5, and Section 6 provides results and conclusions.

## 2. Equipment Upgrade

Under the first phase of the HA-GPS project, FRA Task Order 234, legacy GPS receivers were provided by FHWA. That legacy equipment is now incompatible with the new ground truth network at the TTC. Consequently, this phase of the project required modern survey grade equipment.

This task was accomplished by using a newly procured Trimble R8 GNSS survey receiver and a Trimble S6 robotic total station. The R8 is a high-end survey grade receiver. It was necessary to acquire a quality receiver so that any errors in positional accuracies could be reasonably assumed to be from the HA-GPS broadcast and not from the survey equipment itself. This receiver is also RTK GPS capable, allowing for a direct comparison of HA-GPS position solutions with corresponding survey grade solutions.

The S6 is another survey grade instrument. It is an electronic-optical instrument that measures distance and angle and then calculates the position of an unknown point by means of triangulation between that point and two known points (control points).

Two R8 receivers were used for the testing. One receiver served as an integrity monitor (IM) and was set up on a local control point. This receiver was stationary during all testing, and it was used to monitor the performance of the broadcast. The S6 was used to monitor the position of the IM as an added control.

Figure 3 shows new equipment that was purchased to provide the more accurate track databases needed by PTC. Previously, track at the TTC was mapped using a track inspection cart with two GPS receivers mounted on top of the cart, one over each rail. The data collected using this method then had to be postprocessed to give a centerline position by calculating super-elevation and assuming that track gage was constant. Although this method was quick and relatively effective, it contained inherent errors. For this project, the Trimble GEDO CE trolley system was selected because it was compatible with HA-GPS and could be used to perform a precise and accurate track centerline survey. Also, the GEDO CE trolley has a built-in gage sensor and inclinometer and could be used with a total station or GPS for positioning.


**Figure 3. Purchased GPS Products – R8, S6, and GEDO CE**

## 3. Distance versus Accuracy Testing

The transmitter of the HA-GPS system is purported to have a range of 200 nautical miles at a frequency of 458 kHz and a broadcast power of 1,000 watts. However, the ability of HA-GPS to resolve a position at such a large baseline distance is not solely dependent on the ability to receive the signal, but also the geometry of the satellite vehicles in view and the differences in the ionospheric and tropospheric conditions between the base station and the remote receiver position (rover). Also, since the 458 kHz signal contains a ground wave component, terrain and soil conditions are a factor as well.

Before the test, a radio frequency study of the HA-GPS broadcast was conducted. Figure 4 is a coverage map of the results of the study. It shows the effect mountainous terrain has on a broadcast of 458 kHz.

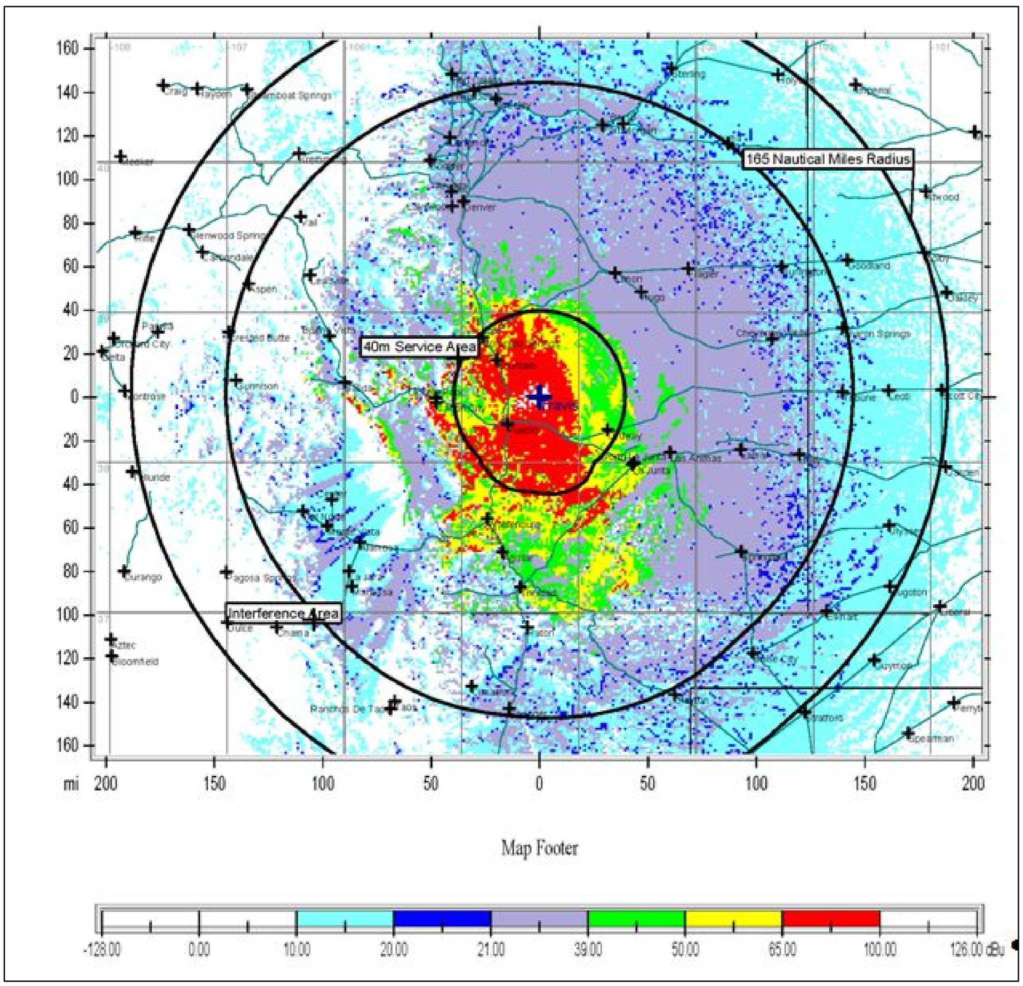


**Figure 4. Radio Frequency Coverage of 458 kHz at 1,000 Watts from the TTC Base**

### 3.1 Test Procedure

The distance versus accuracy task involved starting the base station transmission at the TTC and then driving to locations at approximately 50, 100, 150, and 200 miles north, south, east, and west of the TTC base station. Two measurements were taken at 16 locations: (1) an autonomous measurement that was later processed with CORS data and (2) an HA-GPS measurement. The same receiver was used for both measurements and in the same location. Figure 5 shows the equipment setup for one set of measurements.

