REAL TIME KINEMATIC GLOBAL NAVIGATION SATELLITE SYSTEMS IN RAILROAD TRANSPORTATION

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Dissertation Submitted to the
College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

IN CIVIL ENGINEERING

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Morgantown, West Virginia
2010

Keywords: transportation engineering; rail; railroad; infrastructure; track; trackway; railway; inspection; freight; GPS; GNSS; NDGPS; real time kinematic; RTK; VRS; positive train control; PTC; location determination system; LDS; yard; class yard; classification yard; hump yard; survey; profile; alinement; alignment; track occupancy; FRA; USDOT; degree of curvature; string line

Abstract

Real Time Kinematic Global Navigation Satellite Systems in Railroad Transportation

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Transportation of freight by rail is an exceptionally fuel-efficient mode. Rail's exceptional efficiency comes with a high cost for inspection and maintenance of the railway to insure train safety at design speed. The Federal Railroad Administration (FRA) imposes operational safety by requiring compliance with regulations that rely on timely track inspection.

Further, new standards for train movement authority, known collectively as positive train control, require knowledge of a train's exact location on the railway. This knowledge has traditionally relied on wired track circuits due to the need to distinguish a train's location on two or more parallel tracks.

The research examines a technology to augment signals from navigation satellites in real time, available from many state governmental agencies at little or no cost, yet proclaimed by the US Department of Transportation in 2008 as "unsuitable for transportation applications". The successful application of this technology may enable rail companies to inspect the track way with greater safety at lower cost, and enable train location determination systems in positive train control independent of wired track circuits.

The results of three experiments conducted within the safety and access constraints of a Class I railroad are presented. The first surveys a 58-track hump yard by locomotive during production operations. The second determines horizontal track alignment over 29 miles of mainline track using inspector's Hi-Rail. The third experiment tests the hypothesis that RTK GNSS technology can meet the FRA's stringent requirement as a reliable indicator of track occupancy. The research outcome suggests more efficient techniques for selected track inspection tasks, as well as a wireless method to determine track occupancy.

Acknowledgements

The author wishes to thank the following organizations and individuals for their guidance and assistance.

West Virginia University
Dr. David Martinelli, Dr. Darrell Dean

Nick Joe Rahall Transportation Center
Robert Plymale, Dr. Richard Begley, Dr. Dianna Long, Alejandro Sanchez, Carlos Ramirez, Salvador Djeukeng

Marshall University
Dr. Anthony Szwilski, Dr. William Pierson, Dr. Rick McCormick

CSX Transportation
Michael Ward, John West, Bernie Sanders, Mike Nall, Gil Barnes, Don VanWormer, Ron Bright, Les Miller, Bill Kelly, Rodney VanPelt, JR McCloud

Ohio Department of Transportation, Aerial Engineering
Dave Beiter

Funding provided through the office of Senator Robert C. Byrd and the Federal Railroad Administration.

Dedication

This research is dedicated to the men and women of the railroad industry that go to work thinking of their own and of their coworker's safety; perform their duties while remembering to work safely; and at the end of each shift, return safely home to their loved ones. Then, wake up and do it all again, every day.

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Chapter 1

Introduction

The shipment of freight by rail is an exceptionally fuel efficient transportation mode. The average freight train consumes one gallon of diesel fuel to move one ton 423 miles [USDOT, 2008]. The outstanding efficiency of rail freight comes with a high price in inspection and maintenance of the railway. Rail car loading forces, weather, and time act on the railway and substructure to distort the track geometry. Distortions to the track geometry[1] must be identified and maintenance resources brought to bear to insure safe operation at the design track speed.

FRA[2] mandated visual track inspections rely on a rail company inspector's training, skill, and diligence. Conversely, track geometry car inspections provide an objective, detailed record of relative track position but are performed infrequently due to the limited availability of these specialized measurement systems. The thesis of this research is that, given a sufficiently accurate and reliable augmentation system, railway infrastructure measurement can be performed quickly, with greater safety, and at less cost by determining absolute track position using global satellite positioning systems. Survey-grade track measurement using GNSS[3] instrumentation will remove ground-based surveyors from the hazards inherent to active rail yards; enable monitoring of rail position changes during routine visual inspections; and determine the track occupancy of a train in parallel multi-track segments in signalized or dark territory[4], independent of wired track circuits.

The research results present an investigation into the use of Real Time Kinematic (RTK) augmentation to global satellite navigation systems in the measurement of absolute track position. Survey quality track positions enable the development and demonstration of solutions to rail measurement in an active hump yard and across 29 continuous miles of parallel mainline track.

Space vehicles (SV) that comprise the GPS[5], as well as other global navigation satellite systems:

[1] i.e., gage, profile, alinement, crosslevel, superelevation, and warp.
[2] Federal Railroad Administration
[3] Global Navigation Satellite Systems
[4] No signal control
[5] Sponsored by the United States Department of Defense (USDOD)

GLONASS[6]; Galileo[7]; and the future CNSS[8], are orbiting reference beacons enabling autonomous geo-spatial positioning and timing across the globe. The geo-spatial positioning accuracy of these systems can be improved by augmenting the identifiable distortions to SV signal transmissions through the ionosphere and troposphere with corrections from ground based facilities.

The use of GPS positioning for rail infrastructure measurement has depended on federal government supplied augmentation. The United Stated Department of Transportation (USDOT) has selected the National Differential GPS (NDGPS) augmentation system to increase accuracy in transportation applications. NDGPS has been promoted by the FRA as a means to achieve reliable track occupancy, however no NDGPS equipment demonstrating the requisite accuracy or reliability to insure track occupancy has been publicly disclosed [Allen et al., 2006]. The FRA reported in 1995 that "When [track occupancy is] viewed as a two dimensional area problem, it is unlikely that any economically feasible [GPS] system could achieve this accuracy to the required 0.9_5[9] probability [FRA, 1995, pp.6-7]." The economically feasible reference is interpreted here to mean the existence of commercial off-the-shelf (OTS) technology.

Railway Measurement Problems

Track course smoothness must be held within specific tolerances to avoid undesirable lateral accelerations that lead to additional railway distortions and derailment. A system for track surveying should be cost-effective, provide relative accuracy without interfering with train traffic, and minimize worker exposure to railway hazards. Historically, North American railways use relative measurement methods for track inspection. Track course measurement is based on the idea that track degree of curvature (D_c) irregularity can be determined by the versine[10] [Nair, 1972](see figure 3.5).

The research applies augmented GNSS to measure track elevation in a hump yard for the purpose of track profile measurement; measuring track horizontal position in order to determine the D_c of mainline track across a wide area; and determining track occupancy probability independently of wired track circuits. Three railway measurement problems were investigated during the research.

1. An automatic classification yard uses the force of gravity to propel cars through a complex system of tracks to the intended destination in the yard. Environmental factors[11] act on the motion of a railcar from its release, through a transit of specific yard tracks, to a final rest position. Profile deviation from the design grade occurs over time from settlement as a

[6] GLObal'naya NAvigatsionnaya Sputnikovaya Sistema sponsored by the Russian Space Forces

[7] Sponsored by the European Union

[8] Compass Navigation Satellite System proposed by the Peoples Republic of China

[9] 0.99999 or 99.999%

[10] In rail transportation, versine refers to relationship between the distance (v) measured at right angles from the midpoint of a chord (L) to the arc, with the instantaneous D_c determined from $\lim_{L\to 0} 8\frac{v}{L^2}$

[11] Wind speed, direction, and ambient temperature

result of railcar loading forces and the effects of weather [Szwilski et al., 2005]. Conducting a differential level survey across a 60 track, thousand car per day yard, places workers in harms way, making yard production delays unavoidable in order to accommodate the safety of the survey party. The difficulty and expense in conducting a yard survey to quantify production delays attributable to grade irregularities can be prohibitive [Barnes, 2007].

A hump yard profile survey was conducted by locomotive equipped with RTK GPS survey instruments. The survey was conducted during production, inclement weather resulting in the production of 58 track profiles.

2. Track superintendents rely on an occasional traverse by a specialized track geometry car and routine visual inspections to identify track defects for directing maintenance resources. A method of recording track alinement during routine visual inspections by Hi-Rail and producing a record of track alinement provides insight into the identification of track shift or compliance irregularities attributable to car loading, weather, or geologic processes.

   COTS surveying instruments and infrastructure were used during a track inspector's normal visual inspection by Hi-Rail to determine degree of curvature D_c. A instrument mounted to a Hi-Rail recording track position across a track inspectors 29 mile area of responsibility. A software modeling the string lining method [Bright, 2009; FRA, 2007; USC, 2009a](hereafter referred to as *the model*) determined D_c and mile post reference locations. The RTK Hi-Rail D_c were compared against rail company track charts to verify the model. The accuracy of the Hi-Rail method of determining D_c was compared against measurements by a specialized track inspection vehicle.

3. Locating a train in a parallel, multi-track segment by means of GNSS requires a priori knowledge of each track segment's location. The present US rail transportation system inventory of 95,000 mainline track miles makes monumenting the absolute location of each track centerline to a high degree of accuracy a formidable task. Most rail company's have chosen LiDAR overflights to monument the position of track and wayside assets.

   A track vehicle using wireless position measurement determined a reference track centerline location against which subsequent traverses by the track vehicle where compared. Subsequent track positions met the researcher's interpretation of the FRA positioning guidlines for a location determination system (LDS) as might be used for positive train control (PTC) [FRA, 1995, pp.3].

Research Questions

The researcher sought to wirelessly assess railway infrastructure and use wireless location to act as a reliable track vehicle locator.

The solution to many track measurement and rail vehicle location problems requires absolute track and vehicle position measurement over wide areas. The research integrated wireless track measurement within the operational and safety constraints of a Class I rail company for the purpose of developing a method to survey track location with common track vehicles. The rail transportation problems addressed by the research seek to decrease on-track worker hazard exposure, increase track inspection efficiency, and reduced the cost of track measurement. The research employed locomotives and HiRail vehicles equipped with COTS survey equipment to evaluate the relative vertical precision, horizontal accuracy, and position reliability of RTK augmentation. The research used a wireless measurement system to meet the "...high integrity, and high reliability for safety-critical train control applications [Pruitt and Fly, 2008, pp.11]."

Objectives of the research developed procedures and supporting models for assessment of wireless track measurement integration within a Class I railroad environment.

1. A literature review of previous rail survey experimental results as well as a search of intellectual property claims regarding train location were used to investigate factors that indicated the need for research into the wireless measurement of railway position. The review was used to determine a wireless method using COTS instruments with sufficient accuracy to meet the measurement goals.
2. Experts in the field of hump yard engineering were interviewed, and a review of the literature was used to identify methods of increasing humpyard efficiency and throughput. Railcar motion was studied through a humpyard in an effort to identify operational problems that may be related to profile degradation.
3. A method was developed and demonstrated to safely and precisely determine track grades across the bowl area of an automatic classification yard. The selected wireless method was used to produce individual profiles for each bowl track in the yard. The relative vertical precision of the mobile receiver and the signals recorded by a reference station in the yard were evaluated for evidence of signal distortions in the hump yard environment.
4. Experts in the field of track inspection and wide area RTK augmentation delivery were interviewed to identify methods for measuring rail position over wide areas of mainline track.
5. A method was developed and demonstrated for safely determining horizontal track alinement across a wide area.
6. A model was developed to determine horizontal track alinement based on the string lining method using RTK GNSS observations. Factors affecting GNSS measurement over mainline track were analyzed.
7. A methodology was developed to assess wireless measurement methods as part of a location determination system suitable for supporting positive train control. COTS RTK GNSS VRS infrastructure and instrumentation were evaluated in parallel multi-track mainline segments for the ability to meet FRA tolerances [FRA, 1995, 4-5].

Development and demonstration of wireless method of track position is significant to providing the rail industry with a practical and reliable standard for rail position measurement over a wide area. Several tools were developed enabling a solution to railway infrastructure measurement and monitoring problems that has not been demonstrated with US government provided GPS augmentation. Intelligent rail transportation initiatives will benefit from survey-quality positioning in the command, control, communications, and track information domains. Freight transportation will derive benefit from improved power and braking systems which will result in improved energy efficiency and decreased emissions; improved systems for track defect detection and track movement prediction; improved efficiency in the deployment of maintenance assets; examination of track substructure through determination of the track modulus between lightly loaded (as with a HiRail) and loaded (as with a locomotive) track measurements; and safety improvements derived from Positive Train Control (PTC) systems with the potential to significantly reduce the probability of collisions between trains, casualties to roadway workers, damage to equipment, and reduction in the occurrence of overspeed accidents through the wireless differentiation of track vehicle location over parallel multi-track segments.

Reliable wireless measurement of track position, when contrasted with the present use of dedicated track circuits[12], provides and opportunity to use wireless measurement technology to enhance railway infrastructure management practices. Track vehicle location and control benefits from survey quality wireless measurement, coupled with the use of existing wayside radio infrastructure, has the potential to provide economic benefit by reducing a rail company's dependance on existing hard-wired infrastructure[13] and attendant labor costs.

Other cited benefits of accurate train location may include:

- Higher quality service, through continuous tracking of car movements.
- Reduced fuel consumption, through better pacing of trains (avoiding the need to take away momentum through braking and restore it through use of diesel power).
- More efficient use of existing physical plant, increasing effective capacity while avoiding further outlays to build additional tracks or sidings. [FRA, 1995, pp.12-13]

Operational Definitions

1. Hump yard: This study specifically refers to the Hamlet Terminal, owned by CSX and located in Hamlet, North Carolina.
2. Mainline track: A track extending through yards and between stations which must not be occupied without authority or protection. This study refers to mainline track as C&O Ohio Subdivision from mile post (MP) 211 to MP 207 (Guyendotte, West Virginia), and C&O Kanawha Subdivision from MP494 to MP 523 (Barborsville, WV to Russell, KY).
3. Mapping-grade accuracy: An observed position within 3-16 feet (1-5 meters) horizontally and 6-33 feet (2-10 meters) vertically of the true value with 95% confidence.

[12] i.e., insulated track circuits, loop detectors, magnetic proximity switches, transponders

[13] Estimated replacement mainline cost of $125,000 per mile × 95,000 miles = $12 billion [Resor et al., 2005]

4. Survey-grade accuracy: The combined measurement errors from instrumentation and the measurement process producing a position to within 0.1 feet or less of the true value in the horizontal and vertical plane with 95% confidence.
5. Track occupancy: FRA LDS guideline for differentiating between parallel tracks with a 11.50 foot centerline-to-centerline track spacing using GPS. The FRA track spacing requirement is interpreted in this study as a point obtained from a mobile track vehicle no greater than $\pm\frac{11.50}{2}$ feet left(-) or right(+) of a track centerline with 99.999% confidence [FRA, 1995, pp.6-7].

Research Questions

The research conducted in this investigation was an analytical study supplemented by the acquisition of wireless track observations. The research focused on the integration of RTK augmented GNSS within the operational constraints of a Class I railroad. As a result of this research, a methodology for the assessment of railway infrastructure was developed.

The problems solved by the determination of absolute track location to a high degree of accuracy in a hump yard and over mainline track answered these questions.

1) *Hump Yard Profile:* Can a locomotive use wireless position measurement to determine the vertical profile of bowl tracks in an automatic classification yard to an accuracy of tenth of a foot during production activities?

2) *Horizontal Track Alinement:* Can a common track vehicle use wireless position measurement to determine the horizontal degree of curvature (D_c) comparable with specialized track geometry vehicles?

3) *Track Occupancy:* Can a common track vehicle use wireless position measurement to meet the FRA [FRA, 1995, pp.6-7] accuracy and confidence guidelines for track occupancy as might be used in a location determination system?

Chapter 2

Literature Review

The literature review supported answering these research questions:

1) *Hump Yard Profile:* Can a locomotive use wireless position measurement to determine the vertical profile of bowl tracks in an automatic classification yard to an accuracy of tenth of a foot during production activities?

2) *Horizontal Track Alinement:* Can a common track vehicle use wireless position measurement to determine the horizontal degree of curvature (D_c) comparable with specialized track geometry vehicles?

3) *Track Occupancy:* Can a common track vehicle use wireless position measurement to meet the FRA [FRA, 1995, pp.6-7] accuracy and confidence guidelines for track occupancy as might be used in a location determination system?

Manifest Freight and Hump Yard Efficiency

Car load freight traffic requires a systematic method for handling the distribution of car destinations, the return of empties, and redirecting cars to their originating industry. On-time delivery in carload service requires minimizing delay during a series of independent car handling events. Beshers notes that each transit through a terminal decreases the probability of an on-time delivery, and provides a statistical determination of overall freight service reliability as the product of the probability-of-delay each time a car is handled along the way to its destination [Beshers et al., 2004]. Moorman points to the difficulty rail freight carriers have in achieving acceptable carload service levels in retaining market share [Moorman, 2006].

Automated classification yards[1], are facilities engineered to continuously process incoming freight cars into outbound trains. Car processing in a hump yard uses the force of gravity to propel cars through a complex of tracks to the intended destination in the yard.

[1] Commonly referred to as hump yards.

Beshers point to the degradation of car-load service quality and movement away from boxcars to inter-model freight as factors that have resulted in a clear trend towards rail company closure or repurposing of hump yards rather than investing in new facilities [Beshers et al., 2004]. Several older hump facilities remain in use but have been repurposed as flat switching yards, as in Russell, KY, Dewitt, NY, and Enola, PA. Others have been converted into intermodal facilities, such as Norfolk Southern Atlanta, GA and Rutherford, PA yards [TRAINS, 2002].

Dr. Edwin Kraft in a patent claiming to increase yard throughput through a multi-stage sorting algorithm, points out that surviving hump yards operate at close to maximum throughput and operate under a state of constant congestion, to the point that they often cannot accept newly arriving trains. In these circumstances cars are parked on main line track and wait to be processed. Hump yard congestion affects rail service reliability across the network, which in turn contributes to further loss of rail traffic to the trucking industry [Kraft, 2002].

A hump yard's profile deviation and settlement away from the design grade can be attributed to the effects of car loading forces and weather. Szwilski and Kerchof's observation that yard delays attributable to grade irregularities are difficult to identify due to limited yard profile data available to the hump yard engineer [Szwilski et al., 2005]. When interviewed, Barnes echoed Szwilski and Kerchof in noting that the limited availability of profile data is due primarily to the difficulty in conducting a survey to profile track [Barnes, 2007].

Szwilski and Kerchof estimated a differential level survey across a 72-track hump yard would take 4 to 6 weeks of field work by a three-person survey crew. A differential level survey point density is typically measured on 100' stations, resulting in the observation of approximately 3,000 points within the bowl area of the yard. An estimated 480 to 720 man-hours of exposure to rolling stock in an active yard evidences the need to insure the survey party's safety by closing groups of tracks to production activity. Extended track closures require rerouting railcars away from the yard to prevent yard congestion. The associated cost to reroute railcars is difficult to estimate [Szwilski et al., 2005]. Safety consideration for the survey party require the yard manager to dedicate specifically trained workers from the yard's labor pool to act as a safety escort. The specter of six continuous weeks of negative production due to track survey activity limits a manager's tolerance for obtaining track profiles, no matter how well intentioned the survey intrusion [Barnes, 2007].

The hump end of an automatic classification yard controls the motion of a railcar through the yard. Hump end yard operations are described visually in this video[2] and provide a graphic understanding of railcar pacing, car variety, and braking [Dailey, 2008a]. The video follows several railcars from release by the pin puller, through the main, intermediate, and group retarders, passing lead and group switches into the bowl to couple at a controlled speed intended to be no greater than 4 mph. The requirement for personal protective equipment in or near a hump yard is obvious from the retarder/wheel flange squeal in the audio track.

[2] $http://www.youtube.com/watch?v=ndryMwF41Kk$

Anecdotal inference of yard infrastructure problems is the usual mechanism by which grade renewal is scheduled. An experienced observer might use the reaction of a car's truck and bolster as an aid in revealing underlying track irregularities.

Modern hump yard control systems, such as the ProYard and ProYardII systems, are able to count car transits through the yard network as cars pass wheel detectors (magnetic proximity switches) linked to PLCs[3] programmed with timing logic. Misroutes and car stalls recorded by modern hump control systems are metrics used to gauge overall yard performance as well as distinguishing individual track irregularity.

A time lapse video[4] [Dailey, 2008b] shows a series of stalled flatcars. The opening frames show a flatcar moving away from the hump, striking a group of stalled flatcars. As a result of insufficient coupling speed, the flatcar rolls back toward the hump, with the car's final rest position blocking the group switch. The blocked switch prevents any additional railcars from classification into the blocked group. The stall effectively shuts down humping operations when the next car sequenced for the blocked group reaches the pin puller. The time-lapse sequence from stall to the trim locomotive kicking the cars into the alley represents 21 minutes of delay, indicative of the cumulative effects from profile-induced delay affecting the on-time quality of car load service.

An FRA sponsored study examined the effects of locomotive electromagnetic fields on the NDGPS signal, finding a reduction of some 10db in particular antenna configurations [FRA, 2000]. Radio-reflective structures and the metal railcars may affect GPS signals in a hump yard. GPS signal reflections from fixed an moving surfaces present an opportunity to introduce complex multipath distortion to GPS receiver, in addition to the effect of electromagnetic fields generated by a locomotive from the generator and traction motors.

Absolute Track Location Measurement Systems

The "other supplemental techniques" referenced in the USDOT NDGPS Assessment are reflected in patents that integrate differential GPS, inertial systems, and wheel mounted tachometers to produce optimal estimators for determining locomotive track occupancy [Meyer and Metzger, 2007]. Supplemental techniques were demonstrated across a wide area of mainline track in an asset mapping system demonstrated by Allen, Mason, and Stevens.

Allen, Mason, and Stevens developed a rail borne track-mapping system as a cost saving alternative to remote sensing from an aerial platform. Their survey platform consisted of a HiRail vehicle equipped to utilized publicly available real time correctors from the NDGPS in addition to post processed observations from a cooperative[5] Continuously Operating Reference Station (CORS). The

[3] Programable Logic Controllers

[4] $http://www.youtube.com/watch?v = ygl_X9RER70$

[5] http://www.ngs.noaa.gov/CORS/Coop/

GPS instrument was augmented with tachometer and inertial measurement unit (IMU) inputs. Allen reported that an initial calibration on a dedicated survey vehicle took two days.

Rail positions measured by Allen's HiRail were compared against 26 centerline targets previously surveyed using RTK GPS. NDGPS correctors were available during 80% of the 120 mile traverse of Norfolk Southern mainline track. Two Post-Processed Kinematic (PPK) positions were divided into two categories by distance to the CORS. A first category of observations was processed against a CORS at under 65 miles distant from the survey vehicle, with a second category of PPK positions processed against a CORS between 65 and 130 miles distant from the survey vehicle.

Table 2.1: Track Measurement Results [Allen et al., 2006]

Measurement	Cross-Track*	Along-Track*	Elevation*	Absolute*
NDGPS	5.2418	5.4766	13.5308	8.0834
PPK < 65 mi.	1.5758	1.4766	4.4049	1.8917
PPK 65−130 mi.	2.9084	2.5003	10.2528	3.8505

* Feet, 95th percentile. Significant figures reported by Allen.

The cross-track differences between previously surveyed RTK track locations and those measured by HiRail summarized in table 2.1. No determination for LDS suitability was reported.

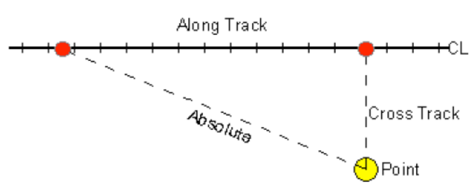

Figure 2.1: Track Centerline Accuracy Parameters [Allen et al., 2006]

Other track asset mapping systems exist for determining the location and type of of assets held by railroads. The Union Pacific Railroad has developed and markets a HiRail-based measurement vehicle built on a SUV chassis and referred to as the Precision Measurement Vehicle (PMV). The PMV is used to provide location and description of all assets that can be measured from the railway. While occupying active mainline track, PMV operators use several measurement technologies to determine asset location. Four independent encoded wheels provide linear referenced track position inputs by by accumulating the slope distance between wayside monuments. A differential GPS receiver provides mapping-grade absolute position, while a fiber optic gyroscope (OG) is used to measure grade. The OG also serves to dampen the elevation observations from the DGPS receiver.

A video interface provides the operator with a view through optical distance measuring instruments. A video recorder provides a record for milepost tracking and a survey log. Comparative positions generated by the PMV were not available for examination [Union Pacific Railroad, 2008].

Glaus details the development of a lightweight multi-sensor track surveying platform. The 99-pound (45 kg) hand-propelled device, nicknamed the *Swiss Trolley*, tested several sensors and the development of a rigorous mathematical model for calculating kinematic track location. Close tolerance rail alinements are required for high speed passenger rail service. The *Swiss Trolley* fills the need for precision track surveying by demonstrated the ability to determine absolute track axis[6] position to a high degree of precision. The *Swiss Trolley* sensor suite is summarized in table 2.2.

Table 2.2: Swiss Trolley Instruments [Glaus, 2006]

Measurement	Sensor	Range/Resolution
Absolute position	RTK GPS Total Station	1 mm [sic]
Absolute/relative position	Tracking Total Station	1 mm
Linear distance	Odometer	0.08 mm
Cross level/Grade	Inclinometer	±15°
Asset location	Laser scanner	180°
		1 mm @ 32 m
		10 mm @ 80 m
Gauge	Angular transducer/rail contact	0-45°

Analog sensors on the *Swiss Trolley* are linked to a control and data acquisition computer by means of an analog to digital multiplexor. Sensors are synchronized with 1 pps timing pulses generated by the GPS receiver. The sensor suite provides inputs to the model to calculate track axis, grade, cross level, and gauge. Points of concern are raised by the author in dealing with thermal and electrical noise on the analog-to-digital (ADC) converter inputs from a variety of sensors. Electromagnetic compatibility interaction between instruments was addressed by reducing the length and attention to the orientation of cables between sensors and ADCs. Two fluid-damped pendulum sensors provide cross-level and grade inputs. These inclinometers are subject to errors from nuisance vibrations, temperature, and collimation (axis alignment) error. Thermal instability errors were reduced by installing the sensors in an instrument oven to maintain a constant temperature regardless of ambient conditions. Grade and cross-level sensor vibration is modeled as a pendulum and applied to track position corrections. Significant is Glaus's method of integrating auxiliary instruments using Kalman filtering techniques to produce spatial accuracies in the range of several millimeters in a complex dynamic application.

The *Swiss Trolley* is capable of producing exceptional track position accuracies, but the hand propelled sensor suit is limited to a maximum speed of 3.3 mph. Survey speeds are intentionally

[6] Referred to here as centerline top-of-rail.

kept at a minimal to reduce sensor synchronization uncertainty for the platform. The reduced rate also aids in providing an accurate absolute time tag for kinematic data collection [Glaus, 2006]. In its present form, the tight instrument integration and slow survey speed of the *Swiss Trolley* make this approach impractical for track inspections across wide areas.

Mainline Track Horizontal Alinement

Mainline railways are periodically inspected with specialized "track geometry cars" for compliance with FRA mandated track alinement criteria or to meet more stringent rail company specifications [USC, 2009a] [Bright, 2009]. Alinement data recorded by a track geometry car determines position by use of an odometer for track location within a linear reference system relative to wayside monuments. Wayside references commonly referred to as mile posts range from permanent cast concrete to steel signposts inserted into the ballast. Mile markers are subject to destruction or displacement from routine track maintenance and vandalism. Resetting mile posts is many times a best guess effort. Track geometry car measurements are typically referenced to these reference marks. Track defects referencing offsets from these marks are sometimes difficult to locate by Hi-Rail odometer. [Van Pelt, 2009].

The linear measurement system of a track geometry car produces accurate relative positions in the search to alinement defects. A geometry car will use GPS to provide a global reference frame to map alinement exceptions, however the accuracy of these GPS measurements are not adequate for use as a primary alinement tool. Track geometry vehicle inspections are limited in frequency due to the number of vehicles available, with those focused on higher traffic segments. [Bright, 2009].

Track Occupancy

The FRA has established that any location determination system suitable for supporting positive train control must establish track occupancy with a very high degree of certainty. In a given parallel, multitrack segment, an LDS must be able to determine which track a given train is on without error. The FRA therefore requires a LDS to demonstrate track position that assumes a minimum track separation (center to center spacing) of 11.5 feet with 99.999% confidence [FRA, 1995, 4-5].

A method of autonomous locomotive location referenced by US patent 6,641,090 and follow on 7,209,810 *Locomotive Location System and Method* disclose an apparatus integrating inertial navigation, GPS, and a wheel mounted odometer as a method by which track occupancy can be determined by a train traveling proximal to a turnout. The patent claims teach that the method is able to determine track occupancy when a locomotive travels through a turnout by engaging a Kalman filter to process noisy inputs from accelerometers orthogonal to the direction of travel as the locomotive is diverted from the tangent track into a turnout. The output is compared with predefined track parameters by computing the location and corresponding estimated error states derived from the inertial navigation system until the estimated error state matches a pre-determined feature, indicating the track for that instance is not the track occupied by the locomotive. The method does not teach how to distinguish track occupancy between parallel trackways [Meyer and Metzger, 2007].

Improving the USDOD[7] guarantee of 12.8 meter horizontal accuracy from the Global Positioning System Standard Positioning Service requires that positions calculated by a GPS receiver be augmented to correct for delays induced in the SV[8] signal's travel through the ionosphere and troposphere and a variety of instrument errors [USDOD, 2001]. Correctors transmitted to and processed by a capable receiver are able to compensate for errors and improve the position determined at the receiver's antenna. Correctors are derived from the difference between the instantaneous position calculated at a stationary reference receiver antenna and the actual location of the stationary antenna. The reference receiver determines the signal error for each SV in view of the antenna. The position differential is the product of all "signals in space" errors induced in the signal, zeros the clock error between the reference and mobile reciever. SV signal errors accumulate from orbit irregularities (i.e. gravitational effects, solar wind, or outdated ephemerides); satellite and receiver clock errors; ionospheric and tropospheric delay; and other identifiable factors [Leick, 2004]. The reference and mobile receivers must receive the same SV signals for correctors to have an effect on the mobile receiver position accuracy [Pruitt and Fly, 2008].

Current federal government augmentation systems, the Wide Area Augmentation Systems (WAAS) sponsored by the Federal Aviation Administration and the National Differential GPS (NDGPS) sponsored by the US Coast Guard, provide civilian users with mapping-grade[9] position accuracy. The USDOT[10] was given presidential authority to develop and promote the use of civilian GPS augmentation systems.

Presidential Decision Directive National Science and Technology Council (NSTC-6), designating USDOT to serve as the lead agency within the U.S. Government for all Federal civilian GPS matters. NSTC-6 commissioned the USDOT to:

> "Develop and implement U.S. Government augmentations to the basic GPS for transportation applications.
>
> - In cooperation with the Departments of Commerce, Defense and State, take the lead in promoting commercial applications of GPS technologies and the acceptance of GPS and U.S. Government augmentations as standards in domestic and international transportation systems.
> - In cooperation with other departments and agencies, coordinate U.S. Government-provided GPS civil augmentation systems to minimize cost and duplication of

[7] United States Department of Defense

[8] Space vehicle

[9] Defined here and generally accepted as 1 to 3 meter horizontal accuracy

[10] United States Department of Transportation

effort [NSC Office of Science and Technology Policy, 1996]."

Federal government provided GPS[11] signal augmentation can be categorized by the augmenting signal transmitter location into 1) Space Based Augmentation Systems (SBAS) which use geosynchronous satellites to relay corrections from ground reference stations to the user, and 2) Ground Based Augmentation Systems (GBAS) which transmit corrections from ground reference stations directly to the user.

Space-Based Augmentation Systems

Government sponsored and privately funded SBAS are available to civilian and commercial users. The FAA[12] sponsors WAAS[13] for aviation users and consists of an integrity reference monitoring network, processing facilities, geostationary satellites, and control facilities. The central data processing sites generate navigation messages for retransmission to users by geostationary satellites. The information is modulated on the GPS-like signal and broadcast to the users from geostationary satellites. WAAS corrections result in horizontal accuracies of 0.481 to 1.521 meters with 95% confidence across the continental United States [WAAS Test Team, 2009].

WAAS is limited to broadcasting differential corrections for only GPS SVs. As with any SV signal, the reception of correctors broadcast from a geostationary SBAS satellite can be adversely affected by foliage, terrain, and building shadowing along the signal path from the SBAS SV to the user. The USDOT cites signal shadowing effects from a single geostationary point source as an objectionable characteristic for the use in railroad applications. The signal shadowing characteristic is a primary objection to the use of an SBAS as part of an LDS by the FRA [Pruitt and Fly, 2008].

Commercial SBAS subscription services enable horizontal accuracies to 6 cm @95%and are used primarily in precision agriculture applications which, due to their use in open fields, are relatively unaffected by loss of the correction signal on the north side[14] of tree lines or terrain, and under heavy foliage cover [Fugro N.V., 2009].

Ground-Based Augmentation Systems

The National Differential GPS (NDGPS) is a GBAS that uses terrestrial Low Frequency (LF) radio in the 285-325 kHz band for transmitting correctors to NDGPS capable receivers. A desirable aspect of long wavelength[15] LF radio is ground wave propagation. LF digital signals are favored by the USDOT for communicating correctors due to signal reception at distances up to 250 miles distant from a terrestrial reference station transmitter and LF.

[11] Non-GPS augmentation to GNSS systems is not provided by federal government systems
[12] Federal Aviation Administration
[13] Wide Area Augmentation System
[14] SV orbits viewed from the ground, are not present in northern segments.
[15] λ=922 to 1052 m (3,025 to 3,451 ft)

The accuracy of NDGPS augmentation degrades at a rate of ± 6.6 parts per million (ppm) distant from the reference receiver[16] [FRA, 2000]. A USDOT report recognizes other problems in addition to the low data rate of the NDGPS signal, in that the signal

> "...is further degraded by computational and other uncertainties in user equipment and the ability of user equipment to compensate for other error sources such as multipath interference and propagation distortions" [Pruitt and Fly, 2008].

With these considerations, the USDOT selected NDGPS as the GBAS for transportation applications. The USDOT promotes NDGPS as the augmentation system of choice for enabling positive train control location determination systems. The FRA qualifies its support for NDGPS use in PTC by understanding the need for "other supplemental techniques" to meet the high degree of confidence required of an LDS [FRA, 1995]. The USDOT *2008 NDGPS Assessment Final Report* states that "NDGPS with its current level of accuracy has not proven adequate for safety-level track separation information [Pruitt and Fly, 2008]."

Measurement Technology Selection

A number of methods are available for assessing rail position. Table 2.3 compares candidate technology characteristics relevant to railway measurement.

Table 2.3: Comparison of Measurement Technologies

	Differential Level	Trigonometric Leveling	GNSS	LiDAR
Speed	slow	slow	moderate	fast
Safety	poor	poor	good	good
Equipment Cost	low	moderate	moderate	high
Support Infrastructure	minimal	minimal	extensive	minimal
Mobilization Cost	moderate	moderate	low	high
Ground Truth	high	high	moderate	none
Measurment Density	low	low	high	very high
Operational Disruption	high	high	low	none
Real Time XYZ Positioning	no	yes	yes	no
Wide Area Monument Availability	sporadic	sporadic	CORS	ad hoc
Coordinate Availability				
X	×	√	√	√
Y	×	√	√	√
Z	√	√	√	√
Feature Coding of Coordinate	×	√	√	×

[16] At a distance of 250 miles, a user could expect an additional horizontal error of ±8.7 feet ($6.6 \cdot \frac{250 \cdot 5{,}280}{1{,}000{,}000}$)

To be considered as a viable technology, a GPS/GNSS augmentation system was required to have COTS receivers available to the researcher through standard commercial distribution channels. GNSS measurement technology was selected because of the need for real time positioning in tracking rail vehicles and the availability of reference monuments over wide areas.

Table 2.4 evaluates the accuracies available from space and ground based augmentation systems. As previously noted, Allen used Post Processed Kinematic (PPK) GPS and NDGPS during railway measurement by HiRail. Both augmentation technologies were rejected by the researcher as failing to meet the requisite positioning accuracy.

