

Real Time Kinematic Global Navigation Satellite Systems in Railroad Transportation

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Agenda

- Motivation for the Research
- Research Purpose and Objectives
- Experiments 1-3
 - Research question to be answered
 - Specific Objectives & Method
 - Results
 - Conclusions
 - Implications

Motivation

1. Loss of carload freight revenue relative to overall freight growth

Carload freight has quality of service issues (Moorman)

2. Inspection of railway is critical and labor intensive

Labor intensive reliance on inspector skill and diligence

3. Dependence on wired track circuits for train location

Est. replacement cost of track signals: \$125,000/mile

Yard Profile Survey

Differential Level



CSX/NS SOA Track Measurement for Defect Detection



CSX/NS SOA Track Measurement for Defect Detection

- CSX TGC-2
 - heavy / train / \$\$\$



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- NS TGC
 - heavy / train / \$\$\$



CSX/NS SOA Track Measurement for Defect Detection

- CSX TGC-2
 - heavy / train / \$\$\$
- NS TGC
 - heavy / train / \$\$\$
- CSX GRMS-2
 - light / self-propelled / \$\$\$



CSX/NS SOA Track Measurement for Defect Detection

- CSX TGC-2
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- NS TGC
 - heavy / train / \$\$\$
- CSX GRMS-2
 - light / self-propelled / \$\$\$
- CSX GRMS-1
 - light / self-propelled / \$\$\$



RTK GPS Railway Measurement

May 2010



The Swiss Trolley - Glauss

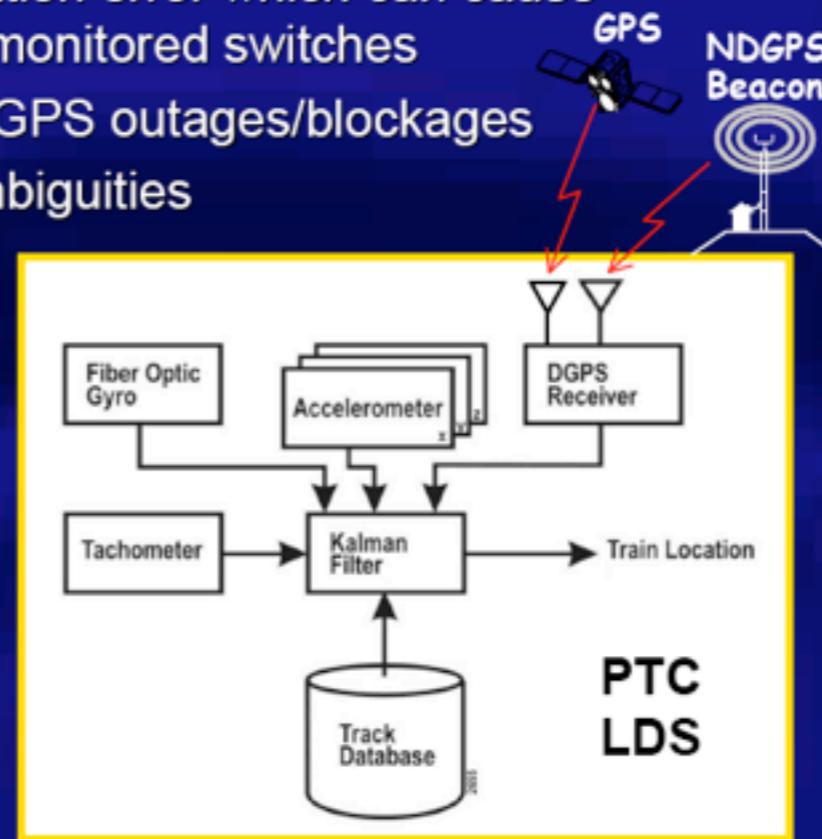
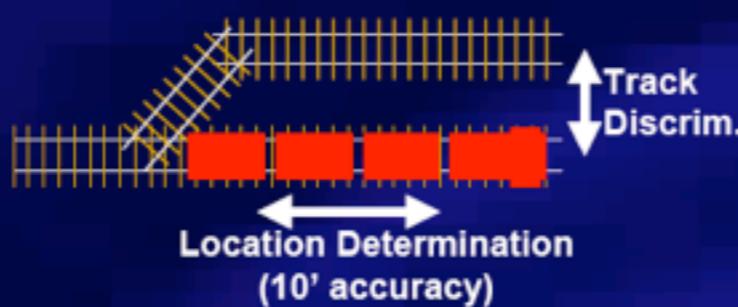
FRA LDS Concept

2005

Location Determination System (LDS)

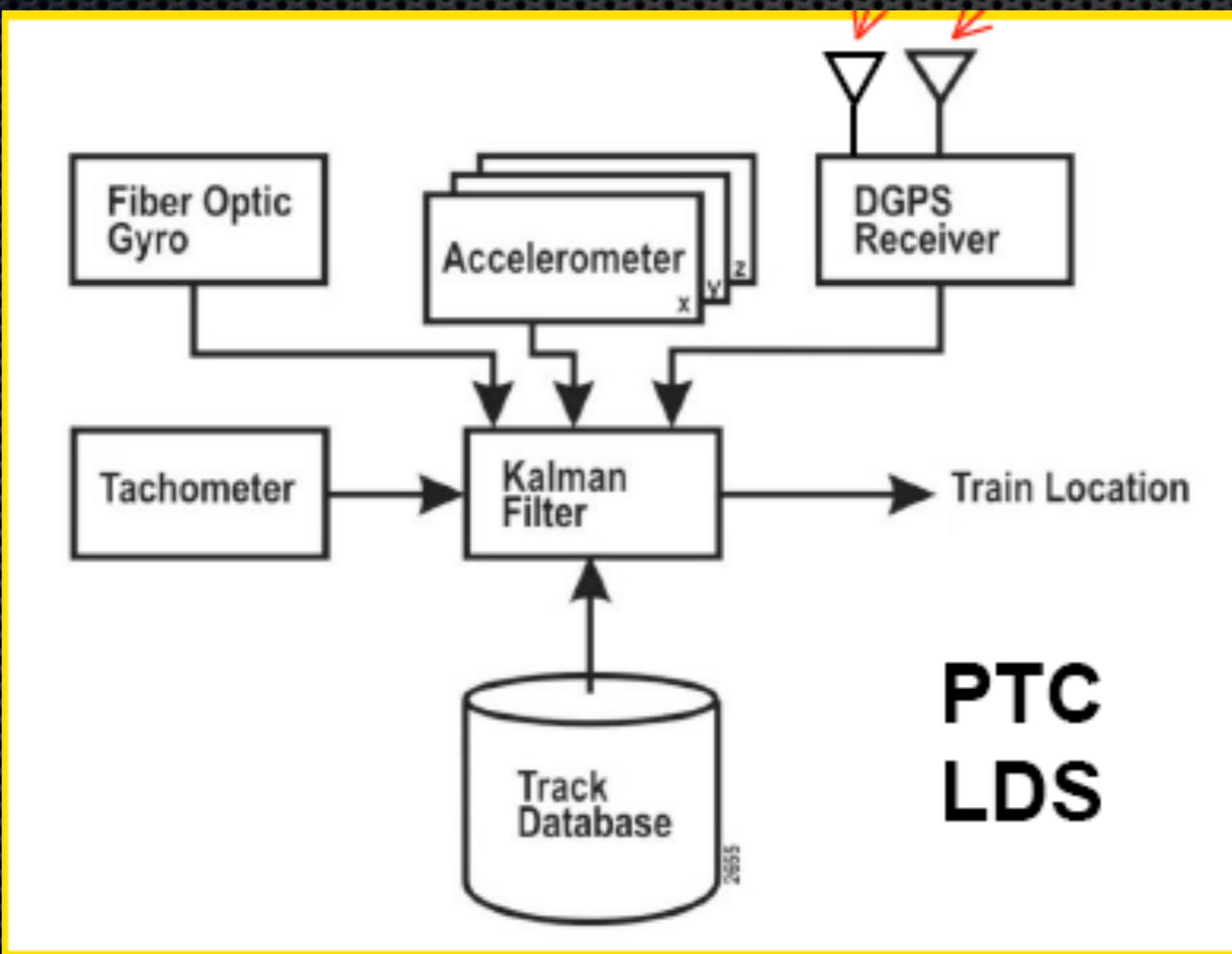
- ◆ NAJPTC uses a Multi-Sensor LDS which offers the following advantages over DGPS and Tachometer alone:

- Lower probability of discrimination error which can cause unnecessary train stops at unmonitored switches
- Dead reckons through longer GPS outages/blockages
- Eliminates forward/reverse ambiguities
- Permits tighter fit in sidings
- Improved fault detection