**Figure 5. Equipment Setup**

For the HA-GPS measurement, the R8 receiver was connected to the HA-GPS beacon receiver by an RS-232 serial port. The two measurements were then compared. Figure 6 and Figure 7 show the locations of the measurements relative to the TTC base station. Figure 6 is a planar view and Figure 7 is a view of the measurements overlaid on an aerial photograph (Google Earth).

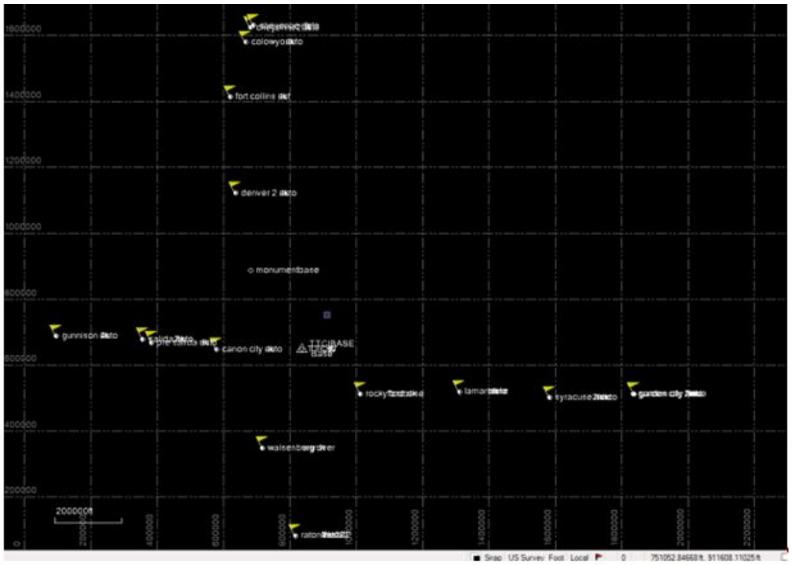

**Figure 6. Planar View of Measurements at Various Distances**

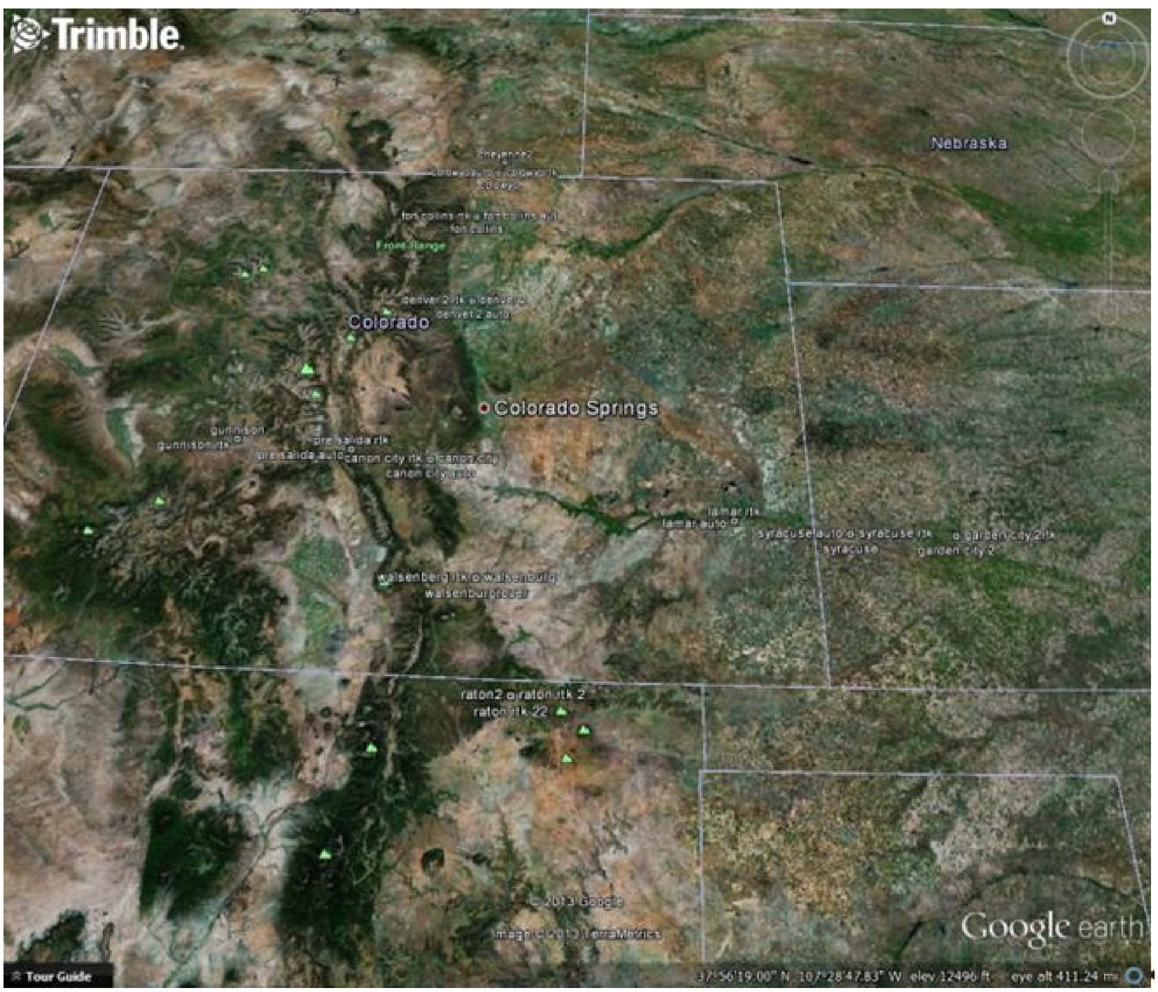


**Figure 7. Aerial View of Measurements**

The distance between each pair of measurements was computed to show the error in measurement (the distance between HA-GPS and postprocessed solutions). When no HA-GPS signal was present, no comparison could be made. The postprocessed solutions are more accurate because the final orbits of the satellites (ephemeris) were used to compute position. Table 1 and Figure 8 show the results. Figure 8 indicates a clear relationship between distance from the base station and the accuracy of the measurement.