Table 2.4: Comparison of GNSS Accuracies

Augmentation	Min. Horiz. Error (ft)	Max. Horiz. Error (ft)	Min. Horiz. Error (m)	Max. Horiz. Error (m)
GPS SPS[1]	72	105	22	32
GPS WAAS[2]	10	16	3	5
NDGPS[3]	7	16	2	5
GNSS RTK[4, 6]	0.07	0.20	0.02	0.06
GNSS RTK VRS[5, 7]	0.03	0.05	0.01	0.02
Augmentation	**Min. Vert. Error (ft)**	**Max. Vert. Error (ft)**	**Min. Vert. Error (m)**	**Max. Vert. Error (m)**
GPS SPS[1]	118	253	36	77
GPS WAAS[2]	16	33	5	10
NDGPS	13	33	4	10
GNSS RTK[4, 6]	0.07	0.23	0.02	0.07
GNSS RTK VRS[5, 7]	0.07	0.05	0.02	0.02

[1] [USDOD, 2001]

[2] [WAAS Test Team, 2009]

[3] [USDoTFHA Highway Research Center, 2010]

[4] [Trimble Navigation Limited, 2006]

[5] [Trimble Navigation Limited, 2010]

[6] Single reference station, rover 10k (min) to 50k (max) distant.

[7] CORS network with Virtual Reference Station server software.

The accuracies displayed in Table 2.4 indicate the selection of Real Time Kinematic augmentation of GPS/GNSS has the potential to produce relevant track position measurement enabling the determination of actionable alinement, cross-level, grade, and twist measurements.

Real Time Kinematic Technology

Real Time Kinematic (RTK) augmentation provides the capability of centimeter-level positioning in real time with the receiver in motion. However, RTK technology was assessed in the USDOT Final Report on NDGPS as poorly suited for positive train control. The reports states that

> "As railroads continue to deploy CBTC[17] and similar GPS-based train management and asset management systems, they must survey the railroad in GPS coordinates. Railroads cover too much territory to practically employ mobile survey-grade reference stations for these surveys [Pruitt and Fly, 2008, pp.12]."

The USDOT report characterized the transmission of RTK correctors to mobile users as requiring

> "...their own wireless link between the reference station and the user receiver, which is typically limited to line-of-sight. If the user moves out of range (radio range or line of sight) of the reference station, the reference station must be re-positioned, and the user must again wait for the reference station to achieve "lock" with the GPS satellites required for high accuracy [Pruitt and Fly, 2008]."

The USDOTs summary disclaims the use of RTK augmentation as "not usable for general transportation applications"[Pruitt and Fly, 2008, ES-7].

This research takes issue with the 2008 USDOT assessment as failing to acknowledge the convergence of several technological factors enabling survey-grade absolute position measurement over wide areas. Demand for high quality positioning from satellite systems has lead to a growth in the availability of public and private alternatives to mapping-grade federal augmentation services. A number of state transportation and geodetic survey departments are building their own GPS/GNSS reference networks, providing survey-grade augmentation at no or nominal cost KGS [2009]; MDOT [2009]; NCGS [2009]; ODOT [2009]. Unlike federal systems, state and private systems are not limited to providing augmentation for only GPS SVs. State government systems provide correctors for both US and Russian SVs, as well as future GNSSs like Galileo and Compass.

Private investment in networked reference systems provides a market opportunity to profit from the need for survey quality GNSS. Delivering real time correctors to a mobile receiver is enabled by the increased capacity to transmit data to users in the field by a number of means. Wireless data transmission comes at a reasonable price, with data transmission rates several orders of magnitude greater than NDGPS. Data rates are an important consideration in planning for the increase in corrector quantity due to new GPS signals[18], an increase in the number of modernized GLONASS SV launches, and future signals from Galileo and Compass.

CORS, networked within in a geographic area, deliver observations as real time inputs to virtual reference station server (VRS), which provides the capability of continuously estimating the distor-

[17] Communications Based Train Control

[18] L2C and L5

tions of SV carrier phase observables and supply correctors to mobile receivers. Mobile receivers are capable of applying VRS server transmitted correctors to instantaneously refine local observations to an accuracy of several centimeters. Mobile RTK users can expect to achieve position accuracies of 1-2 centimeters horizontal and 2-3 centimeters vertical across an entire regional VRS network with 95% confidence.

Literature Review Summary

RTK infrastructure receivers networked to a VRS server combined with ubiquitous wireless data form a relatively new technology that enable absolute position measurement to within a centimeter over wide areas. The unexplored capability of RTK GNSS railway measurement establishes the need for this research in railroad transportation. Recent negative reports from the USDOT regarding the use of Real Time Kinematic global satellite navigation systems to produce track measurements indicates a gap exists between the use of US government sponsored GBAS and the use of regional state and private RTK VRS systems.

There is a gap between visual track inspection; dedicated systems such as track geometry cars; NDGPS augmented IMUs like Allen's Hi-Rail; and sophisticated, multi sensor arrays like the *Swiss Trolley*. A review of intellectual property claims indicate addition development work exists integrating federally provided augmentation with IMUs, however it is unclear whether any of the intellectual property claims have been incorporated into commercial locomotive location products.

The research bridges a cap between mapping-grade track asset surveys with their reliance on mapping-grade US government provided GPS correctors, and track survey systems. This study examined the ability of RTK augmentation to bridge gaps in wireless GNSS track measurement enabling actionable track defect detection not achievable through US government supplied augmentation services.

Chapter 3

Methodology

The researcher sought to determine the viability wireless position measurement to assess railway infrastructure and to act as a reliable track vehicle locator capable of meeting the requirements of a location determination system as defined by the FRA by answering these questions:

1) *Hump Yard Profile:* Can a locomotive use wireless position measurement to determine the vertical profile of bowl tracks in an automatic classification yard to an accuracy of tenth of a foot during production activities?

2) *Horizontal Track Alinement:* Can a common track vehicle use wireless position measurement to determine the horizontal degree of curvature (D_c) comparable with specialized track geometry vehicles?

3) *Track Occupancy:* Can a common track vehicle use wireless position measurement to meet the FRA [FRA, 1995, pp.6-7] accuracy and confidence guidelines for track occupancy as might be used in a location determination system?

The researcher evaluated the capability of Real Time Kinematic (RTK) augmentation applied to Global Navigation Satellite Systems (GNSS) to safely, rapidly, and precisely measure track position employing common track vehicles such as Hi-Rails and locomotives as a survey platforms. Figure 3.1 describes the major goals and their relationship in meeting the research objectives. Rail transportation needs were identified from interviews with rail company experts; an assessment of current railroad process and capabilities; observation of yard operations in light of the expert interviews; and the identification of a statewide CORS network accessible to researchers. Interviews with subject matter experts has led to the design of experiments that were performed within the safety and access constraints of a Class I railroad.

This chapter contains the method for how:

1. A hump yard was profiled by an RTK GPS equipped locomotive to measure track position during humping operations.
2. A RTK GNSS equipped Hi-Rail was used to define D_c across 29 continuous miles of mainline track.

3. Multiple traverses by a RTK GNSS equipped Hi-Rail were evaluated for the statistical likelihood of reliably determining track occupancy in parallel multitrack segments.

Research Design and Data Collection

The research investigated the use of RTK augmentation to the GPS and to GPS plus GLONASS (Referred to collectively as GNSS). The research investigated the capabilities of wireless measure-

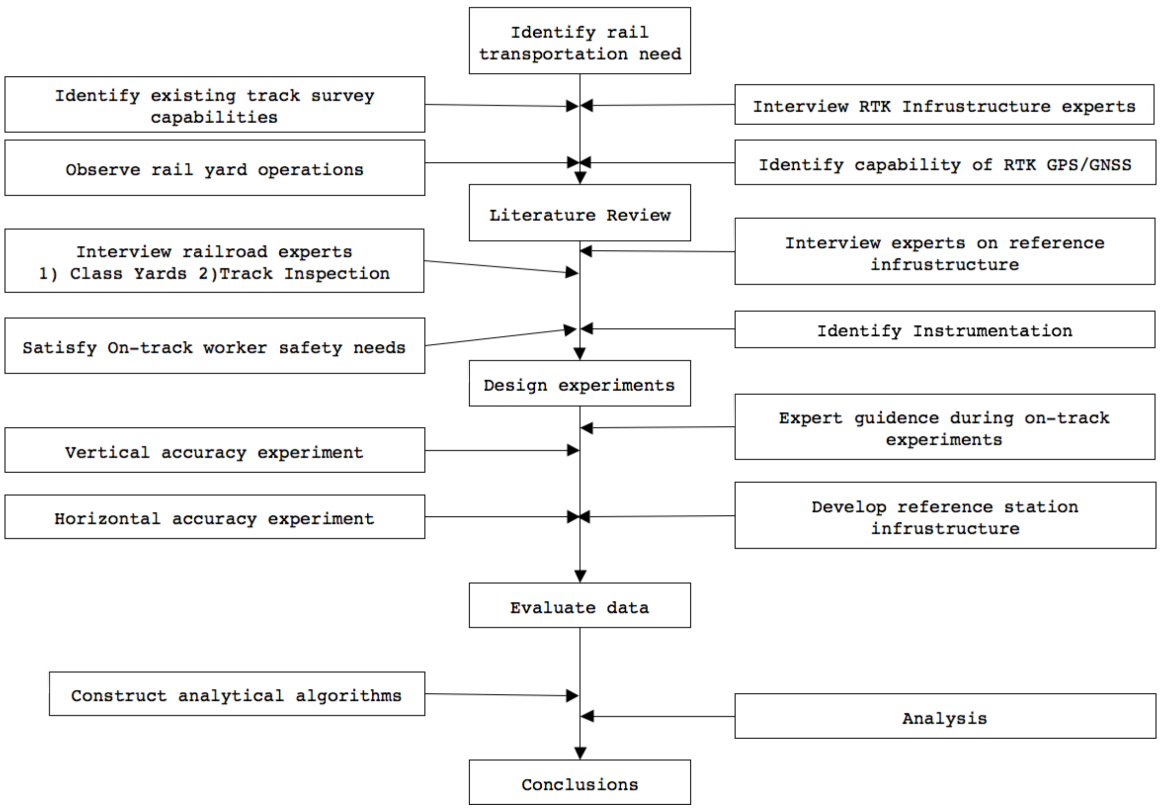

Figure 3.1: Research Plan

ment, in particular RTK GPS/GNSS, over active track. Due to federal and private property laws restricting access to active track, all research activities were performed adhering to the provisions of 49 CFR §214 railroad workplace safety regulations, subpart C *Roadway Worker Protection* [USC, 2009b] and subpart D *On Track Roadway Maintenance Machines and Hi-Rail Vehicles* [USC, 2009c] as well as specific rail company rules and procedures set out by the employee in charge during job safety briefings.

Track location of bowl tracks in a hump yard was determined from single epoch track observations from a GPS mounted on a locomotive traversing an active hump yard. The track positions were used to produce profiles for each bowl track in the yard. Relative vertical precision and base station observations were used to evaluate the yard environment for RTK GPS surveying by locomotive.

RTK augmented horizontal track measurements used single epoch RTK observations from an antenna mounted on the centerline of a track inspector's Hi-Rail. Mainline track alinement was evaluated by means of a software modeling the string lining method to determine the degree of curve from X, Y, Z track coordinates. Degree of curve (D_c) determined by the string line model was compared with D_c determined by a track geometry car over an identical tangent segment.

An evaluation of RTK GNSS to determine track occupancy was made by multiple Hi-Rail traverses with RTK GNSS instruments across multiple parallel segments of mainline track. Positions observed over identical and parallel segments of tangent and circular track were evaluated for cross-track error[1] for the likelihood of determining track occupancy by an RTK GNSS equipped mobile rail vehicle.

The electrical point of reference for a GPS/GNSS antenna is the phase center. The phase center is offset some distance from a physical reference location on the antenna housing. The physical antenna reference for each of these experiments was the mounting surface or antenna reference point (ARP). The survey controller contains a table of offset distances between phase center and ARP for the antennas used during each experiment. A procedure to align the ARP on the track vehicle to a selected railway reference location[2] was performed as part of the mobile track vehicle setup.

Estimates for the relative horizontal and vertical precision[3] are calculated by the *Survey Controller* software in the Trimble TSC2 controller. *Trimble Survey Controller* software uses a algorithm to compute vertical precision:

$$VerticalPrecision(m) = ErrorScale * VDOP * ScaleFactor \tag{3.1}$$

Where:
$ErrorScale = \frac{\sqrt{ErrorE+ErrorN+ErrorU}}{PDOP}$
ErrorE = CovENU[x][x]
ErrorN = CovENU[y][y]
ErrorU = CovENU[z][z]

Where CovENU is the aposteriori covariance matrix of the RTK solution from the RTK engine in the GNSS receiver.
ScaleFactor is either 1 or 1/3 depending on whether the RTK engine is giving *Survey Controller* 1-sigma or 3-sigma precisions, which depends on the version of RTK engine. The *Survey Controller* display shows 1-sigma precisions. [Butvidas, 2010]

[1] per Allen et al., 10
[2] i.e., Track centerline, left (port) gauge side or right (starboard) rail.
[3] Relative errors are errors and precisions expressed for and between pairs of network adjusted control points.

The observation procedure for these experiments progress from setup of an ad hoc reference station in the case of experiment 1, or accessing a VRS reference network as in experiments 2 and 3; establishing a means of communication between the reference station/VRS and the track vehicle; aligning the antenna with a track reference point; and configuring the mobile receiver onboard the track vehicle.

Experiment One: Hump Yard Profile Survey

Experiment one asked whether RTK augmented GPS mounted to a locomotive could measure the vertical profile of bowl tracks in an automatic classification yard without the need for track closures.

The objective of experiment one was to use RTK GPS instrumentation mounted to a locomotive to survey an active hump yard in order to produce track profiles. The survey data was used to create information products which were handed off to the rail company sponsor in preparation for a yard-wide resurfacing project.

The hump yard survey used a single RTK reference station transmitting correctors via UHF radio to a mobile receiver onboard a locomotive. The ad hoc reference station components are listed in table 3.1. A fixed-height tripod at 1.5 meters supported the GPS and UHF antennas. The ad hoc reference station was set on top of a two story masonry structure to maximize height above average terrain (HAAT) for UHF data reception by the roving receiver aboard the locomotive as shown in figure figure 3.2. The elevated location provided sufficient HAAT to enable reception of correctors across the yard and to NGS benchmark EB1559 located 8,500 feet from the 25 watt UHF transmitter.

The autonomous horizontal position of the reference station (CP1) was adjusted by using the results of NGS OPUS from observations recorded during two sessions. The first session was 2008/05/26 14:21:00 to 21:44:00 UTC with the second session 2008/05/27 12:12:00 to 18:50:00 UTC. The compressed observation files were converted[4] to the Receiver INdependent EXchange (RINEX) format and submitted to the National Geodetic Survey Online Position User Service (NGS OPUS) for position determination. The autonomous horizontal position of the ad hoc reference station (CP1) was adjusted to the mean northing and easting of the two NGS OPUS reports exhibited in Appendix A, pages 66 and 67.

The autonomous vertical position of the reference station was adjusted using RTK observations on a NGS benchmark, permanent identifier (PID) EB1559. The benchmark was located 8,508 from the ad hoc RTK reference station. The elevation of CP1 was adjusted to minimize the difference between the observed and the published NAVD88 elevation for the first order class II benchmark. The PID datasheet for EB1559 is exhibited in Appendix A, page 68.

[4]Using Trimble *runpkr00* under Unix.

Multipath concerns were examined at the reference stations by generating a full TEQC [Estey, Ph.D, 2010] (Translation, Editing, and Quality Check) report from the reference station RINEX observation and navigation files. The TEQC report is exhibited in Appendix A.

Figure 3.2: Ad hoc Reference Station

An EMD SD60 yard locomotive was equipped with the mobile#1 instrument indicated in table 3.1. The mobile GPS antenna mount was collocated with an omnidirectional UHF antenna and secured to a SECO magnetic base as illustrated in figure 3.3. The antenna mount was fitted with a wire rope safety lead to secure the antenna assembly to a fixed member on the locomotive cab to prevented injury to locomotive operators or ground personnel in the event the antenna was dislodged by handling rail cars. The antenna was aligned with the track centerline in an area designated by the yardmaster and blue flagged during installation to insure the safety of research and railroad company personnel working around the locomotive. The generalized procedure for aligning a GPS/GNSS antenna mounted to a track vehicle with a horizontal track reference and

Figure 3.3: GPS/UHF Antenna Setup on Locomotive

determining the antenna reference point from the top-of-rail elevation is described following and referencing figure 3.4.

Antenna Alignment Procedure

1. A job safety briefing is conducted by the rail company employee-in-charge.
2. A frequency in the 450 Mhz band is selected by monitoring voice traffic on available channels, as data is a secondary use of this spectrum. The ad hoc reference station is programed with an autonomous position, and corrector transmission initiated.
3. A section of tangent track approximately 300 feet long is blue flagged and made safe by setting a derail and locking out the track switch as discussed during the job safety briefing.
4. Track centerline points are measured on either end of the calibration area, figure 3.4 points A and A'. The centerline points are observed with a Trimble R8 instrument for 180 epochs.
5. A line feature representing the track centerline is created in the survey controller between points A and A'.
6. The center point of the line feature is determined. Two points, referenced in figure 3.4 as points B and B', are observed at the the top of each rail for 180 epochs.
7. A second line feature between points B and B' is created in the survey controller.
8. A point located by intersecting lines A-A' and B-B', figure 3.4 point C, is determined by the *Survey Controller* software.
9. The mean elevation of the top of rail observations is calculated and assigned to point C.

10. The GPS/UHF antennas and magnetic base mount are placed in the approximate center of the top of the locomotive cab. A wire rope safety harness connecting the antenna mount to the locomotive horn or other suitable anchor point is secured.
11. The survey controller is connected to the GPS receiver in the track vehicle. The previously created data file with the alignment features described above is opened.
12. Blue flags are removed from the locomotive by the persons that placed them. Derails are stowed and facing point track switch operators are unlocked. Movement authority is obtained from the yardmaster by the locomotive engineer.
13. The locomotive is moved to locate the GPS/UHF antenna mount over point C.
14. The locomotive is secured and the antenna mount moved in small increments to intersect the centerline by observing the instantaneous antenna location in the map view of the controller. A period of ten seconds between movements is allowed for the position to settle in the map display.
15. The survey controller antenna height is set to zero. Figure 3.4 point D is observed for 180-epochs. An inverse calculation is performed between points C and D. The elevation difference is recorded as the antenna height.
16. A survey style is created in the *Survey Controller* software containing the antenna height above the top-of-rail elevation. Due to variation in cab height above top-of-rail, the survey style is named for the particular locomotive unit number used in the antenna alignment. Likewise for individual Hi-Rail vehicles.

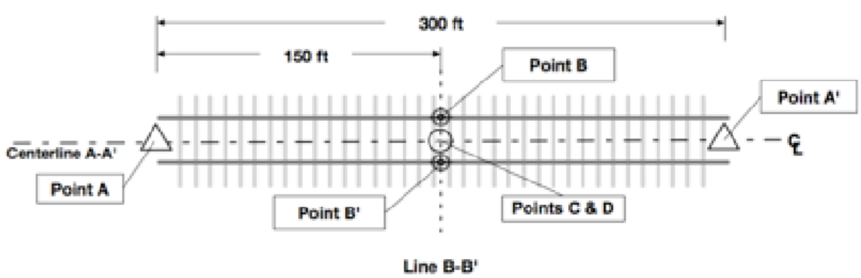

Figure 3.4: Track Vehicle Antenna Alinement Procedure

RTK correctors were broadcast from the single reference station by UHF data radio and used to augment the GPS receiver aboard the locomotive. A survey controller connected to the receiver managed and automated data collection by recording single epoch observations with a nominal horizontal separation of ten feet. Track profiles originated at a common reference point at the hump end of the bowl and terminated at the pullout-end switch for each track.

The pullout end of the bowl was surveyed first, from pullout switch to foul point[5]. The hump

[5]The track foul point is the demarcation between hump and pullout end movement authority. CSX standard is a 7-11 rule; which defines the foul point to be determined 11 feet beyond the point where the field side rails of adjacent track are 7 feet apart. [VanWormer, 2007]

end of the bowl was surveyed during a shift change, from the hump to foul point, to minimize disruption to humping operations. Locomotive movement across the pullout end of the yard was coordinated between the locomotive operator and pullout end humpmaster[6]. Track traverses began at the pullout end switch and progressed to the foul point. The automatic numeric sequencing of the survey controller was used to produce unique point identifiers. The controller sequence was constructed by concatenating: 1) the two digit track number; 2) a single digit traverse counter; 3) a three digit point sequence beginning at 000 and incremented by one at each observation in sequence. Points recorded onboard the locomotive were feature coded as centerlines.

The hump end survey was performed in coordination with the hump end humpmaster[7] during the yard shift change to minimize the impact of the survey interrupting yard production. The locomotive traverse of the hump end began at the hump, through the retarder and track leads, finishing at the track foul point. The unique point identification scheme previously described was not performed due to time constraints. The hump, leads, and track points were separated post survey.

Points of interest (POI) were surveyed on the ground with the static module referenced in table 3.1. The static receiver was mounted to a 2 meter range pole. Multiple epoch observations (3-6) were recorded at each point of interest. Feature codes distinguished switch points, wheel detectors, retarder inlet/outlet, and foul points. Switch points and retarders were identified by rail company reference number. Wheel detectors were identified by track and sequence number. Ground point safety was superintended by a rail company employee.

Variables of analysis: The mobile instrument #1, table 3.1 produced these variables:

Horizontal coordinates : US State Plane, North Carolina 3200,US survey feet.

Vertical datum : NAVD 88, height above ellipsoid 2003, in US survey feet.

Estimated Vertical Precision : Determined by *Survey Controller* software, US survey feet.

Time & Date : Local, EST of observation.

Count : SVs in view of the mobile#1 GPS antenna.

Vertical Dilution of Precision : VDOP, A unit-less figure of merit expressing the relationship between error in in user position, and the error in satellite position.

Yard observations were exported from the *Survey Controller* software and separated into layers organized by lead, group, and track. Deconstructing the aggregate observations enabled individual tracks to be configured as a continuous series of points by activating the particular layers in TGO.

- Hump lead
- Main retarder
- Intermediate retarders
- Group retarders
- Group leads

[6]Responsible for outgoing train makeup and movement.
[7]Responsible for railcar sequencing and switching into the bowl.

- Bowl tracks

A properly configured track was apparent as a continuous series of points extending from the hump through the desired track to the pullout end switch.

Locations of track POI (i.e., track switch points, retarder inlet and outlet, wheel detectors) were associated with a position nearest a particular rail. The POI was observed at the center top-of-rail nearest the POI physical location using the static survey instrument. The position of each POI was adjusted post survey to be coincident with the track centerline.

Continuous track observation names were renumbered in the TGO software, in series progressing from hump to pull out. Feature codes enabled separation by feature. The *TGO* software was used to create line work by connecting consecutive centerline points. The line work and observation data were exported from TGO in the ESRI[8] shapefile format. The point data was also exported as a comma delimited (CSV) format and imported to a *Google Docs* spreadsheet. A linear reference was determined for each point according to equation 3.2. Elevations and linear references were scaled and input as an overlay to a CAD drawing containing the track design grade[9].

Each track profile was plotted as an overlay to the provided CAD drawing. The design profile in the CAD drawing is relevant to the rail company in a making a volumetric assessment of surfacing material required to bring the relief of each track into vertical alignment with the design grade. Calculation of surfacing material quantity is outside the scope of the experiment. The design grade and locomotive survey result will be used as a comparative tool, limited to providing track profile deviation from design grade.

The shapefiles will be added to ESRI ArcMap software where a plan view of of the bowl area track elevation and vertical precision estimate will be represented in plan view. The vertical precision map will show lower quality vertical precision for points > 0.1 feet in a contrasting color to those of greater precision. The plot will be examined for the distribution of lower quality data patterns.

Acceptable elevation quality will be apparent as a smooth track profile. Poor quality observations will appear with greater variation between points, resulting in a jagged or sawtooth profile. Poor quality elevations will be identified and correlated with: observation time; vertical precision estimated by the receiver; and reference station observations during the period.

The vertical precision calculated by the *Survey Controller* software was used to determine descriptive statistics and to plot a histogram for analyzing the quality of GPS observations by the mobile instruments.

$$sta_k = match\ point\ offset + \sum_{k=2}^{n} \sqrt{(x_k - x_{k-1})^2 + (y_k - y_{k-1})^2} \tag{3.2}$$

[8]Environmental Systems Research Institute, Inc.
[9]Provided by the rail company sponsor.

Where k = a point in the ordered sequence of observations, and n = the number of observations in the track segment, and the match point offset is the horizontal distance from the top of the hump to switch point 1574.

Experiment one:

1. Produced an alignment procedure for alignment of the GPS antenna with the centerline top-of-rail location.
2. Collected continuous single epoch observations on a nominal 10 foot horizontal spacing with RTK augmented GPS onboard a locomotive in an active hump yard.
3. Resulted in the production of a plan-view color-map of track elevation for the bowl area of a hump yard.
4. Resulted in the production of a plan-view color-map of relative vertical precision as determined by the *Survey Controller* software for points measured in the bowl area of the yard.
5. Resulted in the production of a two-dimensional profile drawings for each track in 1:1 and 1:5 vertical scale.
6. Determined the descriptive statistics of the relative vertical precision as determined by the *Survey Controller* software for the locomotive mounted GPS .
7. Resulted in the production of TEQC reports for two ad hoc reference station observation sessions.

Experiment Two: Determining Horizontal Track Alinement

This research asks whether RTK augmented GPS and GNSS instruments mounted to a common track vehicle can determine horizontal track alinement comparable those achieved by specialized track geometry vehicles. The objective of the experiment was to perform multiple mainline track surveys with RTK instruments mounted to a Hi-Rail vehicle; the development and demonstration of a software model using the string lining procedure in order to produce horizontal track alinement. The track alinement survey employed a series of CORS RTK reference stations along the survey route, networked to the Ohio Department of Transportation, Aerial Mapping Virtual Reference Station (ODOT VRS) server.

The ODOT VRS was used to minimize the ± 1 ppm error incurred as distance increases from a reference station. The VRS creates a new virtual reference station when the baseline between the track vehicle and the previous VRS created reference station increased beyond a distance programmed in the VRS. A public cellular data service was used to exchange security credentials with the ODOT VRS server, receive correctors, and apply them to a mobile receiver onboard a track inspector's Hi-Rail. A survey controller connected to the mobile receiver recorded single epoch observations with a nominal horizontal point separation of five feet with mobile instrument#2 (table 3.1) and ten feet with mobile instrument#1. Nominal point separation was based on the receiver processing speed for Hi-Rail traverses in the range of 10 to 30 mph.

Two mainline track segments of different character were traversed during this experiment. The first segment can be characterized as multiple parallel track, signalized, Class 4, with a maximum allowable track speed between 30 and 50 mph, carrying a freight volume of 25 to 35 MGT/yr[10]. This segment is referenced as C&O Kanawha subdivision, from mile post 494 to 523 (MP494-523). Continuous observations over this segment demonstrates the capability of an RTK VRS over a wide area.

A second segment, characterized as single track, dark territory, Class 3, with allowable track speed between 10-30 mph, carrying a freight volume of less than 10 MGT/yr, is referenced as C&O Ohio River subdivision from mile post 210 to 207 (MP210-207). This segment was selected for study as the segment had been examined previously by Szwilski [Szwilski et al., 2003]. Additionally, data was made available from CSX's Gauge Restraint Measurement System[11] (GMRS) across this segment. Degree of curvature (D_c) from the GMRS was compared with the horizontal alinement model by selecting a tangent segment for comparision. An ideal measurement across a tangent segment would result in a D_c of zero. Therefore, the D_c deviation from zero across the tangent segment was used to compare the GMRS measurement with RTK modeled D_c measurements.

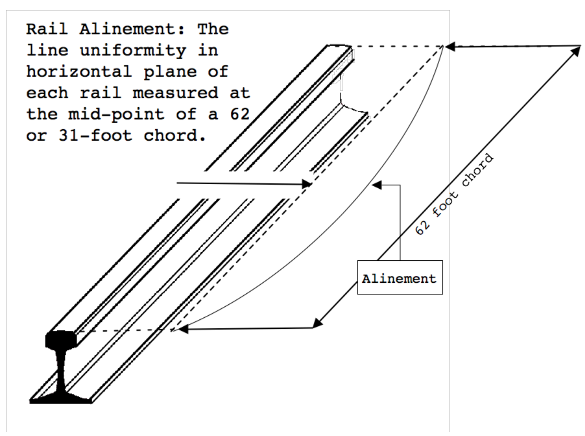

Figure 3.5: Horizontal Alinement

The track observations were used as inputs to a software to determine the D_c modeling the FRA guidance manual instructions for using the string line method. Experiment two objectives sought to:

1. Collect continuous single epoch observations with RTK augmented GPS/GNSS mounted to a track inspector's Hi-Rail over at least 29 continuous miles of mainline track. Point spacing

[10]Million Gross Tons per year

[11]A specialized, self-propelled, track geometry car.

was a nominal 10 foot for mobile configuration#1 and 5 foot horizontal spacing for mobile configuration #2 (see table 3.1).

2. Develop a software model for calculating degree of curvature (D_c) from X, Y, and Z coordinates obtained from track vehicle observations. The software model replicated the string lining method described in FRA *Track Safety Standards Compliance Manual* [FRA, 2007, pp.26-30] using a 62 foot chord length and 15.5 foot stations.
3. Compare two methods of measuring D_c over tangent track. The first method utilized data from a specialized track geometry car, CSX's GMRS. The self propelled GMRS is designed specifically for the purpose of obtaining D_c (and other track alinement parameters[12]) from the string lining method. The second method utilized data obtained from an RTK GNSS instrument mounted to a track inspector's Hi-Rail and a software to model the string line method from the Hi-Rail data. A traverse of identical tangent track segments was compared for cross-track[13] centerline deviation using descriptive statistics. Identical segments were determined by selecting beginning and ending mile post reference locations.
4. The D_c was determined and track elevation measured using RTK survey equipment mounted to a track inspector's Hi-Rail across a continuous 29 mile track segment. The modeled D_c was compared with company supplied track charts to correlate the location and magnitude of curves. Structures responsible for loss of signal (LOS) were identified.

Variables of analysis: The mobile instrument #1 and #2, table 3.1 produced these variables:

Horizontal coordinates : UTM, Zone 17 North, US survey feet.

Vertical datum : NAVD 88, height above ellipsoid 2003, US survey feet.

Time & Date : Local, EST.

Variables of analysis: The CSX GMRS produced these variables of analysis:

MP : Mile post offset distance, decimal miles.

D_c : Degree of curve, 62 foot chord.

The mobile antenna (table 3.1 mobile #2) was alined using the generalized procedure listed on page 24, and mounted to a track inspector's Hi-Rail vehicle as illustrated in figure 3.6. The receiver was programmed to process observations in "low latency" mode, which uses approximately 20 milliseconds to compute each observation, degrading the manufacture's stated horizontal accuracy of ± 1 cm by an additional centimeter [Trimble Navigation Limited, 2006, pp.8] [Trimble, 2009, pp.9].

The controller was programmed to collect observations on a nominal 5 foot spacing. Mile post centerline locations were determined during a traverse of the research area. Mile post centerline locations were determined by positioning the Hi-Rail perpendicular with a mile post and observing the location for five seconds, resulting in 3 to 6 epoch observations.

[12] Gage, crosslevel, profile, D_c

[13] See Allen, et al., figure 2.1, page 10

Figure 3.6: GNSS Antenna Mount, Hi-Rail

The observations recorded by survey controller were transferred to *Trimble Geomatic Office* (TGO) software. Observations were separated into centerline and mile post layers, then exported in an ASCII comma delimited text format that included observation ID, feature code[14], northing, easting, elevation, time and date, and number of observed SVs.

Mainline track locations are reported as a linear reference from a wayside mile post monument. A track reference reports the mile post number plus the offset from the monument in decimal miles. Mile post references are typically measured by odometer, therefore the offset distance from a mile post is the accumulated slope distance. An additional novelty of mile post distances in the United States is the inconsistent measure between reference marks. To determine a mile post reference location, the accumulated slope distance between observations from a mile post to the location of interest is divided by the distance between mile posts in feet, then added to or subtracted from the mile post number depending on the direction of travel[15]. The calculation is illustrated in equation 3.3.

Track position variables processed by the model to determined the degree of curve (D_c), following the string lining method described in FRA *Track Safety Standards Compliance Manual for*

[14]centerline, mile post

[15]Milepost offset is added to the mile post when the direction of travel is with increasing mile post numbers, offset is subtracted with decreasing mile post numbers.

Track Classes 1-5 per 49CFR§213.55 [FRA, 2007].

$$MP_k = MP_{num} \pm \frac{\sum_{k=1}^{n} \sqrt{(x_k - x_{k-1})^2 + (y_k - y_{k-1})^2 + (z_k - z_{k-1})^2}}{\sum_{1}^{n} \sqrt{\Delta x_n^2 + \Delta y_n^2 + \Delta z_n^2}} \tag{3.3}$$

Where n = the total number of observations between mile monuments.

The string lining method as practiced by track inspectors and superintendents as described in the FRA *Track Safety Compliance Manual* determines points of greatest alinement deviation by moving a 62 foot string along the track in increments until the point with maximum deviation is found. The software model uses a similar approach, incrementally moving a chord along lines connecting an ordered series of RTK track observations. The distance from a chord's middle ordinate to a line segment determines the mid-chord offset (MCO). The software model determination of MCO from RTK observations as represented by figure 3.7.

End point coordinates for a 62 foot chord are determined by extending a 62 foot radius circle originating from the beginning station coordinate, represented by figure 3.7 station (x_o, y_o) and intersection a line segment defined by:

- An endpoint defined by the farthest point from the chord circle origin inside the chord circle.
- An end point defined by the the nearest point outside the circle.

The intersection is indicated at point (x_{int}, y_{int}) in figure 3.7, lying between points D and E.

The MCO is determined from an line orthogonal with the mid point of the chord, and the mean of the intersection with the nearest and farthest of two lines projected from the three observations nearest to the middle ordinate (figure 3.7 points B, C, and D). The distance from the chord mid point and the mean intersection determines the MCO. The degree of curve (chord definition) is then found from the MCO and chord length in feet by the relationship [Hickerson, 1964].

$$D_c = \frac{45840 \times MCO}{chord^2} \tag{3.4}$$

The model assigns a mile post reference to D_c using the location of the mean intersection and equation 3.3.

The coordinates of the next station are found by intersecting the stationing distance in a similar fashion to the chord circle intersection. Figure 3.7 illustrates determination of a 15.5 foot station.

A railway can be described as a smooth, continuous shape. As an aid to exploring the D_c, a smoothing algorithm is applied to the D_c verses mile post reference. The *rlowess*[16] method of the *smooth* function in the Matlab *Curve Fitting Toolbox*^{TM} was selected as a data exploration tool.

Experiment two:

[16] The *rlowess* method is a local regression using weighted linear least squares and a 1st degree polynomial model that assigns lower weight to outliers in the regression. The method assigns zero weight to data outside six mean absolute deviations [The Mathworks, Inc., 2009].