FRA LDS Concept

2005



COTS GPS/GNSS Augmentation Services

- Standard Positioning Service, USDOD no augmentation
 - 25 m stated, **12.8 m** horizontal in practice
- Space Based Augmentation Systems (SBAS), geosynchronous
 - WAAS, FAA: **3-5 meters** horizontal
 - Subscription services: OmniStar
- Ground Based Augmentation Systems (GBAS)
 - NDGPS, USDOT: **1-5 meters**, experimental (noCOTS) **10 cm** horizontal.
GPS correctors only via MF radio - 200 baud limitation
 - RTK GPS/GNSS VRS: **1-2 cm** horizontal. GPS, GLONASS, Galileo
correctors via VHF or cellular

Research Purpose

Determine RTK GPS/GNSS's ability to

1. Measure yard profiles

Affect hump yard throughput, resulting in increased service reliability

2. Bridge a gap in mainline railway inspection methods

Track geometry cars & visual inspection

3. Provide a reliable wireless location determination system

Research Objectives

- Design an experiment to asses RTK GPS onboard a locomotive
 - Obtain a data set for profiling the bowl area of a hump yard during car handling operations
- Design an experiment to asses RTK GNSS onboard a track inspector's Hi-Rail
 - Track XYZ data > String line model > track information
- Design an experiment to asses RTK GNSS as the sole measurement component of a wireless track vehicle location determination system (LDS)

Commercial Constraints on Research Activity

Safety and access considerations of a Class I railroad

- Availability of track foul time (\$1,500 fine per occurrence)
- Training Requirements of USC 49§214 On-Track-Worker Safety
- All field work superintended by a rail company employee-in-charge (subject to availability)
- \$5M insurance policy, required by rail company for access

Instrument Constraints

- Commercial, off the shelf (COTS) GPS/GNSS instruments and systems
- Dual frequency RTK GPS/GNSS receivers
 - ‘survey grade’
- RTK VRS server
 - Networked CORS and IT infrastructure

Experiment 1

Hump Yard Profile Survey

Determine track grades in a hump yard by an RTK equipped locomotive during humping operations.

The Hump Yard

An efficient mechanism engineered and constructed for the specific purpose of breaking apart a consist and reassigning individual units for outbound shipment

- AKA: Automatic Classification Yard, Freight Terminal, Class Yard
- Characterized by
 - An elevated inlet
 - Remotely operated electro-mechanical switching
 - Automated railcar speed control

Hamlet Terminal Video Study

Influence of Grade on Throughput

Hamlet Terminal Video Study

Influence of Grade on Throughput

1. Car stall blocks group switch, classification to blocked group impossible
2. Hump operations interrupted
3. Trim engine moves to clear stall
4. Total of 21 minutes to clear switch



Hump Yard Grades Affect Freight Service Quality

- Grade degradation and settlement due to
 - Railcar loading forces
 - Weather & geology & time
 - Outdated grade design
 - Journal bearings to frictionless roller bearings

Research Question

Can RTK GPS instrumentation attached to a locomotive, be used to survey an automatic classification yard during humping operations?

Hump Yard Profile Survey

Purpose & Objectives

Profile the bowl area of a humpyard in support of yard-wide resurfacing project

- Develop antenna alignment procedure
- Collect a data set by RTK GPS equipped locomotive
- Maximize safety for surveyors
- Minimize impact on continuous car handling operation
- Minimize use of trained safety support personnel
- Determine multipath influence on GPS elevation

Experiment 1

Hump Yard Survey



Experiment 1

Hump Yard Survey

- COTS RTK GPS Reference Station



Experiment 1

Hump Yard Survey

- COTS RTK GPS Reference Station
- COTS RTK static instruments



Experiment 1

Hump Yard Survey

- COTS RTK GPS Reference Station
- COTS RTK static instruments
- COTS RTK mobile instruments and mount



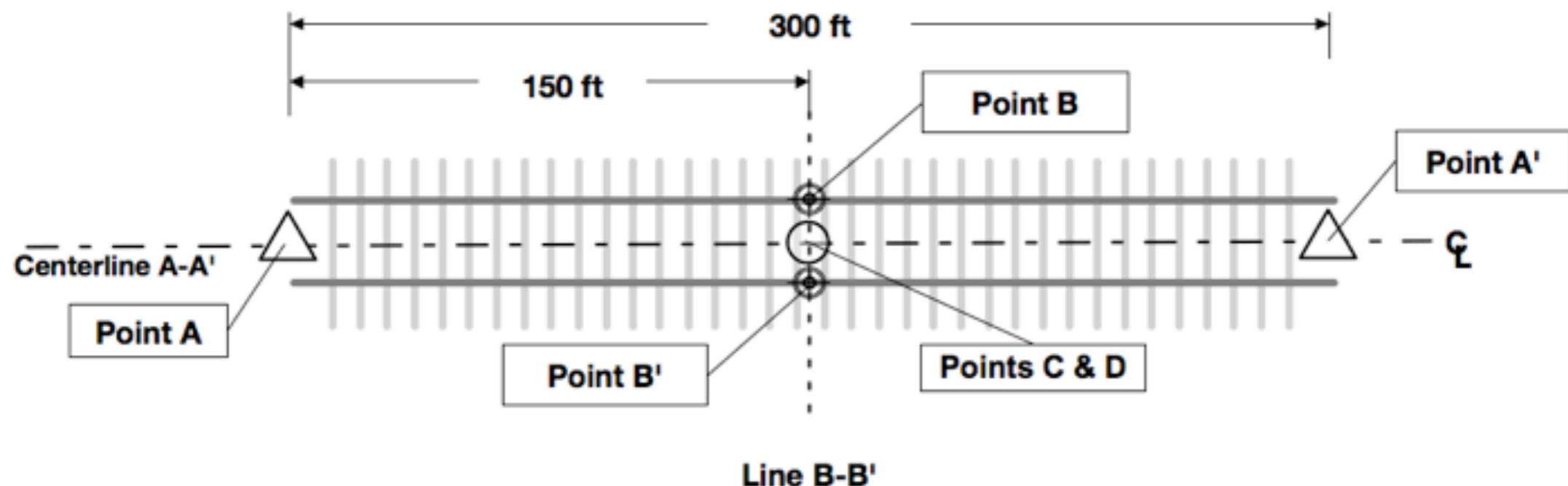
Antenna Alignment Procedure

Tangent calibration area

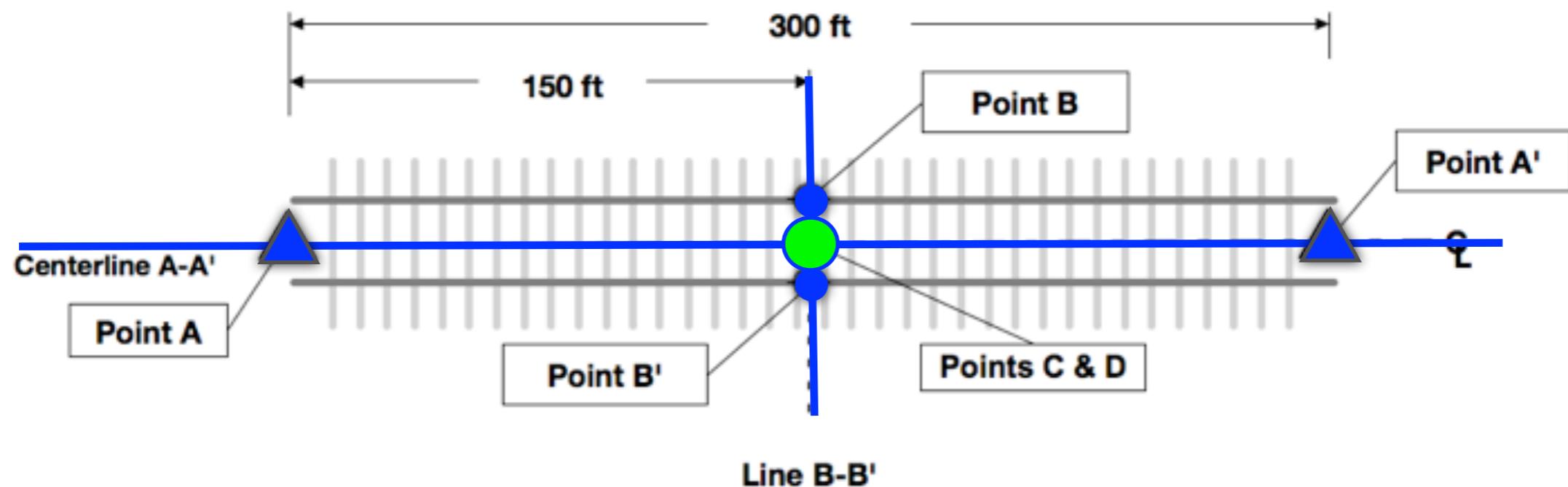
Aline locomotive antenna
with track centerline top-
of-rail.