**Table 1. Error Between HA-GPS and Postprocessed Solutions**

| Location | Difference (cm) | Difference (in) | Baseline (ft) | Baseline (mi) |
|---|---|---|---|---|
| Canon City | 8.83010048 | 3.476417512 | 257312.7051 | 48.73346687 |
| Cheyenne | 30.25561448 | 12.10224579 | 988,693.6918 | 187.2525931 |
| Albuquerque | No Signal | No Signal | No Signal | No Signal |
| Santa Fe | No Signal | No Signal | No Signal | No Signal |
| Fort Collins | 24.93016987 | 9.972067947 | 795,429.4725 | 150.6495213 |
| Garden City | 31.12015356 | 12.44806142 | 1,010,240.9780 | 191.3335185 |
| Gunnison | No Signal | No Signal | No Signal | No Signal |
| Lamar | 15.07241019 | 6.028964074 | 491,465.0366 | 93.08049936 |
| Salida | 14.09806295 | 5.639225181 | 453,565.9831 | 85.90264832 |
| Raton | 17.48622833 | 6.994491333 | 565,943.0717 | 107.1861878 |
| Rocky Ford | 6.900633907 | 2.760253563 | 222,870.4504 | 42.21031258 |
| Grand Junction | No Signal | No Signal | No Signal | No Signal |
| Syracuse | 23.45166205 | 9.380664819 | 761,174.4705 | 144.1618315 |
| Walsenberg | 10.85352657 | 4.341410629 | 322,514.2219 | 61.082239 |

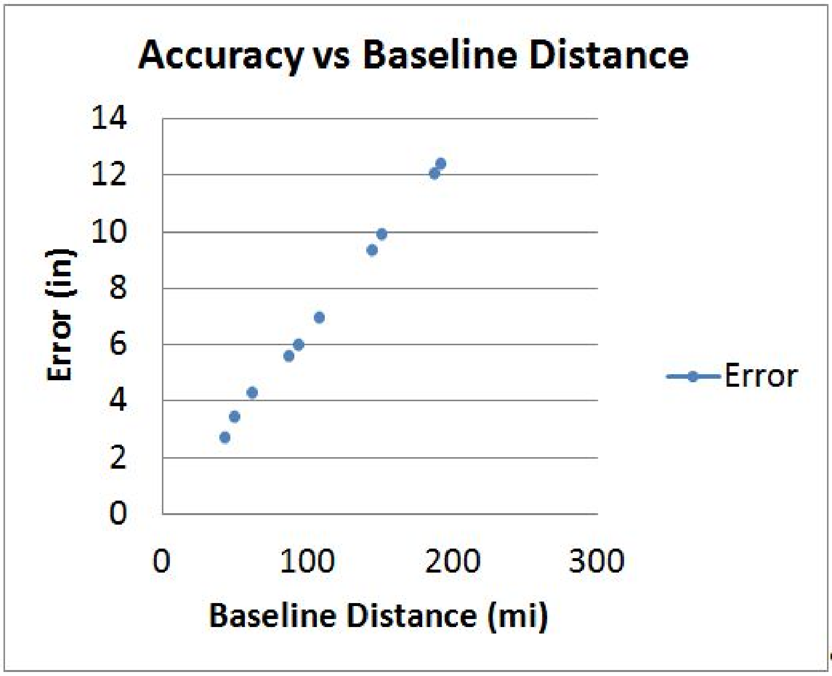


**Figure 8. Error vs. Distance to the TTC Base Station**

## 4. Track Mapping

HA-GPS can perform precise surveys without any need to set up a base station to broadcast RTK GPS data. With a continuously operating HA-GPS base, the surveyor simply needs to start the roving receiver and wait for initialization before beginning normal surveying procedures. This becomes particularly convenient when remote area track and/or large sections of track need to be surveyed.


**Figure 9. Survey Trolley with HA-GPS Installed**

Figure 9 shows the GEDO CE trolley used to survey the track at the TTC where feasible. This method allowed for the centerline to be calculated effortlessly.

Some of the larger sections of track were surveyed using a track inspection cart instrumented with HA-GPS over each rail (Figure 10). With this method, the centerline had to be calculated using superelevation, and positional data from each receiver and gage was assumed to be constant. Once all the data was collected, a centerline map of the TTC track was generated. Figure 11 shows the results of this mapping.