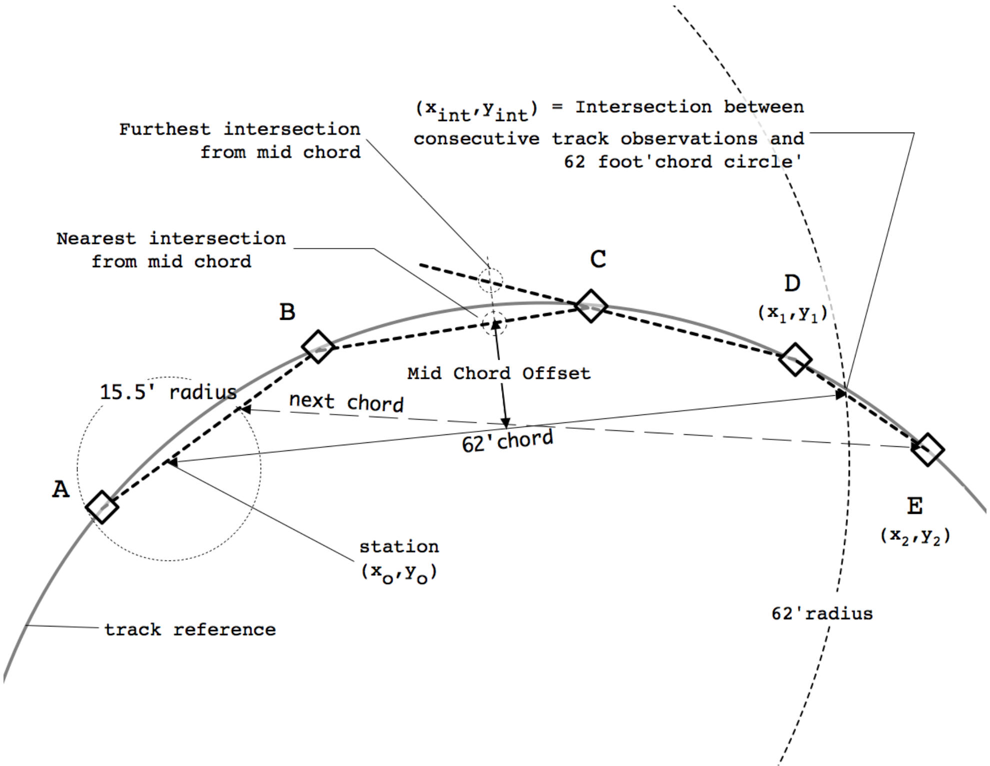

Figure 3.7: Modeling the String Line Method from RTK Track Observations

- Compared RTK observations by Hi-Rail with company track charts. The comparison between the model and track charts was examined to verify curve location, magnitude, and location of infrastructure affecting SV reception. Mile length was compared to the published track chart length.
- Determined descriptive statistics for D_c across a tangent segment for a geometry car and a RTK equipped Hi-Rail.
- Constructed a graphic solution for comparing D_c measured by geometry car and RTK equipped Hi-Rail by plotting D_c vs. mile post reference concurrently.
- Determined the variability between D_c measured by geometry car and RTK equipped Hi-Rail across tangent track.

Experiment Three: Determining Track Occupancy

This experiment asked whether a common track vehicle using RTK augmented GPS/GNSS was able determine track occupancy by obtaining position accuracy defined by the FRA for a location determination system. The FRA LDS requirement stated in *Differential GPS: An Aid To Positive*

Train Control [FRA, 1995] page 6, establishes the criteria to

> "...determine which of two tracks a given train is occupying with a very high degree of assurance (an assurance that must be greater than 0.99999 or (0.9_5)). The minimum center-to-center spacing of parallel tracks is 11.5 feet..." [FRA, 1995]

The FRA specification is interpreted here to mean an observation must have a cross-track error no greater than $\pm\frac{11.5}{2}$ feet within a confidence interval 100*(1-α)%, with α = 0.00001 or 99.999%.

Variables of analysis: The mobile instrument #2, table 3.1 produced these variables:

Horizontal coordinates : UTM, Zone 17 North, US survey feet.

Time & Date : Local, EST.

Several traverses of a parallel multitrack segment were made by RTK GNSS equipped Hi-Rail. A track segment was selected based on the length of the tangent or curve and existence of adjacent parallel track traverses. The first traverse was designated as a reference centerline, and the centerline coefficients for tangent track determined by regression using the Matlab function *regress*, taking the general form:

$$[b, bint, r, rint, stats] = regress(y, X) \tag{3.5}$$

where;

y is a *n by 1* vector of observed Northings for each of n observations.

X is a *n by 2* matrix of observed Northings of the form $[Northing,\ 1]$ for each of n observations.

The function output b containes the coefficient estimates, and *bint* contains the upper and lower confidence bounds of the coefficient estimates. The residuals r and residual intervals *rint* that have no meaning in the analysis as physically, the residuals represent the distance from the track centerline to the observation along the Northing axis. The statistics in *stats* contain the R^2 statistic, the F statistic and its p-value, and an estimate of the error variance.

The slope is converted to an azimuth and back bearing by the function *slope2Az*, listed in Appendix B. The azimuth of the tangent was verified by means of a graphical solution in *TGO* software.

The cross-track[17] distance between subsequent observations and the baseline was determined by the Matlab function *perpDist2line*, code listing Appendix B, page 108. The function equation 3.6 determines the cross-track distance from a reference tangent and an X, Y coordinate pair obtained from a subsequent track traverse.

$$d_{xt} = \left| \frac{ax + by + c}{\sqrt{a^2 + b^2}} \right| \tag{3.6}$$

where;

[17]See Allen, et al, Figure 2.1, page 10

a, b, c are the reference tangent centerline coefficients.

x, y are the Easting and Northing coordinates of the observations.

For the circular curve case, the coefficients of the centerline reference origin and radius are determined from Northing and Easting observations using Matlab function *regress*. *Regress.* For the circular curve case, the function takes the general form:

$$[b, bint, r, rint, stats] = regress(y, X) \tag{3.7}$$

where;

y is an *n by 1* matrix of observed Northings and Eastings of the form $[Easting^2 + Northing^2]$ for each of n observations.

X is an *n by 3* matrix of observed Northings of the form $[2 * Easting,\ 2 * Northing,\ -1]$ for each of n observations.

The cross-track distance (d_{xt}) is determined from the difference between the circular curve radius and coordinate distance to the origin of the curve:

$$d_{xt} = r - \sqrt{(x_p - X_o)^2 + (y_p - Y_o)} \tag{3.8}$$

The null hypothesis statement is the reference track is occupied if the distance between an RTK GNSS observation and the reference centerline is less than or equal to $\frac{11.5}{2}$ feet at a confidence of 100(1-α)%. The Matlab function *ztest* was used for the z-test of the null hypothesis. The function output indicates whether the null hypothesis is a random sample from a normal distribution with mean cross track distance (μ_d) less than 5.75 feet and standard deviation σ of the reference tangent distances, against the alternative that the mean is not less than 5.75 feet. The result of the test indicates a rejection of the null hypothesis at the 100*(1 - 0.00001)% significance level.

$$h_0 : \mu_{xt} < \frac{11.5}{2} \tag{3.9}$$

$$h_1 : \mu_{xt} \geq \frac{11.5}{2} \tag{3.10}$$

The null hypothesis asserts that the cross-track error population parameter is equal to or less than half the FRA guideline for minimum centerline-to-centerline track spacing. Rejection of the null hypothesis indicates insufficient statistical evidence exists to assert same track occupancy to the confidence interval suggested by the FRA [FRA, 1995, pp. 6].

The Z-test hypothesis procedure assumes that the RTK GNSS position data represents independent samples from the same normal distribution. The standard deviation determined from the reference tangent cross track error is an indication of the reference tangent's centerline trueness.

The Matlab *Statistics Toolbox* function *ztest* performs a z-test of the null hypothesis, testing whether the cross-track error data is a random sample from a normal distribution with mean *m* and standard deviation σ, against the alternative that the mean is not m. The result of the test indicates a rejection of the null hypothesis at the (1-α) significance level. The *ztest* function is called using the general form:

$$[h, sig, ci, zval] = ztest(d_t, m, \sigma, \alpha, tail) \tag{3.11}$$

where;

d_t is the population of distances between the reference centerline and subsequent observations.

m is the test mean.

σ is the known standard deviation of the population.

α is the significance level.

tail specifies whether to apply one or two-tailed test. The the tangent case, single the cross-track error distance of equation 3.8 is always positive, the right tail is specified. For the circular curve case the cross-track error can be positive and negative, both tails are specified.

Experiment three:

- Observed track positions of three parallel tracks by RTK GNSS equipped Hi-Rail.
- Determined the coefficients for a reference tangent and circular track centerlines from an initial traverse.
- Determined the cross-track error between subsequent RTK Hi-Rail observations and the reference tangent curve centerline.
- Determined by a hypothesis test if statistical evidence exists to indicate if RTK GNSS is capable of determining track occupancy meeting FRA performance standards for a location determination system.

Instrumentation

Instruments used in the research are summarized in table 3.1.

Table 3.1: Instrumentation and Software

Designation	Instrument	Description	Experiment
Ad hoc	Trimble 5700	24 ch. GPS receiver	1
Reference	Zephyr Geodetic	GPS antenna	
Station	Trimmark III UHF radio	450Mhz band, 25 watt	
CORS	NetRS/NetR5	24/72 ch. GPS†/GNSS‡	2, 3
	Trimble Zephyr Geodetic /2	GPS/GNSS antenna	
VRS	Trimble Network Infrastructure	Virtual Reference Station	
	VRS Net	version 2.83†	2, 3
Static Module	Trimble R8	24 ch. GPS w/int. radio	1
	Trimble TSC2	Survey Controller	
Mobile#1	Trimble 5700	24 ch. GPS w/int. radio	1
	Trimble TSC2	*Survey Controller*v12.1x	
	Trimble Zehyr	GPS antenna	
Mobile#2	Trimble R7	72 ch. GNSS receiver	2, 3
	Trimble TSC2	*Survey Controller*v12.1x	1, 2, 3
	Trimble Zephyr 2	GNSS antenna	2, 3
Software			
	National Geodetic Survey	Online User Positioning Service	1
	Trimble *Geomatic Office*	version 1.63	1, 2, 3
	Google Docs	Collaborative spreadsheet	1
	ESRI *ArcMap*	version 9.2	1
	Matlab 32-bit (maci)	version 7.8.0.347 (R2009a)	1, 2, 3

† Owned and operated by the Ohio Department of Transportation, Aerial Mapping

‡ Owned and operated by the N.J. Rahall Appalachian Transportation Institute

- An ad hoc reference station (AhRS) as listed in table 3.1 is a stationary antenna mounted to a fixed height tripod for reception of SV signals for manipulation by a GPS receiver. The receiver produces correctors for transmission over UHF data radio to a capable mobile GPS receiver.
- A single *continuously operating reference station* (CORS) is a permanently mounted antenna providing continuous data for RTK surveying.

- A *Virtual Reference Station* (VRS) server provides RTK positioning services across a wide area defined by the extent of numerous CORS networked and synchronized by infrastructure software. Observations from each CORS in the network are pre-processed to generate models of the distance-dependent biases. Based on the model parameters and the user's approximate position, individual corrections can then be predicted, which enables RTK positioning. The differential errors caused by ionospheric and tropospheric refraction, in addition to satellite orbit errors, are precisely estimated within the network. RTK model parameters are determined to allow the prediction of the differential errors for the baseline between a master reference station and the user's position. Applying these corrections to code and carrier phase observations of the master reference station, VRS measurements are generated for RTK positioning of the rover receiver.
- A *static survey* unit is an RTK enabled GPS or GNSS receiver used by a surveyor to determine the coordinate of a position by recording multiple-epoch observations while occupying the point of interest.
- A *mobile survey unit* is an RTK enabled GPS orGNSS receiver used to determine the coordinates of a position while in motion by recording single epoch observations.

Data Validity and Integrity

Validity

Insuring the the validity of RTK GPS/GLONASS data relied on the quality control performed by the data collector software. A field notebook was kept to record various instrument and initial values (i.e., antenna height from top of rail, locomotive number, track points of interest) found during antenna alinement. The recorded values were programmed into the controller as a specific survey style to insure the use of identical calibration values between observation files during multi-day surveys and spanning months using a particular Hi-Rail.

The survey controller was programmed to reject observations that fell outside a threshold relative horizontal and vertical precision as determined by the receiver. A threshold value of 0.15 feet horizontal and 0.50 feet vertical was selected for the hump yard survey, and 0.10 feet horizontal and 0.20 feet vertical was selected for the alinement surveys. The threshold values were selected based on the manufacture's stated accuracy, the expected degradation due to reference station distance, the receiver type, plus overhead. Receivers designated as GPS are capable of receiving and decoding only GPS SVs, while a GNSS receiver is capable of receiving GPS and GLONASS SVs. In all cases, the vertical threshold allowance is twice the horizontal value.

The hump yard observations were plotted using ESRI ArcMap software to produce color-mapped plan views of the yard. The color-mapped plot is similar to a contour map. However, where a contour map utilizes a triangulated irregular network to provide elevations over an area feature, the centerline top-of-rail line feature is of interest in a hump yard. Elevations were plotted as colored dots indicating an elevation range.

Color mapping relative vertical precision provides a graphical method of analysis for time-related SV reception quality. RTK GPS quality is dependent on satellite geometry, so serial observations of lower quality would be expected to appear together.

The track alinement model processes observations that are determined to be sequence by the software model. Changes in bearing between any two observations that approached 180° indicated the Hi-Rail reversed direction while recording of track observations. Points recorded in the reverse direction were not used.

Integrity

A check on point sequencing in the alinement model plots the sequence in three dimensions. The ordered sequence for each mile can be verified graphically by examining the 3D plot.

Summary

The research method explores track measurement using commercial off-the-shelf RTK augmented GPS and GNSS instrumentation in railway measurements.

Experiment 1 traverses an active hump yard with a locomotive equipped with RTK GPS instruments. Recorded positions are used to produce a profile for each track. The relative vertical precision of the locomotive observations as well as the reference station observations were analyzed for the influence of multi-path signal reflections.

Experiment 2 traverses a 29 mile segment of mainline track by a track inspector's Hi-Rail equipped with RTK GNSS instruments. A model was used to determine the D_c. The model was verified against rail company track charts for location, magnitude, and direction of track features. The model was used to evaluate the performance of RTK GNSS against a specialized track geometry car across tangent track.

Experiment 3 evaluated the ability to determine track occupancy by RTK GNSS. Five surveys traversed a parallel multitrack segment. The cross-track error between a baseline survey and subsequent surveys was evaluated in both a tangent and circular curved segment. The statistical likelihood of estimating track occupancy meeting FRA guidelines for a location determination system was determined.

Chapter 4

Results

The researcher sought to determine the viability of RTK GNSS augmentation to asses railway infrastructure and act as a reliable track vehicle locator capable of meeting the requirements of a location determination system as defined by the FRA by answering these questions:

1)*Hump Yard Profile:* Can a locomotive use wireless position measurement to determine the vertical profile of bowl tracks in an automatic classification yard to an accuracy of tenth of a foot during production activities?

2)*Horizontal Track Alinement:* Can a common track vehicle use wireless position measurement to determine the horizontal degree of curvature (D_c) comparable with specialized track geometry vehicles?

3)*Track Occupancy:* Can a common track vehicle use wireless position measurement to meet the positioning requirements for track occupancy outlined by the FRA [FRA, 1995, pp.6-7] for a location determination system?

These experiments used common track vehicles equipped with survey-grade RTK GPS/GNSS instrumentation across yard and mainline track. The research examined three absolute positioning applications using RTK augmented GPS/GNSS in the context of a Class I railroad. The experiments addressed these questions:

1. *Hump Yard Profile*

Can a locomotive equipped with RTK GPS instrumentation be used to measure the vertical profile of bowl tracks in an automatic classification yard during humping operations? The question was answered through the completion of several objectives:

- A method was developed for measuring track profiles in the bowl area of an active hump yard.
- The method was demonstrated by use of an ad hoc GPS reference station transmitting correctors to a RTK GPS receiver aboard a yard locomotive.
- A relative vertical precision distribution was determined from the RTK GPS observations.
- Track profiles were developed from the locomotive survey data.

2. *Horizontal Track Alinement*

Can a common track vehicle use RTK augmented GPS/GNSS observations to determine the horizontal degree of curvature over tangent track comparable with specialized track geometry vehicles? The question was answered through the completion of several objectives:

- A method was developed for measuring track horizontal position from a track inspector's Hi-Rail vehicle.
- A software model was developed to determine the degree of curvature using the string lining method.
- A parameter estimation of the D_c variability of the model and a track geometry car was determined for selected tangent track segments.

3. *Track Occupancy*

Can a common track vehicle using RTK augmented GPS/GNSS instrumentation meet the positioning requirements for track occupancy outlined by the FRA for a location determination system? The question was answered through the completion of several objectives:

- An analytical method was developed to determine the variance in a series of RTK GNSS measured track positions from specific geometric segments.
- A hypothesis test was used to determine the likelihood of RTK GNSS position measurements to meet the FRA criteria for reliable track occupancy.

Hump Yard Profile Results

The objective of experiment one was to use a locomotive to survey an active hump yard producing track profiles from RTK track observations. Individual track profile thumbnails are exhibited in Appendix A. Profile drawing are hyperlinked to the track number in table 1, Appendix A, page 73. The human effort expended during the yard survey is presented in table 4.1.

Table 4.1: Hump Yard Survey Human Resource Utilization

Classification	Labor Hours	Task Description
Surveyor, locomotive	5 shifts of 8 hours	manage locomotive GPS
Locomotive operator	5 shifts of 8 hours	manage locomotive, switches
Surveyor, ground	2 sessions of 3 hours	collect POI, set bench marks
Watchmen lookout	2 sessions of 3 hours	safety lookout for ground surveyor
Company escort	5 hours	safety briefings, guide
Total hours	97 hours	

Adjustments to the autonomous horizontal and vertical GPS position of the ad hoc reference station (CP1) are listed in table 4.2. OPUS output generated from two reference station observation sessions are exhibited in Appendix A, pages 66 and 67.

Table 4.2: Reference Station Adjustment

Point	Northing	Easting	Elevation
CP1 autonomous	426094.534	1802674.100	462.354
OPUS 89691472	426095.398	1802677.668	464.944
OPUS 89691491	426095.376	1802677.685	465.107
mean OPUS	426095.387	1802677.677	465.026
EB1559 published	422425.72	1795001.00	389.537
CP1 to EB1559 vector	-3721.022	-7653.073	-77.070
CP1 adjusted	426095.387	1802677.677	465.081
residuals			
Δ OPUS	0.000	0.000	+0.055
Δ EB1559	+0.068	-0.045	+0.000

TEQC reports generated from the reference station sessions are exhibited in Appendix A. The reports indicate cycle slips due to multi-path effects at the reference station. The first page ASCII time plot provides a visual summary[1] of various types of quality indicators for each satellite as a function of time.

Table 4.3: Relative Vertical Precision Summary

$\alpha = 0.01$ Tracks	N	μ	conf.int. μ	σ	conf.int. σ
58	9,570	0.07753	0.07640 to 0.07866	0.0429	0.04213 to 0.04373

Track workbooks track group with individual worksheets for each track are exhibited by hyperlink in Appendix A, page 73. Algorithms for determining horizontal linear reference and elevation scaling are available in the worksheet formula cell.

Track profiles were plotted with a drawing provided by CSX as the result of a January 2001 survey by others. Attempts at recovering the 2001 benchmarks during the GPS profile were unsuccessful.

The horizontal axis of each drawing represents the horizontal linear track reference, and the vertical axis representing the NAVD88 elevation. A reference mark on the drawing was matched with the track structure observed during the survey. Linear references from the supplied drawing were assigned to the match mark in the spreadsheet, and the linear reference of each track observation was determined by horizontal stationing equation 3.2. Elevations were similarly assigned to the drawing match mark.

[1] See http://facility.unavco.org/software/teqc/tutorial.html section 11 for symbology.

Elevations were plotted twice, first in a 1:1 scale with the previously provided design grade. A second plot, exaggerated 5:1, provided sufficient relief to to better discern profile differences. Entries in table 1 Appendix A, page 73 are hyperlinked to pdf format profile drawings.

The relative vertical precision of each point observed calculated by mobile#1 was recorded. The descriptive statistics for the relative vertical precision for all track observations is listed in table 4.3.

Appendix A figure 10 presents a histogram of the vertical precisions in addition to descriptive statistics for the aggregate observations.

A TEQC report for base station observations between 2008 May 26 14:21:30 and 21:44:00 UTC is exhibited in Appendix A. Values of interest are the MP1 and MP2 cycle slips between elevation angles of 10 and 45 degrees above the horizon.

Table 4.4: Reference Station Multipath Cycle Slip Summary

MP	Elev(deg)	Total Obs.	Slips	MP rms, m
1	10-15	1,542	23	0.68209
1	15-20	1,642	24	0.47830
1	20-25	1,206	14	0.42167
1	25-30	1,408	15	0.37891
1	30-35	1,082	16	0.33576
1	35-40	1,207	17	0.30466
1	40-45	1,025	12	0.27952
	total:	9,112	121	1.32%
2	10-15	1,542	21	0.99321
2	15-20	1,625	24	0.67395
2	20-25	1,206	14	0.59764
2	25-30	1,408	15	0.56963
2	30-35	1,082	16	0.52258
2	35-40	1,207	17	0.41814
2	40-45	1,025	12	0.45189
	total:	9,112	119	1.30%

Summary

An RTK survey of the Hamlet Terminal by locomotive was completed in five, eight hour shifts. The first day was consumed by yard safety, yard facility familiarization, and antenna alignment. Four eight hour shifts were sufficient to complete a traverse of every open track in the bowl. The survey strategy first traversed the pullout end to the foul point. The pull-out end humpmaster preplanned and coordinated runs through alley[2] track with the locomotive engineer, though the survey locomotive was also sporadically used to pull cars during the survey.

[2]A clear track.

The hump end was surveyed during the last day's shift change. During shift change, the pin puller and other hump end personnel undergo a transition period of exchanging relevant yard information, with the oncoming shift receiving a current safety briefing. The hump-end yard master took advantage of the staggered shift change to switch the survey locomotive through each hump and group lead track on the hump end. The brief period between shift changes did not allow time for individual group lead and tracks to be renamed in the survey controller. Consequently the data was separated manually during post-survey office work.

Post survey work consisted of adjusting the reference station position by reference to OPUS and NGS benchmarks; recalculating point positions from point vectors after reference station adjustment; deconstructing the aggregated points by track and lead; separating points into layers based on track and lead; adjusting ground points so as to be coincident with track centerlines; renaming point sequences and exporting each sequence to a spreadsheet; applying a linear reference to each point; scaling the elevations in preparation to plot on an existing CAD drawing; plotting and printing the CAD generated profiles; and processing base station observations with TEQC software.

Horizontal Track Alinement Results

Mainline track was surveyed by using the instruments listed in table 3.1, mobile#2. The antenna was mounted to a track inspector's Hi-Rail and aligned as previously described in chapter 3, antenna alignment.

Continuous data recording during the 20 January 2010 survey was impeded by unexpected receiver operation. The receiver was unable to initialize with a new VRS without cycling receiver power after each VRS update. The problem lead to numerous unexpected data gaps during the traverse. The problem was identified and corrected by updating the receiver firmware. The receiver performed as expected during subsequent surveys. Mainline surveys traversing the Kanawaha Subdivision from mile post (MP) 494 to 523 are summarized in table 4.5.

Table 4.5: RTK Surveys By Hi-Rail

Ref.	Date	Traverse	Track(s)	CL Observations	Note
A	20 January 2010	MP494 to 523	1,2	18,095	f/w 1.02
B	5 February 2010	MP495 to 512	2,1,2	15,225	f/w1.13, traffic
C	14 February 2010	MP495 to 523	1, 2	22,866	f/w1.13
D	3 March 2010	MP495 to 522	2,3,2	19,993	f/w1.13
E	18March 2010	MP494 to 523	1	21,001	f/w1.13

Output generated from processing RTK observations with the model are cataloged in Appendix B. Correlation between model output and rail company charted features is produced in table 4.6.

Two discrepancies between the rail company track chart values and model output were discovered.

- The track chart indicates the curve beginning at MP508.9 is a curve to the right[3]. The model determined the a curve was to the left. The model determined value is verified by examination of a plan view of the track observations between MP 508 and 509, figure 4.1.

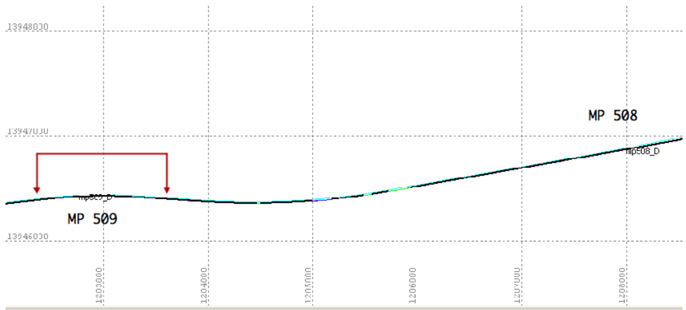

Figure 4.1: Plan View MP 508-509

- The track chart indicates the 1 degree curve to the right at mile post 521.15 extends approximately 0.15 miles. The model determined the curve extends from MP 521.15 to 521.83, or one half mile longer than indicated on the track chart. The model determined value is verified by examination of a plan view of the track observations between MP 521 and 522, as illustrated by figure 4.2.

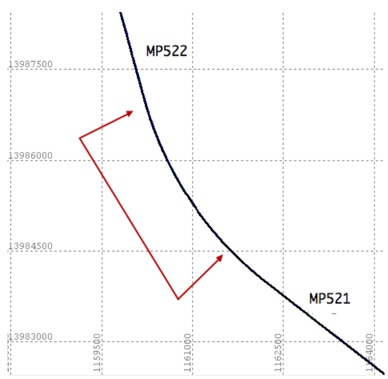

Figure 4.2: Plan View MP 521-522

Features causing loss of GNSS signal (LOS) were documented by referencing the location on the rail company track chart. When not evident from the track chart, the geodetic coordinates of a point before LOS was entered into Google Maps, and the aerial image examined. This method aided in determining the location of signal bridges and several overpasses not indicated on track charts.

[3]When the direction of travel references increasing mile post numbers.

Table 4.6 also references rail company track chart (TC) values for D_c and mile length for comparison with the model output. Track charts do not provide exact values for individual tracks, therefore the comparison serves only to verify the quantity and magnitude of alinement features.

Table 4.6: RTK Hi-Rail Traverse MP 494-523

MP Reference	**Feature**	**TC Value**	**Note**
494-495	mile length	8,858'	Hi-Rail:8,949'
494.05	curve	3°03'R	
494.46	curve	2°45'L	
494.65	curve	2°30'R	
495-496	mile length	5,295'	Hi-Rail:5,414'
495.05	curve	2°30'R	
495.46	curve	2°30'L	
495.6-495.7	I-64 overpass		LOS
496-497	mile length	5,255'	Hi-Rail: 5,323'
496.05	curve	3°45'L	
496.25	curve	1°00'L	
497-498	mile length	5,276'	Hi-Rail: 5,340'
497.3	curve	0°45'L	
497.61			LOS, VRS update
498-499	mile length	5,290'	Hi-Rail: 5,342'
498.6	curve	2°00'R	
499-500	mile length	5,283'	Hi-Rail: 5,342'
500-501	mile length	5,280'	Hi-Rail: 5,356'
500.4	curve	2°32'R	
501.03-501.12	cross over		cross over, track 1 to 1
501.15-501.35	Guyandotte River Bridge		LOS
501.35	curve	4°14'L	
501.6-501.67	29th Street overpass		LOS
501.9	curve	1°33'L	
501.95	curve	1°33'R	
501-502	mile length	5,266'	Hi-Rail: 5,316'
502.62-502.69	cross over		track 2 to 1
502-503	mile length	5,383'	Hi-Rail: 5,208'
503.4	curve	1°15'L	
503.55	curve	1°33'R	

Continued next page...

Table 4.6 – Continued

MP Reference	Feature	TC Value	Note
504-505	mile length	5,196'	Hi-Rail: 5,281'
504.05	curve	2°56'R	
504.15	curve	4°30'L	
504.52	curve	0°55'R	
504.6	curve	1°05'L	
504.85	curve	2°00'L	
504.92-504.96	signal bridge		LOS
505-506	mile length	5,286'	Hi-Rail: 5,335'
505.0	spiral	from 2°00'L	
505.5	curve	1°00'R	LOS@505.55
506-507	mile length	5,189'	Hi-Rail: 5,256'
506.24	curve	0°32'L	
506.34-506.41	17th Street interchange		LOS
506.7-507.78	signal bridge		LOS
506.78	curve	1°55'R	
507-508	mile length	5,255'	Hi-Rail: 5,327'
507.95	curve	0°23'R	
508-509	mile length	5,262'	Hi-Rail: 5,337'
508.37-508.57	Spring Valley Road overpass		LOS
508.57	curve	0°45'R	
508.65	signal bridge		LOS
508.9	curve	1°18'R	TC error, left
509-510	mile length	5,280'	Hi-Rail: 5,355'
509.0	spiral	1°18'R	TC in error, left
509.21	curve	0°18'L	
509.56	curve	0°28'L	
510-511	mile length	5,280'	Hi-Rail: 5,336'
510.2	curve	1°05'R	
510.7	curve	3°23'R	
510.95	signal bridge		LOS
511-512	mile length	5,231'	Hi-Rail: 5,319'
511.72-511.8	Norfolk Southern overpass		LOS
512-513	mile length	5,249'	Hi-Rail: 5,349'
512.52-513	Big Sandy River Bridge		LOS

Continued next page…

Table 4.6 – Continued

MP Reference	Feature	TC Value	Note
513-514	mile length	5,264’	Hi-Rail: 5,408’
513.0	curve	4°51’R	
513.31	signal bridge		multipath
513.6	curve	6°23’L	
513.7	curve	3°00’R	
513.92	curve	3°00’L	
514-515	mile length	5,263’	Hi-Rail: 5,293’
514.0	curve	3°00’L	
514.2	curve	2°00’R	
514.8	curve	2°00’L	
514.55	signal bridge		LOS
515-516	mile length	5,240’	Hi-Rail: 5,318’
515.0	curve	0°45’L	
515.2	curve	1°30’R	
515.5	curve	1°15’R	
515.6	signal bridge		LOS
515.8	curve	0°45’L	
516-517	mile length	5,047’	Hi-Rail: 5,110’
516.12	curve	3°00’R	
516.78-517	curve	1°00’L	LOS
517-518	mile length	5,432’	Hi-Rail: 5,530’
517.0	curve	1°00’L	to 3°00’L
517.43	curve	1°30’L	
517.6	curve	4°15’L	
518-519	mile length	5,733’	Hi-Rail: 5,821’
518.05	curve	1°00’R	
518.23	curve	1°15’L	
518.4	curve	0°00’	<sic>
518.41	signal bridge		multipath
518.5	curve	0°45’R	
519-520	mile length	4973’	Hi-Rail: 5,059’
519.1	curve	1°30’L	
519.15-519.34	2 signal bridges		LOS
519.2	curve	1°00’R	

Continued next page...

Table 4.6 – Continued

MP Reference	Feature	TC Value	Note
519.6	curve	2°00'L	
519.65	curve	2°00'R	
519.8	curve	2°30'L	
519.9	curve	1°45'R	
520-521	mile length	5,322'	Hi-Rail: 5,431'
520.5	curve	2°15'R	
520.55-520.69	Armco overpass		LOS
521-522	mile length	4,972'	Hi-Rail: 5,357.6'
521.12-521.82	curve	1°00'R	TC curve length error
522-523	mile length	5,023'	Hi-Rail: 5,099'
522.1-522.25	AK Steel Entrance Rd		LOS
522.6	curve	1°00'L	
522.9	curve	0°30'L	

Measurements obtained from CSX for a GMRS inspection vehicle were compared with the output from the string line model using observations from a RTK GNSS equipped Hi-Rail. The two methods traversed CSX C&O Ohio Subdivision between mile post 211 and 207. Illustration 4.4 provides a graphic solution to the smoothed D_c vs. mile post values obtained from both methods across the tangent segment.

Table 4.7: GMRS & RTK Hi-Rail Comparision, MP 211-207, Alinement Annotation

MP Reference	Feature	TC Value	Note
211-210	mile length	5,328'	GMRS:5,018' Hi-Rail:5,368'
210.7	curve	2°15'L	
210-209	mile length	5,263'	GMRS:4,973' Hi-Rail:5,314'
209.6	curve	1°15'L	
209.15	curve	1°00'L	
209-208	mile length	5,252'	GMRS:5,027' Hi-Rail:5,318'
208.8	curve	3°15'R	
208.45	curve	1°15'L	
208.0	curve	3°00'R	
208-207	mile length	5,678'	GMRS:5,384' Hi-Rail:5,586'
207.5	curve	5°00'R	

Table 4.8: GMRS and RTK GNSS Hi-Rail Comparison, MP210.4-209.75 tangent

Vehicle	Stationing	N	μ_{D_c}	95% CI	σ_{D_c}	95% CI
GMRS	1 ft	3,253	-0.0264	-0.031 -0.022	0.131	0.128 0.134
Hi-Rail	15.5 ft	222	-0.0042	-0.0411 0.0327	0.279	0.255 0.308

The longest tangent portion of the segment under study extends from MP 210.4 to 209.75, and was selected to determine the variance for the GMRS and the Hi-Rail RTK methods of determining D_c . An ideal measurement over an ideal tangent would result in an instantaneous D_c value of zero at each point of measurement. Assuming the 201.4-209.75 segment as an ideal tangent, the variation around zero D_c was determined for each method. Figures 4.3 and 4.4 illustrate the raw and smoothed D_c vs. Mile Post values, while table 4.8 provides descriptive statistics for D_c values derived from each method.

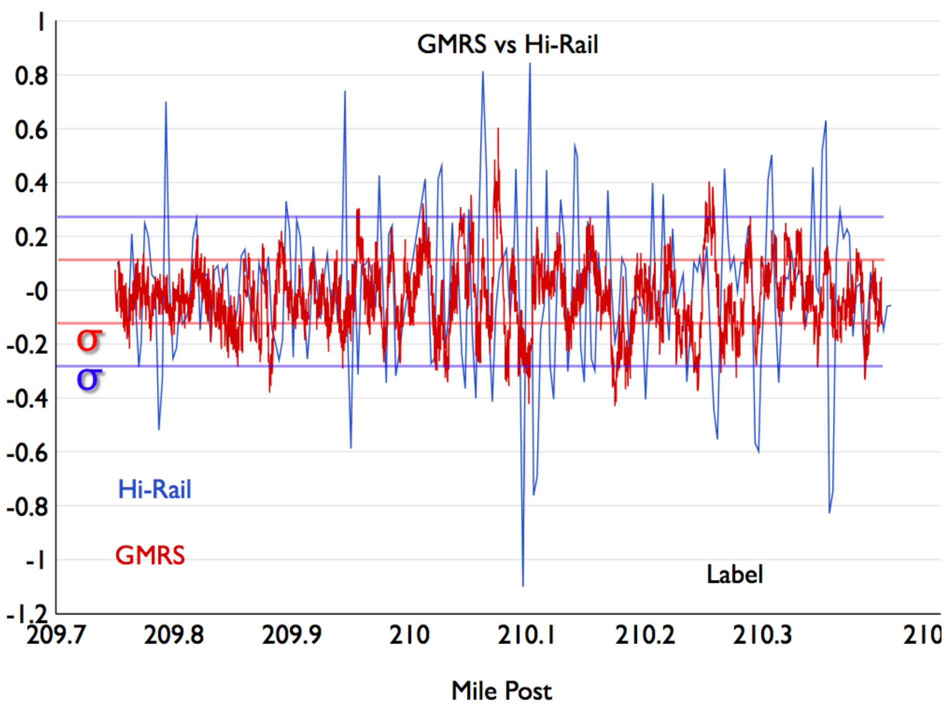

Figure 4.3: GMRS and Hi-Rail, D_c Comparison

A histogram approximates the probability destiny function of the D_c values. GMRS measurement deviation from zero is illustrated in figure 4.5. RTK GNSS Hi-Rail deviation illustrated in figure 4.6.