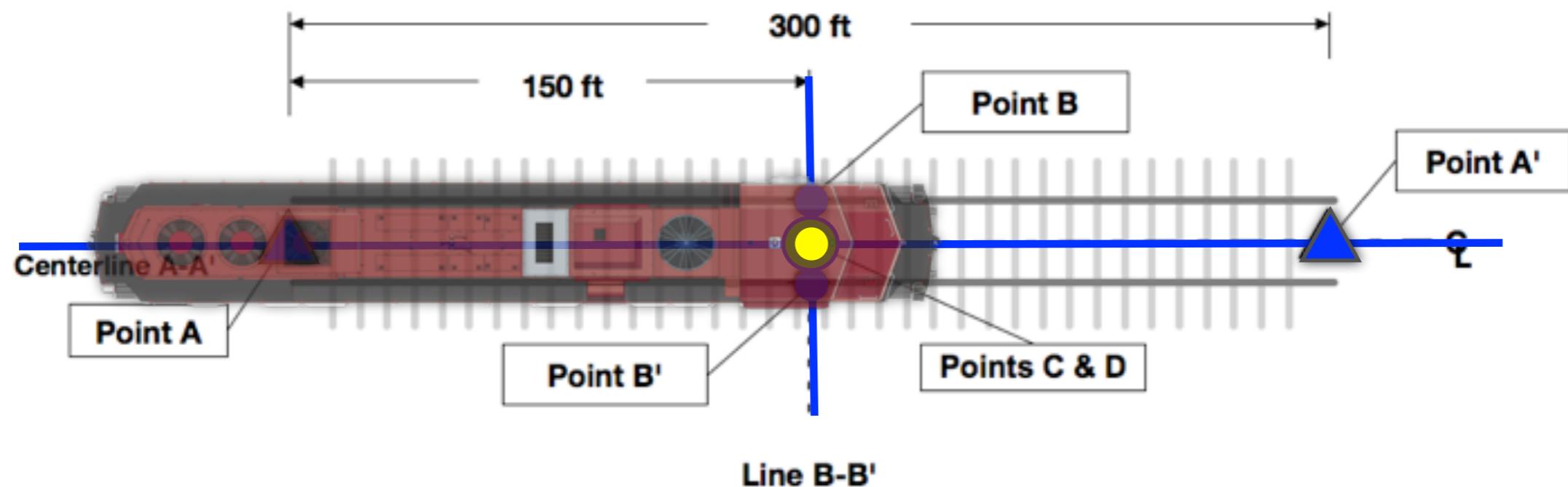
Antenna Alignment Procedure

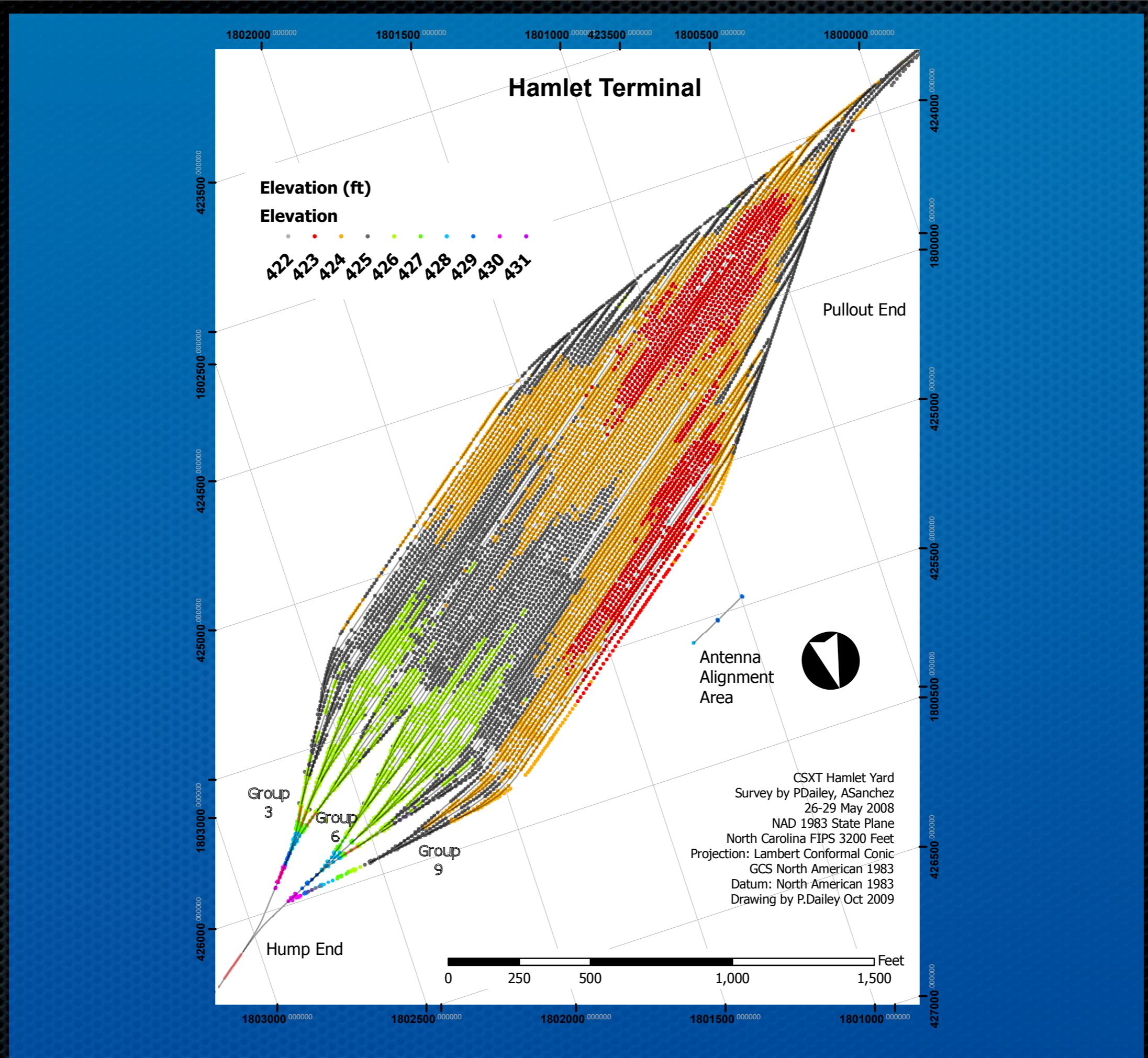


Antenna Alignment Procedure

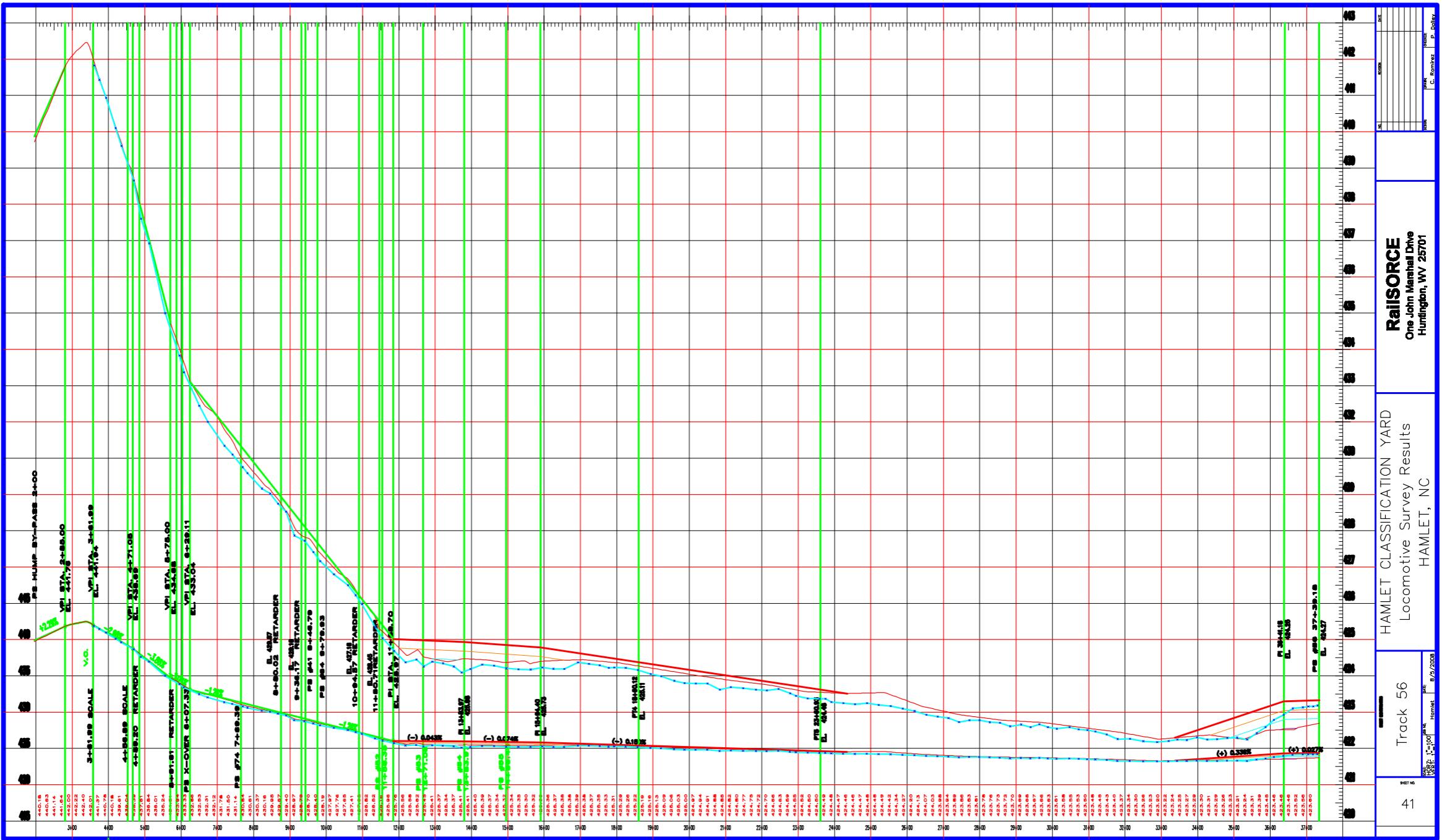


Antenna Alignment Procedure





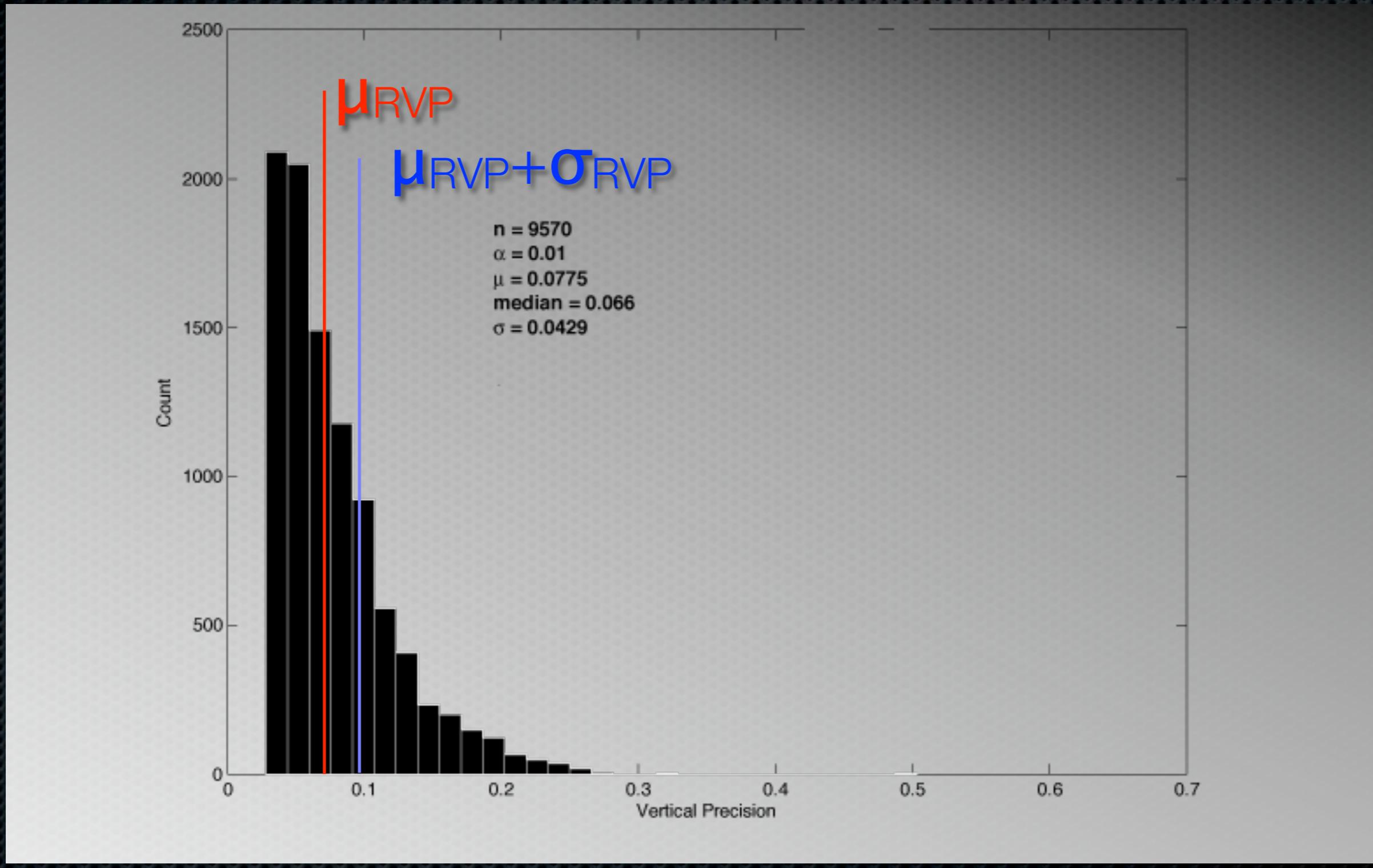
Group 7, Track 56

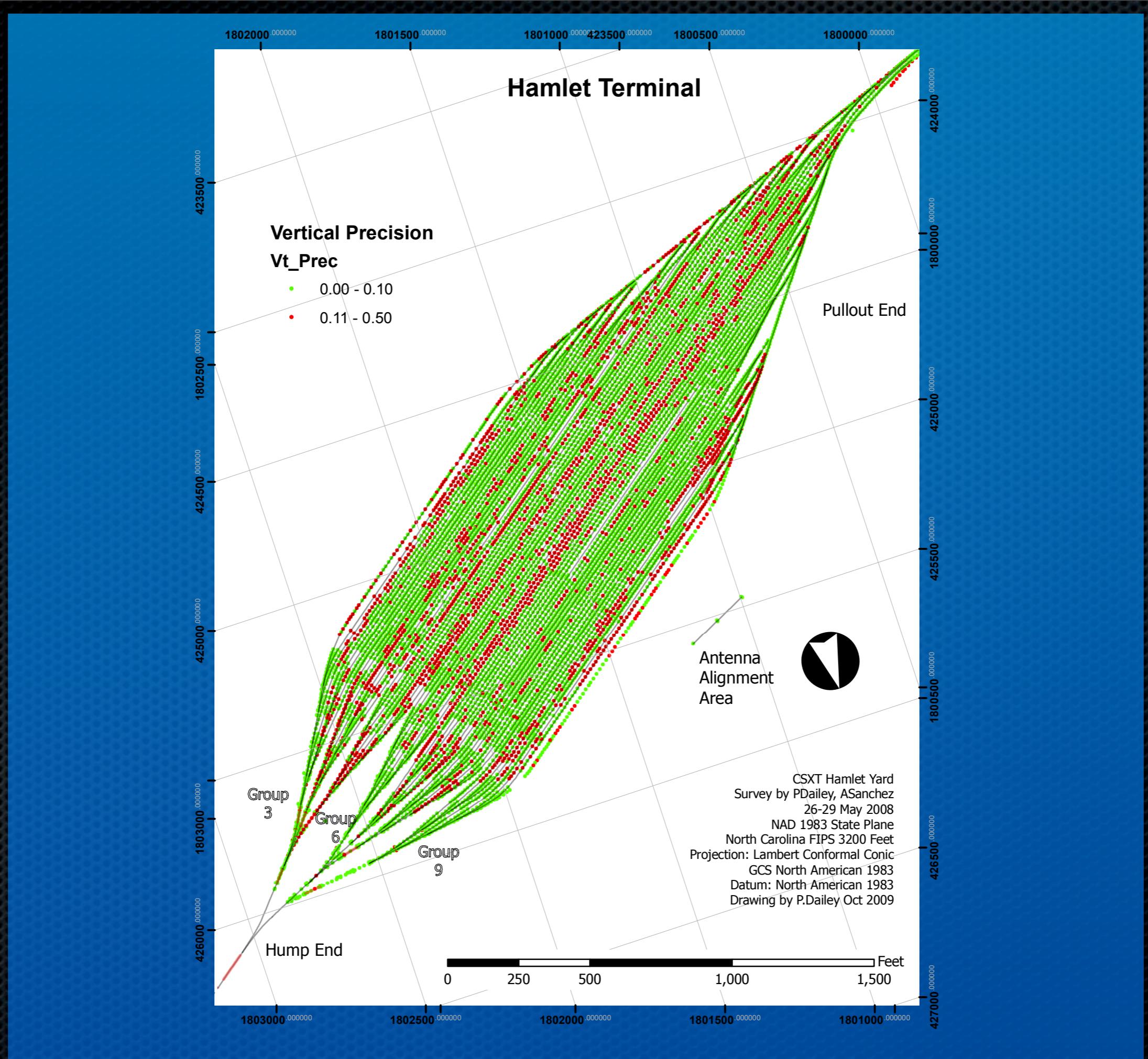


Multipath Analysis

	Reference Station cycle slips / total obs.	Locomotive Relative Vertical Accuracy
μ_{RVP}		0.08 ft (2.4cm)
σ_{RVP}		0.043 ft
MP1 cycle slips 1575.42 MHz, $\lambda = 19$ cm	121 / 9,112 1.32%	
MP2 cycle slips 1227.60 MHz, $\lambda = 24.4$ cm	119 / 9,112 1.30%	