**Figure 10. Track Inspection Cart**

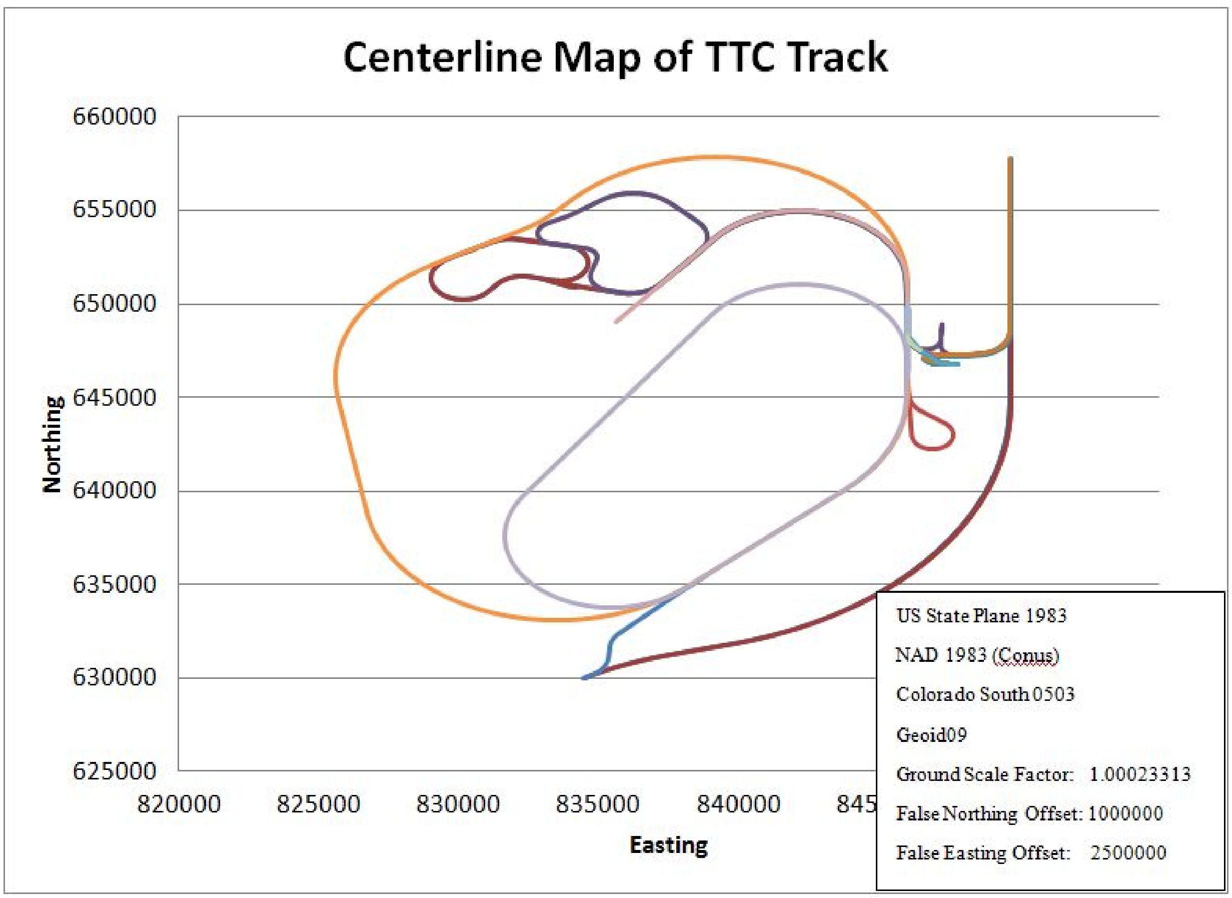


**Figure 11. Track Map of the TTC and Coordinate System Details**

# 5. Effect of Energized Catenary on the Accuracy of HA-GPS

Locomotive positioning tests were conducted with GPS and HA-GPS receivers installed on a GP-40 locomotive. Figure 12 shows the locomotive. Two sets of test runs were conducted. The first set of tests was conducted with the GPS and HA-GPS equipped locomotive with the overhead catenary de-energized, providing an environment in which minimal electromagnetic interference (EMI) from the overhead catenary system was present.

The second set of tests was conducted with the same GPS and HA-GPS equipped locomotive and the overhead catenary system energized, providing an environment in which all the track tested was in close proximity to the electromagnetic field from the overhead catenary system.


**Figure 12. AAR 2000 Locomotive**

## 5.1 Test Plan

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

- Static position measurement
- Runs around the RTT at multiple different speeds (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

Data collected in the test runs was postprocessed using commercially available analysis tools and analysis tools provided as government furnished equipment (e.g., GRIM). The postprocessing evaluated the comparative accuracy of HA-GPS positions during de-energized and energized states versus RTK GPS positions.

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

- Static Performance Evaluation. Data was processed to show the relative accuracy of HA-GPS and RTK GPS for each of the following cases:

- Static position measurement accuracy for each positioning system (HA-GPS and RTK GPS) for low EMI (de-energized overhead catenary) and high EMI (energized overhead catenary)

- Dynamic Location Monitoring. Data was processed to show the relative accuracy of HA-GPS and RTK GPS for each of the following cases:
  - Dynamic position measurement accuracy for each positioning system (HA-GPS and RTK GPS) for low EMI and high EMI

## 5.2 Static Position Integrity Monitoring

During the static testing portion of this project, the integrity of the HA-GPS broadcast was monitored with an additional IM receiver stationed over a control point which was monitored by a total station. The IM for this task consisted of an R8 receiver paired with an HA-GPS receiver stationed over a control point. An MT-1000 prism was connected to the range pole below the R8 and monitored by an S6 robotic total station. The S6 was also stationed over a control point. This configuration provided a redundant IM from a non-GPS instrument, which verified the dynamic measurements. Figure 13 shows the configuration.

**Figure 13. S6 and R8 IM (mockup)**

The data from the IM was collected during the dynamic portion of the project in order to highlight any systematic errors that could have diluted the positional accuracies. No such systematic errors were observed. Figure 14 shows the positions calculated by HA-GPS during the energized and de-energized test runs (red and green, respectively) and the positions calculated by the total station (white). Table 2 shows the difference between the averages of those positions.

Although there are small differences due to the EMI from the overhead catenary, these differences are small enough that the system still gives sub decimeter accuracies while in the static state.