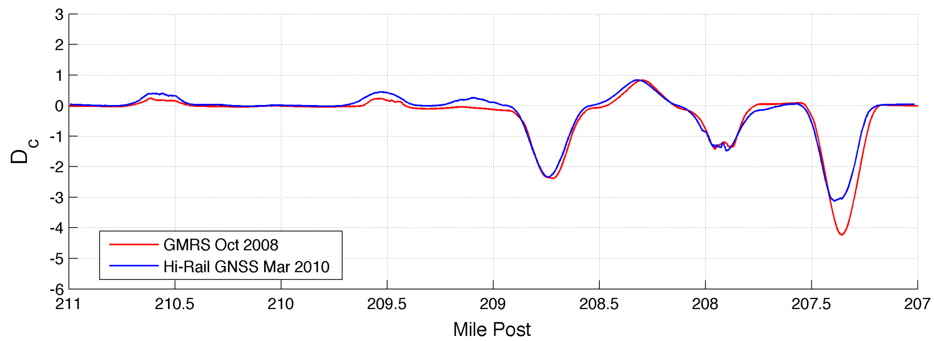

Figure 4.4: GMRS and Hi-Rail, D_c Comparison with Smoothing

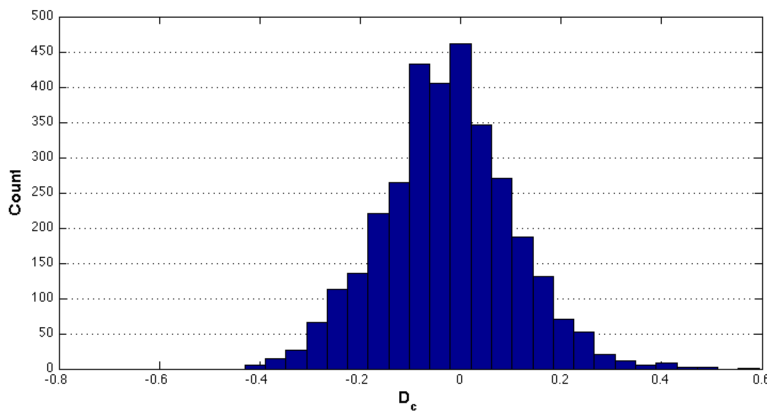

Figure 4.5: GMRS D_c Histogram, 210.4 to 209.75 tangent

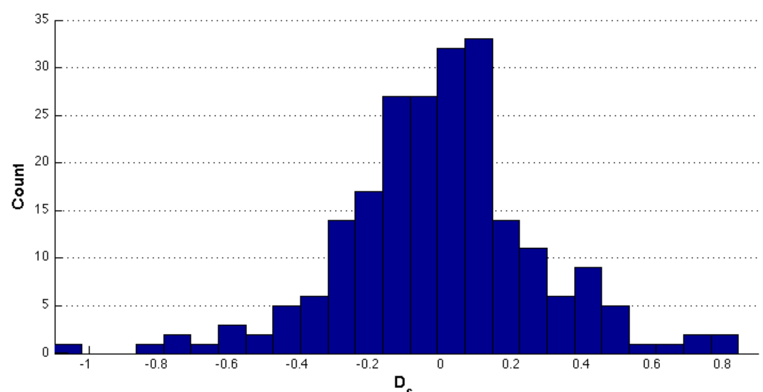

Figure 4.6: Hi-Rail D_c Histogram, 210.4 to 209.75 tangent

Track Occupancy Results

The question answered by experiment 3 was whether statistical evidence exists to determine if a wireless positioning system can act as the sole track vehicle location determination system capable of meeting FRA guidelines for track occupancy as might be used as a location determination system in positive train control.

The question was answered through the completion of several objectives:

- An analytical method was developed to determine the variance in a series of RTK GNSS measured track positions from specific geometric segments surveyed by a common track vehicle.
- A hypothesis test determined the likelihood of RTK GNSS position measurements in tangents and circular curves to meet the FRA criteria for reliable track occupancy.

Table 4.9 presents the result of a linear least squares regression performed on Easting and Northing coordinate pairs between mile post reference 498.9 and 500.2 for each of five traverses. Track position observations traversing three parallel tangent tracks of the same approximate length were recorded during five separate surveys, denoted as traverses A-E. The regression correlation statistic R^2 for each traverse was 0.99998 or better.

Table 4.9: Tangent Regression Coefficients, MP 498.9 to 500.2

Survey	Track	N	Slope	Y Intercept	Variance	Azimuth°
A	2	1,189	0.10220	13825809.25	0.02259	264.1645°
B	2	1,244	0.10219	13825815.49	0.02208	264.1648°
C	3	1,152	0.10208	13825969.10	0.05664	264.1711°
D	1	1,158	0.10214	13825873.25	0.02432	264.1680°
E	3	1,156	0.10210	13825950.11	0.05338	264.1703°

The cross-track error was determined for each point surveyed and a centerline described from the regression coefficients of traverse A. Descriptive statistics for the cross-track distance from each point to the reference centerline for each survey is presented in table 4.9.

Table 4.10 provides the result of the tangent case hypothesis test for each traverse between MP 498.9 and 500.2, with N the number of data points, μ_{xt} the mean cross track distance of the traverse in feet, and σ_{xt} the standard deviation.

Table 4.12 provides the result of the circular curve hypothesis test for each survey between MP500.5 and 500.7.

$$h_0 : \mu_{xt} < \frac{11.5}{2} \tag{4.1}$$

$$h_1 : \mu_{xt} \geq \frac{11.5}{2} \tag{4.2}$$

Table 4.10: Tangent Cross-Track Hypothesis Test

$\alpha = 0.00001$ $Track_{trav} \rightarrow Track_{ref}$	N	μ_{xt}	σ_{xt}	Reject h_0?
$2_A \rightarrow 2_A$	1,189	0.13	0.075	no
$2_B \rightarrow 2_A$	1,244	0.13	0.080	no
$3_B \rightarrow 2_A$	1,152	13.10	0.347	yes
$1_B \rightarrow 2_A$	1,158	13.51	0.203	yes
$3_B \rightarrow 2_A$	1,156	13.05	0.313	yes

Table 4.11: Curve Regression Coefficients, MP 500.5 to 500.7

A radius = 2276.11ft Survey	Track	N	Origin E	Origin N	μ_{xt}	σ_{xt}
A	2	85	1245217.14	13955358.41	0.00	0.033
B	2	98	1245215.55	13955352.03	0.03	0.037
C	3	98	1245203.52	13955318.38	-14.53	0.163
D	1	97	1245207.64	13955326.35	13.93	0.095
E	3	92	1245206.38	13955328.18	-14.57	0.142

Table 4.12: Circular Curve Cross-Track Hypothesis Test

$\alpha = 0.00001$ $Track_{trav} \rightarrow Track_{ref}$	N	μ_{xt}	σ_{xt}	Reject h_0?
$2_A \rightarrow 2_A$	85	0.00	0.033	no
$2_B \rightarrow 2_A$	98	0.03	0.037	no
$3_C \rightarrow 2_A$	98	-14.53	0.163	yes
$1_D \rightarrow 2_A$	97	13.93	0.095	yes
$3_E \rightarrow 2_A$	92	-14.57	0.142	yes

Summary

Experiment 1 traversed an active hump yard with a locomotive equipped with RTK GPS instruments to observe track positions. The recorded positions were used to produce a profile for each track. Reference benchmarks, evaluation of GPS signals at the reference station, a plan view of the yard with color-mapped elevations, a plan view of the relative vertical error, and 58 track profiles are exhibited in Appendix A. The relative vertical precisions of locomotive and reference station observations were examined for the influence of multipath reflections.

Experiment 2 traversed a continuous 29 mile segment of mainline track by a Hi-Rail equipped with RTK GNSS instruments. A model of the string line method was used to determine the D_c for each mile, evaluate the model against rail company track charts for location, magnitude, and direction of curves. The model was used to evaluate the model output against a specialized track geometry car over a comparable segment of tangent track. Company track charts, the output of the string line model for each mile, and the model script is exhibited in Appendix B.

Experiment 3 evaluated the ability to determine track occupancy by RTK GNSS. Five surveys traversed a parallel multitrack segment. The cross-track error between a baseline survey and subsequent surveys was evaluated in a tangent and circular curved segment. The statistical likelihood of estimating track occupancy meeting FRA guidelines for a location determination system was determined.

Chapter 5

Conclusions

This chapter contains a summary of the purpose, procedures, major findings, conclusions and discussion, recommendations, and implications of the research.

Purpose

The researcher explored track measurement using commercial off-the-shelf instrumentation to observe railway positions. The research examines a system for track surveying that minimizes exposure to railway hazards, is cost-effective, and produces accurate repeatable measurements without burdening train movement authority or disrupting yard operations, answering these questions:

1) *Hump Yard Profile:* Can a locomotive use wireless position measurement to determine the vertical profile of bowl tracks in an automatic classification yard to an accuracy of tenth of a foot during production activities?

2) *Horizontal Track Alinement:* Can a common track vehicle use wireless position measurement to determine the horizontal degree of curvature (D_c) comparable with specialized track geometry vehicles?

3) *Track Occupancy:* Can a common track vehicle use wireless position measurement to meet the positioning requirements for track occupancy outlined by the FRA [FRA, 1995, pp.6-7] for a location determination system?

Procedures

The researcher conducted three experiments which used common track vehicles equipped with COTS GNSS survey instruments. To observe track position, a single RTK antenna and receiver were mounted to a locomotive in the case of the hump yard, or to a Hi-Rail in the case of mainline track. Correctors were transmitted to a mobile receiver using two methods; a VHF data radio in the case of the humpyard; and the public cellular network in the case of mainline track. No auxiliary instrumentation was used to modify observations or fill expected data gaps.

1. Experiment 1 traversed an active hump yard with a locomotive equipped with an RTK GPS instrument. Observed track positions were used to produce a profile for each track. The relative vertical precision of the locomotive observations and the reference station observations were examined for the influence of multi-path signal reflections. Experiment 1:
   - Developed a procedure for aligning a GPS antenna mounted to a locomotive with the track centerline top-of-rail location.
   - Collected continuous single epoch observations on a nominal 10 foot horizontal spacing with RTK augmented GPS onboard a locomotive in an active hump yard.
   - Produced a plan-view color-map of track elevation for the bowl area of a hump yard.
   - Produced a two-dimensional profile drawings for each track in 1:1 and 1:5 vertical scale.
   - Produced a plan-view color-map of relative vertical precision as determined by the *Survey Controller* software for points measured in the bowl area of the yard.
   - Determined the descriptive statistics of the relative vertical precision estimate as determined by *Survey Controller* software for the locomotive mounted GPS.
   - Produced a TEQC report for the ad hoc reference station during an observation session for the purpose of determining clock resets due to multi-path GPS signal reflection.

2. Experiment 2 traversed a 29 mile segment of mainline track by an inspector's Hi-Rail equipped with RTK GNSS instruments. A software model was used to determine the degree of curvature (D_c). The model output was verified against rail company track charts for location, magnitude, and direction of track features. The model was used to evaluate the performance of RTK GNSS against a specialized track geometry car across tangent track. Experiment 2:
   - Developed a procedure for aligning a GNSS antenna mounted to a Hi-Rail with the track centerline top-of-rail location.
   - Developed a procedure for RTK measurement by Hi-Rail across mainline track.
   - Developed a software model of the string line method as described by the FRA *Track Safety Standards Compliance Manual.* [FRA, 2007]
   - Compared the model output from RTK Hi-Rail inputs with company track charts. The comparison between the model and track charts was verified for curve location, magnitude, and location. Mile length determined by the model was compared with the published track chart mile length.
   - Produced descriptive statistics for D_c variation across a tangent segment for a track geometry car and RTK Hi-Rail modeled D_c.
   - Produced a graphic solution for comparing D_c measured by geometry car and RTK equipped Hi-Rail by plotting D_c vs. mile post reference.

   - Determined the variability of D_c as measured by a geometry car and RTK equipped Hi-Rail across tangent track.

3. Experiment 3 evaluated the ability of RTK GNSS to determine track occupancy. Five surveys traversed a parallel multitrack section of mainline track. The cross-track error between a baseline survey and subsequent surveys was evaluated in both a tangent and circular curved segments. The statistical likelihood of estimating track occupancy meeting FRA guidelines for a location determination system was determined. Experiment 3:
   - Observed track positions for three parallel tracks by RTK GNSS equipped Hi-Rail.
   - Determined the coefficients for a reference tangent and circular track centerlines from an initial traverse.
   - Determined the cross-track error between subsequent RTK Hi-Rail observations and the reference tangent curve centerline.
   - Determined by hypothesis test if statistical evidence exists to indicate if RTK GNSS is capable of determining track occupancy meeting FRA performance standards for a location determination system.

Major Findings

The research answered the questions:

1. Can a locomotive use wireless position measurement to determine the vertical profile of bowl tracks in an automatic classification yard to an accuracy of tenth of a foot during production activities?

   The experiment was successful in using a single reference station located at the rail terminal with a RTK equipped locomotive to define the grades of 58 tracks in an automatic classification yard during production activity to a mean relative vertical accuracy of 0.078 feet.
   - The hump yard profile survey resulted in a ground hazard exposure of six man-hours.
   - The hump yard profile survey resulted in ten thousand single epoch observations.
   - The hump yard profile survey was completed in 5 working days.
   - The hump yard profile survey cost 100 man hours and 4-1/2 locomotive shifts.
   - The hump yard profile survey interrupted humping operations for less than 2 hours.
   - Distortions from multi-path reflection were not detected.

2. Can a common track vehicle in using networked RTK GNSS to determine the horizontal degree of curvature (D_c) comparable with specialized track geometry vehicles?

   The experiment was successful in determining D_c from measurements utilizing a track inspector's Hi-Rail equipped with a RTK GNSS instrument. Correctors received from a state sponsored VRS network transmitted through a public cellular network provided continuous coverage across 29 miles of mainline track.

The comparison of D_c between the X,Y,Z coordinates modeled from a RTK GNSS traverse by Hi-Rail and a specialized track geometry car over an identical segment of tangent track were comparable in terms of approximate result. However, the D_c standard deviation modeled from RTK X, Y, Z coordinates was twice the valus as the D_c standard deviation obtained from the CSX GMRS-1 track geometry car.

- Five traverses of multiple parallel track resulted in 97,180 single epoch observations.
- The software model determined D_c by 62 foot chords and 15.5 foot stations. The model output compared favorably with published rail company track charts.
- Data gaps in the model output were identified. Each obstruction was identified as a fixed overhead structure such as a highway overpass, bridge superstructure, or signal bridge.
- RTK D_c measurements by Hi-Rail across a tangent track segment were found to have a 2σ confidence interval of the mean between -0.041 and 0.033 feet, with a standard deviation of 0.279 feet. The CSX GMRS-1 track geometry car traversing the identical tangent segment was found to have a 2σ confidence interval of the mean between -0.031 and -0.022 feet with a standard deviation of 0.131 feet.

3. Can a common track vehicle use wireless position measurement to meet the positioning requirements for track occupancy outlined by the FRA [FRA, 1995, pp.6-7] for a location determination system?

   The experiment was successful in using RTK GNSS to meet the wireless positioning guidelines for a location determination system (LDS). Track occupancy between three parallel tracks, in tangent and circular curve segments, was determined within the significance level suggested by the FRA.

   - Track occupancy was determined between three parallel tracks by five traverses of a RTK GNSS equipped Hi-Rail.
   - The coefficients describing the reference tangent on track 2 between MP498.9 and 500.2 were determined to have a slope of 0.1022017 (azimuth = 264.1645°) and a Y-intercept of 13825809.25. The R^2 statistic for the regression was determined to be 0.99998.
   - The mean cross-track error for a traverse of track 2 referencing the track 2 tangent between between MP498.9 and 500.2 was found to be 0.13 feet with a standard deviation of 0.080 feet. The alternate hypothesis $h_1 : \mu_{xt} \geq \frac{11.5}{2}$ was rejected at a 99.999% confidence level.
   - The mean cross-track error for a traverse of track 3 referencing the track 2 tangent between between MP498.9 and 500.2 was found to be 13.10 feet with a standard deviation of 0.347 feet. The null hypothesis $h_0 : \mu_{xt} < \frac{11.5}{2}$ was rejected at a 99.999% confidence level.
   - The mean cross-track error for a second traverse of of track 3 referencing the track 2 tangent between between MP498.9 and 500.2 was found to be 13.05 feet with a standard

deviation of 0.313 feet. The null hypothesis $h_0 : \mu_{xt} < \frac{11.5}{2}$ was rejected at a 99.999% confidence level.

- The mean cross-track error for a traverse of a track of track 1 referencing the track 2 tangent between between MP498.9 and 500.2 was found to be 13.51 feet with a standard deviation of 0.203 feet. The null hypothesis $h_0 : \mu_{xt} < \frac{11.5}{2}$ was rejected at a 99.999% confidence level.
- The coefficients describing the reference circular curve on track 2 between MP500.5 to 500.7 were determined to have an origin located at Northing 13955358.41, Easting 1245217.14 and a radius of 2276.11 feet.
- The mean cross-track error for a traverse of track 2 referencing the track 2 circular curve between between MP500.5 to 500.7 was found to be 0.03 feet with a standard deviation of 0.037 feet. The alternate hypothesis $h_1 : \mu_{xt} \geq \frac{11.5}{2}$ was rejected at a 99.999% confidence level.
- The mean cross-track error for a traverse of track 3 referencing the track 2 circular curve between between MP500.5 to 500.7 was found to be -14.53 feet with a standard deviation of 0.163 feet. The null hypothesis $h_0 : \mu_{xt} < \frac{11.5}{2}$ was rejected at a 99.999% confidence level.
- The mean cross-track error for a second traverse of track 3 referencing the track 2 circular curve between between MP500.5 to 500.7 was found to be -14.57 feet with a standard deviation of 0.142 feet. The null hypothesis $h_0 : \mu_{xt} < \frac{11.5}{2}$ was rejected at a 99.999% confidence level.
- The mean cross-track error for a traverse of track 1 referencing the track 2 circular curve between between MP500.5 to 500.7 was found to be 13.93 feet with a standard deviation of 0.095 feet. The null hypothesis The null hypothesis $h_0 : \mu_{xt} < \frac{11.5}{2}$ was rejected at a 99.999% confidence level.

Conclusions and Discussion

A number of conclusions may be drawn for an analysis of the data generated by the study.

1. It may be concluded that the method of using a RTK equipped locomotive to survey an active hump yard was able to measure track elevation with a relative vertical accuracy less than 0.1 feet.
2. It may be concluded that the method of using a RTK equipped locomotive to survey an active hump yard is safer than a traditional differential level survey.

   The use of a locomotive to survey the yard considerably reduced on-track worker exposure to hazards when compared with a differential level survey. The method of using an RTK locomotive resulted in a ground exposure of 6 man-hours compared with an estimated 500 man-hours for a differential level survey.

3. It may be concluded that the method of using a RTK equipped locomotive to survey an active hump yard provides greater observation density than a typical differential level survey.

   The nominal observation distance between observations by RTK locomotive was 10 feet compared with the common practice of using 100 foot stations during a traditional differential level survey.

4. It may be concluded that the method of using a RTK equipped locomotive to survey an active hump yard reduces time-to-completion from an estimated 4-6 weeks to one week.

   A related finding was that the use of a RTK equipped locomotive to survey an active hump yard was unaffected by a full day of torrential rain.

5. It may be concluded that the method of using a RTK equipped locomotive to survey an active hump yard reduces labor cost from 500 man-hours to 100 man hours.

6. It may be concluded that the method of using a RTK equipped locomotive to survey an active hump yard increases equipment costs by using a locomotive for 36 hours.

   A related finding was that the use of a RTK equipped locomotive to survey an active hump yard could use the survey locomotive to pull cuts of cars, kick stalls, and attend to many of the normal duties assigned to a yard engine without affecting track observations.

7. It may be concluded that the method of using a RTK equipped locomotive to survey an active hump yard interrupted hump operations for less than two hours.

8. It may be concluded that the reference station and roving receiver used during the locomotive survey of an active hump yard did not exhibit gross positioning errors attributable to multipath signal reflections.

9. It may be concluded that the use of a RTK equipped Hi-Rail during an inspector's routine visual track inspection had no impact on train operations.

10. It may be concluded that the use of a RTK equipped Hi-Rail during an inspector's routine visual track inspection to model D_c by the string line method was successfully verified by reference to the location, direction, and D_c in company track charts.

11. It may be concluded that the use of a RTK equipped Hi-Rail observations modeling D_c was not precisely equivalent to the D_c determined by the CSX GMRS-1track geometry car.

    A related finding was that the track geometry car 95% confidence interval of the mean over the tangent segment failed to capture zero D_c. It may be concluded that; either the track geometry car measurement of D_c exhibits a slight bias to the left, or that the tangent track segment under study has a slight left curve.

12. It may be concluded that, given; a priori track centerline locations determined by RTK GNSS; the use of a network RTK VRS server; RTK GNSS equipped track vehicles; and a method of communicating correctors to a track vehicle, that track occupancy can be determined by single epoch RTK GNSS observation to the accuracy suggested for a wireless determination system by the FRA for a location determination system [FRA, 1995, pp.6-7] .

Recommendations

Recommendations for further study, implementation, and improvements regarding the use of RTK GNSS in railroad transportation as a result of research outcomes.

- Can track surfacing equipment be adapted to use automated machine guidance methods? It is not unusual in the railroad industry to rely on operator skill and judgment to establish grade during yard wide resurfacing projects. Operator skill and judgement are not data driven, and do not fully take advantage of available technologies, such as RTK GNSS. A track surfacing system, borrowing from the technology present in 3D machine control methods, would produce data-driven guidance for machine operators.
- Do improvement in track grade lead to increased yard throughput? In general, grades closer to design reduce the need to resurface as frequency; reduce retarder maintenance; and produce closer to the design coupling speed, in turn reducing damage to draft gear and yard derailments leading to a decrease in yard delay. An analysis of pre-surfacing and post-surfacing hump yard throughput would produce evidence of the contribution of grade deterioration on freight service delay.
- How do grade issues affect car handling in flat yards, particularly in light of increasing reliance on remote control locomotive? Flat yards typically handle lower quantities of rail cars than hump yards but share a similar reliance on track grade quality for predictable rail car movement.
- Is a string line model the correct method for determining D_c? String lining is accepted as a standard for measurement of D_c, and until recently, the only practical method for a track inspector to flag or find alinement exceptions. More computationally efficient methods are available (by deflection angles) for determining D_c, and might be more readily adapted for real-time determination of D_c from RTK GNSS observations.
- Is D_c the correct measurement for determining track alinement? D_c is determined in two dimensions, while the railway guides rolling stock in three dimensions. Modeling the trackway in four dimensions (x, y, z, time) may provide a more comprehensive perspective as shown in this video[1]. The video fly through of the Hamlet Terminal before resurfacing enables the discovery of relationships between tracks not readily apparent in two dimensional profiles.
- Can RTK track observations be considering as a diagnostics tool to provide actionable information for identifying track defects? Additional study and a more refined model for determining D_c is required to determine if reliable actionable information can be derived from RTK GNSS track observations for the identification of track alinement defects. The experimental results here indicate that RTK GNSS has the capability to locate defects in track classes 1-4.
- How can RTK add value as a change management tool? RTK GNSS provides the ability to ground-truth asset locations determined from LiDAR surveys, and accurately record the work

[1] http://www.youtube.com/watch?v=mOeuHxUPRBc

typically performed during track inspections, such as replacing sheared frog bolts or insulated track joints. Further study in recording track maintenance activity over time may provide the ability to perform geographic trend analysis leading to the identification of geologic, alinement, or weather induced factors affecting particular railway segments.

- Can RTK be used to observe the behavior of CWR[2] movement due to seasonal temperature effects? Rail expands and contracts with temperature. Anecdotal evidence of track shift in response to long-term seasonal temperature differences can be quantified through further study of this phenomenon by RTK GNSS.
- Can areas of rail breakage or warping[3] be modeled using RTK track observations? Short-term temperature fluctuations that exceed the railway neutral temperature limits impart tensive/compressive forces in the rail. Further study of short-term temperature fluctuation by RTK GNSS may provide sufficient position accuracy to identify factors contributing to this phenomena.
- To what extent will GPS Block IIF satellites reduce data dropouts from overhead structures as experienced during experiment 2 mainline surveys? The addition of the L5 signal and higher power (+3db) of the 12 scheduled[4] Block IIF and Block III[5] satellites will have a positive benefit for RTK users. Further study would indicate the expected improvement in eliminating data dropouts from overhead structures.
- Is an RTK GNSS survey by Hi-Rail possible in deep mountain valleys, as in the southern coal fields of West Virginia? Coal accounts for the majority of freight carried by rail [USDOT, 2008]. The narrow, steep valleys of southern West Virginia present a challenge for maintaining continuous GNSS and data coverage. Further study could identify the major factors impacting the use of RTK GNSS in similar challenged areas.
- Can mobile RTK GNSS, in conjunction with LiDAR derived track centerlines, be used as a basis for a wireless LDS? Class I railroads are flying LiDAR missions over track to quickly produce baseline locations of track and wayside assets in anticipation of meeting PTC regulation by 2015. Further study in looking a the combination of LiDAR derived centerlines with mobile RTK GNSS would establish if the combination is suitable for use as a wireless LDS.
- Can RTK enabled locomotives take advantage of the unused bandwidth of wayside repeaters to transmit train location as part of an LDS? Wayside repeaters relay digitized voice packet to rail company movement authority. Unused capacity exists for transmitting other data through existing infrastructure. Additionally, narrow banding requirements by the FCC will double and eventually quadruple the communication channels available in the AAR VHF and UHF bands. Additionally, Class 1 railroads have obtained spectrum in the 220Mhz band for use in PTC.

[2]Continuously Welded Rail
[3]Aka "sun kinks".
[4]first L5 capable SV launch May 2010
[5]First scheduled launch 2013.

Further study exploiting existing wayside radio assets for communicating RTK correctors to mobile units would provide knowledge as to the extent and communication demands for covering areas underserved by public wireless or cellular networks.

- Is the civilian-use safety-of-life signal from GPS BlockIIF sufficient to insure the use of GPS as part of a vital LDS? New GPS signals beginning with the May 2010 launch of the Block IIF series provide a method to signal users of service interruptions. Research defining the needs and performance these signals would determine the suitability of GNSS as a vital system for PTC.
- Can determining the track occupancy of a railcar in transit across a yard assist "right track, right train" consist makeup? Correctors transmitted by a rail yard communications system would enable low-cost GPS receivers with sub-meter accuracy.

Implications

1. Hump yard stakeholders can consider the relative safety costs when selecting a survey method in preparation for yard-wide resurfacing or to identify grade problems.
2. The safety aspects of a yard survey by RTK have implications for yard managers, hump yard engineers, and on-track workers. Personnel safety is improved by removing them from potentially hazardous situations. Track closures and railcar reroutes are not mandatory to determine yard grades.
3. Increased observation density during a hump yard survey has implications in improving material take-offs estimates and the finished grade quality for yard resurfacing projects.
4. Increased observation density, combined with a diligent attention to as-build grades during resurfacing, has implications for reducing variability during the humping process.
5. Reducing time-to-completion for a yard survey is of importance to planners and hump yard engineers in estimating yard survey costs.
6. The use of a yard trim locomotive is of importance to yard managers in estimating the demand on yard resources in supporting a profile survey.
7. The low impact on yard operations is of importance to traffic planners, managers, and hump yard engineering management in eliminated unidentifiable costs caused by track closures and car rerouting.
8. The inability to detect anomalous track position due to multi-path signal reflections is of importance to hump yard engineers by eliminating a potential measurement error source when performing a RTK survey.
9. Track engineering and maintenance implications in determining track alinement by RTK GNSS provides: the means to deploy commercial off-the-shelf products; an immediately accessible and proven method for monitoring track behavior monitoring.

10. Increased track position monitoring frequency has implications for track engineering managers and superintendents in studying the behavior of track and as a method for establishing track asset change management procedures.
11. Wayside track references rely on established fixed locations for mile post reference positions. Establishing “virtual mileposts” has implications for track engineering managers and superintendents in considering how to bridge legacy track reference marks with modern absolute positioning measurement.
12. With few exceptions, dense CORS networks are available from each state in the contiguous US, either as a free service or from private for-profit firms. The growing availability of wireless data and the use of localized VHF/UHF or utilization of the unused bandwidth of wayside repeaters removes the usefulness of NDGPS in all but the most remote locations. The wide availability of RTK services has implications for the need for continued funding of NDGPS.
13. Track location transmitted by rolling stock combined with accurate yard centerlines has implications for hump control systems using continuous rail car occupancy rather than timers and switches or video analytics in determining “right track, right train” consist makeup.

Appendix A

NGS OPUS Output

NGS OPUS Solution 1

```
FILE: 89691472.08o 000062901

                              NGS OPUS SOLUTION REPORT
                              ========================
All computed coordinate accuracies are listed as peak-to-peak values.
For additional information: http://www.ngs.noaa.gov/OPUS/about.html#accuracy

     USER: pdailey@njrati.org                      DATE: February 21, 2010
RINEX FILE: 8969147o.08o                            TIME: 14:11:44 UTC

 SOFTWARE: page5  0909.08 master50.pl 081023      START: 2008/05/26  14:21:00
EPHEMERIS: igs14811.eph [precise]                  STOP: 2008/05/26  21:44:00
 NAV FILE: brdc1470.08n                        OBS USED: 18491 / 19236   :  96\%
 ANT NAME: TRM41249.00     NONE             # FIXED AMB:    61 /    72   :  85\%
ARP HEIGHT: 1.5                              OVERALL RMS: 0.017(m)

REF FRAME: NAD_83(CORS96)(EPOCH:2002.0000)           ITRF00 (EPOCH:2008.4010)

        X:       939900.948(m)   0.025(m)           939900.245(m)   0.025(m)
        Y:     -5150611.988(m)   0.008(m)         -5150610.502(m)   0.008(m)
        Z:      3630563.038(m)   0.021(m)          3630562.883(m)   0.021(m)

      LAT:   34 55  8.30878      0.017(m)       34 55  8.33416      0.017(m)
    E LON:  280 20 30.24278      0.026(m)      280 20 30.22604      0.026(m)
    W LON:   79 39 29.75722      0.026(m)       79 39 29.77396      0.026(m)
   EL HGT:          110.196(m)   0.012(m)              108.805(m)   0.012(m)
ORTHO HGT:          141.772(m)   0.028(m) [NAVD88 (Computed using GEOID03)]

                       UTM COORDINATES    STATE PLANE COORDINATES
                        UTM (Zone 17)         SPC (3200 NC  )
Northing (Y) [meters]     3864879.250          129874.137
Easting (X)  [meters]      622559.919          549457.252
Convergence  [degrees]     0.76812771         -0.37993149
Point Scale                0.99978513          0.99988936
Combined Factor            0.99976784          0.99987206

US NATIONAL GRID DESIGNATOR: 17SPU2255964879(NAD 83)

                              BASE STATIONS USED
PID       DESIGNATION                        LATITUDE    LONGITUDE DISTANCE(m)
DG7402 NCPO POLKTON CORS ARP               N345933.173 W0801037.858   48094.7
DK4045 NCTR TROY CORS ARP                  N352201.845 W0795212.771   53345.6
DG5938 NCCA CARTHAGE CORS ARP              N352030.048 W0792305.085   53111.4

                NEAREST NGS PUBLISHED CONTROL POINT
EB2854      FRUITLAND RM 2 AZIMUTH         N345516.664 W0793924.904     286.2

This position and the above vector components were computed without any
knowledge by the National Geodetic Survey regarding the equipment or
field operating procedures used.
```

NGS OPUS Solution 2

```
FILE: 89691491.08o 000062905

                             NGS OPUS SOLUTION REPORT
                             ========================
All computed coordinate accuracies are listed as peak-to-peak values.
For additional information: http://www.ngs.noaa.gov/OPUS/about.html#accuracy

     USER: pdailey@njrati.org                     DATE: February 21, 2010
RINEX FILE: 8969149w.08o                           TIME: 14:15:33 UTC

 SOFTWARE: page5  0909.08 master40.pl 081023      START: 2008/05/28  22:20:00
EPHEMERIS: igs14813.eph [precise]                  STOP: 2008/05/29  20:40:00
 NAV FILE: brdc1490.08n                        OBS USED: 58256 / 60076   :  97\%
 ANT NAME: TRM41249.00     NONE             # FIXED AMB:   157 /   181   :  87\%
ARP HEIGHT: 1.5                              OVERALL RMS: 0.017(m)

REF FRAME: NAD_83(CORS96)(EPOCH:2002.0000)            ITRF00 (EPOCH:2008.4082)

        X:       939900.953(m)   0.013(m)           939900.250(m)   0.013(m)
        Y:     -5150611.985(m)   0.034(m)         -5150610.499(m)   0.034(m)
        Z:      3630563.028(m)   0.016(m)          3630562.873(m)   0.016(m)

      LAT:   34 55  8.30856      0.008(m)        34 55  8.33393      0.008(m)
    E LON:  280 20 30.24299      0.008(m)       280 20 30.22626      0.008(m)
    W LON:   79 39 29.75701      0.008(m)        79 39 29.77374      0.008(m)
   EL HGT:          110.189(m)   0.037(m)              108.798(m)   0.037(m)
ORTHO HGT:          141.765(m)   0.045(m) [NAVD88 (Computed using GEOID03)]

                       UTM COORDINATES    STATE PLANE COORDINATES
                        UTM (Zone 17)        SPC (3200 NC  )
Northing (Y)  [meters]     3864879.243          129874.130
Easting (X)   [meters]      622559.924          549457.257
Convergence   [degrees]     0.76812774         -0.37993146
Point Scale                 0.99978513          0.99988936
Combined Factor             0.99976784          0.99987206

US NATIONAL GRID DESIGNATOR: 17SPU2255964879(NAD 83)

                             BASE STATIONS USED
PID       DESIGNATION                        LATITUDE    LONGITUDE DISTANCE(m)
DG7402 NCPO POLKTON CORS ARP              N345933.173 W0801037.858   48094.7
DK4045 NCTR TROY CORS ARP                 N352201.845 W0795212.771   53345.6
DI1682 NCLU LUMBERTON CORS ARP            N343736.336 W0790439.695   62252.3

                NEAREST NGS PUBLISHED CONTROL POINT
EB2854      FRUITLAND RM 2 AZIMUTH        N345516.664 W0793924.904     286.2

This position and the above vector components were computed without any
knowledge by the National Geodetic Survey regarding the equipment or
field operating procedures used.
```