Relative Vertical Precision





Result

Objective	Value
Track observations	9,570
Safety, exposure hours	6
Labor efficiency, man hours	97
Time to completion, days	4-1/2
Nominal observation stationing, feet	10
Operation disruption, hours	2

Conclusions

- Greater data density than differential level survey
 - 10 ft vs 100 ft stations
- Safer than differential level survey
 - 6 vs 1500 exposure hours to ground hazards (est. Kerchoff & Szwilski)
- Faster than differential level survey
 - 4-1/2 days vs 25 days
- Fewer labor hours than differential level survey
 - 100 vs 500 man-hours (est. Kerchoff & Szwilski)
- Less disruptive to yard operations
 - 2 vs 500 hours

Conclusions

- RTK GPS elevations do not indicate abnormal distortion from multipath signal reflections
- RTK GPS unaffected by weather
 - Day-long locomotive survey in torrential rain

Implications

- Follow up on resurfacing project:
 - Operator skill and judgement used during regrading
 - Not data driven - what are the as-built grades?
- Implies additional research needed to implement RTK GNSS measurement on track resurfacing equipment
 - Similar to COTS machine control in construction applications

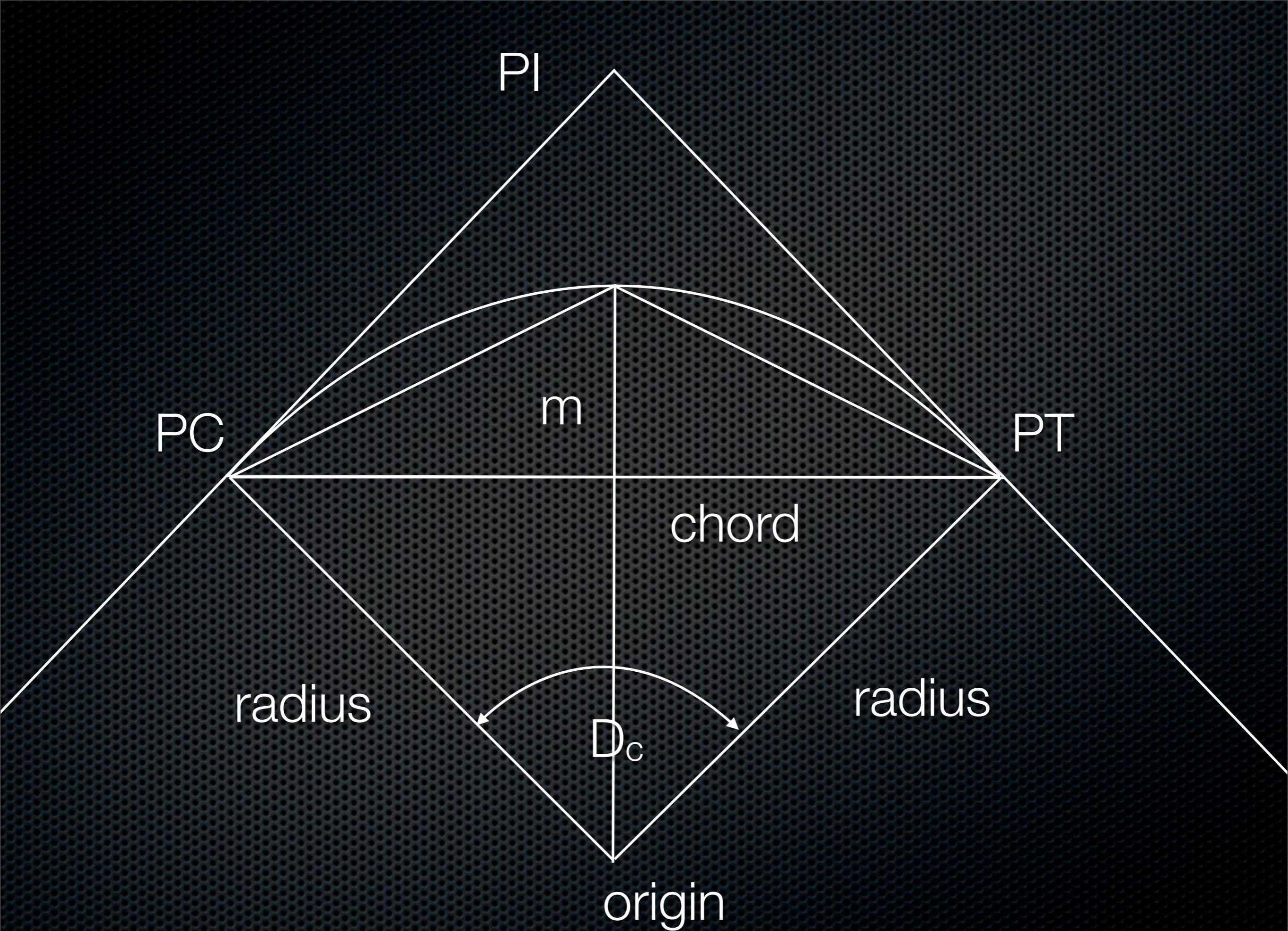
Experiment 2

Track Alignment

Determine degree of curvature (D_c) from an RTK equipped track inspector's Hi-Rail during routine inspection of mainline track.

Visual Track Inspection

- FRA Mandate
 - Every track at least every 2 weeks
 - Inspection duties include light repair
- Rail companies specify increased frequency based on
 - Load MGT/yr
 - Cargo
 - Inspection History



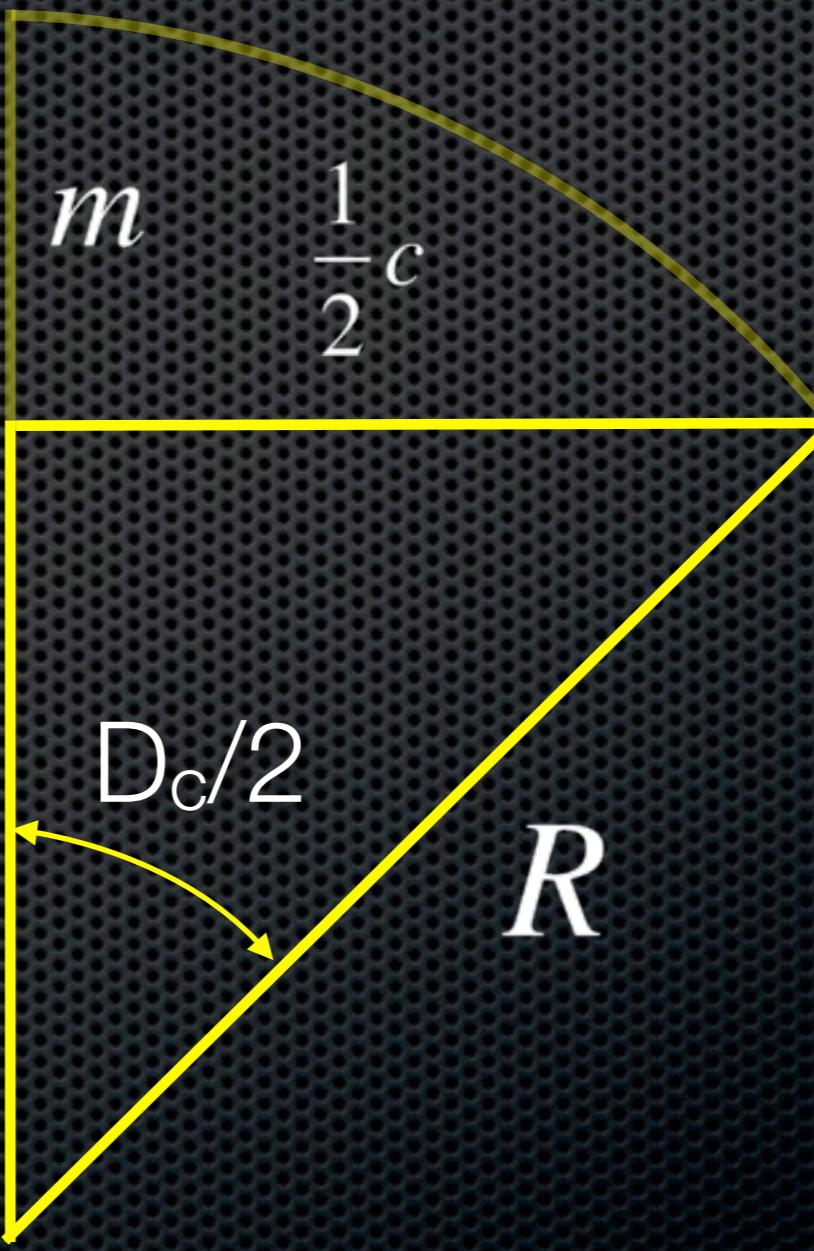
$$R^2 = (R - m)^2 + \frac{1}{4}c^2$$

$$R = \frac{m^2 + \frac{1}{4}c^2}{2m}$$

$m^2 \ll c$ omit,

$$R = \frac{c^2}{8m}$$

$$\text{substitute } R = \frac{5729.651}{D}$$



String Line Method

Degree of Curvature (D_c)