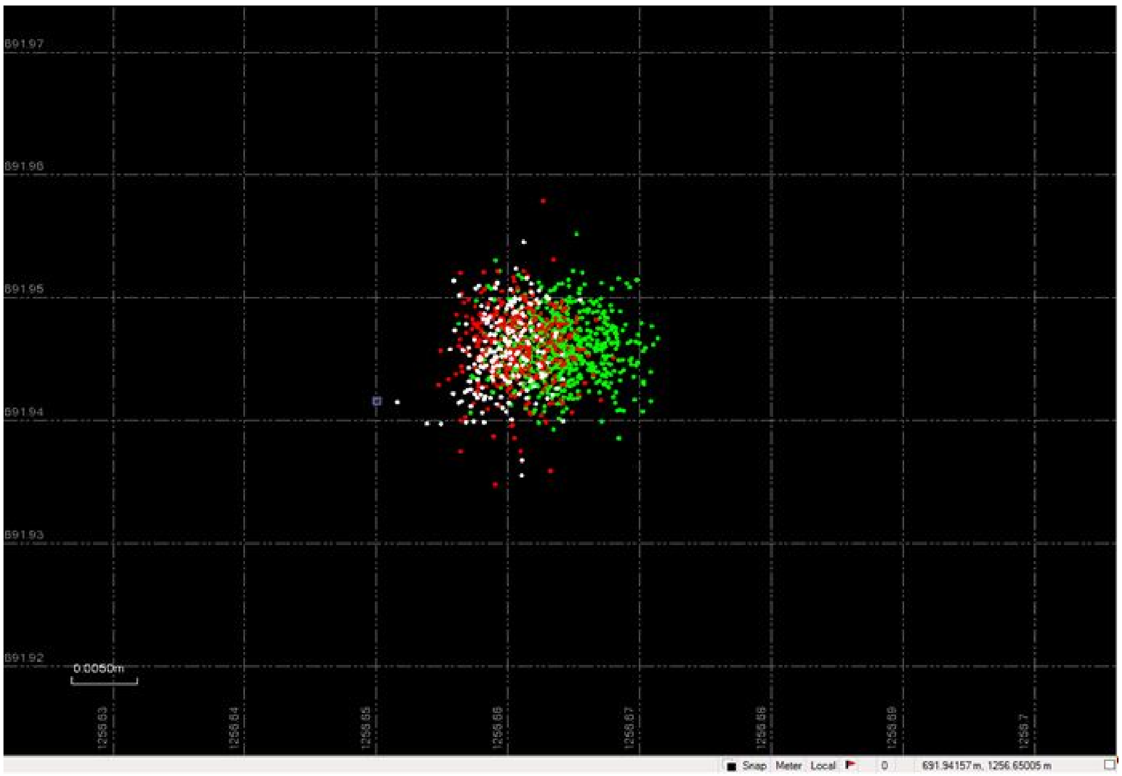

**Figure 14. Integrity Monitor De-energized (green), Energized (red), Total Station (white)**

**Table 2. Integrity Monitor – Relative Error Compared with Total Station**

| | Horizontal Error | | | Vertical Error | | |
|---|---|---|---|---|---|---|
| | cm | ft | in | cm | ft | in |
| Energized | 0.409703 | 0.013442 | 0.1613 | 0.014331 | 0.00047 | 0.005642 |
| De-energized | 0.126458 | 0.004149 | 0.049787 | 0.086874 | 0.00285 | 0.034202 |

## 5.3 Static Locomotive Testing

At the beginning of the locomotive testing, two static measurements were taken with the HA-GPS equipped locomotive. These measurements were taken with all locomotive systems powered and with the locomotive at the same location. The measurements served as a “check-in” to evaluate the performance of the HA-GPS system under the overhead catenary system and in each energized state before dynamic testing began. Figure 15, Figure 16, and Table 3 show the results of those measurements.

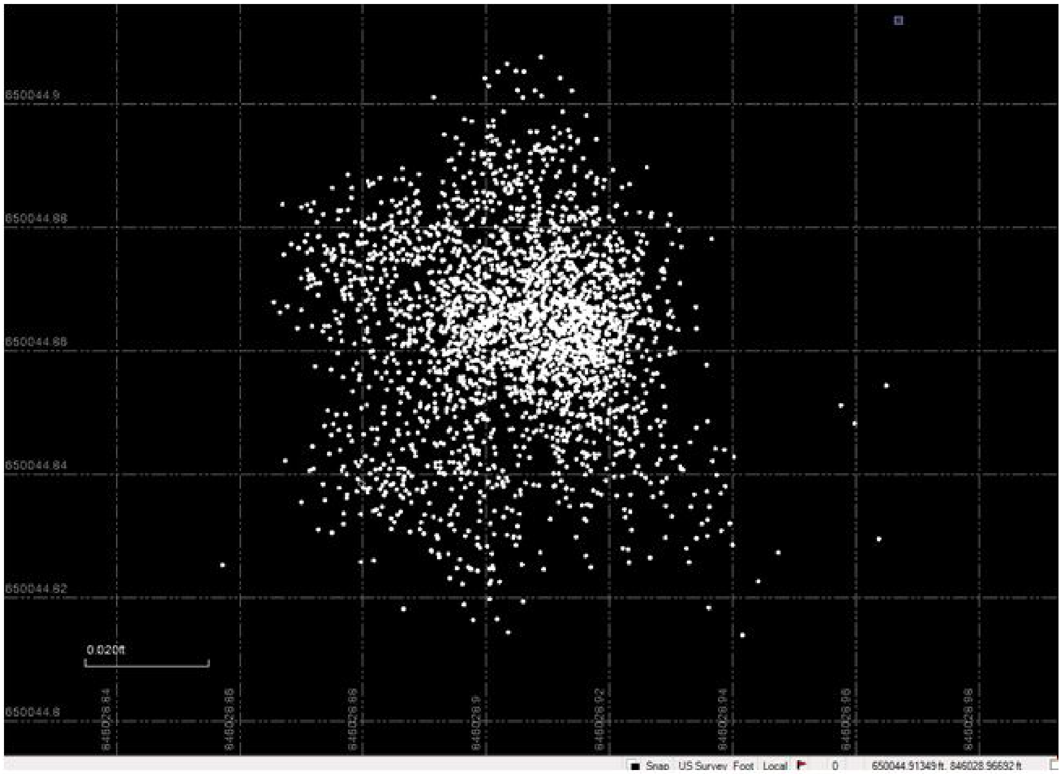


**Figure 15. Static Locomotive Measurements, De-energized**

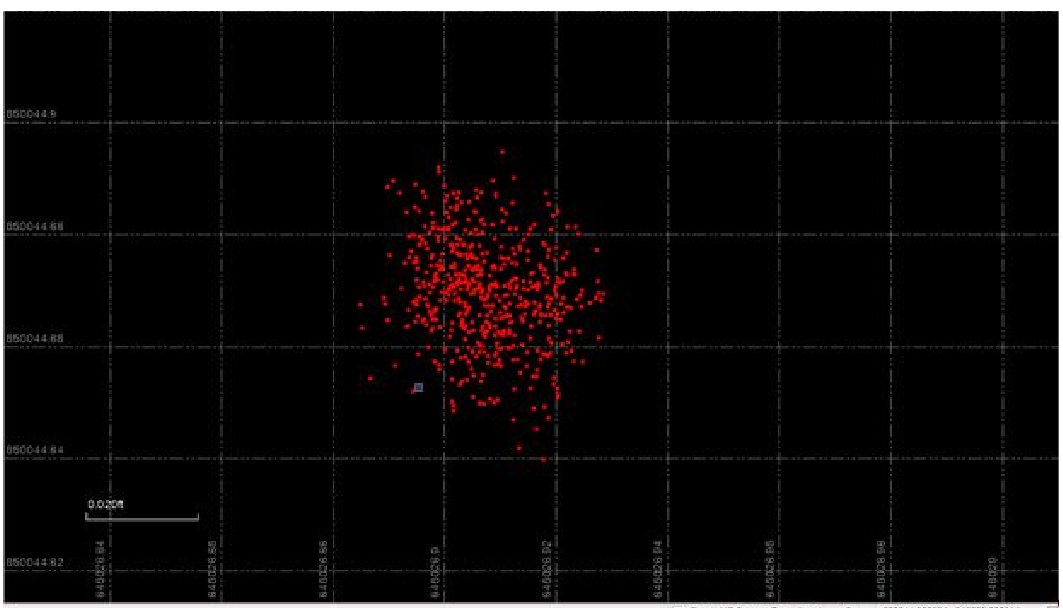


**Figure 16. Static Locomotive Measurements, Energized**

**Table 3. Horizontal and Vertical Errors of Static Locomotive Measurements**

| Horizontal Error | | | Vertical Error | | |
|---|---|---|---|---|---|
| ft | in | cm | ft | in | cm |
| 0.00717 | 0.08604 | 0.21854 | 0.00252 | 0.03026 | 0.07685 |