NGS Data Sheet EB1559

```
DATABASE =  ,PROGRAM = datasheet, VERSION = 7.60
1        National Geodetic Survey,   Retrieval Date = MAY 27, 2008
 EB1559 ***********************************************************************
 EB1559  DESIGNATION -  ROCKINGHAM RESET
 EB1559  PID         -  EB1559
 EB1559  STATE/COUNTY-  NC/RICHMOND
 EB1559  USGS QUAD   -  HAMLET (1982)
 EB1559
 EB1559                         *CURRENT SURVEY CONTROL
 EB1559  ___________________________________________________________________
 EB1559* NAD 83(2007)-  34 54 31.49602(N)    079 41 01.64429(W)     ADJUSTED
 EB1559* NAVD 88     -       118.731  (meters)     389.54   (feet)  ADJUSTED
 EB1559  ___________________________________________________________________
 EB1559  EPOCH DATE  -       2002.00
 EB1559  X           -     937,719.254 (meters)                     COMP
 EB1559  Y           -  -5,151,650.434 (meters)                     COMP
 EB1559  Z           -   3,629,619.608 (meters)                     COMP
 EB1559  LAPLACE CORR-          -4.82  (seconds)                    DEFLEC99
 EB1559  ELLIP HEIGHT-          87.199 (meters)         (02/10/07) ADJUSTED
 EB1559  GEOID HEIGHT-         -31.48  (meters)                     GEOID03
 EB1559  DYNAMIC HT  -         118.622 (meters)     389.18  (feet)  COMP
 EB1559
 EB1559  ------- Accuracy Estimates (at 95\% Confidence Level in cm) --------
 EB1559  Type    PID    Designation                      North   East  Ellip
 EB1559  -------------------------------------------------------------------
 EB1559  NETWORK EB1559 ROCKINGHAM RESET                  1.29   1.06   2.74
 EB1559  -------------------------------------------------------------------
 EB1559  MODELED GRAV-     979,707.4   (mgal)                       NAVD 88
 EB1559
 EB1559  VERT ORDER  -  FIRST     CLASS II
 EB1559
 EB1559.The horizontal coordinates were established by GPS observations
 EB1559.and adjusted by the National Geodetic Survey in February 2007.
 EB1559
 EB1559.The datum tag of NAD 83(2007) is equivalent to NAD 83(NSRS2007).
 EB1559.The horizontal coordinates are valid at the epoch date displayed above.
 EB1559.The epoch date for horizontal control is a decimal equivalence
 EB1559.of Year/Month/Day.
 EB1559
 EB1559.The orthometric height was determined by differential leveling
 EB1559.and adjusted in June 1991.
 EB1559
 EB1559.The X, Y, and Z were computed from the position and the ellipsoidal ht.
 EB1559
 EB1559.The Laplace correction was computed from DEFLEC99 derived deflections.
 EB1559
 EB1559.The ellipsoidal height was determined by GPS observations
 EB1559.and is referenced to NAD 83.
 EB1559
 EB1559.The geoid height was determined by GEOID03.
 EB1559
 EB1559.The dynamic height is computed by dividing the NAVD 88
 EB1559.geopotential number by the normal gravity value computed on the
 EB1559.Geodetic Reference System of 1980 (GRS 80) ellipsoid at 45
 EB1559.degrees latitude (g = 980.6199 gals.).
 EB1559
 EB1559.The modeled gravity was interpolated from observed gravity values.
 EB1559
 EB1559;                    North         East     Units Scale Factor Converg.
 EB1559;SPC NC       -   128,755.617   547,117.399   MT  0.99989040   -0 23 40.8
 EB1559;SPC NC       -   422,425.72  1,795,001.00   sFT  0.99989040   -0 23 40.8
```

```
EB1559;UTM  17      - 3,863,714.200   620,243.197   MT  0.99977820   +0 45 11.9
EB1559
EB1559!             -  Elev Factor  x  Scale Factor =   Combined Factor
EB1559!SPC NC       -   0.99998631  x   0.99989040  =   0.99987671
EB1559!UTM  17      -   0.99998631  x   0.99977820  =   0.99976452
EB1559
EB1559:                Primary Azimuth Mark                    Grid Az
EB1559:SPC NC       -  ROCKINGHAM RM 1 AZIMUTH                 063 44 34.0
EB1559:UTM  17      -  ROCKINGHAM RM 1 AZIMUTH                 062 35 41.3
EB1559
EB1559|---------------------------------------------------------------------|
EB1559| PID    Reference Object                     Distance      Geod. Az  |
EB1559|                                                           dddmmss.s |
EB1559| EB3564 ROCKINGHAM RM 1 AZIMUTH                            0632053.2 |
EB1559| EB3565 ROCKINGHAM RM 2                     25.344 METERS 08611      |
EB1559| EB1561 ROCKINGHAM RM 4                     18.703 METERS 09503      |
EB1559| EB3563 ROCKINGHAM RM                       20.840 METERS 16626      |
EB1559| EB1560 ROCKINGHAM RM 3                     30.681 METERS 19004      |
EB1559| EB2850 HAMLET SEABOARD RR WATER TANK       APPROX. 3.1 KM 2044531.0 |
EB1559| EB1562 PACE                                APPROX. 0.7 KM 2144024.4 |
EB1559|---------------------------------------------------------------------|
EB1559
EB1559                          SUPERSEDED SURVEY CONTROL
EB1559
EB1559  NAD 83(2001)-  34 54 31.49597(N)    079 41 01.64418(W) AD(       ) 1
EB1559  ELLIP H (03/13/03)   87.214  (m)                       GP(       ) 4 2
EB1559  NAD 83(1986)-  34 54 31.50606(N)    079 41 01.64801(W) AD(       ) 1
EB1559  NAD 83(1986)-  34 54 31.50078(N)    079 41 01.65069(W) AD(       ) 1
EB1559  NAD 27      -  34 54 30.94100(N)    079 41 02.45300(W) AD(       ) 1
EB1559  NAVD 88 (07/24/98)  118.73   (m)          389.5    (f) LEVELING    3
EB1559  NGVD 29 (10/06/93)  118.999  (m)          390.42   (f) ADJUSTED    1 2
EB1559
EB1559.Superseded values are not recommended for survey control.
EB1559.NGS no longer adjusts projects to the NAD 27 or NGVD 29 datums.
EB1559
EB1559_U.S. NATIONAL GRID SPATIAL ADDRESS: 17SPU2024363714(NAD 83)
EB1559_MARKER: DS = TRIANGULATION STATION DISK
EB1559_SETTING: 7 = SET IN TOP OF CONCRETE MONUMENT
EB1559_SP_SET: CONCRETE POST
EB1559_STAMPING: ROCKINGHAM 1918 1980
EB1559_MARK LOGO: NGS
EB1559_PROJECTION: PROJECTING 5 CENTIMETERS
EB1559_MAGNETIC: N = NO MAGNETIC MATERIAL
EB1559_STABILITY: C = MAY HOLD, BUT OF TYPE COMMONLY SUBJECT TO
EB1559+STABILITY: SURFACE MOTION
EB1559_SATELLITE: THE SITE LOCATION WAS REPORTED AS SUITABLE FOR
EB1559+SATELLITE: SATELLITE OBSERVATIONS - July 28, 1993
EB1559
EB1559  HISTORY     - Date     Condition        Report By
EB1559  HISTORY     - 1980     MONUMENTED       NGS
EB1559  HISTORY     - 1980     GOOD             NGS
EB1559  HISTORY     - 1982     GOOD             LOCENG
EB1559  HISTORY     - 19930728 GOOD             NCGS
EB1559
EB1559                          STATION DESCRIPTION
EB1559
EB1559'DESCRIBED BY NATIONAL GEODETIC SURVEY 1980 (HDM)
EB1559'1.5 MI NE FROM HAMLET.
EB1559'1.6 MILES NORTHEAST ALONG N.C. 177 FROM INTERSECTION WITH U.S. 74
EB1559'IN HAMLET, ACROSS HIGHWAY FROM INTERSECTION WITH SR 1627 AND IN A
EB1559'VACANT LOT BESIDE A VACANT FRAME HOUSE, 74.0 FEET SOUTHEAST OF
EB1559'CENTERLINE OF HIGHWAY, 89.0 FEET NORTHWEST OF NORTHWEST RAIL,
EB1559'63.2 FEET WEST OF POWER POLE 4004 WITH REFERENCE TAG, 30.2 FEET SOUTH
EB1559'OF 18 INCH OAK WITH REFERENCE TAG AND 28.2 FEET NORTH OF 12 INCH
```

```
EB1559'OAK WITH REFERENCE TAG.
EB1559'THE MARK IS 1.3 FT  NE FROM A WITNESS POST.
EB1559'THE MARK IS ABOVE LEVEL WITH HIGHWAY.
EB1559
EB1559                          STATION RECOVERY (1980)
EB1559
EB1559'RECOVERY NOTE BY NATIONAL GEODETIC SURVEY 1980 (CLN)
EB1559'THE STATION MARK AND REFERENCE MARK 3 WERE RECOVERED.  THE STATION
EB1559'MARK HAD BEEN DISTURBED AND WAS DUG OUT AND THE SUB-SURFACE MARK
EB1559'LOWERED AND BOTH MARKS RESET.  REFERENCE MARK 3 WAS FOUND IN GOOD
EB1559'CONDITION.  REFERENCE MARK 2 WAS FOUND WITH TOP OF MARK BROKEN OFF.
EB1559'REFERENCE MARK 1 WAS SEARCHED FOR BUT WAS NOT FOUND.  A REFERENCE MARK
EB1559'4 WAS ESTABLISHED AT THIS TIME.
EB1559'
EB1559'A COMPLETE NEW DESCRIPTION FOLLOWS.
EB1559'
EB1559'STATION IS ABOUT 1-1/2 MILES NORTHEAST OF HAMLET AND 0.05 MILE
EB1559'SOUTHWEST OF THE JUNCTION OF STATE HIGHWAY 177 AND SR1672 AND JUST
EB1559'WEST OF A SMALL FRAME HOUSE THAT IS ABANDONED AND FALLING APART.
EB1559'
EB1559'STATION MARKS ARE STANDARD DISKS STAMPED--ROCKINGHAM 1918 1980--,
EB1559'SURFACE DISK IS SET IN THE TOP OF A CYLINDRICAL CONCRETE POST THAT IS
EB1559'12-INCHES IN DIAMETER AND FLUSH WITH THE GROUND.  SUB-SURFACE MARK IS
EB1559'SET IN AN IRREGULAR MASS OF CONCRETE 3.5 FEET BELOW GROUND SURFACE.
EB1559'THEY ARE 28.2 FEET NORTH OF A 12-INCH OAK TREE WITH A REFERENCE TAG,
EB1559'30.2 FEET SOUTH OF AN 18-INCH OAK TREE WITH A REFERENCE TAG, 63.2 FEET
EB1559'WEST OF POWERLINE POLE 4004 WITH A REFERENCE TAG, 74 FEET SOUTHEAST OF
EB1559'THE CENTERLINE OF STATE ROUTE 177 AND 89 FEET NORTHWEST OF THE
EB1559'NORTHWEST RAIL OF RAILROAD TRACKS AND 1.3 FEET NORTHEAST OF A METAL
EB1559'WITNESS POST.
EB1559'
EB1559'REFERENCE MARK 3 IS A STANDARD DISK STAMPED--ROCKINGHAM NO 3 1933-,
EB1559'SET IN THE TOP OF A 14-INCH SQUARE CONCRETE POST THAT PROJECTS 2
EB1559'INCHES.  IT IS 1.5 FEET WEST SOUTHWEST OF A TELEPHONE LINE POLE WITH A
EB1559'REFERENCE TAG, 34 FEET NORTHWEST OF THE NORTHWEST RAIL OF RAILROAD
EB1559'TRACKS, 63.1 SOUTHWEST OF ANOTHER TELEPHONE POLE WITH A REFERENCE TAG
EB1559'AND 117.8 FEET SOUTHEAST OF THE CENTERLINE OF STATE ROUTE 177.
EB1559'
EB1559'REFERENCE MARK 4 IS A STANDARD DISK STAMPED--ROCKINGHAM 1918 NO 4
EB1559'1980--, SET IN THE TOP OF A CYLINDRICAL CONCRETE POST THAT IS
EB1559'14-INCHES IN DIAMETER AND PROJECTS 3 INCHES.  IT IS 1.7 WEST OF
EB1559'POWERLINE POLE 4004, WITH A REFERENCE TAG, 38 FEET SOUTHEAST OF THE
EB1559'SOUTHEAST CORNER OF A CONCRETE BLOCK, WELL HOUSE, 59.5 FEET NORTHEAST
EB1559'OF A TELEPHONE LINE POLE WITH A REFERENCE TAG AND 40.9 FEET NORTHWEST
EB1559'OF THE NORTHWEST RAIL OF RAILROAD TRACKS.
EB1559'
EB1559'TO REACH THE STATION FROM THE JUNCTION OF US HIGHWAY 74 AND STATE
EB1559'HIGHWAY 177, GO NORTHEASTERLY ON STATE HIGHWAY 177 FOR 1.6 MILES TO
EB1559'THE MARK ON THE RIGHT.
EB1559'
EB1559'THE STATION IS A STANDARD NGS DISK STAMPED--ROCKINGHAM 1918 1980--,
EB1559'SET INTO THE TOP OF A ROUND CONCRETE MONUMENT 12 INCHES IN DIAMETER
EB1559'FLUSH WITH GROUND LOCATED 89 FEET NW OF NW RAIL OF RAILROAD TRACKS, 74
EB1559'FEET SE OF CENTERLINE OF ST 177, 63.2 FT W FROM PLP 4004 W/TAG, 30.2
EB1559'FT S FROM 18 INCH OAK W/TAG, AND 28.2 FT N FROM 12 INCH OAK W/TAG.
EB1559'
EB1559'THE UNDERGROUND MARK IS A STANDARD NGS DISK STAMPED--ROCKINGHAM 1918
EB1559'1980--, SET INTO AN IRREGULAR MASS OF CONCRETE 3.5 FEET BELOW THE
EB1559'SURFACE.
EB1559'
EB1559'REFERENCE MARK NO 3 IS A STANDARD CGS DISK STAMPED--ROCKINGHAM NO 3
EB1559'1933--, SET INTO THE TOP OF A SQUARE CONCRETE MONUMENT 14 INCHES ON
EB1559'SIDE PROJECTING 2 INCHES ABOVE THE GROUND LOCATED 63.1 FT SW FROM TELE
EB1559'POLE W/TAG, 34 FT NW OF NW RAIL, 117.8 FT SE FROM CENTERLINE ST RT
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EB1559'177, AND 1.5 FT WSW FROM TEL POLE W/TAG.
EB1559'
EB1559'REFERENCE MARK NO 4 IS A STANDARD NGS DISK STAMPED--ROCKINGHAM 1918 NO
EB1559'4 1980--, SET INTO THE TOP OF A ROUND CONCRETE MONUMENT 14 INCHES IN
EB1559'DIAMETER PROJECTING 3 INCHES ABOVE THE GROUND LOCATED 40.9 FT NW OF NW
EB1559'RAIL, 1.7 FT W FROM PLP NO 4004 W/TAG, 59.5 FT NE FROM TEL POLE W/TAG,
EB1559'AND 38.0 FT S OF SE CORNER CONCRETE BLOCKWELL HOUSE.
EB1559
EB1559                          STATION RECOVERY (1982)
EB1559
EB1559'RECOVERY NOTE BY LOCAL ENGINEER (INDIVIDUAL OR FIRM) 1982 (DR)
EB1559'STATION WAS RECOVERED IN GOOD SHAPE.  I DID NOT CHECK FOR REFERENCE
EB1559'MARKS, HOWEVER, I DID FIND THAT NCGS STATION SARGES IS VISIBLE FROM
EB1559'ROCKINGHAM.
EB1559
EB1559                          STATION RECOVERY (1993)
EB1559
EB1559'RECOVERY NOTE BY NORTH CAROLINA GEODETIC SURVEY 1993 (LWA)
EB1559'RECOVERED AS DESCRIBED.  THE ROAD IS SR 1627 (EARLE FRANKLIN ROAD)NOT
EB1559'SR 1672. MARK IS IN A JUNK YARD AND LINES-OF-SIGHT ARE BLOCKED TO
EB1559'REFERENCE MARKS.

*** retrieval complete.
Elapsed Time = 00:00:01
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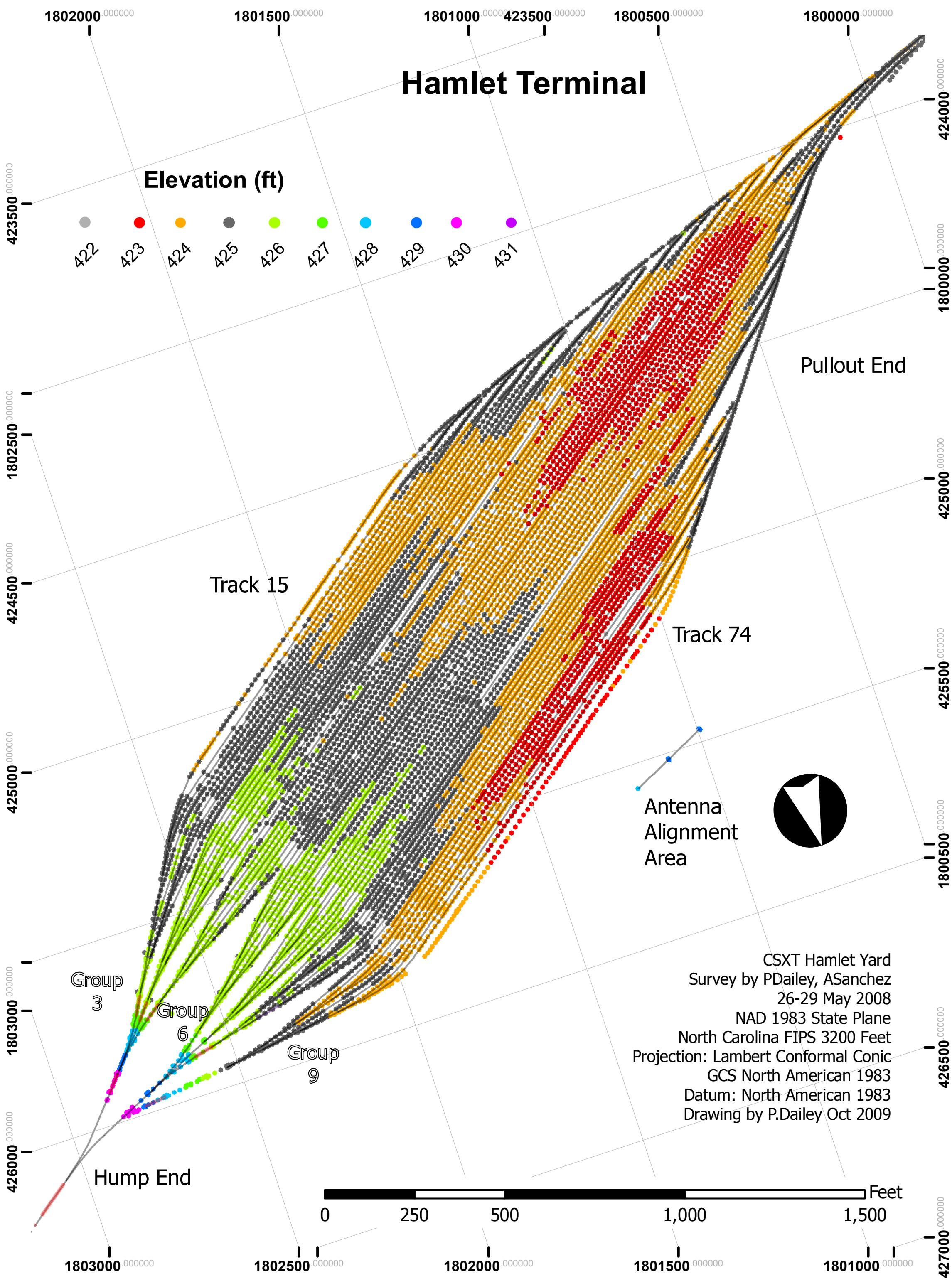


Figure 1: Hump Yard Elevation Color Map

Table 1: Hump Yard Profiles

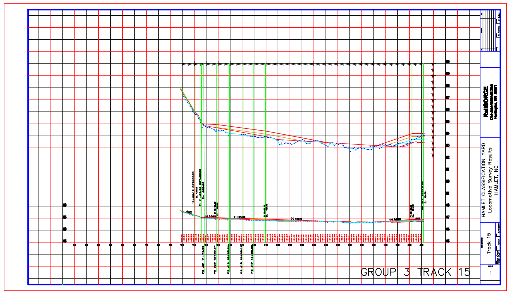
Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9
Track 15	Track 25	Track 33	Track 41	Track 49	Track 57	Track 65
Track 17	Track 26	Track 34	Track 42	Track 50	Track 58	Track 66
Track 18	Track 27	Track 35	Track 43	Track 51	Track 59	Track 67
Track 19	Track 28	Track 36	Track 44	Track 52	Track 60	Track 68
Track 20	Track 29	Track 37	Track 45	Track 53	Track 61	Track 69
Track 21	Track 30	Track 38	Track 46	Track 54	Track 62	Track 70
Track 22	Track 31	Track 39	Track 47	Track 55	Track 63	Track 71
Track 23	Track 32	Track 40	Track 48	Track 56	Track 64	Track 72
Track 24						Track 74

Hump Yard Profiles

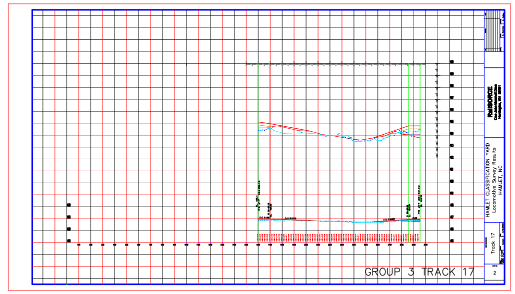
Table 1 note: Track group headings are hyperlinked to Excel workbooks containing track elevation data. Track numbers are hyperlinked to drawings.

Hamlet Terminal track number designation
The 1955 Hamlet terminal design planned for eleven groups. However only seven of the eleven track groups were constructed, totaling 58 tracks. Track groups one and two were never constructed, however track numbering follows the original eleven group numbering convention. Consequently, track numbering begins in group 3 with track 15, skips 16, and continue sequentially from track 17 through track 72, skips 73, concluding with track 74 in group 9.

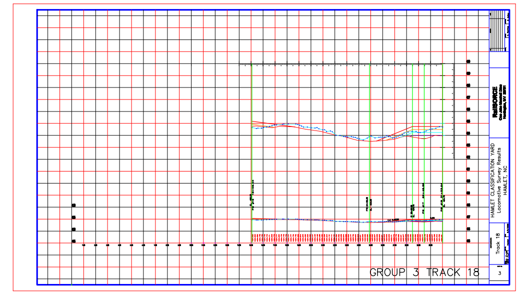
Figure 2: Group 3 Track Profile Thumbnails



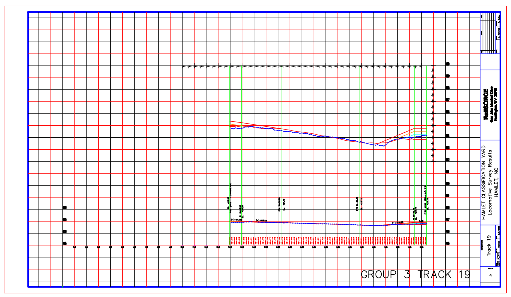
Track 15



Track 17



Track 19



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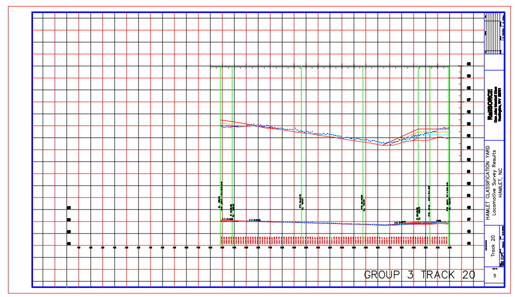
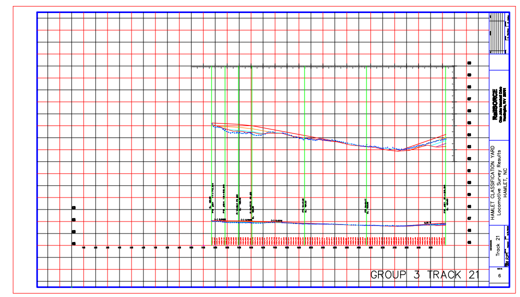


Track 20



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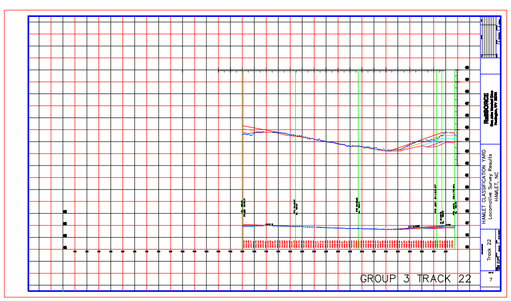
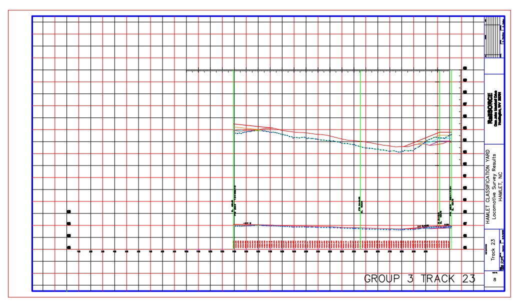


Track 22



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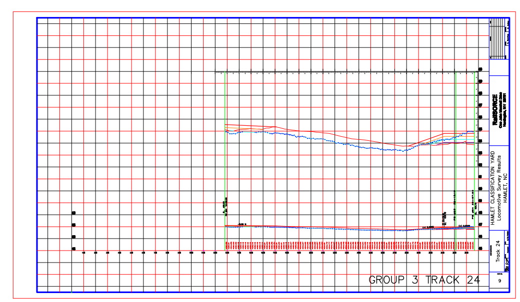
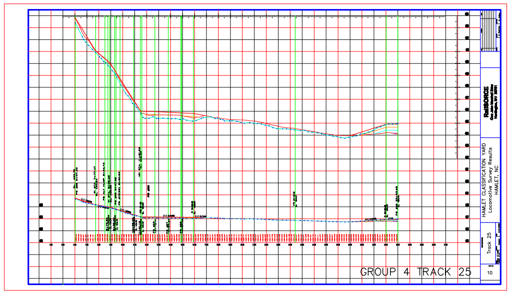
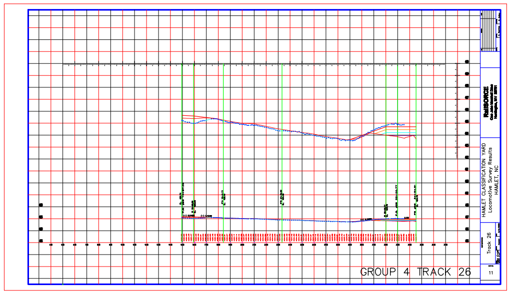


Track 24

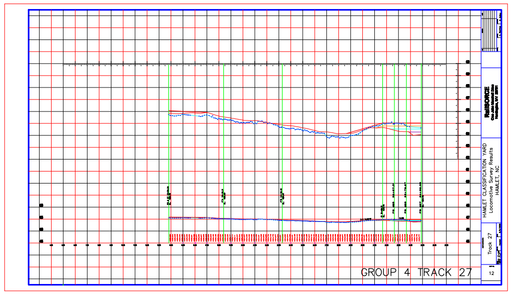
Figure 3: Group 4 Track Profile Thumbnails



Track 25



Track 26



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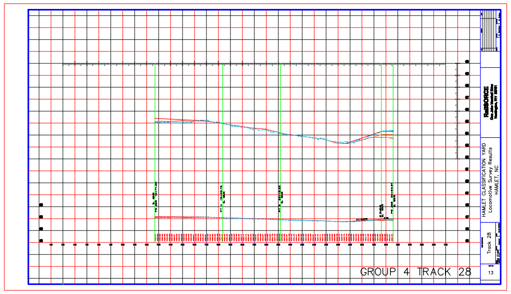

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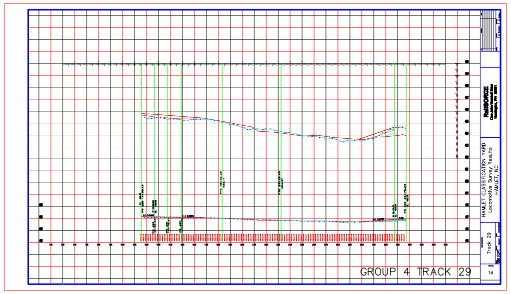

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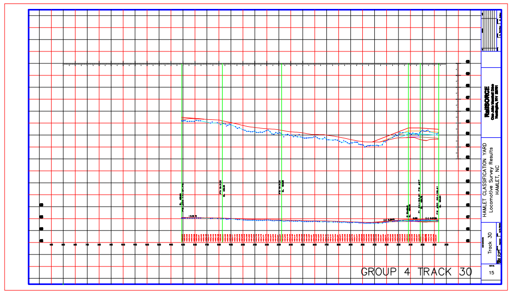

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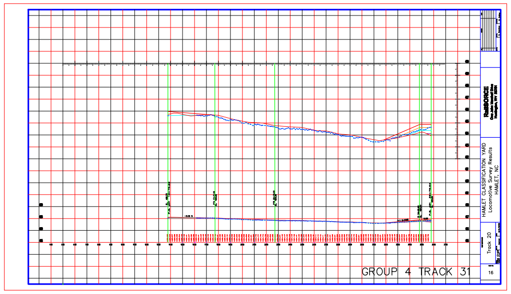

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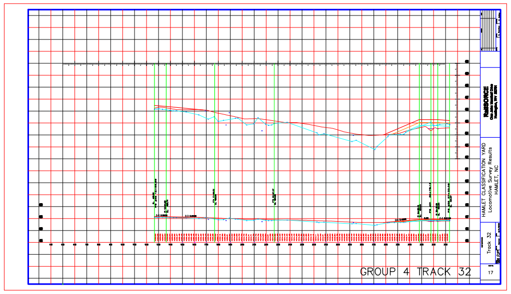
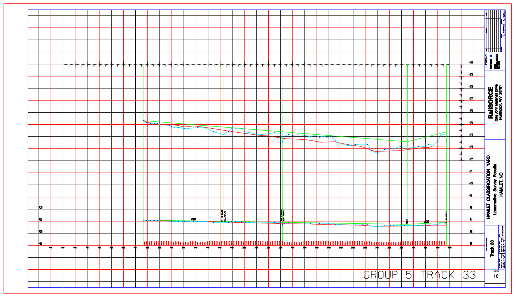
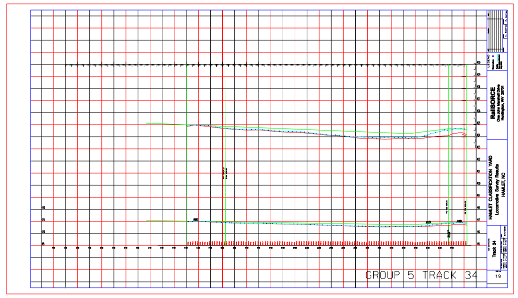


Track 32

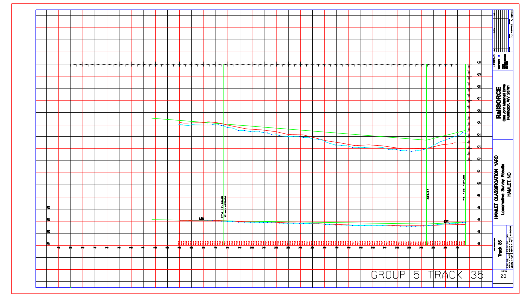
Figure 4: Group 5 Track Profile Thumbnails



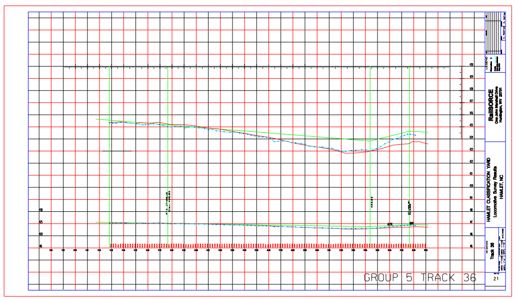
Track 33



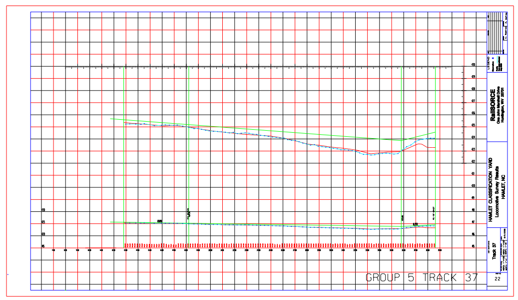
Track 34



Track 35



Track 36



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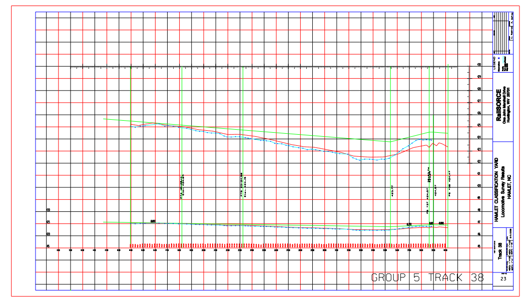

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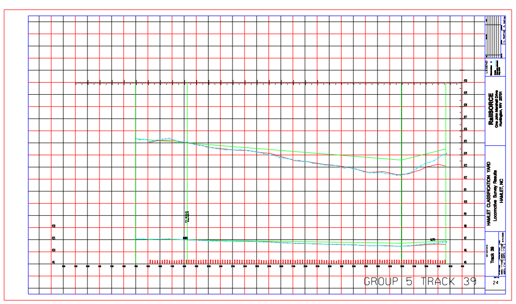

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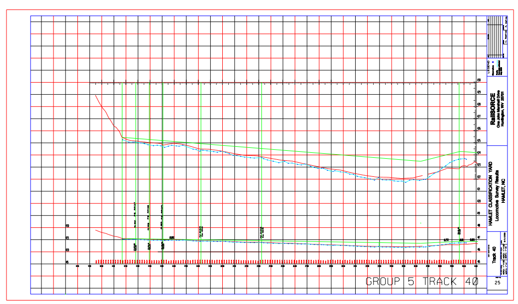
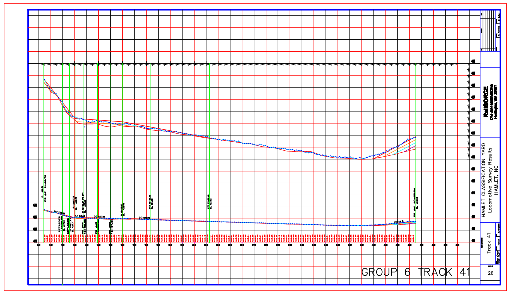


Track 40

Figure 5: Group 6 Track Profile Thumbnails



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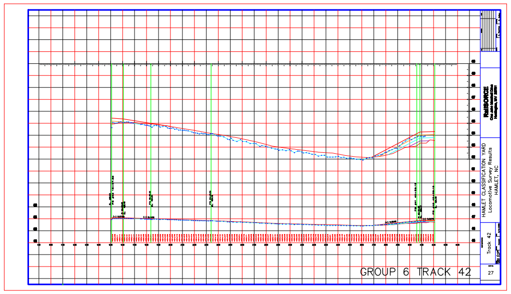

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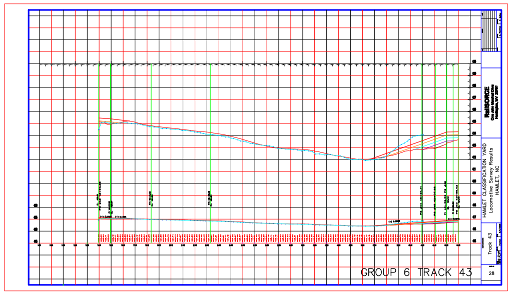

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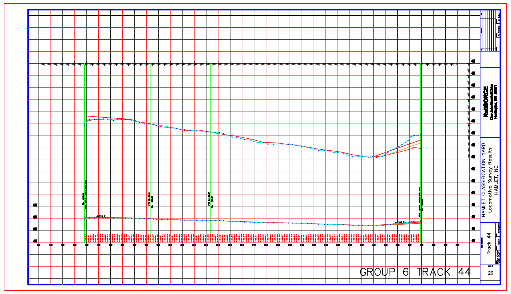

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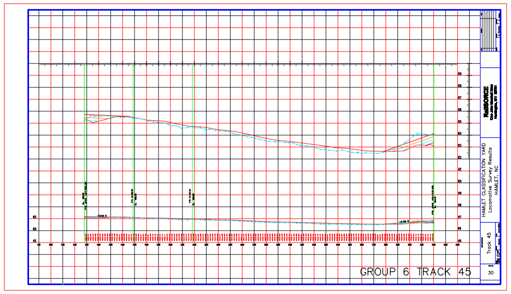

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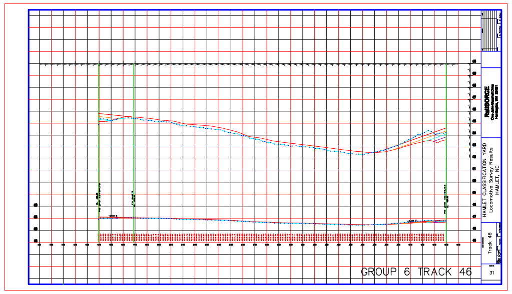

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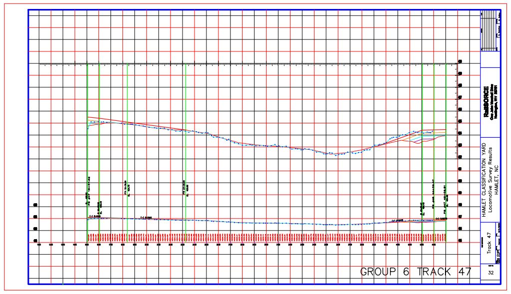

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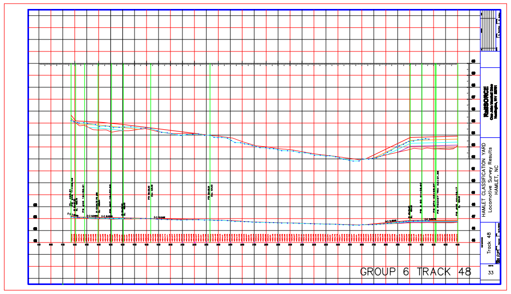
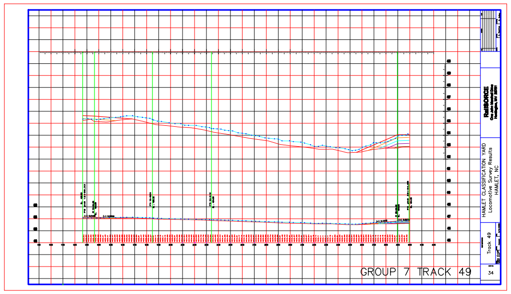


Track 48

Figure 6: Group 7 Track Profile Thumbnails



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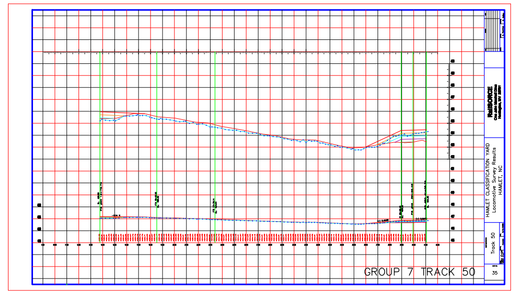
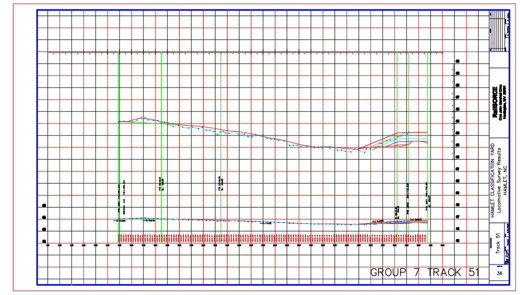


Track 50



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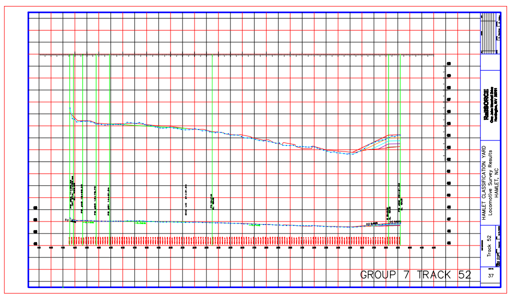

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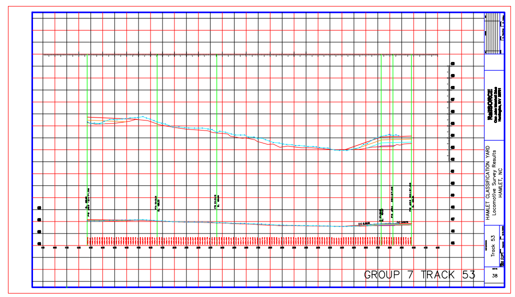

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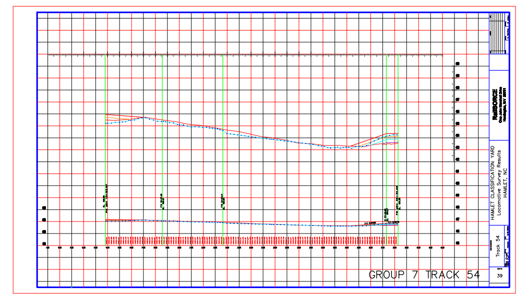

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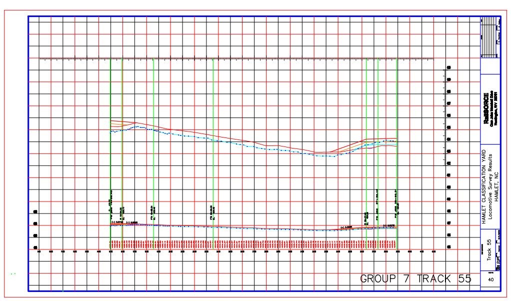

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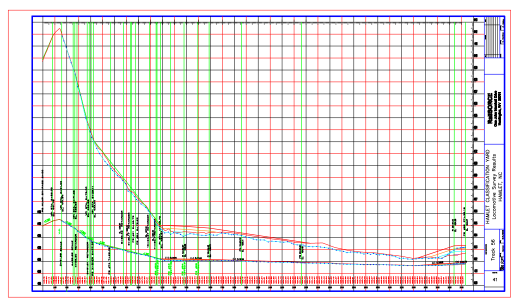
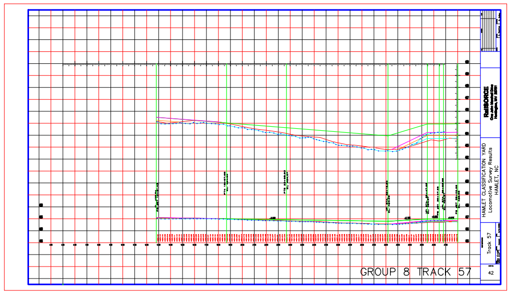


Track 56

Figure 7: Group 8 Track Profile Thumbnails



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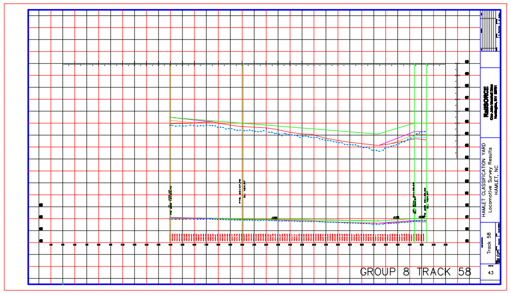

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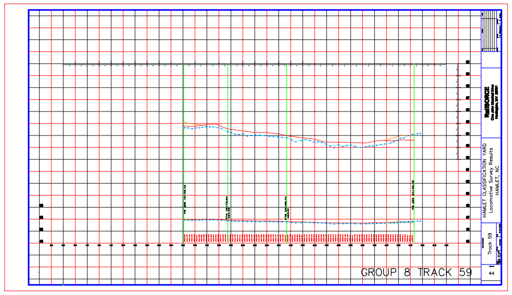

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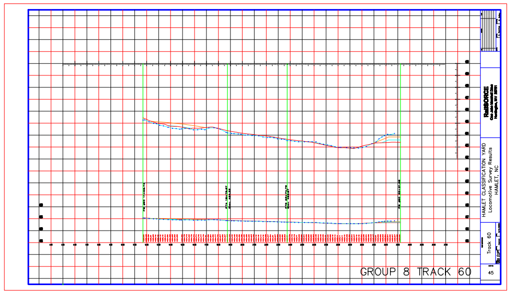

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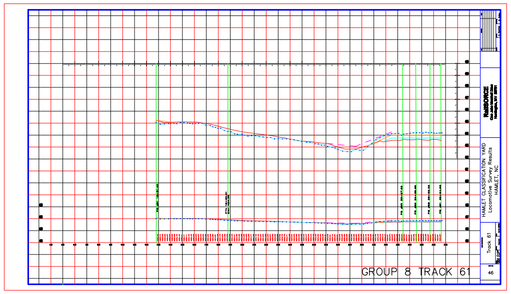

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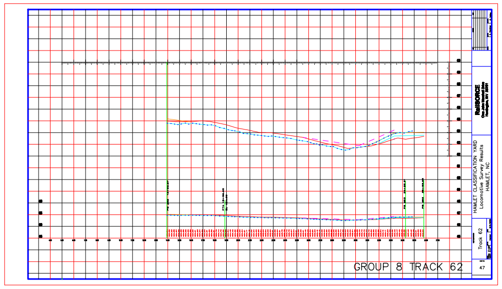

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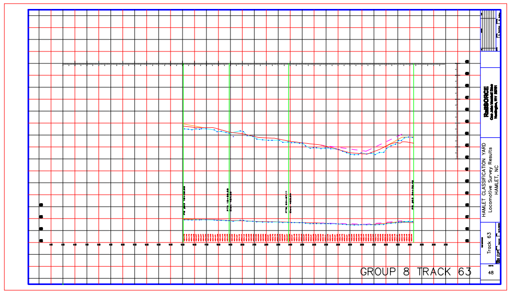

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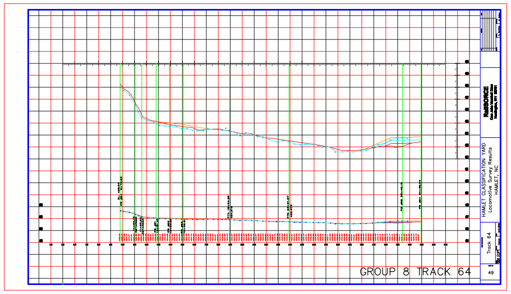
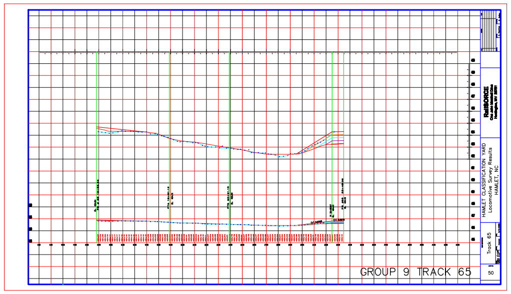


Track 64

Figure 8: Group 9 Track Profile Thumbnails



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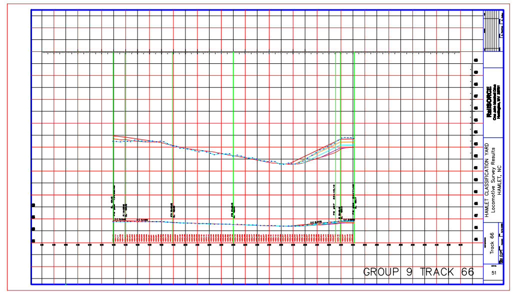

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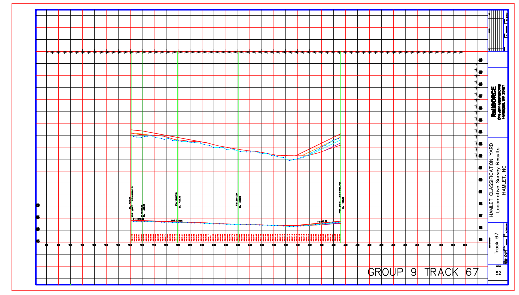

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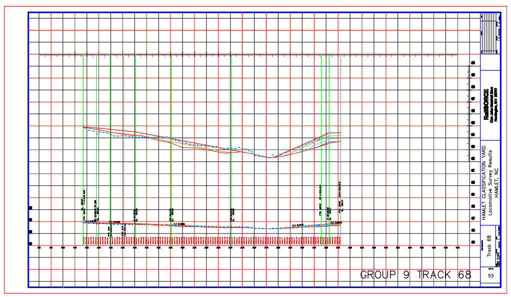

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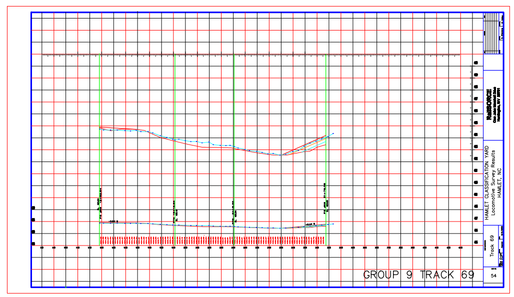

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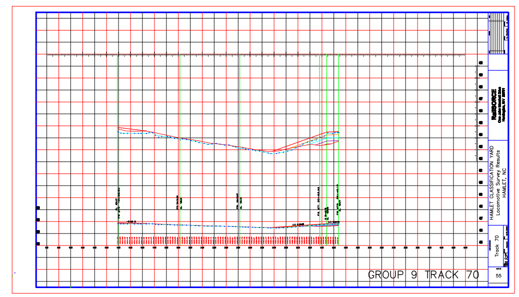

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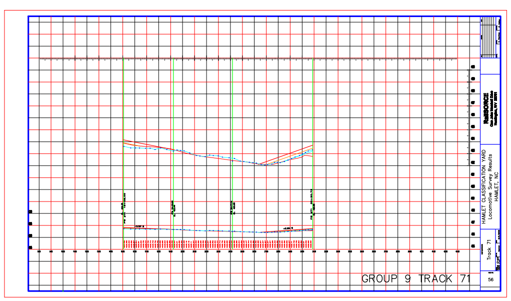

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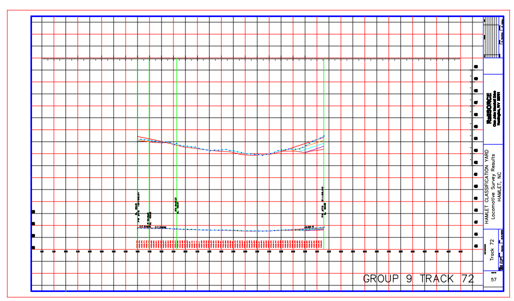

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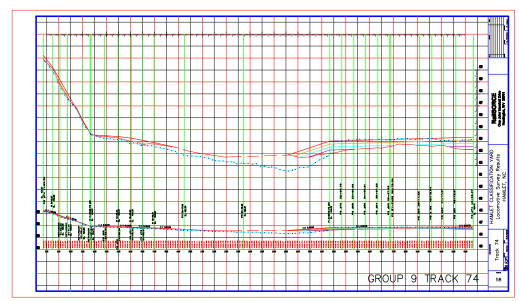


Track 74

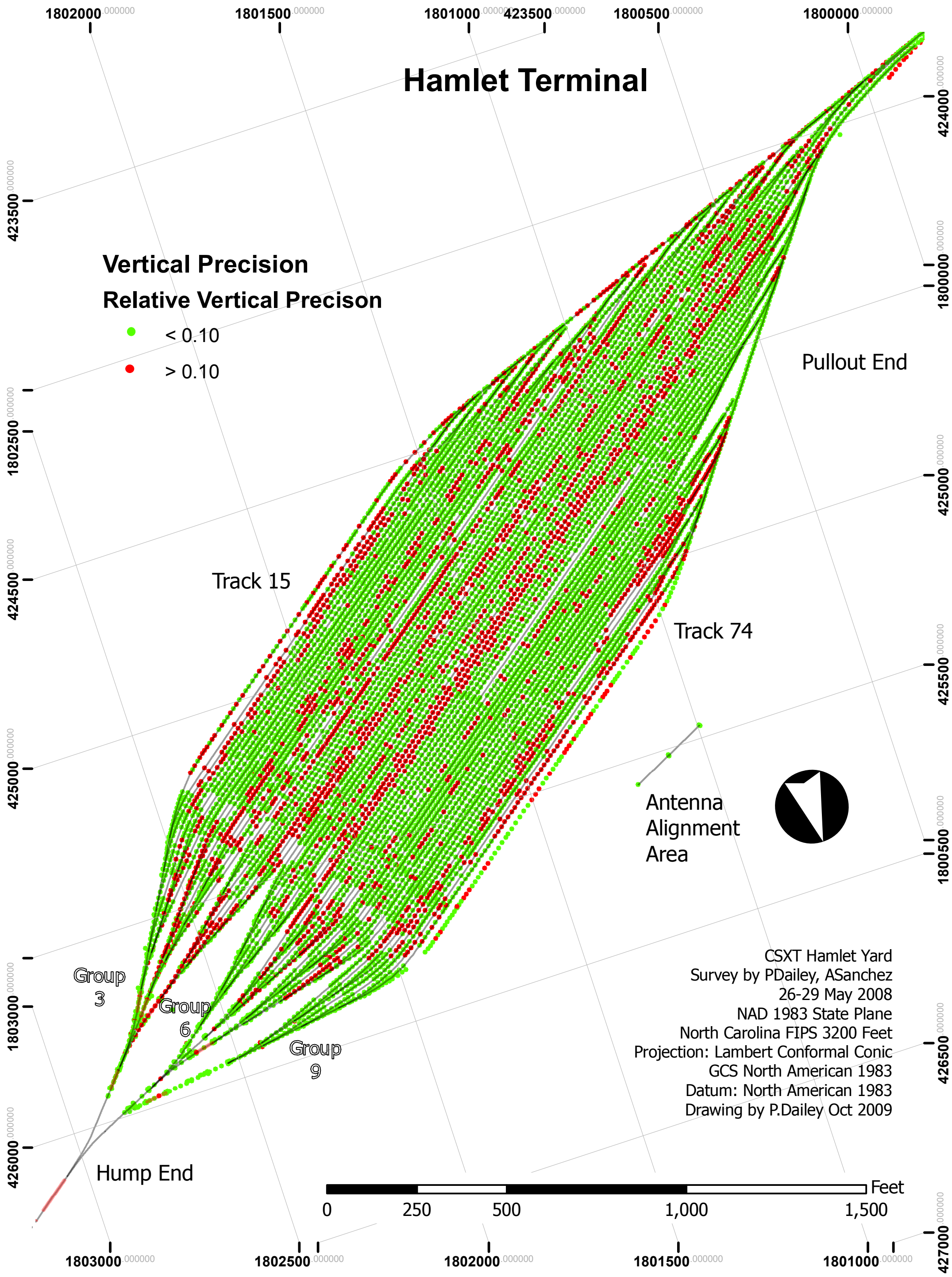


Figure 9: Relative Vertical Precision Color Map

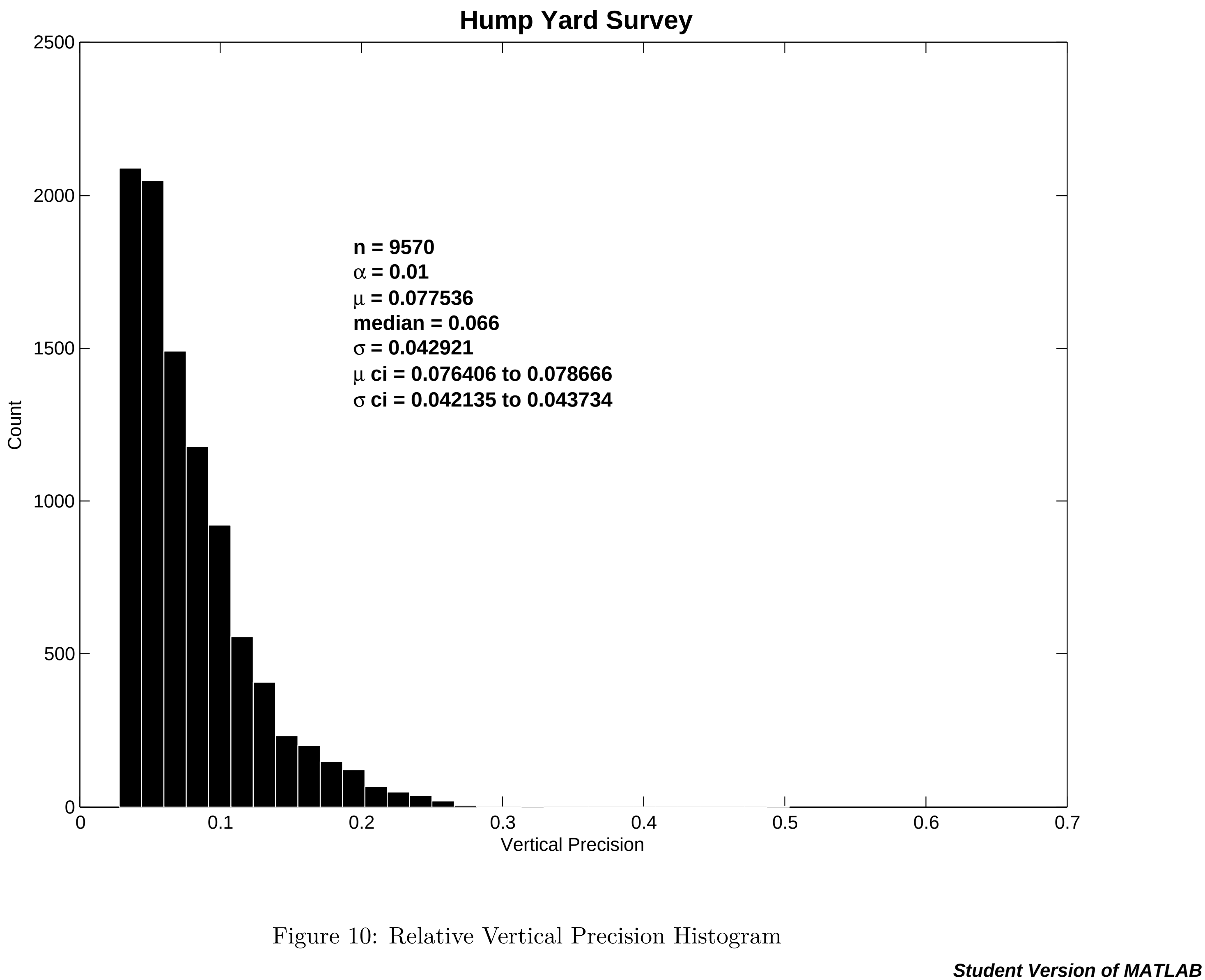


Figure 10: Relative Vertical Precision Histogram

Ad Hoc Reference Station TEQC Report