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

Research Question

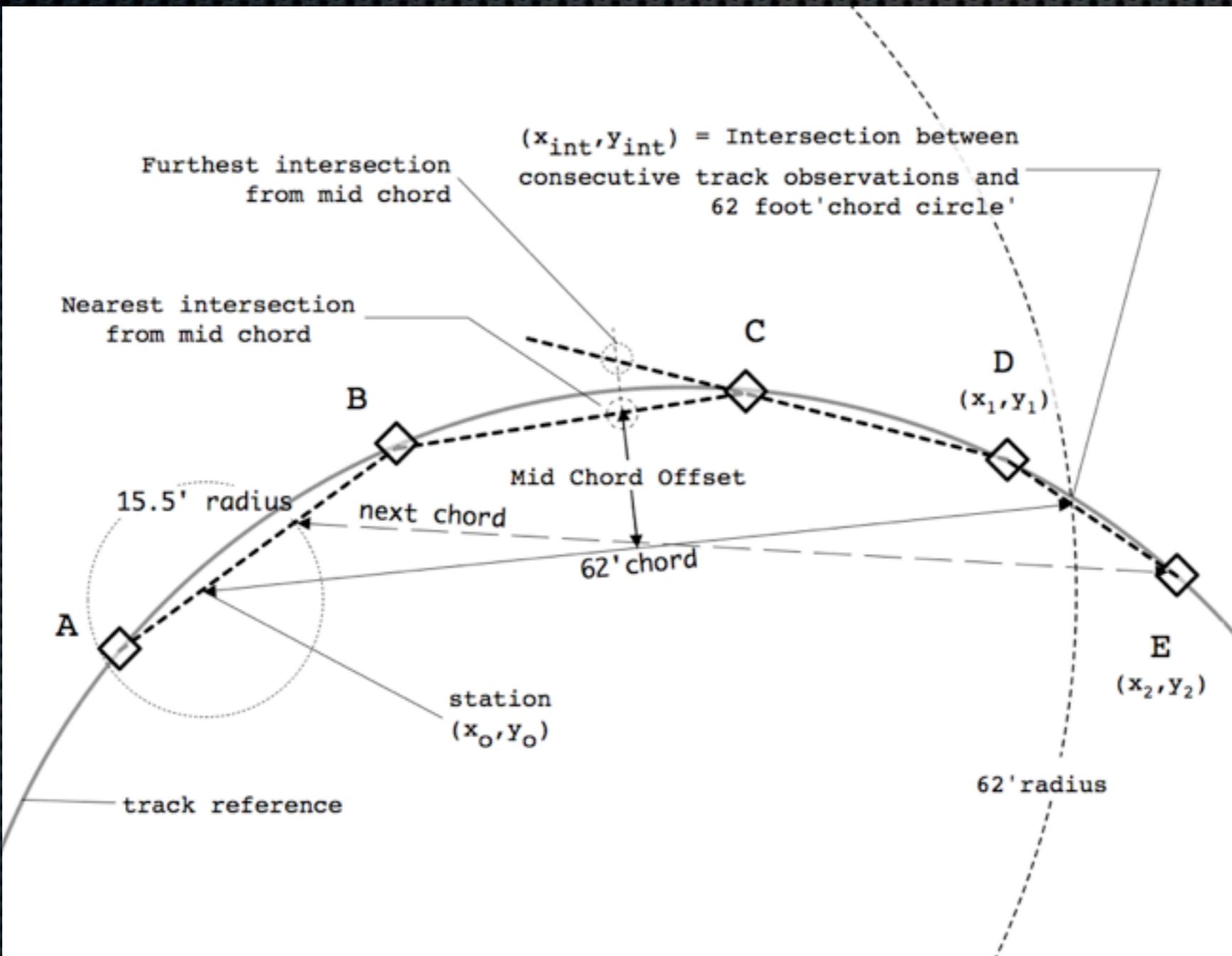
Can RTK GNSS instrumentations mounted to a track inspector's Hi-Rail be used to determine the degree of curvature (D_c) across mainline track comparable with specialized track geometry cars?

Mainline Track Alignment Purpose & Objectives

Determine the D_c across a track inspectors area of responsibility

- Equip a track inspector's Hi-Rail with RTK GNSS instruments in communication with a VRS server to maximize observation accuracy
- Obtain a data set of track position across an inspector's 29 mile area of responsibility.
- Model the FRA sting line method for determining D_c from XYZ
- Develop a method to compare model vs. D_c measured with a track geometry car

Modeling D_c from XYZ



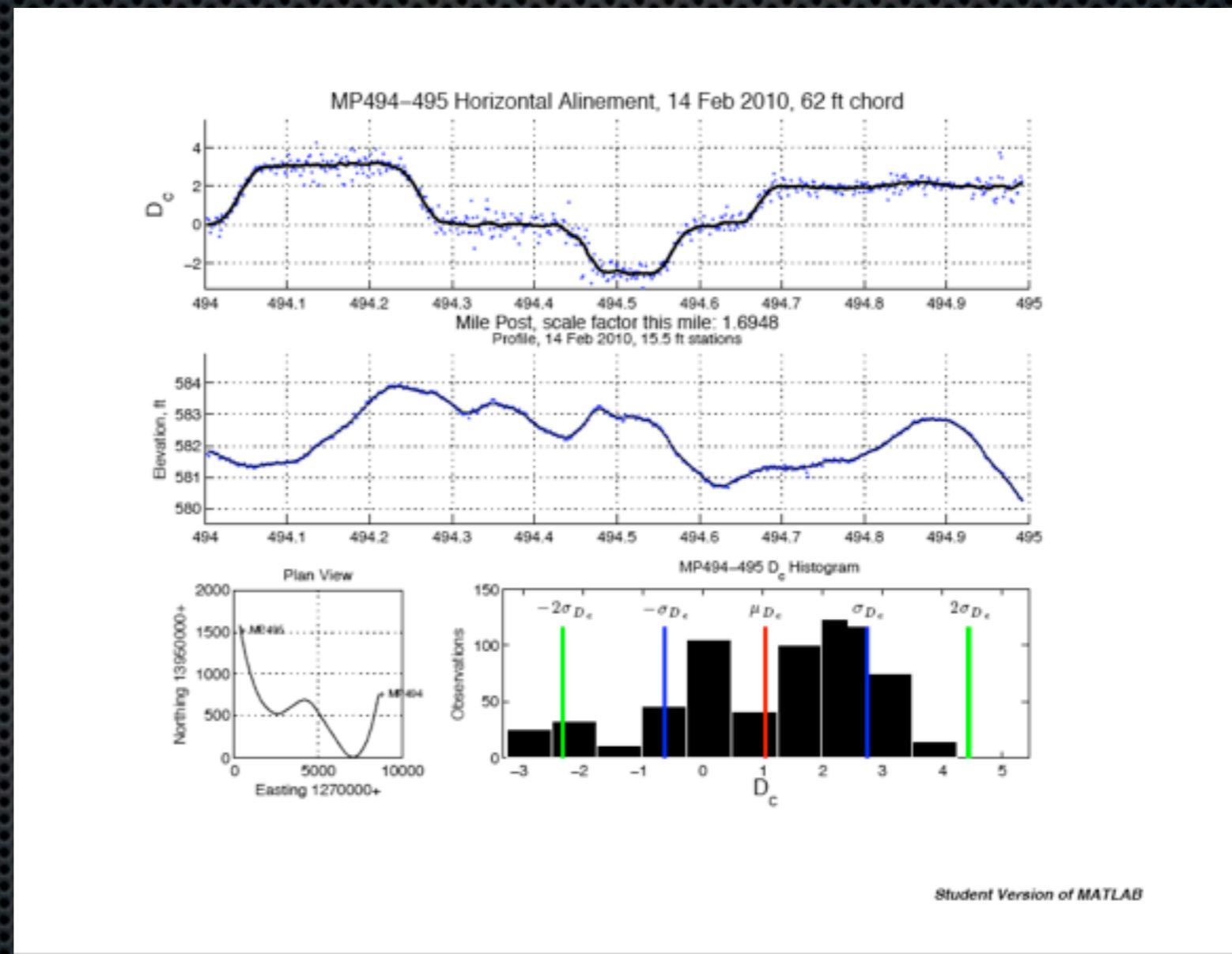
Experiment 2

Results

- Continuous segment of mainline track
 - 29 mile traverse of a track inspector's area of responsibility
- Networked CORS & VRS server minimize proximity error
- Expected LOS due to overhead obstructions