## 5.4 Dynamic Locomotive Testing

For the dynamic portion of the locomotive testing, test runs of 40, 60, 80, and 100 mph were conducted around the RTT. The first set of test runs took place while the overhead catenary was de-energized. The second set of test runs took place while the overhead catenary was energized at full power. HA-GPS positions were recorded simultaneously with RTK GPS positions and the results were compared. Figure 17 through Figure 24 show plots of the HA-GPS and RTK GPS data for each energized state of the overhead catenary (no significance given to color). Table 4 summarizes that data. In Table 4, “Missing Data” refers to the curvilinear length of the polyline of the track that was not recorded by the HA-GPS system.

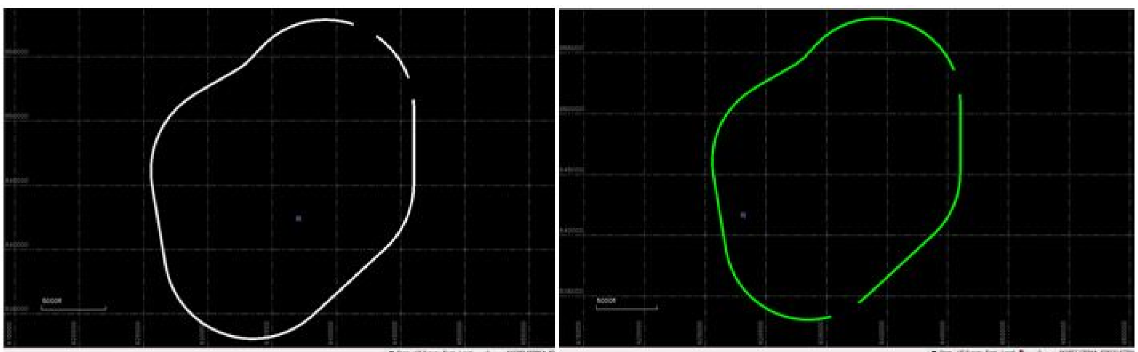

**Figure 17. HA-GPS, 40 mph, De-energized (left), Energized (right)**

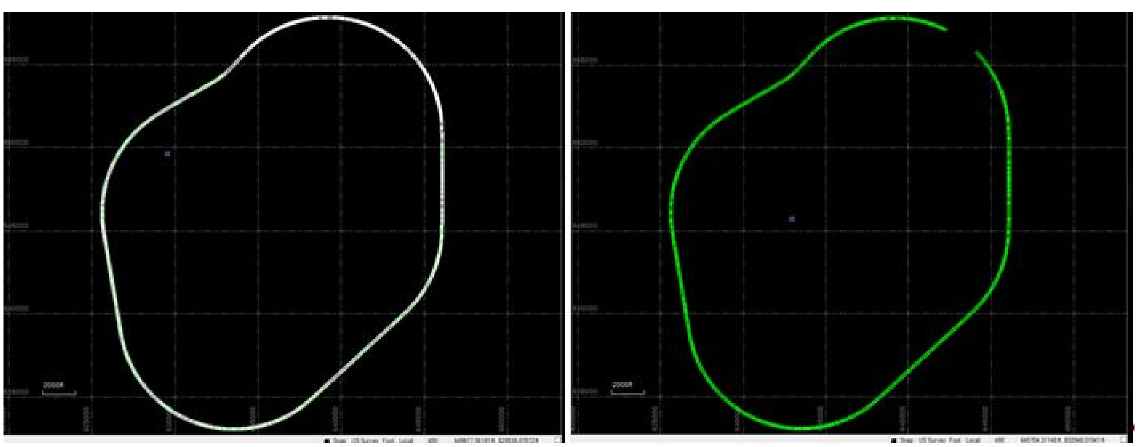

**Figure 18. RTK GPS, 40 mph, De-energized (left), Energized (right)**

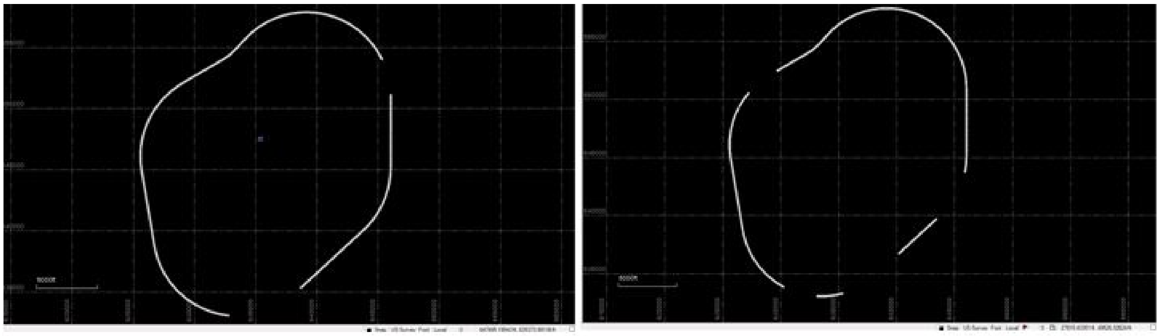

**Figure 19. HA-GPS, 60 mph, De-energized (left), Energized (right)**

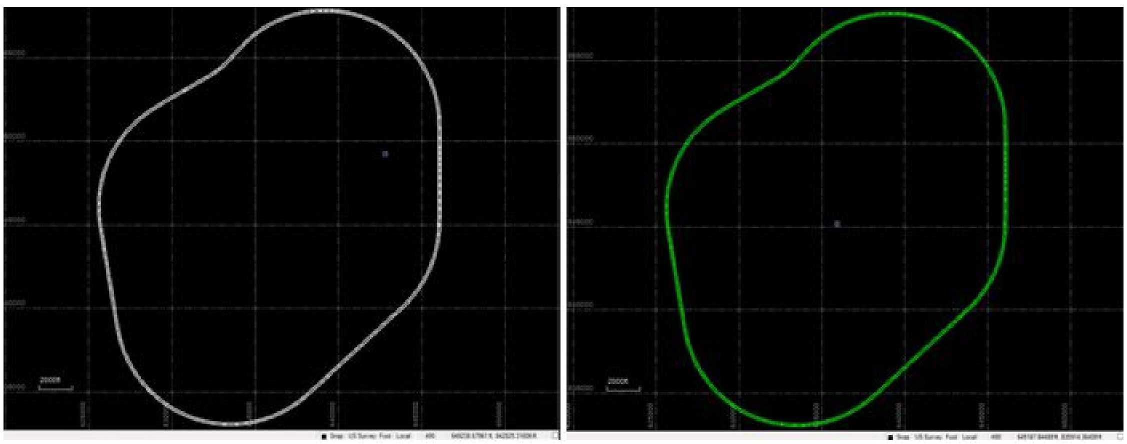

**Figure 20. RTK GPS, 60 mph, De-energized (left), Energized (right)**

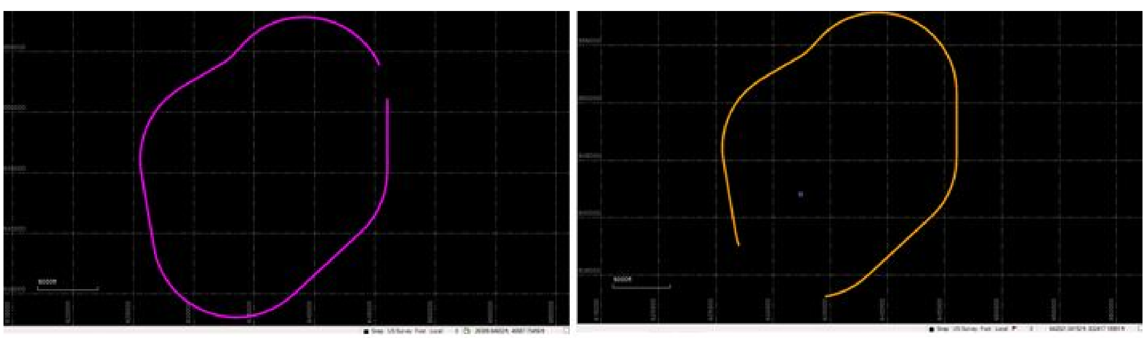

**Figure 21. HA-GPS, 80 mph, De-energized (left), Energized (right)**

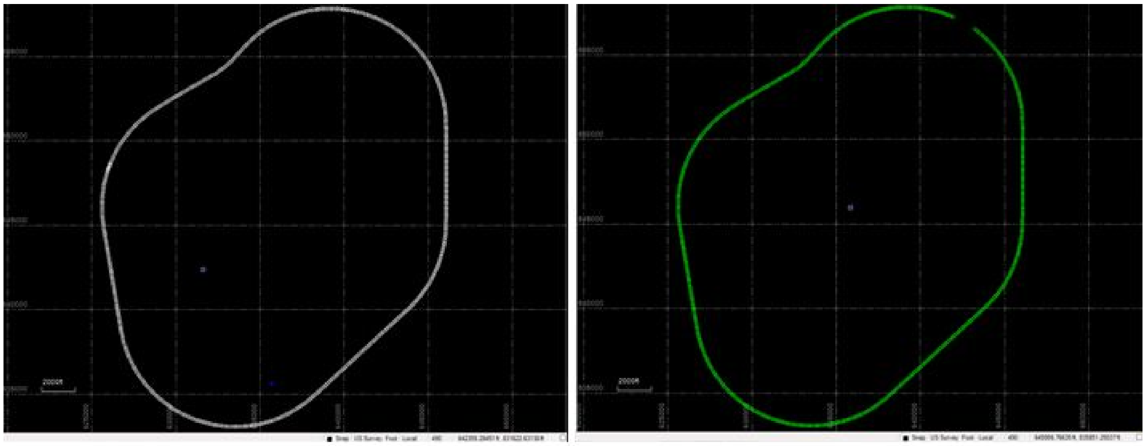

**Figure 22. RTK GPS, 80 mph, De-energized (left), Energized (right)**

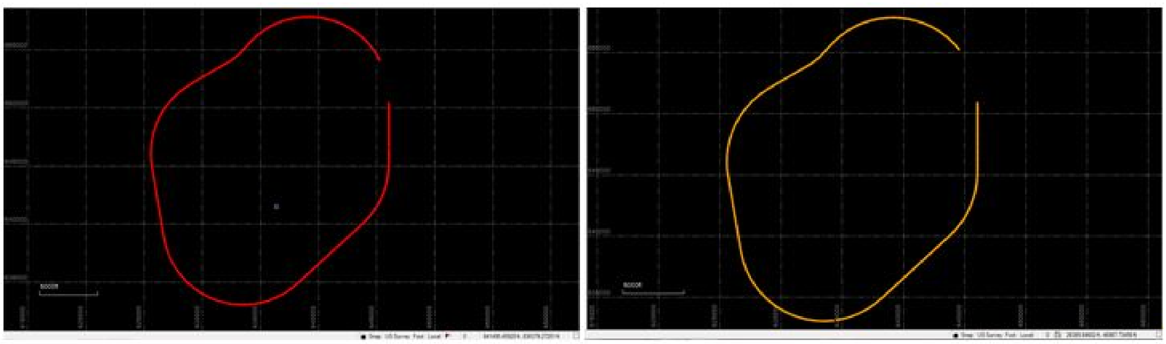

**Figure 23. HA-GPS, 100 mph, De-energized (left), Energized (right)**

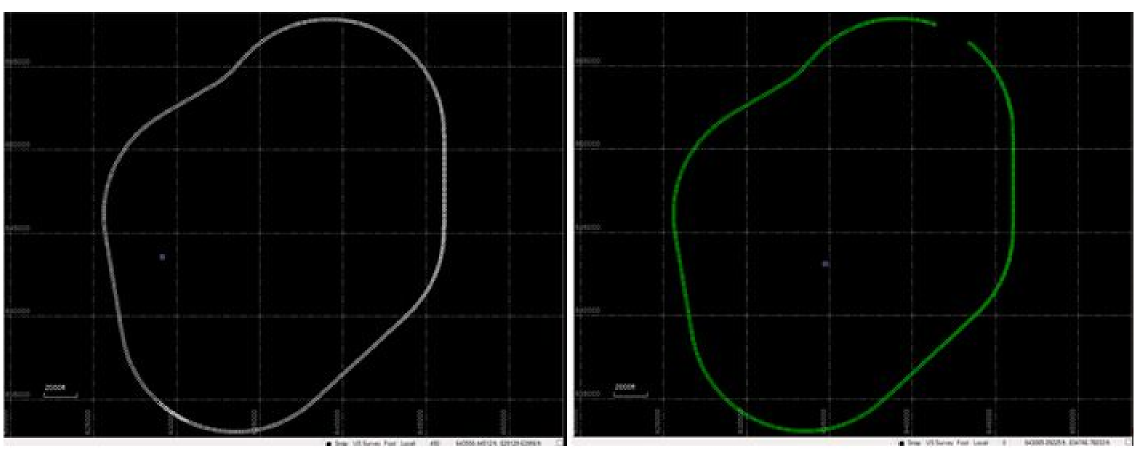

**Figure 24. RTK GPS, 100 mph, De-energized (left), Energized (right)**

**Table 4. Summary of HA-GPS Performance**

| Test Run | Missing Data (length of polyline) | Error (percent) |
|---|---|---|
| 40DE | 3,982 ft | 5.58 |
| 40E | 4,856 ft | 6.81 |
| 60DE | 9,371 ft | 13.14 |
| 60E | 17,019 ft | 23.86 |
| 80DE | 2,967 ft | 4.16 |
| 80E | 9,523 ft | 13.35 |
| 100DE | 3,812 ft | 5.35 |
| 100E | 4,636 ft | 6.50 |

# 6. Conclusion

The FHWA developed the HA-NDGPS project to assess the feasibility of improving the accuracy of the NDGPS service using its existing infrastructure to meet the requirements of additional applications without decreasing its availability and integrity, and still meeting the needs of existing users. The HA-GPS project at the TTC was developed to independently test the high accuracy portion of the HA-NDGPS system's ability to achieve sub decimeter positional accuracy with only relatively minor modifications to an existing NDGPS site.