```
version: teqc  2009Oct19

 SV+------|----------------------------|----------------------------|-------+ SV
 10|Lo+______                                                               | 10
 26|LoCooCooCoooCooC_____                                                   | 26
 15|-oCooCooCoooCooCooCooC+_____                                            | 15
 24|LoCooCooCoooCooCooCooCo+____                                            | 24
 21|LoCooCooCoooCooCooCooCooCooCoooCooC+____                                | 21
  9|LoCooCooCoooCooCooCooCooCooCoooCooCooCooC+____                          |  9
 18|LoCooCooCoooCooCooCooCooCooCoooCooCooCooCooCooCooC+____                 | 18
 22|--CooCooCoooCooCooCooCooCooCoooCooCooCooCooCooCooCoooCooCooCooCo+____   | 22
  6|-oCooCooCoooCooCooCL+________                                   _____LoC|  6
 29|LoCooCooC+_____                                      ________LCooCooCooC| 29
 14|   ____-CoooCooCooCooCooCooCoooCooCooCooCooCooCooCoooCooCooCooCooCooCooC| 14
  5|               ______-1oCooCoooCooCooCooCooCooCooCoooCooCooC-_____      |  5
 12|                ______-oCooCoooCooCooCooCooCooCooCoooCo+____            | 12
 30|                    ______-CoooCooCooCooCooCooCooCoooCooCooCooCooCooC___| 30
 31|                        ____-ooCooCooCooCooCooCooCoooCooCooCooCooCooCooC| 31
 32|                              _____-oCooCooCooCooCoooCooCooCooCooCooCooC| 32
 16|                                                ____-CooCooCooCooCooCooC| 16
 20|                                                 ____-ooCooCooCooCooCooC| 20
 23|                                                            _____-LoCooC| 23
-dn|                                                                        |-dn
+dn|21     1             11   1 1      1                11       1   1   1  |+dn
+10|aaa9999aaa999999888888888778899999 9a99999988888888888789998888888888888888|+10
Pos|ooo    ooo                         o                                    |Pos
Clk|                                                                        |Clk
   +------|----------------------------|----------------------------|-------+
14:21:30.000                                                        21:44:00.000
2008 May 26                                                          2008 May 26\\
*********************
QC of RINEX  file(s) : 89691472.08o
input RnxNAV file(s) : 89691472.08n
*********************

4-character ID          : 8969
Receiver type           : 5700 (# = 0220288969) (fw = Version 2.24)
Antenna type            : TRM41249.00

Time of start of window : 2008 May 26  14:21:30.000
Time of  end  of window : 2008 May 26  21:44:00.000
Time line window length : 7.38 hour(s), ticked every 3.0 hour(s)
  antenna WGS 84 (xyz)  : 939936.1949 -5150619.6704 3630578.8636 (m)
  antenna WGS 84 (geo)  : N  34 deg 55' 08.47"  E 280 deg 20' 31.55"
  antenna WGS 84 (geo)  :   34.919020 deg   280.342098 deg (=  -79.657902 deg)
          WGS 84 height : 130.6405 m
|qc - header| position  : 40 m
Observation interval    : 15.0000 seconds
Total satellites w/ obs : 19
NAVSTAR GPS SVs w/o OBS :  1   2   3   4   7   8  11  13  17  19  25  27  28
NAVSTAR GPS SVs w/o NAV :
Rx tracking capability  : 24 SVs
```

```
Poss. # of obs epochs   :   1771
Epochs w/ observations  :   1771
Epochs repeated         :      0  (0.00\%)
Possible obs >   0.0 deg:  17729
Possible obs >  10.0 deg:  14739
Complete obs >  10.0 deg:  14666
  Missed obs >  10.0 deg:     59
 Deleted obs >  10.0 deg:     14
Obs w/ SV duplication   :      0  (within non-repeated epochs)
Moving average MP1      : 0.379945 m
Moving average MP2      : 0.516314 m
Points in MP moving avg : 50
No. of Rx clock offsets : 0
Total Rx clock drift    :  0.000000 ms
Rate of Rx clock drift  :  0.000 ms/hr
Avg time between resets : Inf minute(s)
Freq no. and timecode   : 2 10368 3fc000
Report gap > than       : 10.00 minute(s)
epochs w/ msec clk slip : 23
other msec mp events    : 0 (: 384)   {expect ~= 1:50}
IOD signifying a slip   : >400.0 cm/minute
IOD slips <  10.0 deg*  :      0
IOD slips >  10.0 deg   :      0
IOD or MP slips <  10.0*:      0
IOD or MP slips >  10.0 :    191
 * or unknown elevation
      first epoch    last epoch    hrs   dt  #expt  #have   \%   mp1   mp2 o/slps
SUM 08  5 26 14:21 08  5 26 21:44 7.379  15  14739  14666 100  0.38  0.52     77

Processing parameters are:
Receiver tracking capability       : 24 SVs
Maximum ionospheric rate (L1)      : 400.00 cm/min
Report data gap greater than       : 10.00 min
Expected rms of MP1 multipath      : 50.00 cm
Expected rms of MP2 multipath      : 65.00 cm
Multipath slip sigma threshold     : 4.00 cm
\% increase in MP rms for C/A | A/S : 100.00 \%
Points in MP moving averages       : 50
Minimum signal to noise for L1     : 0
Minimum signal to noise for L2     : 0
Elevation mask (cutoff)            : 10.00 degrees
Elevation comparison threshold     : 25.00 degrees
Orbit path spline fit sample time  : 10 min
SVs w/ code data for position try  : 5
Width of ASCII summary plot        : 72
Data indicators on summary plot    : yes
Do ionospheric observable          : yes
Do ionospheric derivative          : yes
Do high-pass ionosphere observable : no
Do multipath observables           : yes
Do 1-ms receiver clock slips       : yes
Tolerance for 1-ms clock slips     : 1.00e-02 ms
Do receiver LLI slips              : yes
Do plot file(s)                    : yes
```

```
Observations start   : 2008 May 26 14:21:30.000
Observations  end    : 2008 May 26 21:44:00.000
Observation interval : 15.0000 second(s)

 SV  #+hor <ele> #+mask <ele> #reprt #compl    L1     L2     P1     P2     CA    L2C
--- ------ ----- ------ ----- ------ ------ ------ ------ ------ ------ ------ ------
G10    204  6.67     51 11.76     51     44     47     47      0     47     51      0
G18   1332 47.02   1231 50.47   1231   1231   1231   1231      0   1231   1231      0
G21    980 48.20    875 53.40    875    875    875    875      0    875    875      0
G24    671 35.75    570 41.22    570    570    570    570      0    570    570      0
G26    498 23.02    378 28.77    378    378    378    378      0    378    378      0
G29    812 12.42    498 17.07    497    496    497    496      0    496    497      0
G09   1119 37.70   1012 41.16   1012   1011   1012   1011      0   1011   1012      0
G15    679 29.33    546 35.28    542    542    542    542      0    542    542      0
G06    888 11.65    568 15.42    558    553    557    554      0    554    558      0
G22   1682 43.62   1565 46.47   1553   1553   1553   1553      0   1553   1553      0
G14   1693 42.02   1581 44.64   1578   1578   1578   1578      0   1578   1578      0
G05   1217 22.51    958 27.27    954    954    954    954      0    954    954      0
G12   1077 17.79    806 22.11    803    803    803    803      0    803    803      0
G30   1266 26.70   1046 31.19   1042   1042   1042   1042      0   1042   1042      0
G31   1163 47.77   1064 51.76   1060   1060   1060   1060      0   1060   1060      0
G32   1030 41.03    908 45.88    904    904    904    904      0    904    904      0
G16    578 31.76    476 37.52    472    472    472    472      0    472    472      0
G20    562 24.12    454 28.66    452    452    452    452      0    452    452      0
G23    278 11.33    152 16.66    148    148    148    148      0    148    148      0

Obs below mask ( 10.00 deg)   :     18
Obs above mask w/ no L1       :      5
Obs above mask w/ no L2       :     10
Obs above mask w/ no P1 | CA  :      0
Obs above mask w/ no P2 | L2C :     10
Obs above mask w/ low L1 S/N  :      0
Obs above mask w/ low L2 S/N  :      0

Obs reported w/ code | phase :  14698
Obs deleted (any reason)     :     32
Obs complete                 :  14666

No. of Rx clock offsets : 0
Total Rx clock drift    :  0.000000 ms
Rate of Rx clock drift  :  0.000000 ms/hr

elev (deg)  tot slps <ION rms, m>        5=\%       1|m      15=\%       2|m
 85 - 90      0    0   0.000000
 80 - 85    179    0   0.000000
 75 - 80    225    0   0.000000
 70 - 75    373    0   0.000000
 65 - 70    806    0   0.000000
 60 - 65   1019    0   0.000000
 55 - 60   1163    0   0.000000
 50 - 55    897    0   0.000000
 45 - 50    890    0   0.000000
 40 - 45   1025    0   0.000000
```

```
 35 - 40   1207    0   0.000000
 30 - 35   1082    0   0.000000
 25 - 30   1408    0   0.000000
 20 - 25   1206    0   0.000000
 15 - 20   1625    0   0.000000
 10 - 15   1542    0   0.000000
  5 - 10     18    0   0.000000
  0 -  5      0    0   0.000000
    <  0      0    0   0.000000

MP1  RMS summary (per SV):
                                       slips  L1 rx  L2 rx  slips  L1 rx  L2 rx
 SV  obs>10  # del <elev> MP1  rms [m]  < 25   < 25   < 25   > 25   > 25   > 25
G10     51      7   13.36  0.923253      0      2      5      0      0      0
G18   1231      0   50.50  0.347035      2      0      0     14      1      1
G21    875      0   53.43  0.325922      2      0      0      9      1      1
G24    570      0   41.25  0.397141      2      0      0      5      1      1
G26    378      0   28.88  0.412081      3      0      0      2      1      1
G29    497      1   17.22  0.618820      6      1      1      1      1      1
G09   1012      1   41.24  0.312861      2      1      1     11      0      0
G15    542      0   35.11  0.370183      3      0      0      4      1      1
G06    558      5   15.65  0.610298      7      3      5      0      0      0
G22   1553      0   46.80  0.367457      5      1      1     15      0      0
G14   1578      0   44.76  0.384592      3      1      1     18      0      0
G05    954      0   27.43  0.391200      6      2      2      8      0      0
G12    803      0   22.25  0.414531      6      1      1      4      0      0
G30   1042      0   31.34  0.396713      4      1      1     10      0      0
G31   1060      0   51.99  0.289880      2      1      1     12      0      0
G32    904      0   46.13  0.304541      2      1      1     10      0      0
G16    472      0   37.92  0.357017      2      1      1      5      0      0
G20    452      0   28.92  0.379451      2      1      1      4      0      0
G23    148      0   17.37  0.384658      2      1      1      0      0      0

mean MP1  rms         :  0.379997 m
total mean elevation : 39.02 degrees
# MP1  obs > 10       :  14666
# qc MP1  slips < 25  :     61
# Rvr L1 slips < 25  :     18
# Rvr L2 slips < 25  :     23
# qc MP1  slips > 25  :    132
# Rvr L1 slips > 25  :      6
# Rvr L2 slips > 25  :      6

elev (deg)  tot slps <MP1  rms, m>        5=\%       1|m      15=\%       2|m
 85 - 90      0    0   0.000000
 80 - 85    179    2   0.239693  ##|||
 75 - 80    225    3   0.210178  ##||
 70 - 75    373    4   0.243548  ##|||
 65 - 70    806   12   0.229097  ##|||
 60 - 65   1019   10   0.235793  #||||
 55 - 60   1163   19   0.257506  ###||
 50 - 55    897    8   0.301766  #|||||
 45 - 50    890   14   0.313660  ###|||
 40 - 45   1025   12   0.279523  ##||||
```

```
 35 - 40   1207   17   0.304659  ##||||
 30 - 35   1082   16   0.335762  ##|||||
 25 - 30   1408   15   0.378914  ##||||||
 20 - 25   1206   14   0.421666  ##||||||
 15 - 20   1625   24   0.478295  ##||||||||
 10 - 15   1542   23   0.682098  ##||||||||||||
  5 - 10     18    0   0.643854  |||||||||||||
  0 -  5      0    0   0.000000
    <  0      0    0   0.000000

MP2  RMS summary (per SV):
                                      slips  L1 rx  L2 rx  slips  L1 rx  L2 rx
 SV  obs>10  # del <elev> MP2  rms [m]  < 25   < 25   < 25   > 25   > 25   > 25
G10     51      7   13.36  1.413000      0      2      5      0      0      0
G18   1231      0   50.50  0.396074      2      0      0     14      1      1
G21    875      0   53.43  0.388736      2      0      0      9      1      1
G24    570      0   41.25  0.385116      2      0      0      5      1      1
G26    378      0   28.88  0.464846      3      0      0      2      1      1
G29    497      1   17.22  0.962715      6      1      1      1      1      1
G09   1012      1   41.24  0.436712      2      1      1     11      0      0
G15    542      0   35.11  0.562902      3      0      0      4      1      1
G06    558      5   15.65  1.008073      7      3      5      0      0      0
G22   1553      0   46.80  0.463067      5      1      1     15      0      0
G14   1578      0   44.76  0.501127      3      1      1     18      0      0
G05    954      0   27.43  0.622019      4      2      2      8      0      0
G12    803      0   22.25  0.632334      6      1      1      4      0      0
G30   1042      0   31.34  0.606855      4      1      1     10      0      0
G31   1060      0   51.99  0.417034      2      1      1     12      0      0
G32    904      0   46.13  0.376080      2      1      1     10      0      0
G16    472      0   37.92  0.464800      2      1      1      5      0      0
G20    452      0   28.92  0.395601      2      1      1      4      0      0
G23    148      0   17.37  0.561845      2      1      1      0      0      0

mean MP2  rms         :  0.516399 m
total mean elevation : 39.02 degrees
# MP2  obs > 10       :  14666
# qc MP2  slips < 25  :     59
# Rvr L1 slips < 25  :     18
# Rvr L2 slips < 25  :     23
# qc MP2  slips > 25  :    132
# Rvr L1 slips > 25  :      6
# Rvr L2 slips > 25  :      6

elev (deg)  tot slps <MP2  rms, m>       5=\%       1|m      15=\%       2|m
 85 - 90      0    0   0.000000
 80 - 85    179    2   0.206162  ##||
 75 - 80    225    3   0.253823  ##|||
 70 - 75    373    4   0.242799  ##|||
 65 - 70    806   12   0.258877  ##|||
 60 - 65   1019   10   0.265736  #||||
 55 - 60   1163   19   0.272441  ###||
 50 - 55    897    8   0.318394  #|||||
 45 - 50    890   14   0.347364  ###||||
 40 - 45   1025   12   0.451888  ##|||||||
```

```
 35 - 40   1207   17   0.418142  ##||||||
 30 - 35   1082   16   0.522575  ##||||||||
 25 - 30   1408   15   0.569631  ##|||||||||
 20 - 25   1206   14   0.597640  ##||||||||||
 15 - 20   1625   24   0.673954  ##|||||||||||
 10 - 15   1542   21   0.993207  ##||||||||||||||||||
  5 - 10     18    0   0.735622  |||||||||||||||
  0 -  5      0    0   0.000000
    <  0      0    0   0.000000

S/N L1 summary (per elevation bin):
elev (deg)  tot SN1 sig    mean                    0|5                 1|0
 85 - 90      0   0.000    0.000
 80 - 85    179   0.686    6.966 ###|||||||||||||||||||||||||
 75 - 80    225   0.511    6.920 ##||||||||||||||||||||||||||
 70 - 75    374   0.456    6.893 ##||||||||||||||||||||||||||
 65 - 70    806   0.342    6.931 #|||||||||||||||||||||||||||
 60 - 65   1020   0.388    6.888 ##||||||||||||||||||||||||||
 55 - 60   1164   0.358    6.912 #|||||||||||||||||||||||||||
 50 - 55    897   0.432    6.833 ##|||||||||||||||||||||||||
 45 - 50    891   0.500    6.718 ##|||||||||||||||||||||||||
 40 - 45   1026   0.526    6.620 ##||||||||||||||||||||||||
 35 - 40   1207   0.509    6.307 ##|||||||||||||||||||||||
 30 - 35   1083   0.361    6.014 #|||||||||||||||||||||||
 25 - 30   1408   0.342    5.929 #|||||||||||||||||||||||
 20 - 25   1208   0.556    5.617 ##||||||||||||||||||||
 15 - 20   1625   0.684    5.297 ###||||||||||||||||||
 10 - 15   1562   0.924    4.624 ####||||||||||||||
  5 - 10     18   1.339    4.167 #####||||||||||||
  0 -  5      0   0.000    0.000