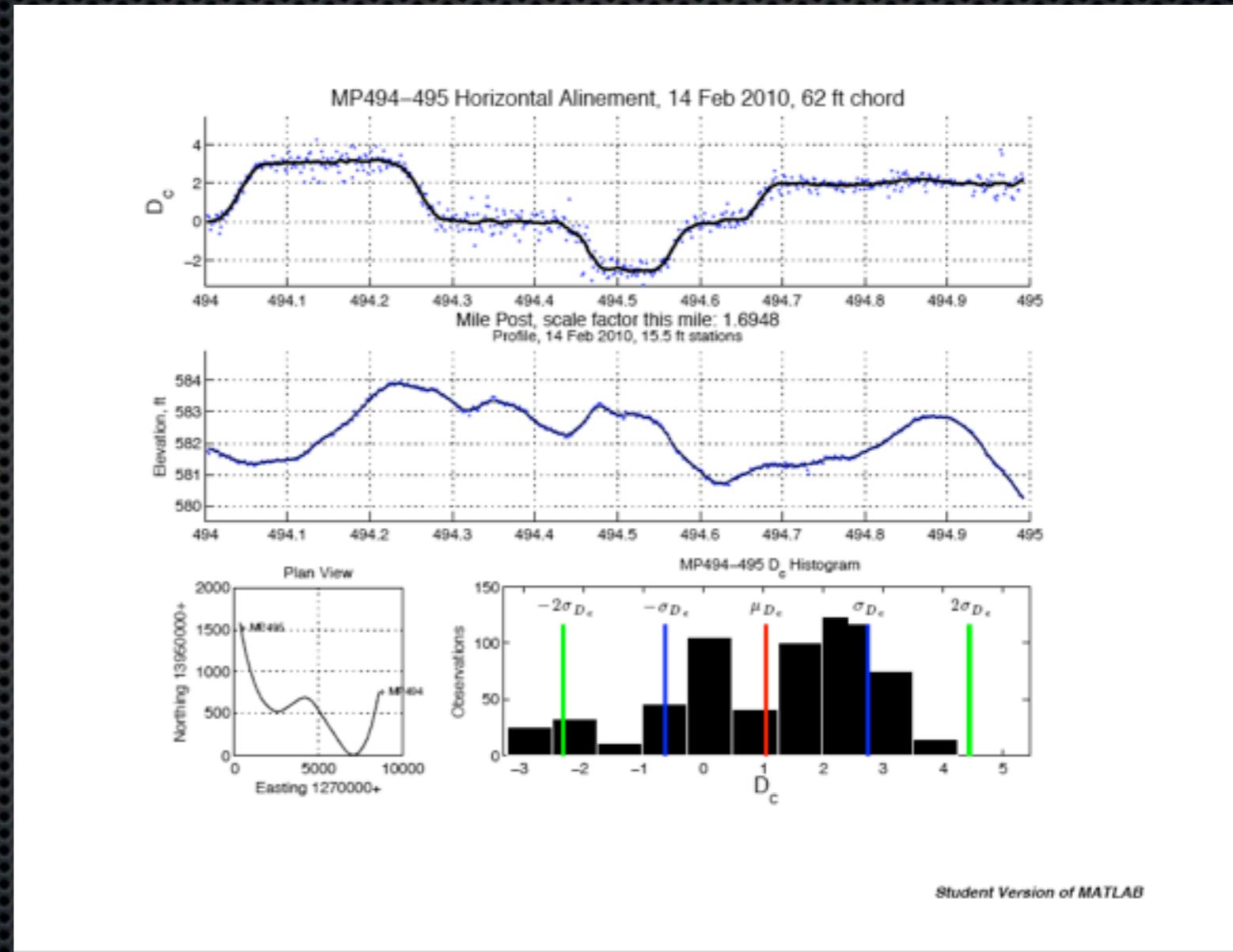
Survey	Observations
A	18,095
B	15,225
C	22,866
D	19,993
E	21,001