The equipment upgrade for the HA-GPS system worked reasonably well. The new RTK GPS survey grade equipment purchased for this project was able to take the RTCM input from the HA-GPS broadcast and produce a real-time solution. However, since the HA-GPS software is no longer supported, new compression and modulator programs need to be obtained for future testing.

The distance versus accuracy testing showed a clear relationship between baseline distance and the accuracy of the measurement. The closer a user is to the broadcasting base station, the more accurate the positional solution. So, for HA-GPS to meet the needs of its users nationwide, hundreds of base stations with overlapping broadcasts would be required to provide sub decimeter positional accuracies across the country.

An HA-GPS equipped track survey system proved to be an effective means of collecting track feature information. It allowed a very accurate centerline, top of rail measurement that was calculated easily, thus eliminating the need to conduct a track survey of both rails in order to compute superelevation and centerline.

The HA-GPS system did not perform to the level of positional accuracy demonstrated by survey grade GNSS RTK GPS equipment. Although the RTK GPS system reliably calculated a position over 99.99 percent of the track during dynamic testing of both the energized and de-energized overhead catenary states, the percentage of track for which the HA-GPS system successfully calculated a position varied from 76.14 percent to 95.84 percent of the track.

No relationship was observed between the influence of an energized overhead catenary system and positional accuracies. The energized overhead catenary did, however, affect the reception of the broadcasted signal, resulting in several non-receptive (dark) sections of track. The locations of the dark sections varied significantly, which may be due to the differing geometry of the satellite vehicles during each of the test runs. Currently, HA-GPS only uses NAVSTAR GPS constellation of satellites in its solution. Modern survey equipment can use all or most of the GNSS satellites, which include the Russian GLONASS constellation. While there may only be four NAVSTAR GPS satellites in view at any one time, there may be dozens of GNSS satellites. This can account for some of the discrepancy in the integrity of the HA-GPS system compared with the RTK GPS.

