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.

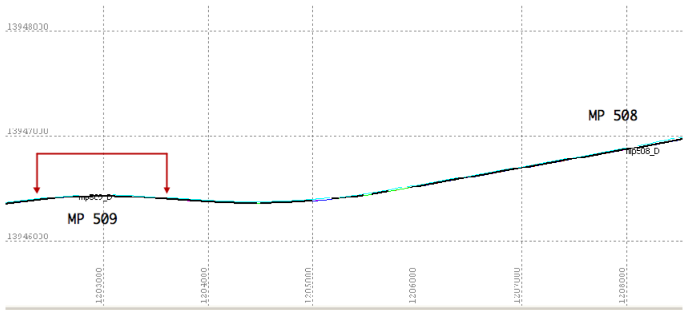

Figure 4.1: Plan View MP 508-509

- 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.

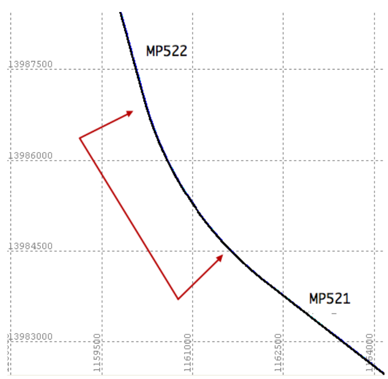

Figure 4.2: Plan View MP 521-522

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	

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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	

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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.

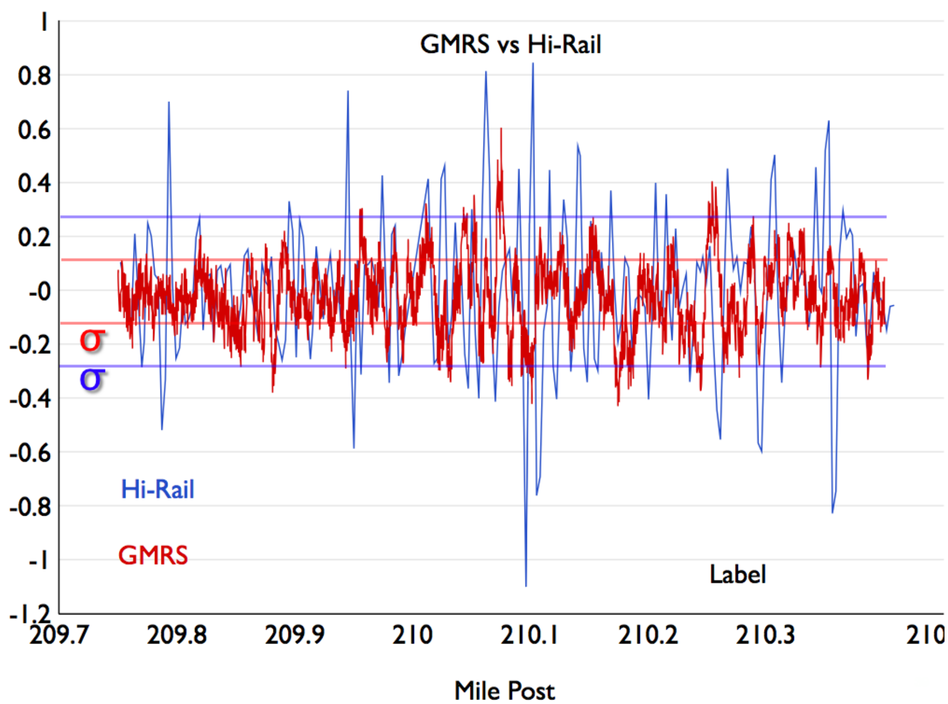

Figure 4.3: GMRS and Hi-Rail, D_c Comparison

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.

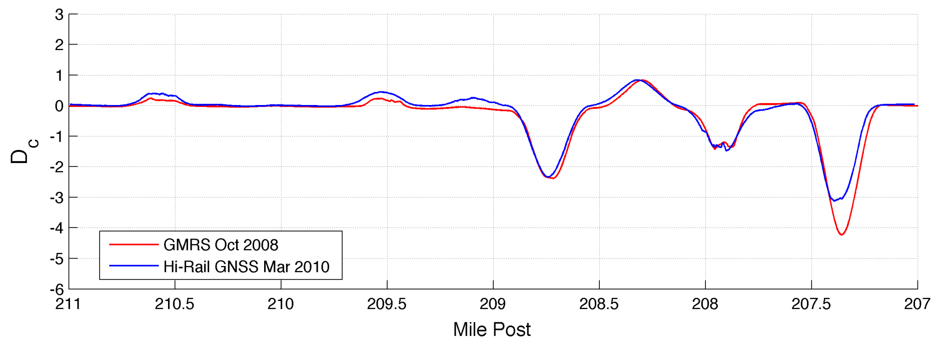

Figure 4.4: GMRS and Hi-Rail, D_c Comparison with Smoothing

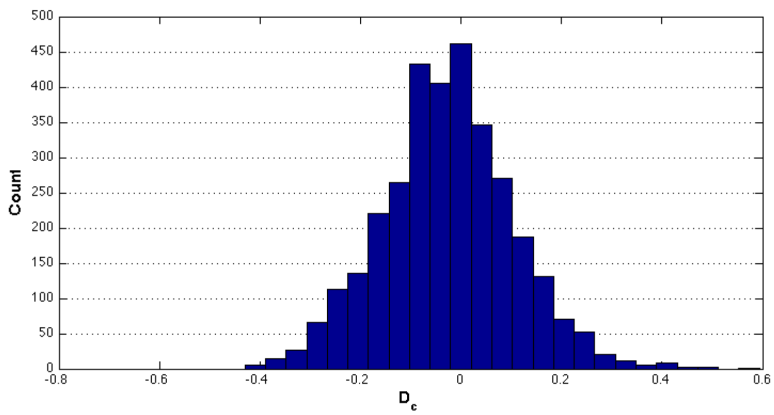

Figure 4.5: GMRS D_c Histogram, 210.4 to 209.75 tangent

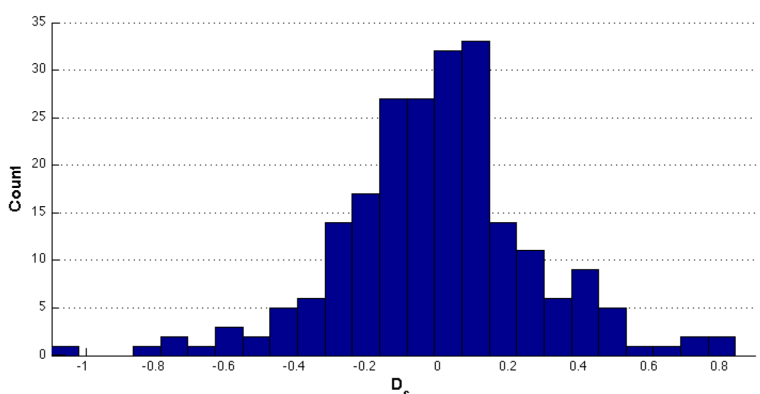

Figure 4.6: Hi-Rail D_c Histogram, 210.4 to 209.75 tangent

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.