S/N L2 summary (per elevation bin):
elev (deg)  tot SN2 sig    mean                    0|5                 1|0
 85 - 90      0   0.000    0.000
 80 - 85    179   0.796    8.648 ###||||||||||||||||||||||||||||||||
 75 - 80    225   0.744    8.364 ###||||||||||||||||||||||||||||||
 70 - 75    374   0.665    8.535 ###|||||||||||||||||||||||||||||||
 65 - 70    806   0.485    8.176 ##|||||||||||||||||||||||||||||||
 60 - 65   1020   0.293    8.016 #|||||||||||||||||||||||||||||||
 55 - 60   1164   0.431    8.145 ##|||||||||||||||||||||||||||||||
 50 - 55    897   0.330    8.020 #|||||||||||||||||||||||||||||||
 45 - 50    891   0.309    7.969 #|||||||||||||||||||||||||||||||
 40 - 45   1026   0.439    7.834 ##|||||||||||||||||||||||||||||
 35 - 40   1207   0.516    7.326 ##|||||||||||||||||||||||||||
 30 - 35   1083   0.454    7.141 ##|||||||||||||||||||||||||||
 25 - 30   1408   0.488    6.959 ##||||||||||||||||||||||||||
 20 - 25   1207   0.529    6.574 ##||||||||||||||||||||||||
 15 - 20   1625   0.466    6.226 ##|||||||||||||||||||||||
 10 - 15   1558   0.436    5.937 ##||||||||||||||||||||||
  5 - 10     18   1.420    5.389 ######||||||||||||||||
  0 -  5      0   0.000    0.000
```

Appendix B

String Line Model Output

CSX Huntington Division East, Kanawha Subdivision

Mile Post 494 to 523

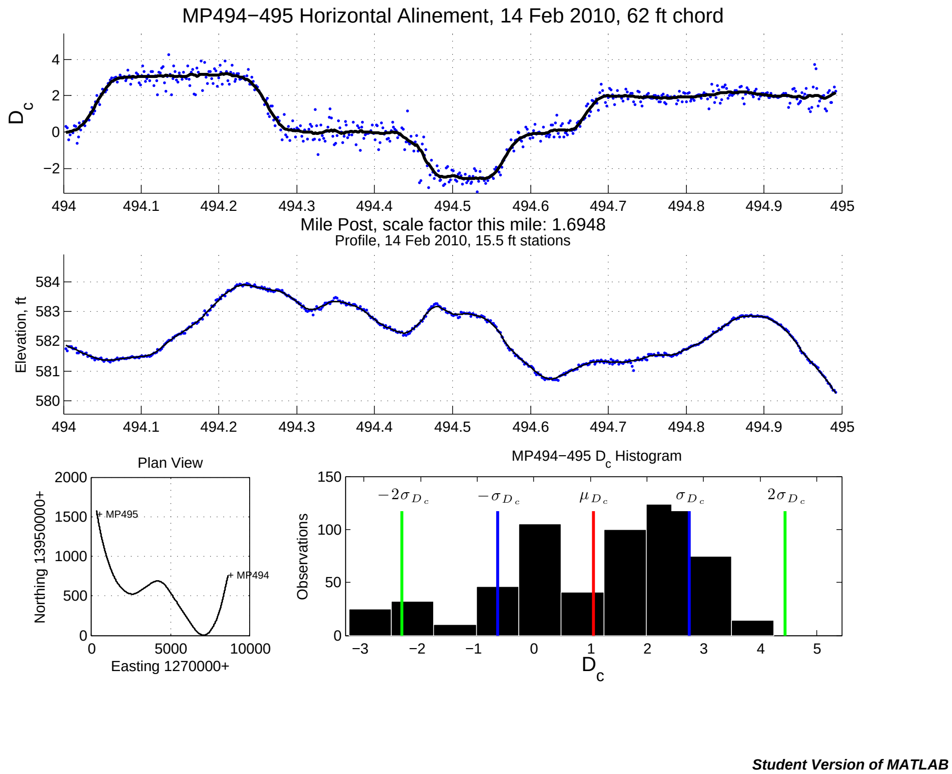


Figure 11: Hi-Rail Alinement, Kanawha Sub, MP 494-495

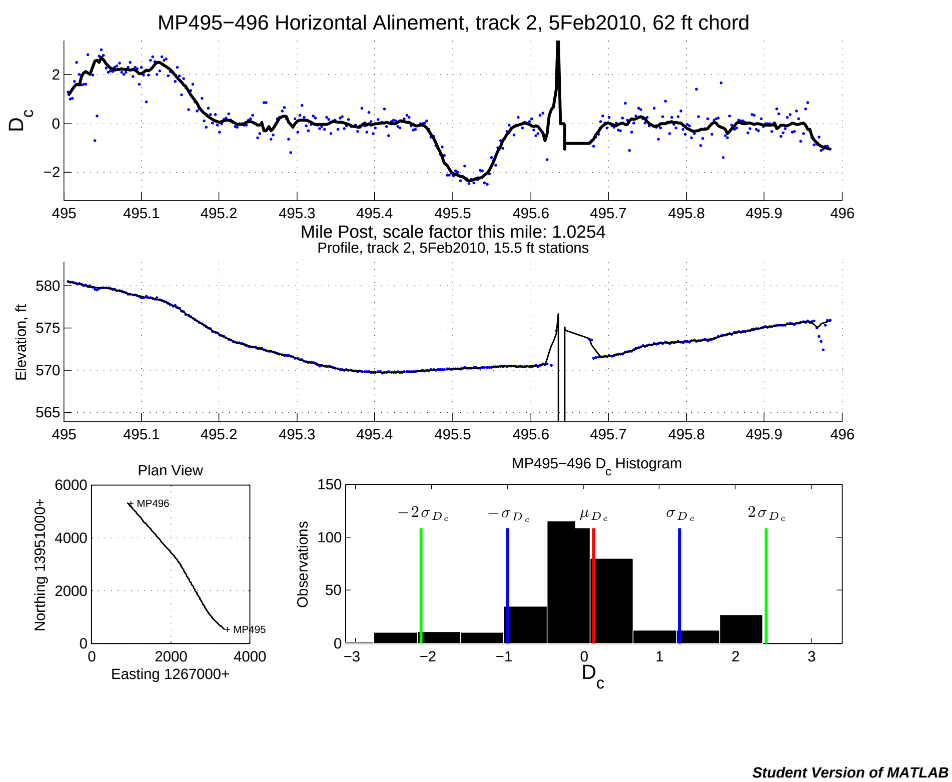


Figure 12: Hi-Rail Alinement, Kanawha Sub, MP 495-496

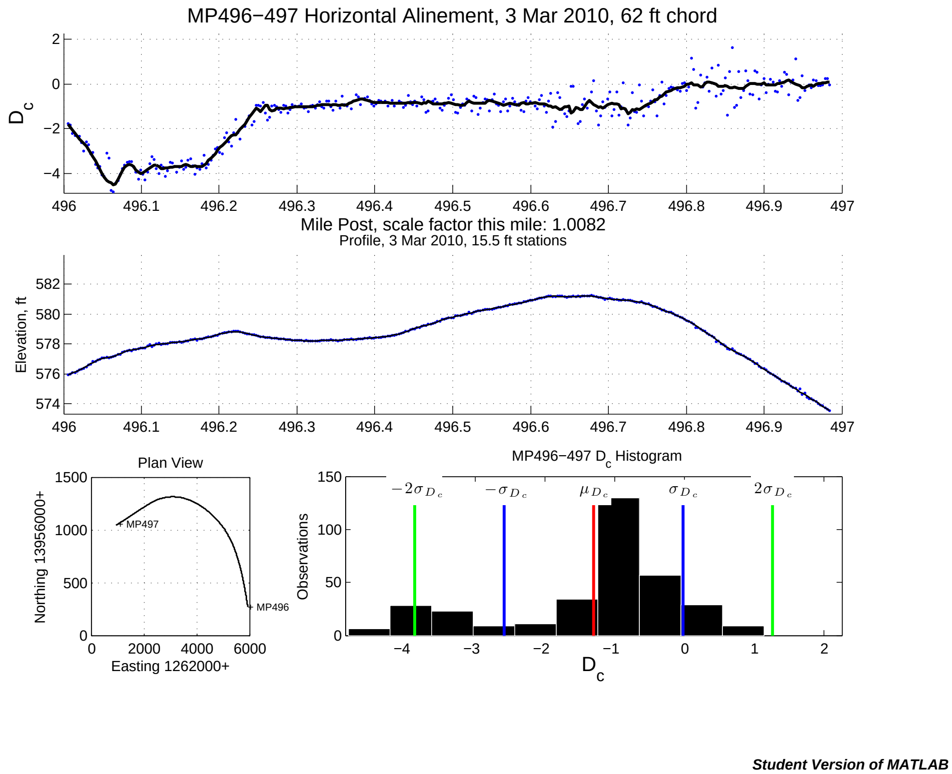


Figure 13: Hi-Rail Alinement, Kanawha Sub, MP 496-497

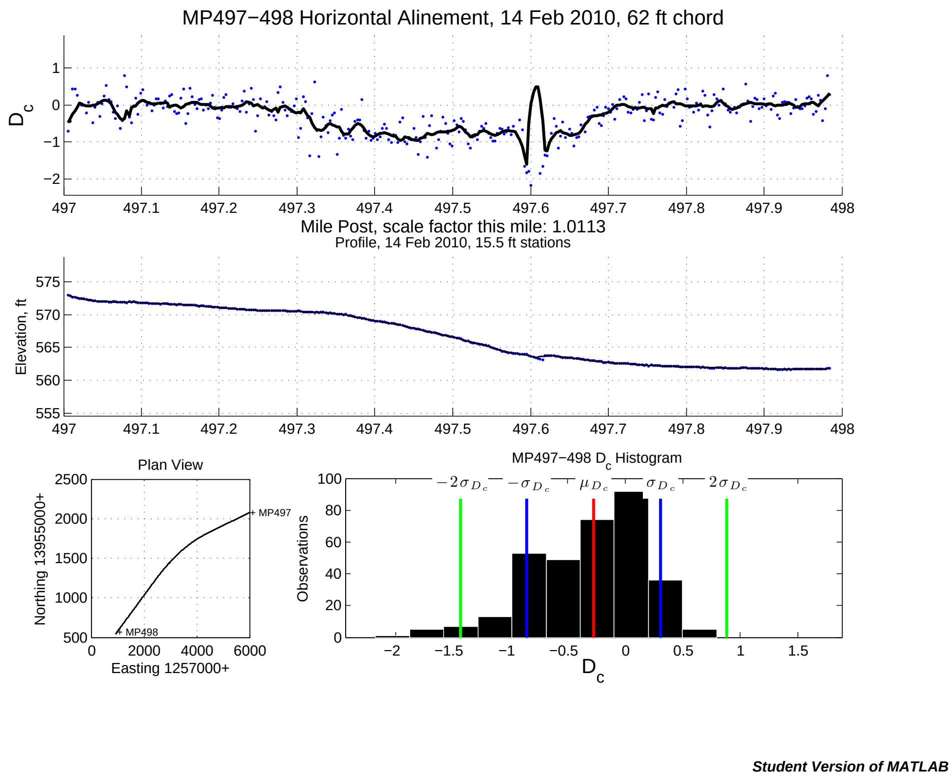


Figure 14: Hi-Rail Alinement, Kanawha Sub, MP 497-498

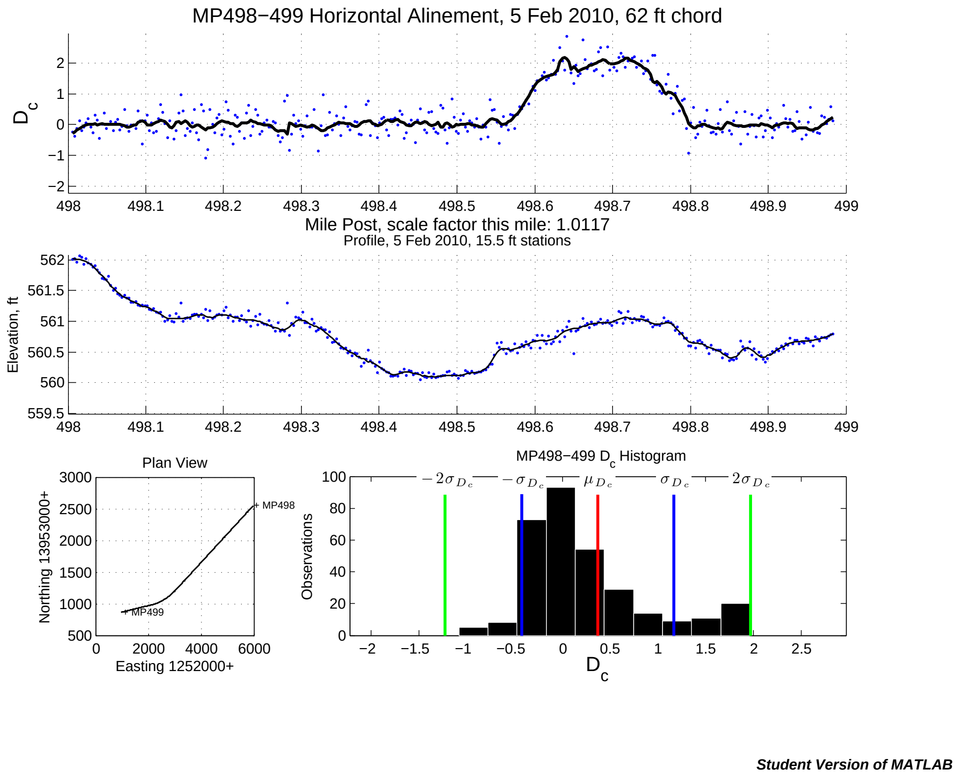


Figure 15: Hi-Rail Alinement, Kanawha Sub, MP 498-499

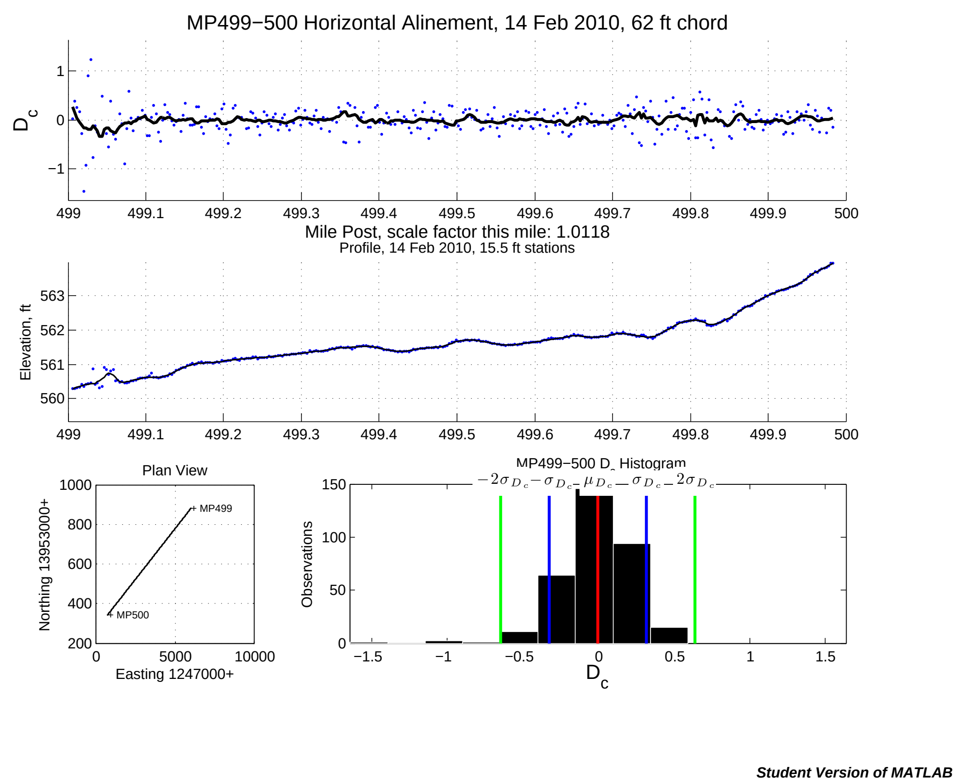


Figure 16: Hi-Rail Alinement, Kanawha Sub, MP 499-500

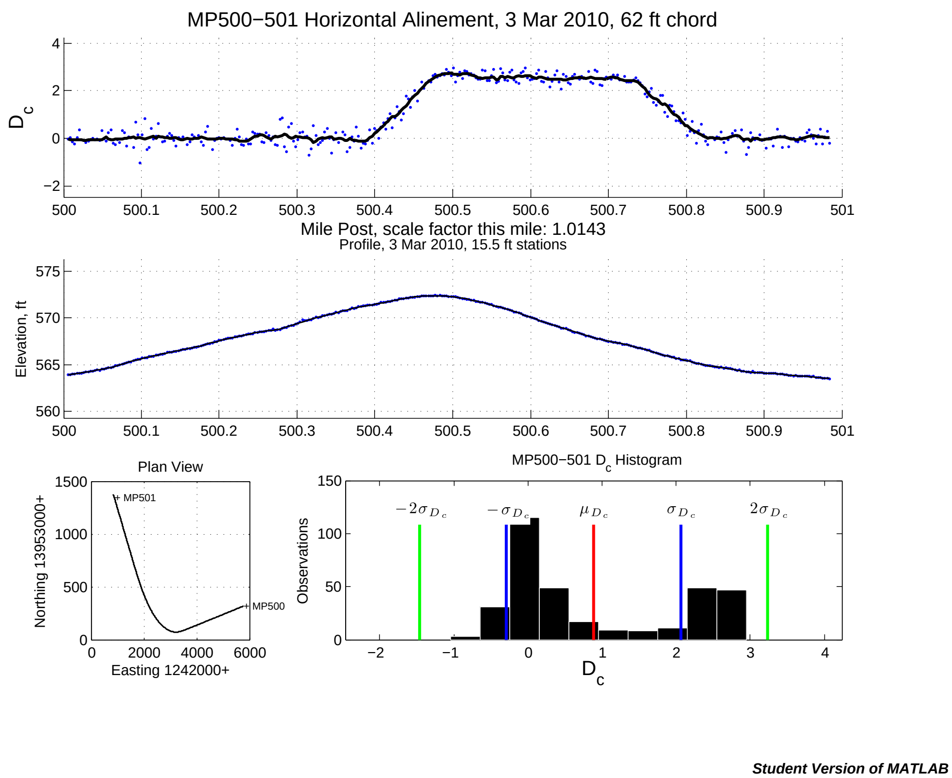


Figure 17: Hi-Rail Alinement, Kanawha Sub, MP 500-501

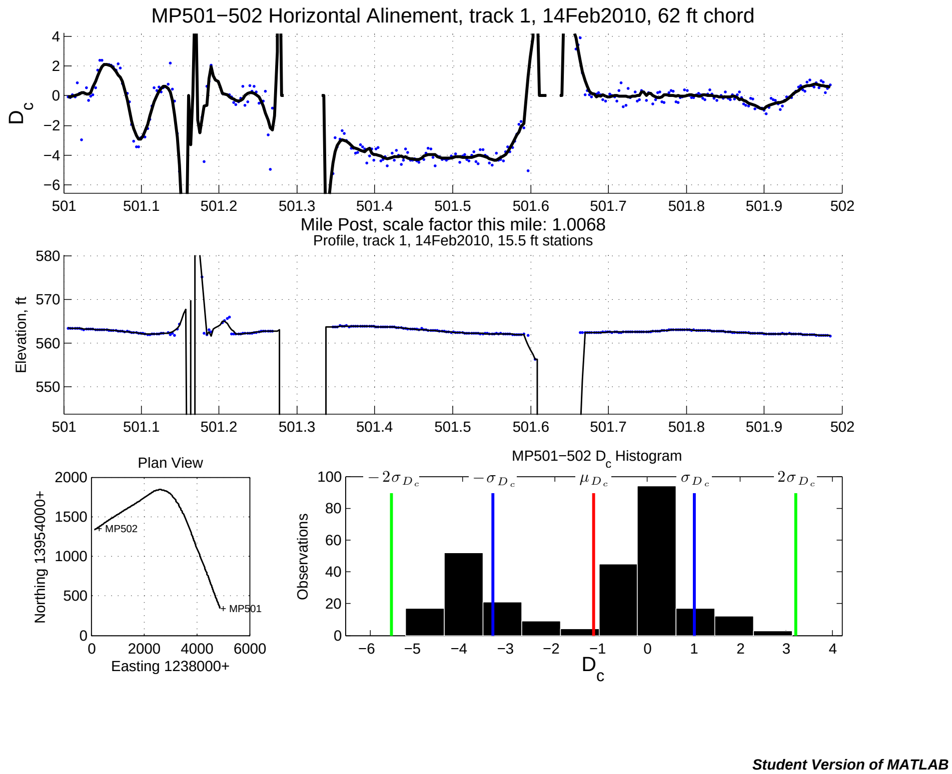


Figure 18: Hi-Rail Alinement, Kanawha Sub, MP 501-502

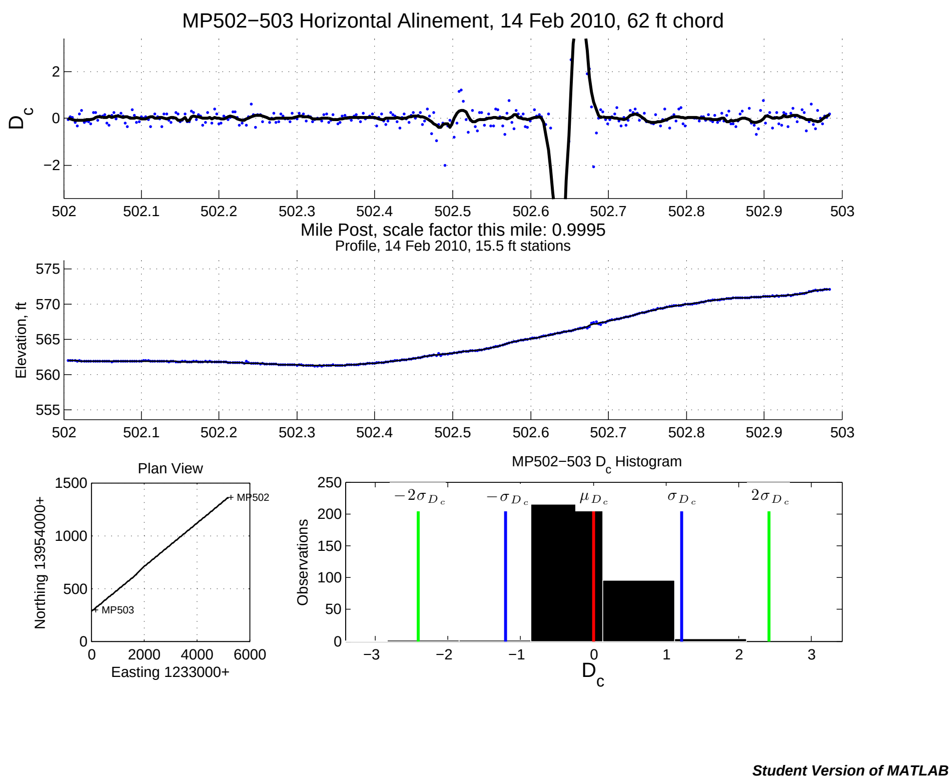


Figure 19: Hi-Rail Alinement, Kanawha Sub, MP 502-503

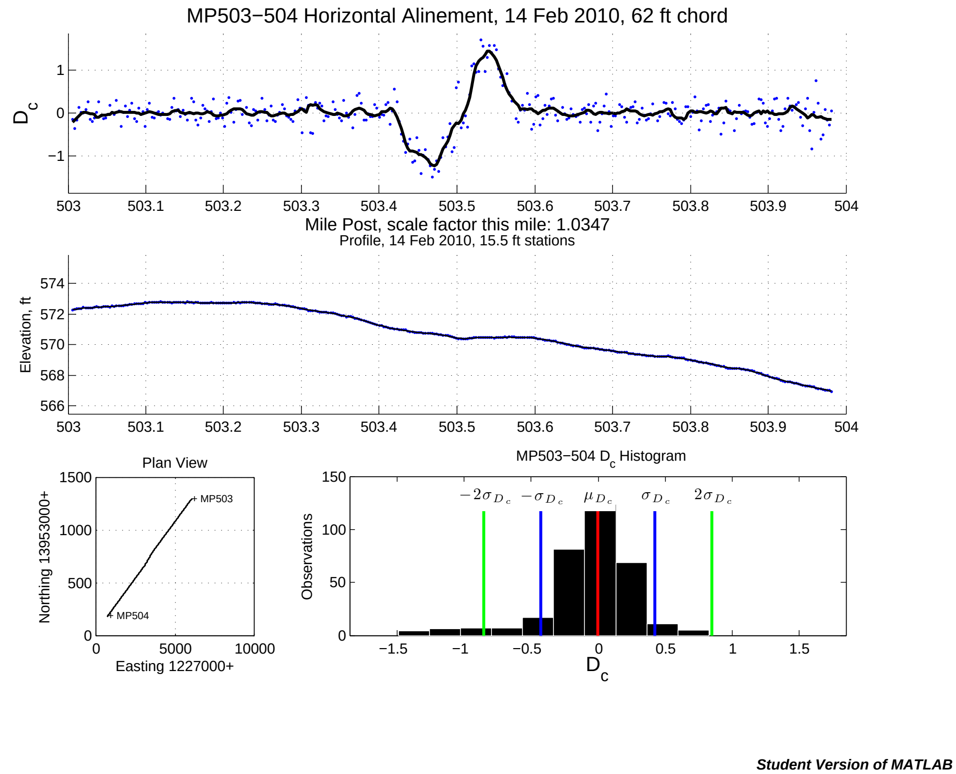


Figure 20: Hi-Rail Alinement, Kanawha Sub, MP 503-504

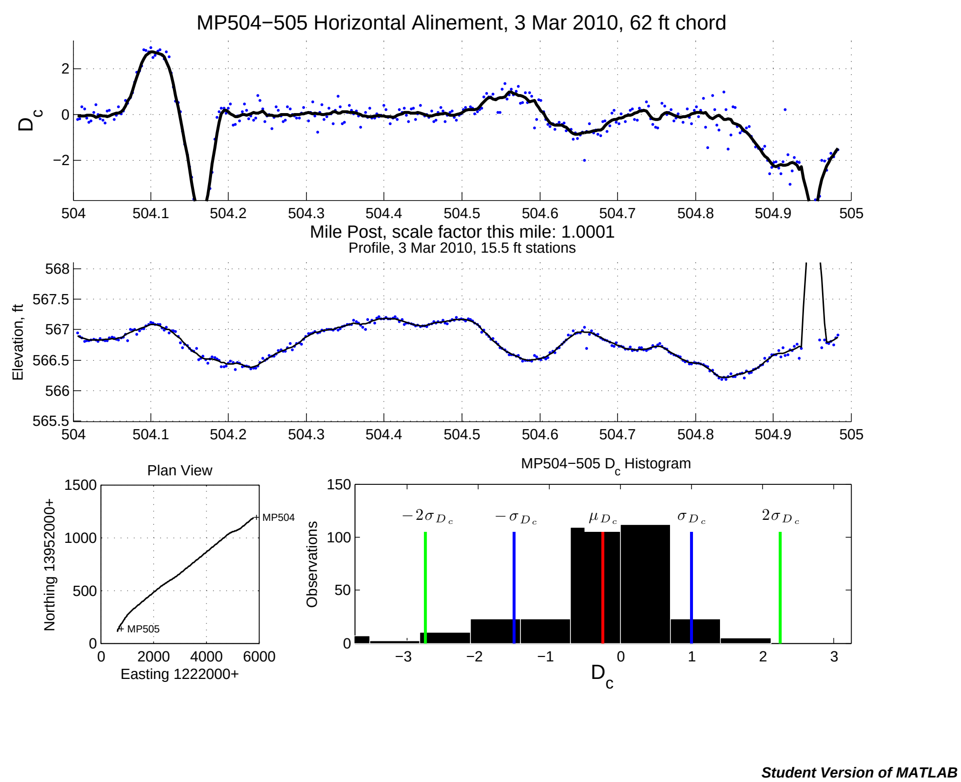


Figure 21: Hi-Rail Alinement, Kanawha Sub, MP 504-505

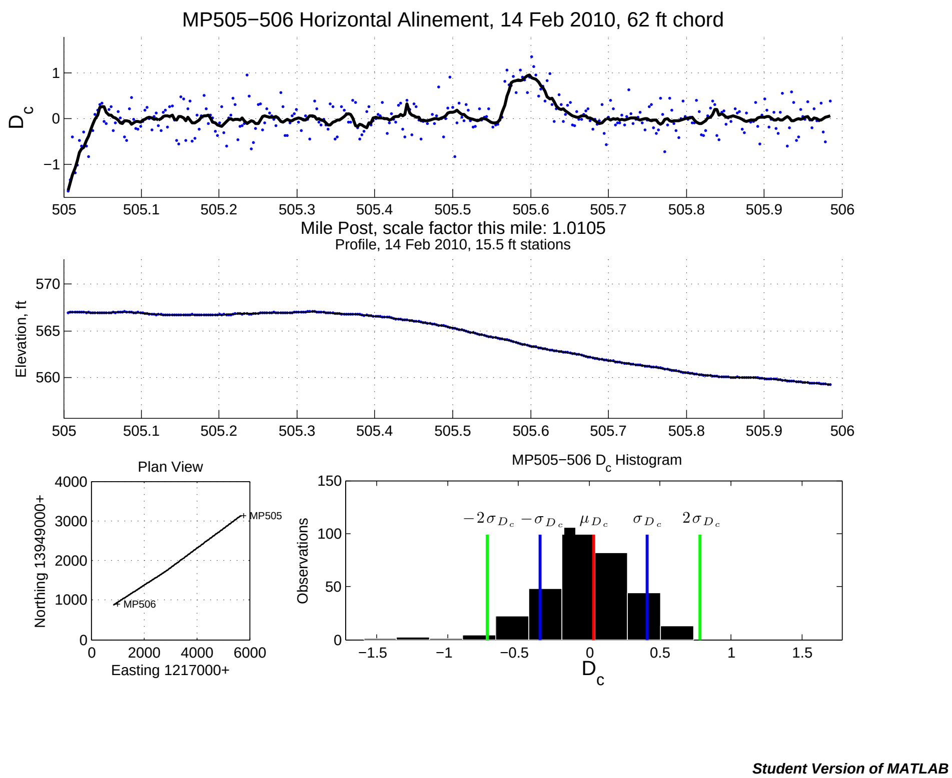


Figure 22: Hi-Rail Alinement, Kanawha Sub, MP 505-506

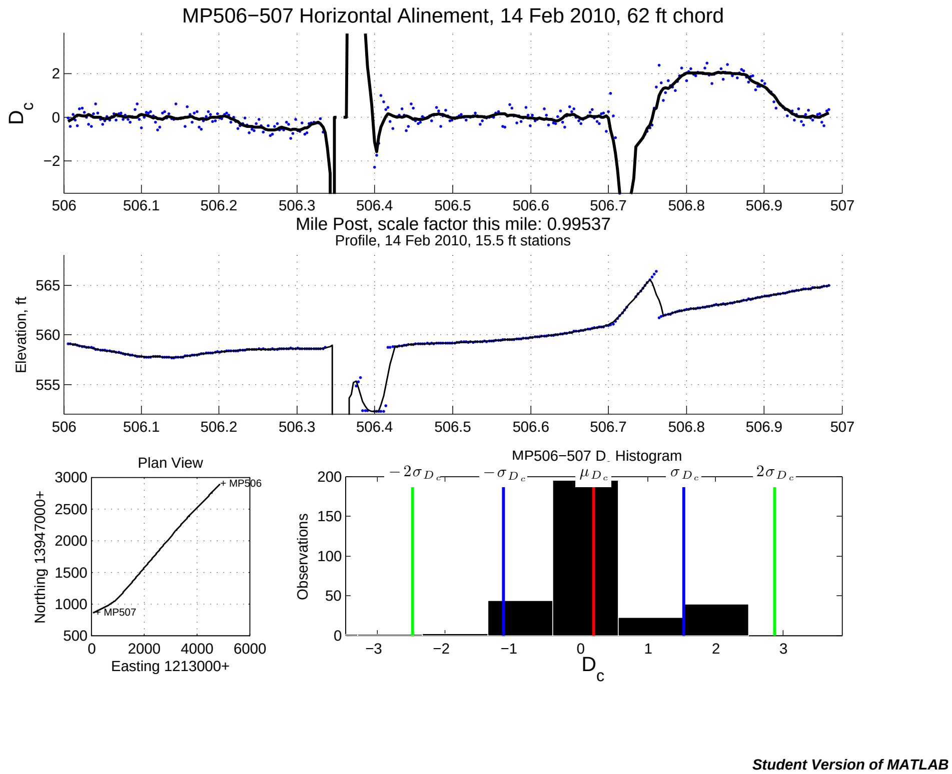


Figure 23: Hi-Rail Alinement, Kanawha Sub, MP 506-507

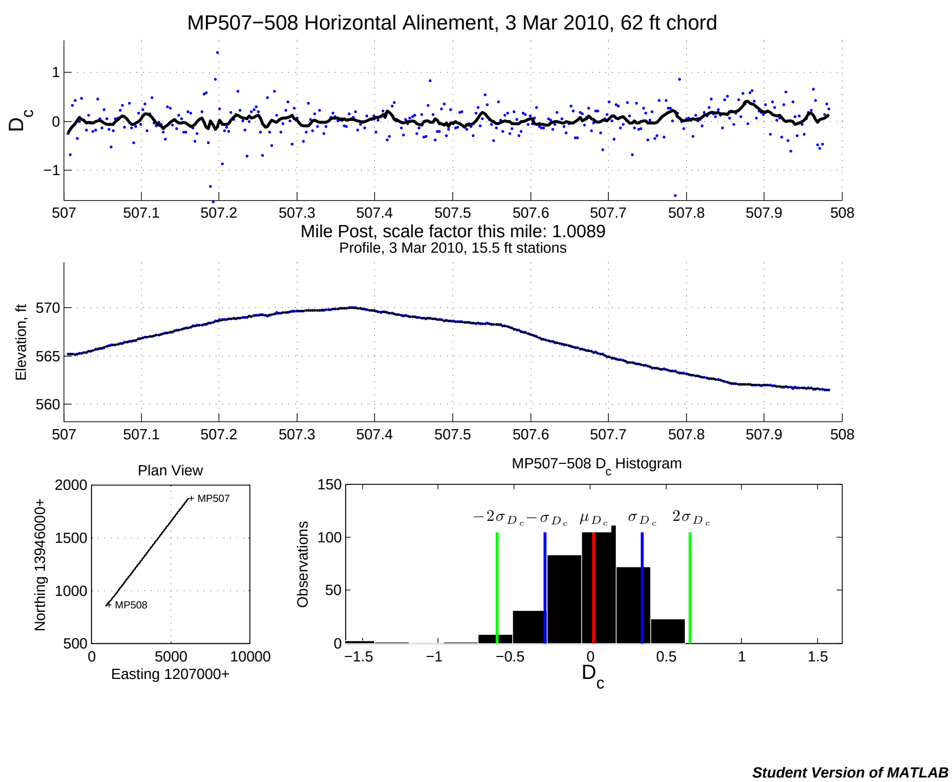


Figure 24: Hi-Rail Alinement, Kanawha Sub, MP 507-508

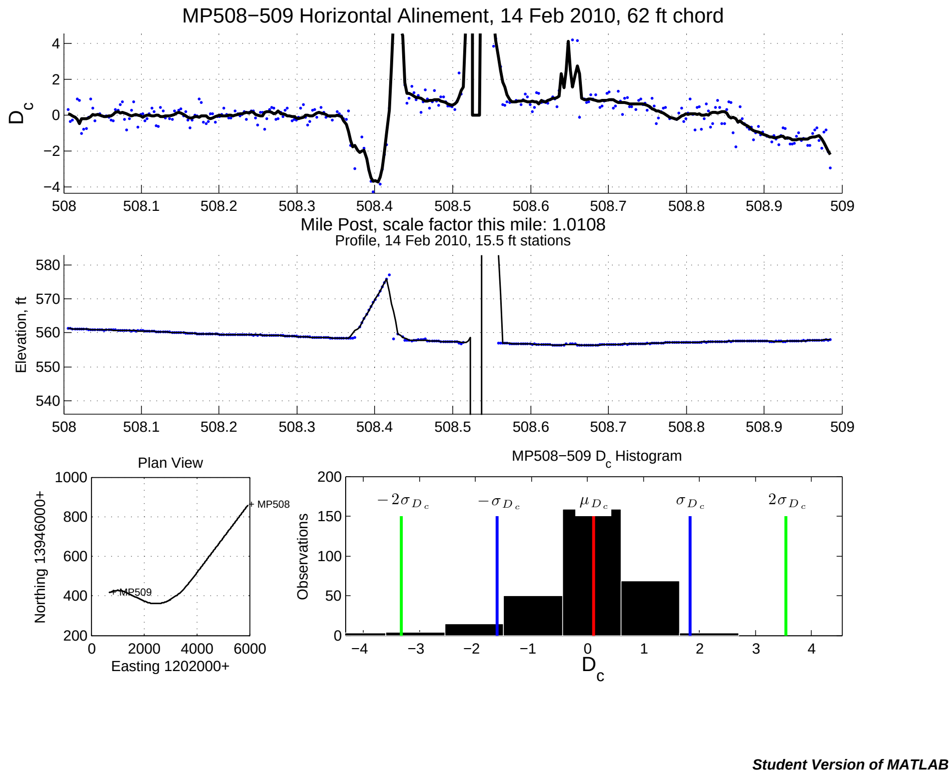


Figure 25: Hi-Rail Alinement, Kanawha Sub, MP 508-509