The HA-GPS system could be employed nationwide for railroad applications, but it is questionable whether deploying such a system would be cost effective, especially in light of the number of base stations required and the cost of the equipment needed to upgrade the existing NDGPS sites. The future of HA-GPS at the TTC is also in question. The site still serves as the base for RTK broadcasts, but the HA-GPS software is out of date and unsupported. A new compression algorithm and modulation program would have to be created in order to conduct HA-GPS operations in the future. As a note of interest, a more cost-effective approach may be to utilize space-based augmentation systems (SBAS) for positional accuracies comparable to those available from HA-GPS systems. There are several SBAS systems currently employed and most modern satellite navigation systems have the ability to use SBAS solutions.

# 7. References


1. Boardman, Joseph H. *FRA's Requirements and Support for the Inland Portion of the Nationwide Differential Global Positioning System (NDGPS)*, Memorandum from the former FRA Administrator to the Administrator of the Research and Innovative Technology Administration. Washington, DC, February 22, 2008.
2. Bidwell, Ron. "Test Plans for HA GPS Locomotive and EOT Testing." Transportation Technology Center, Inc., Pueblo, CO. June 2010.
3. Federal Railroad Administration. "High Accuracy Global Positioning System Tests: Phase I." Technical Report No. DOT/FRA/ORD-21/19. U.S. Department of Transportation, Washington, DC, May 2021.

## Abbreviations and Acronyms

| ACRONYMS | EXPLANATION |
|---|---|
| CORS | Continuously Operating Reference Station |
| EMI | Electromagnetic Interference |
| FHWA | Federal Highway Administration |
| FRA | Federal Railroad Administration |
| GNSS | Global Navigation Satellite System |
| GPS | Global Positioning System |
| GRIM | GPS Receiver Interface Module |
| HA-GPS | High Accuracy GPS |
| HA-NDGPS | High Accuracy Nationwide Differential GPS |
| IM | Integrity Monitor |
| kHz | Kilohertz |
| NGS | National Geodetic Society |
| NAVSTAR GPS | Navigation Signal Timing and Ranging GPS |
| PTC | Positive Train Control |
| RTCM | Radio Technical Commission for Maritime Services |
| RTT | Railroad Test Track |
| RTK GPS | Real-time Kinematic GPS |
| SBAS | Space-based Augmentation Systems |
| TTC | Transportation Technology Center (the site) |
| R8 | Trimble R8 GNSS receiver |
| S6 | Trimble S6 Robotic Total Station |