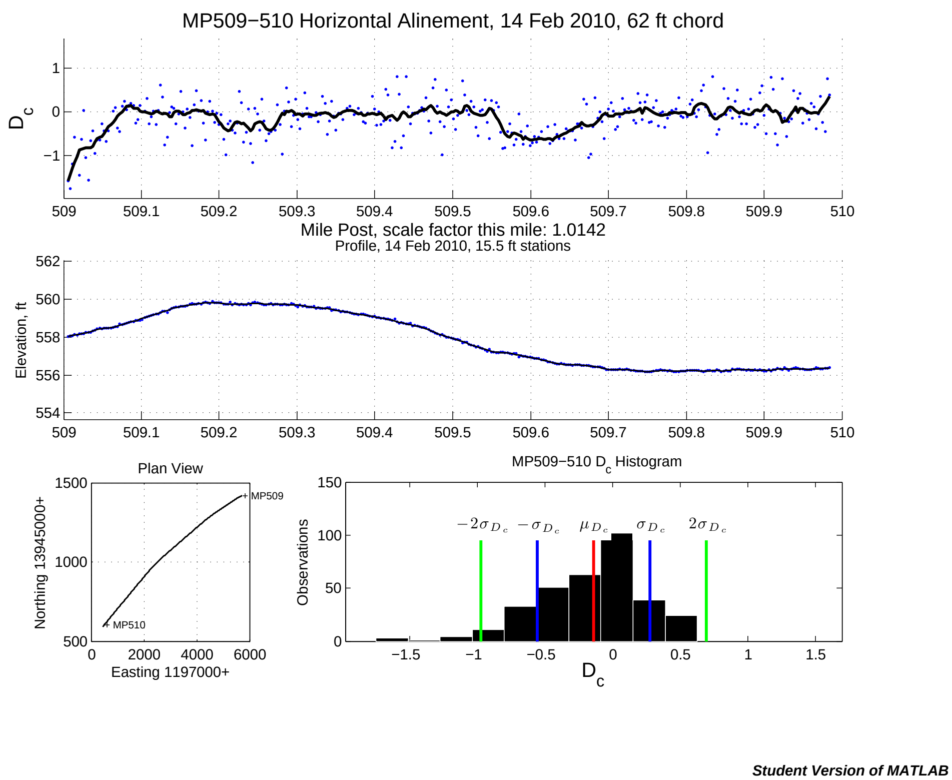


Figure 26: Hi-Rail Alinement, Kanawha Sub, MP 509-510

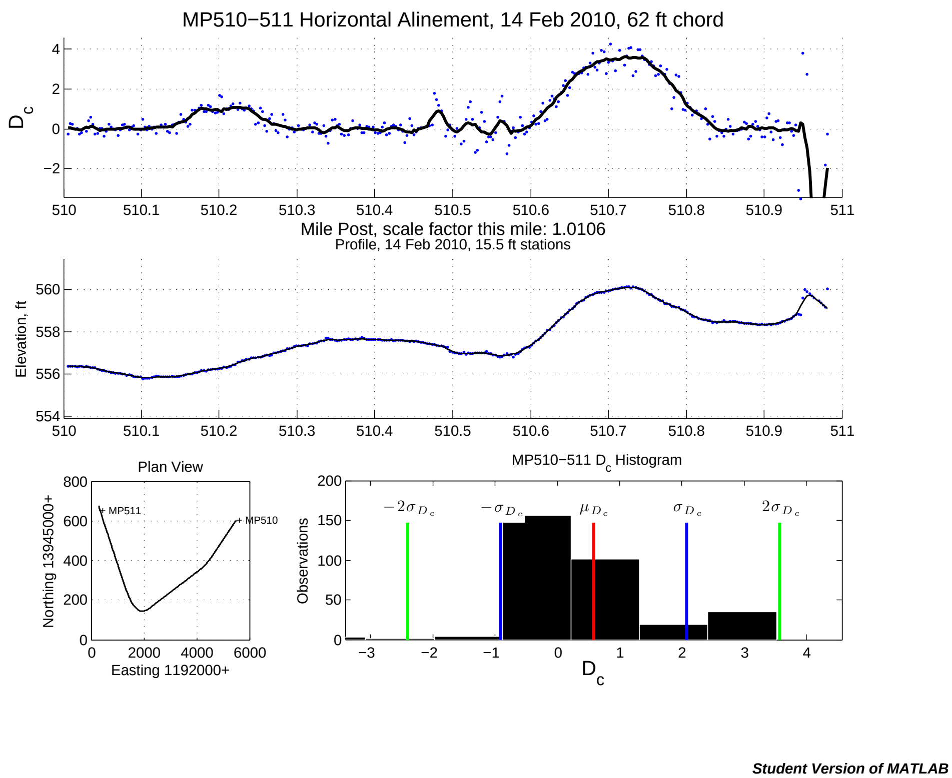


Figure 27: Hi-Rail Alinement, Kanawha Sub, MP 510-511

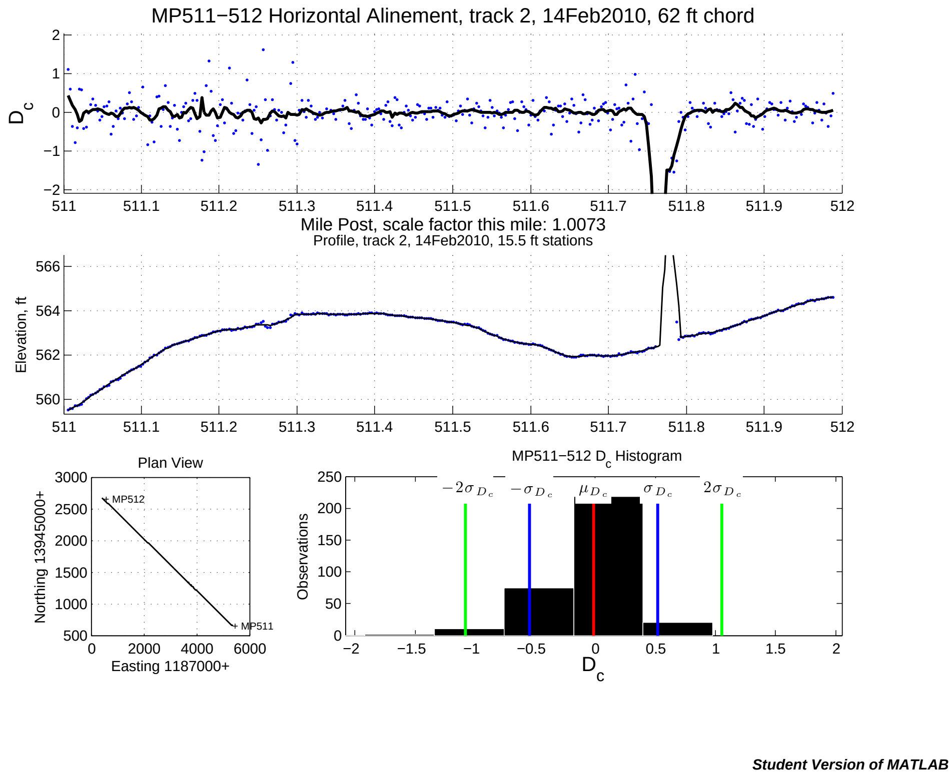


Figure 28: Hi-Rail Alinement, Kanawha Sub, MP 511-512

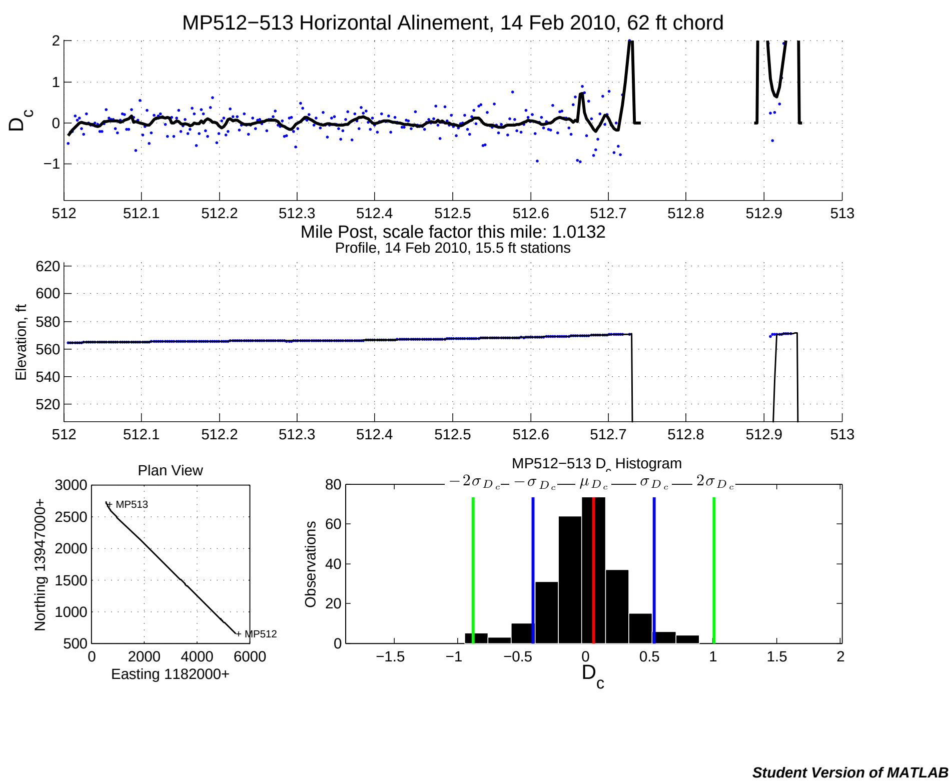


Figure 29: Hi-Rail Alinement, Kanawha Sub, MP 512-513

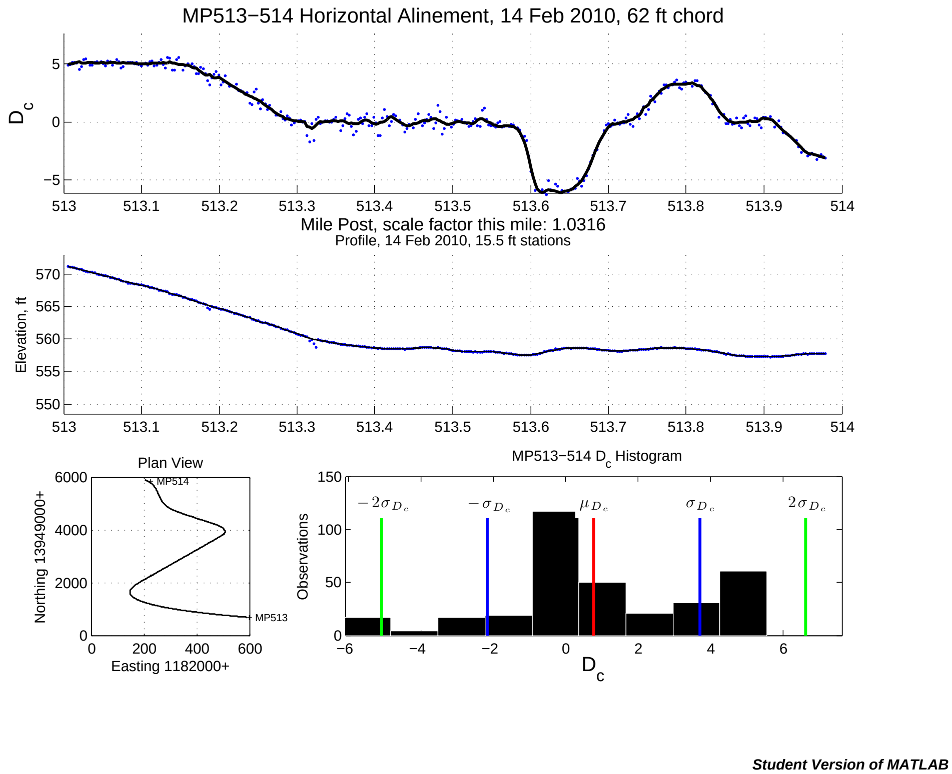


Figure 30: Hi-Rail Alinement, Kanawha Sub, MP 513-514

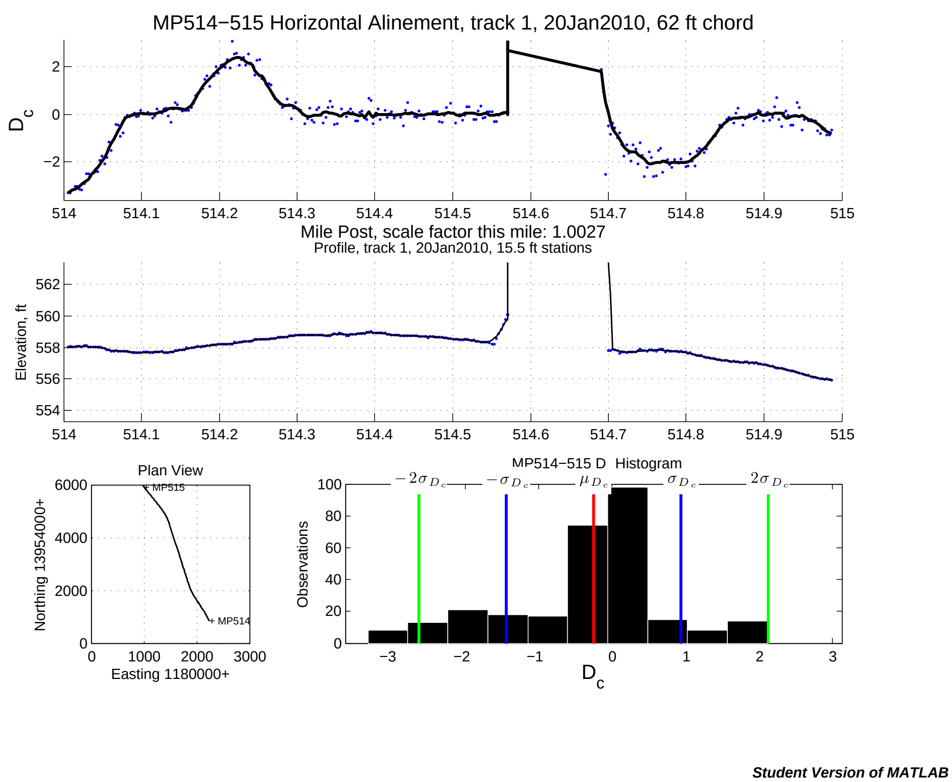


Figure 31: Hi-Rail Alinement, Kanawha Sub, MP 514-515

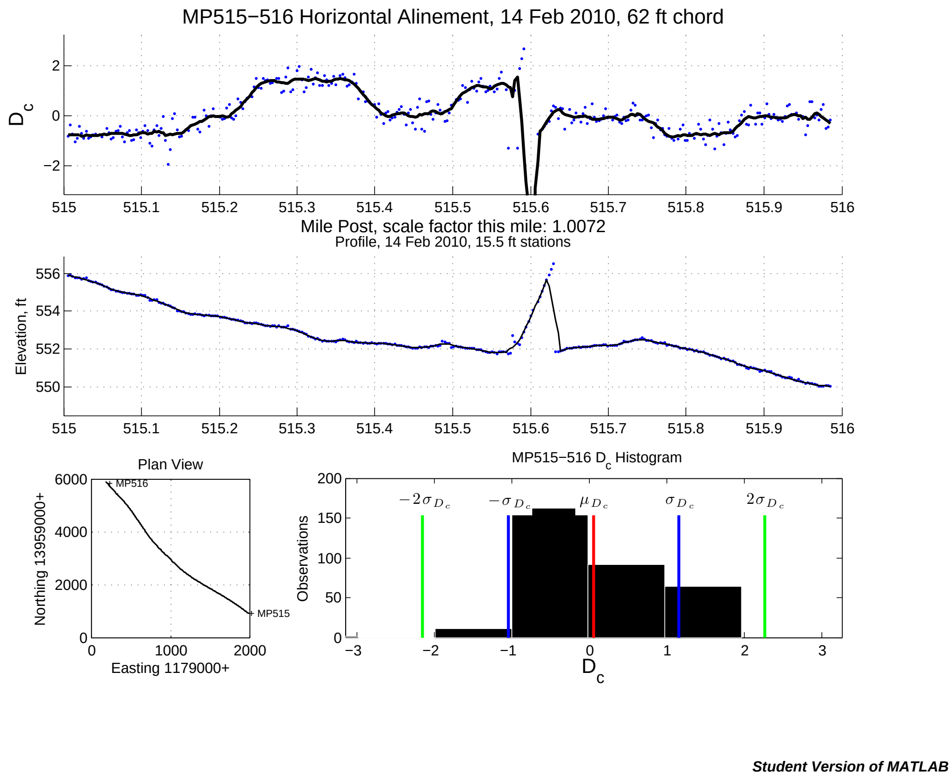


Figure 32: Hi-Rail Alinement, Kanawha Sub, MP 515-516

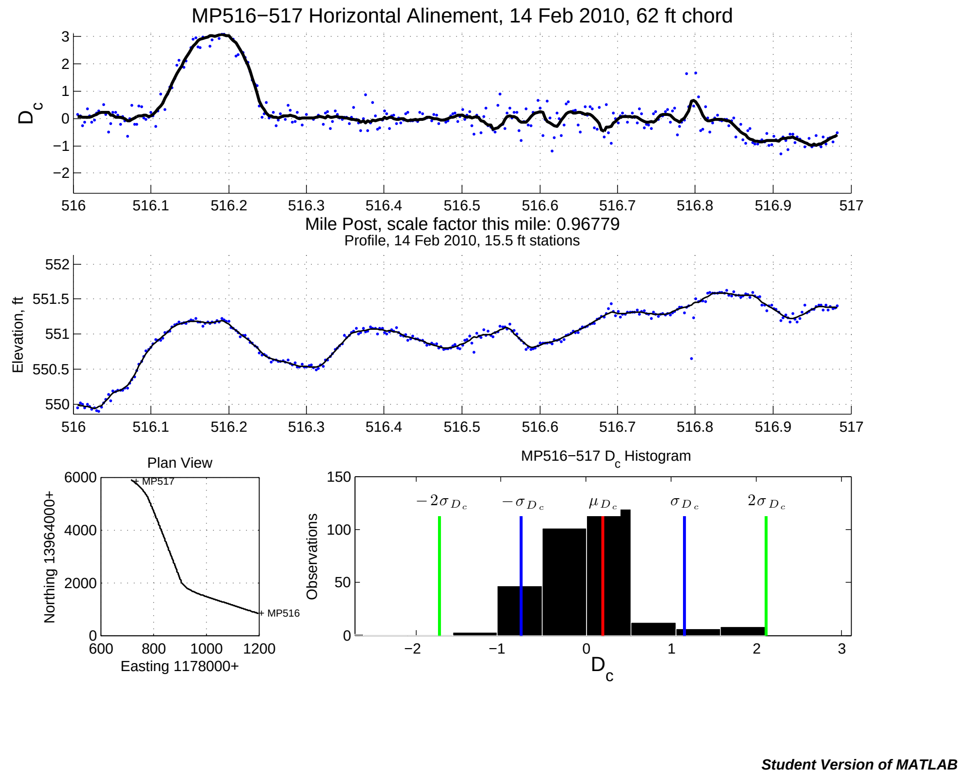


Figure 33: Hi-Rail Alinement, Kanawha Sub, MP 516-517

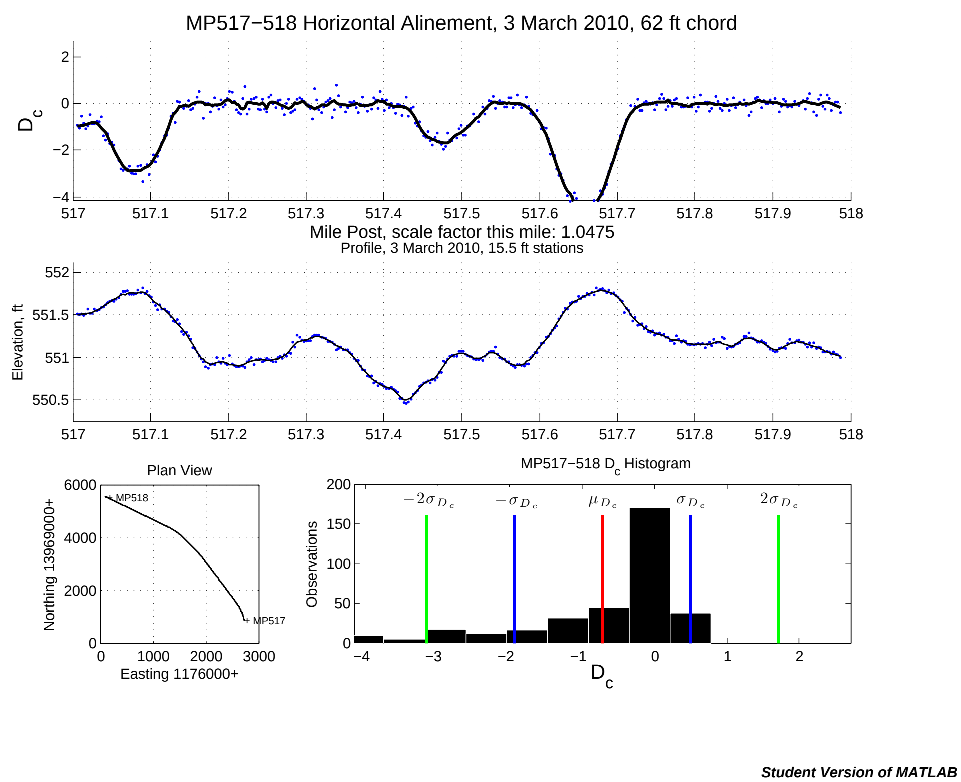


Figure 34: Hi-Rail Alinement, Kanawha Sub, MP 517-518

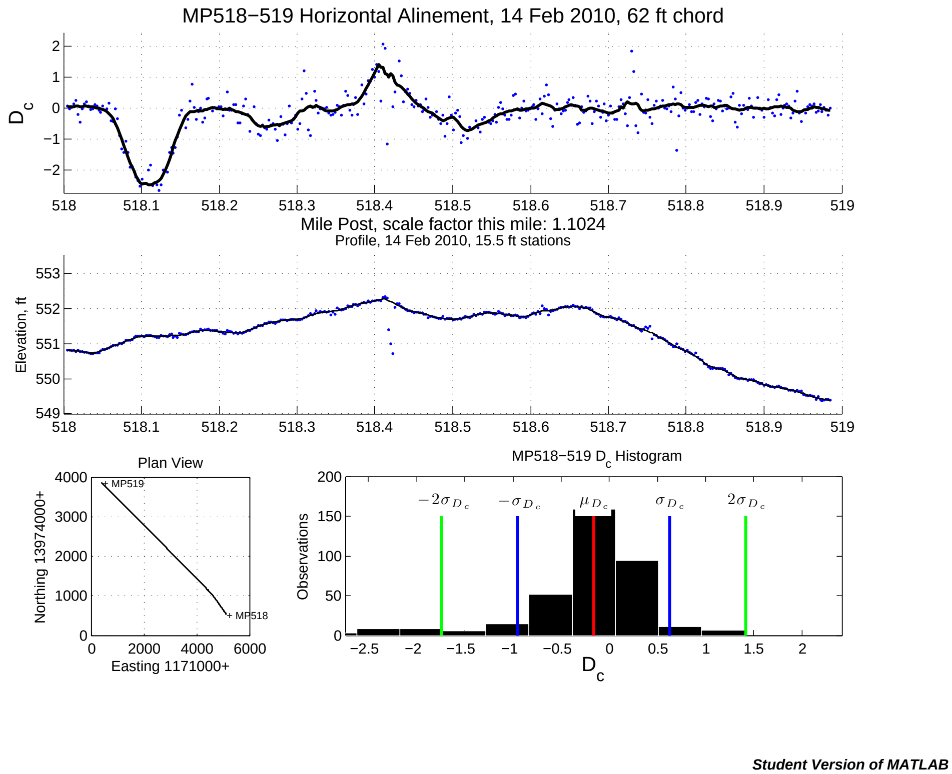


Figure 35: Hi-Rail Alinement, Kanawha Sub, MP 518-519

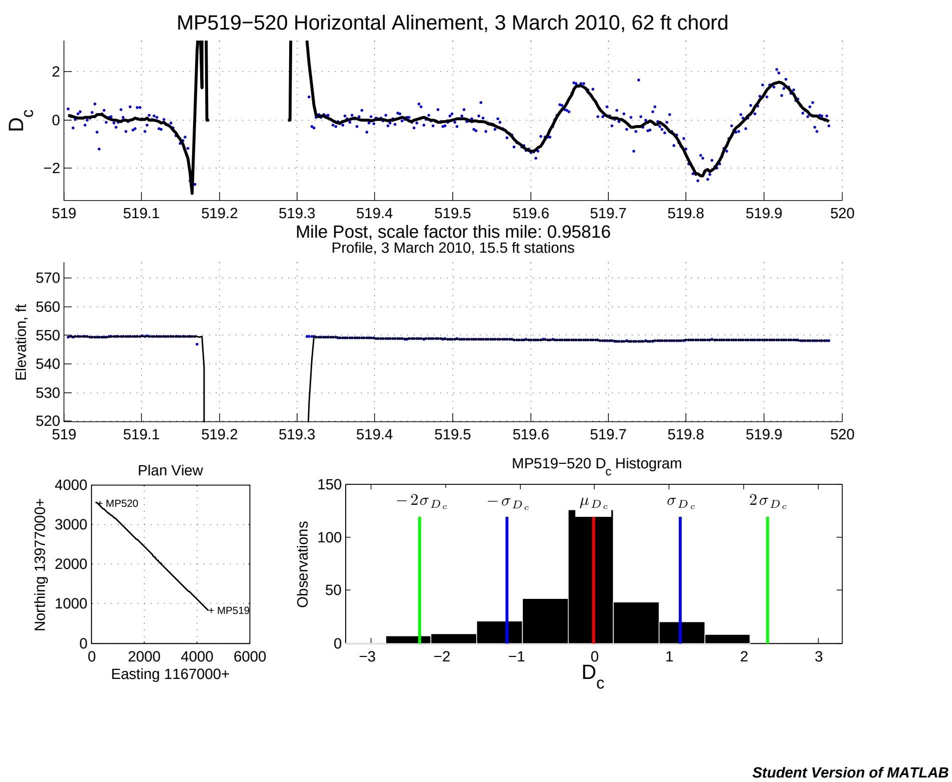
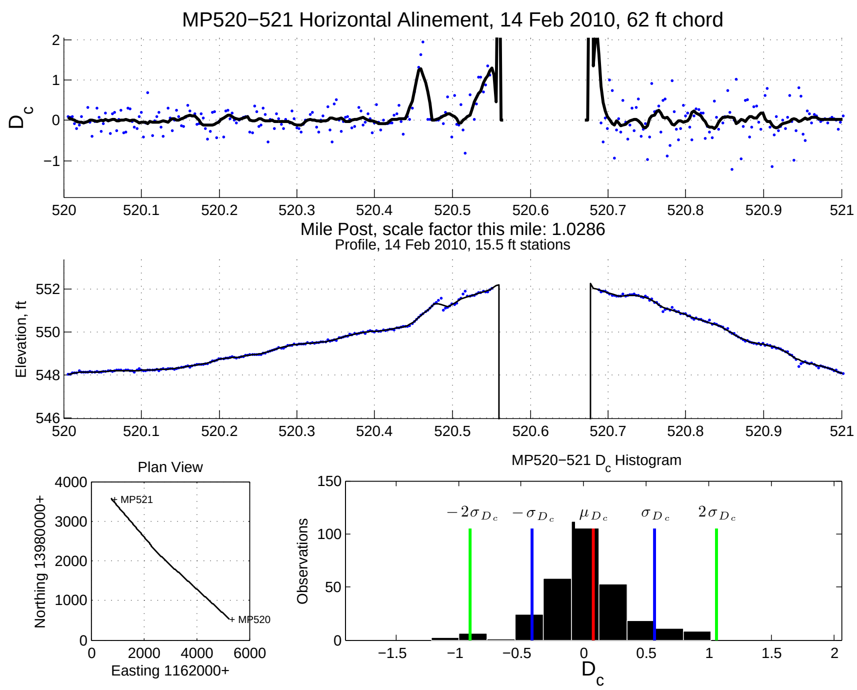


Figure 36: Hi-Rail Alinement, Kanawha Sub, MP 519-520



Student Version of MATLAB

Figure 37: Hi-Rail Alinement, Kanawha Sub, MP 520-521

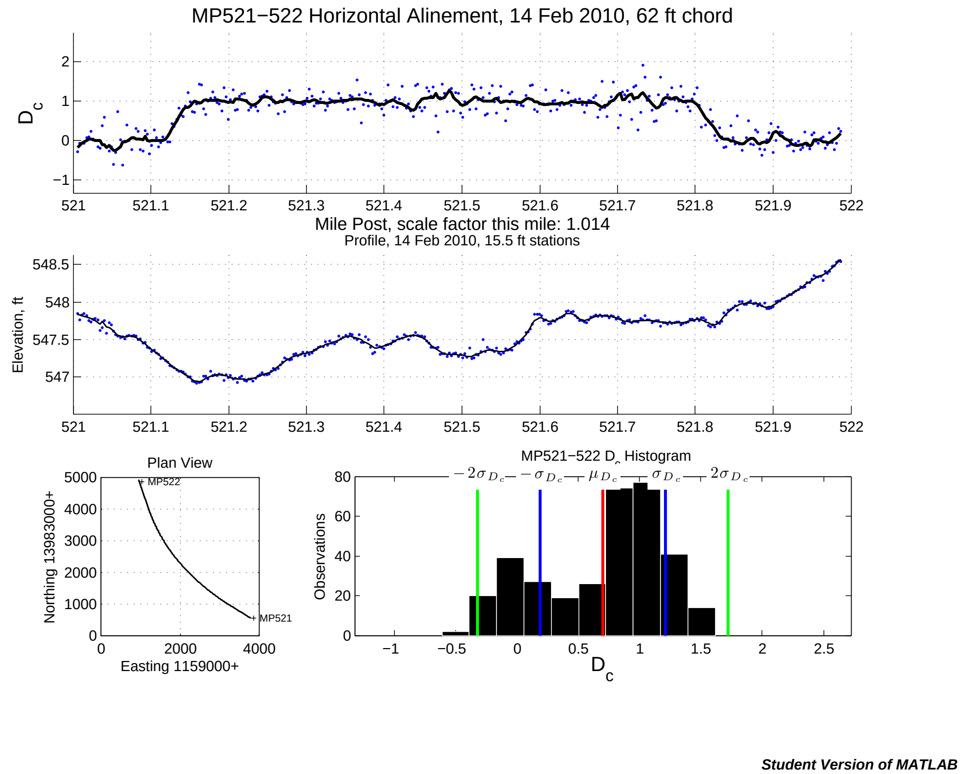


Figure 38: Hi-Rail Alinement, Kanawha Sub, MP 521-522

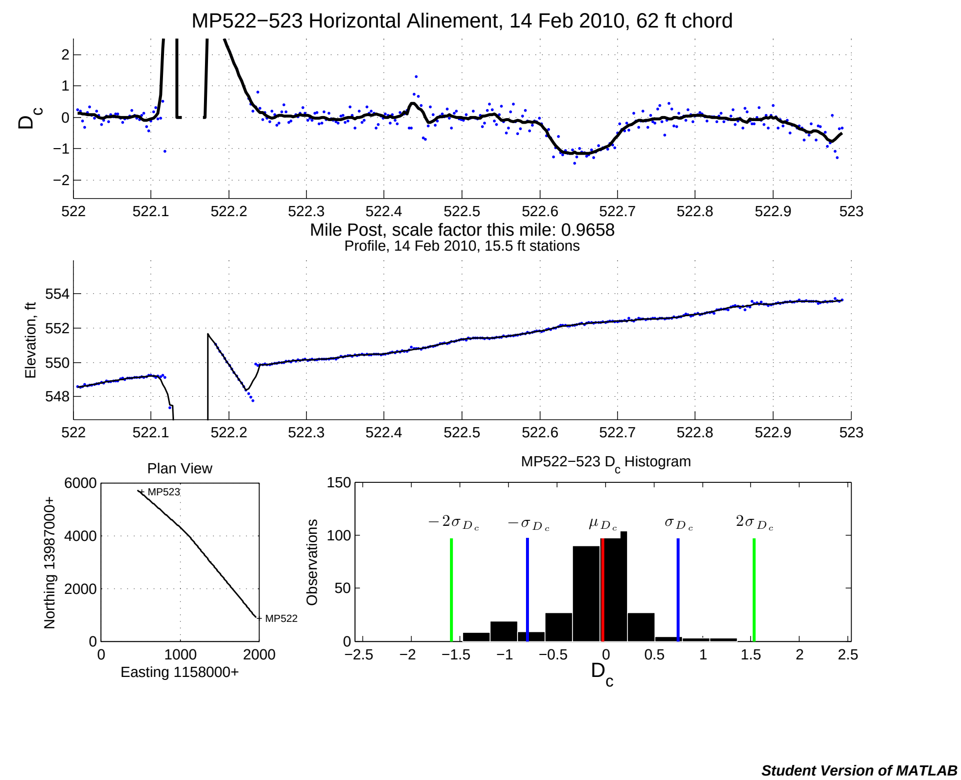


Figure 39: Hi-Rail Alinement, Kanawha Sub, MP 522-523

String Line Model Functions

Code listings available by following embedded hyperlink to PDF in code segment title.

- Track alinement runner.m: A Matlab script that reads a file containing track mile post locations, reads a file containing center line[6] observations, call various sub functions to determine and display the D_c vs. mile post reference modeled after the string line method.
- getIntLinesCircle.m: A Matlab function that returns the coordinates of the intersection between a circle, given the origin and radius, with an ordered series of lines defined by Cartesian coordinate pairs. [Hull, 2008] [Anderson and Mikhail, 2007]
- findMidOrdDistance.m: A Matlab function that returns distance between a chord's mid ordinate and an ordered series of line segments defined by (x, y) coordinate pairs. [Anderson and Mikhail, 2007]
- plotDOC.m: A Matlab function that plots track D_c and elevation profile vs mile post reference; a plan view of track observations; and histogram of D_c.
- slope2Az.m: A Matlab function that determines an azimuth (and back azimuth) from north in degrees given the input in radians from the +X-axis.
- perpDist2line.m: A Matlab function that determines the perpendicular distance from a point to a line. [Anderson and Mikhail, 2007]

[6] Or other track reference i.e., right, left, gauge, or field side of rail.

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