Results XYZ to D_c Model Output



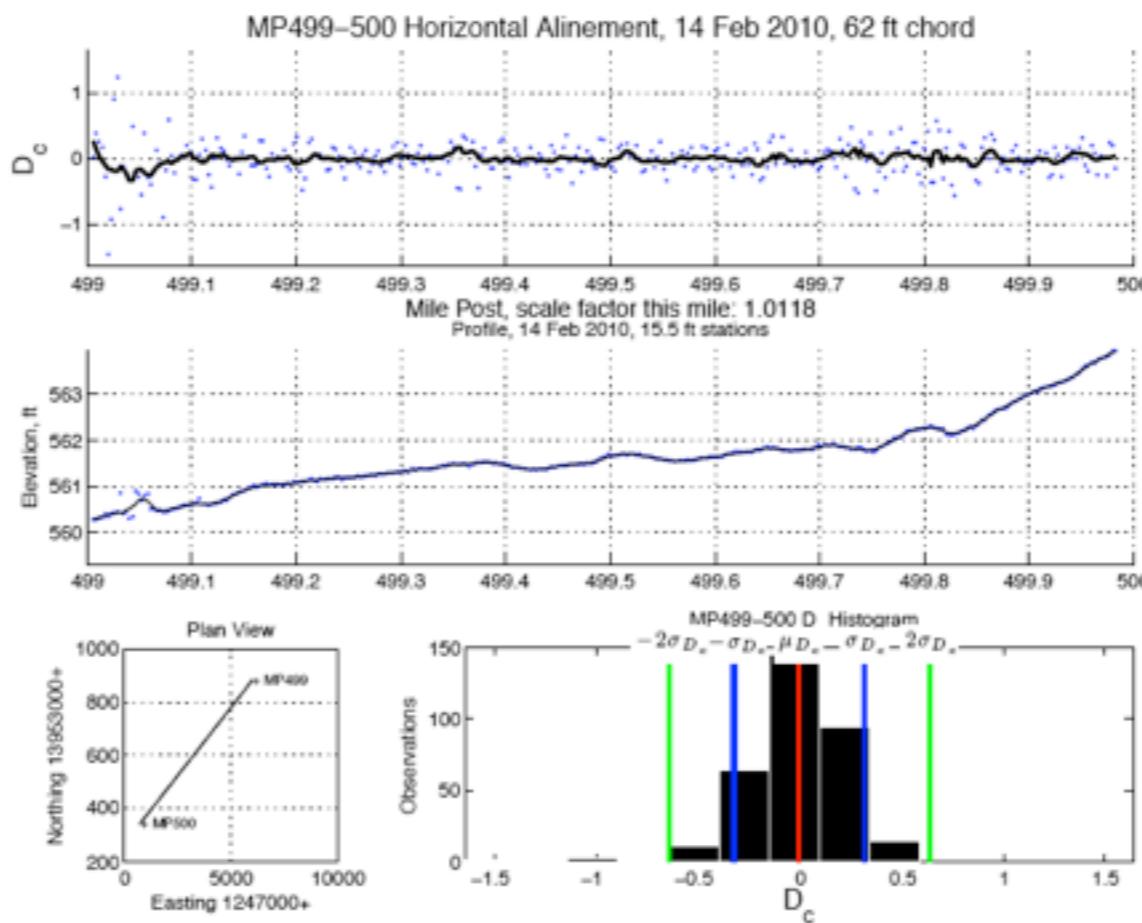
Results XYZ to D_c Model Output

- MP 494-495
 - curves



Results XYZ to D_c Model Output

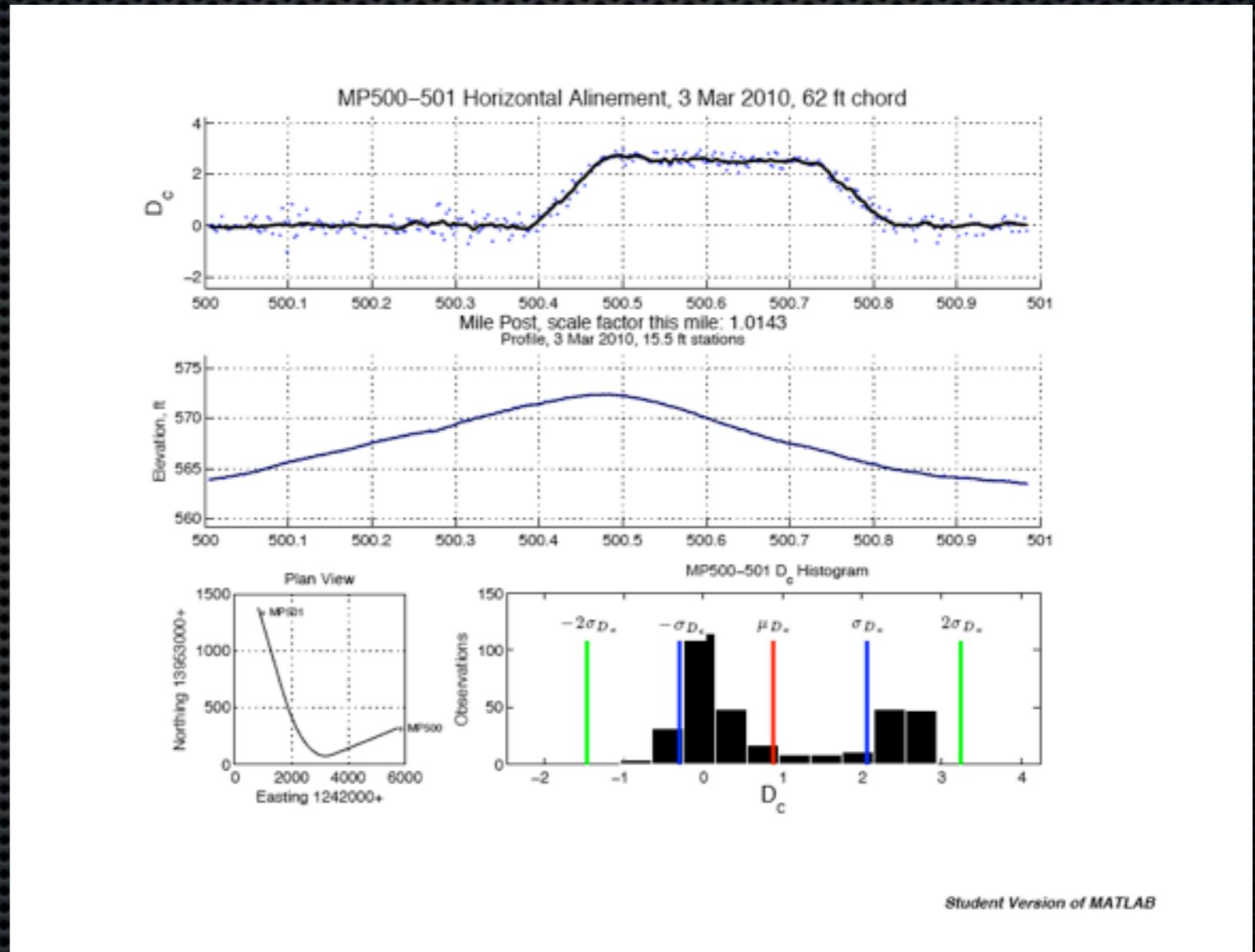
- MP 494-495
 - curves
- MP 499-500
 - tangent



Student Version of MATLAB

Results XYZ to D_c Model Output

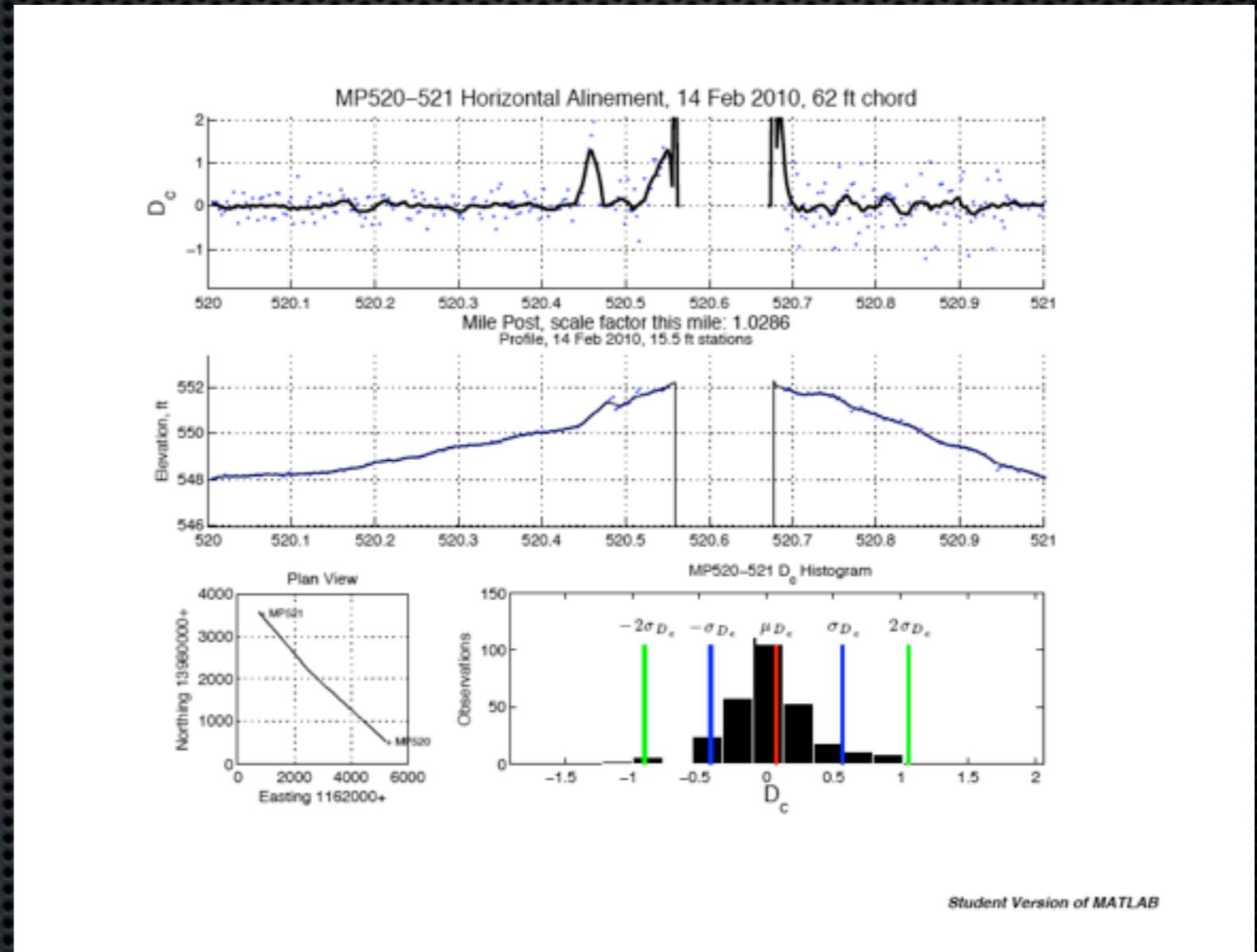
- MP 494-495
 - curves
- MP 499-500
 - tangent
- MP 500-501
 - exit spiral



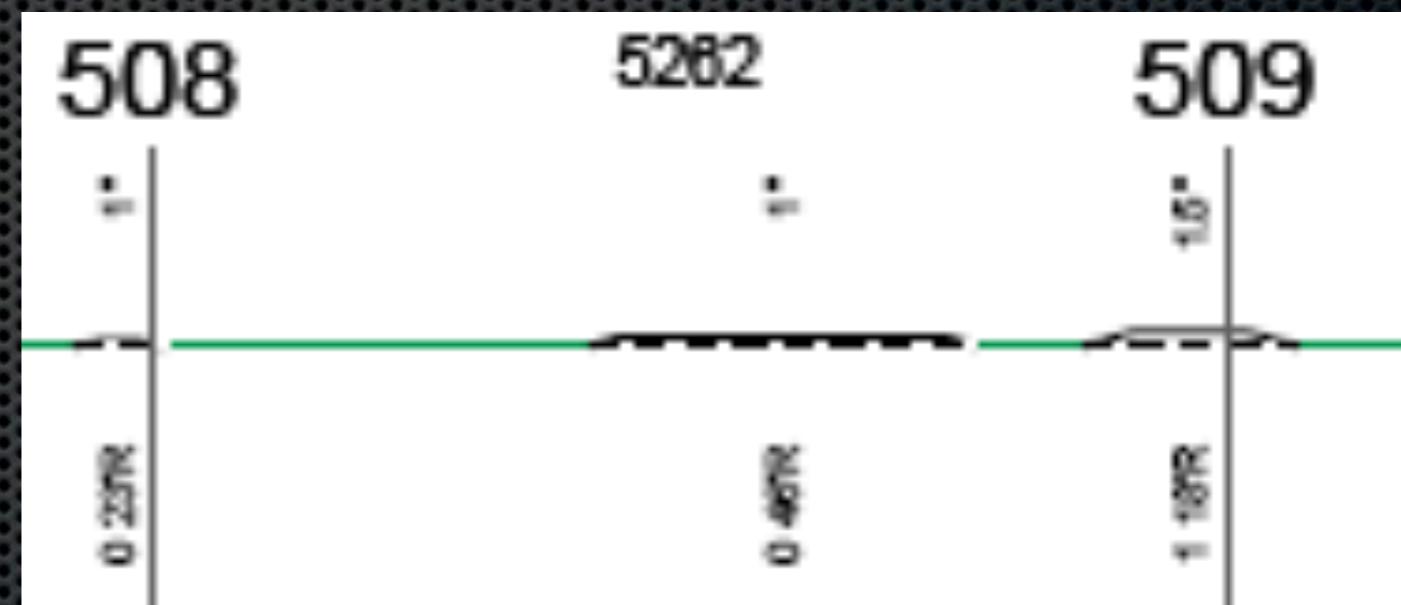
Student Version of MATLAB

Results XYZ to D_c Model Output

- MP 494-495
 - curves
- MP 499-500
 - tangent
- MP 500-501
 - exit spiral
- MP 521-522
 - LOS

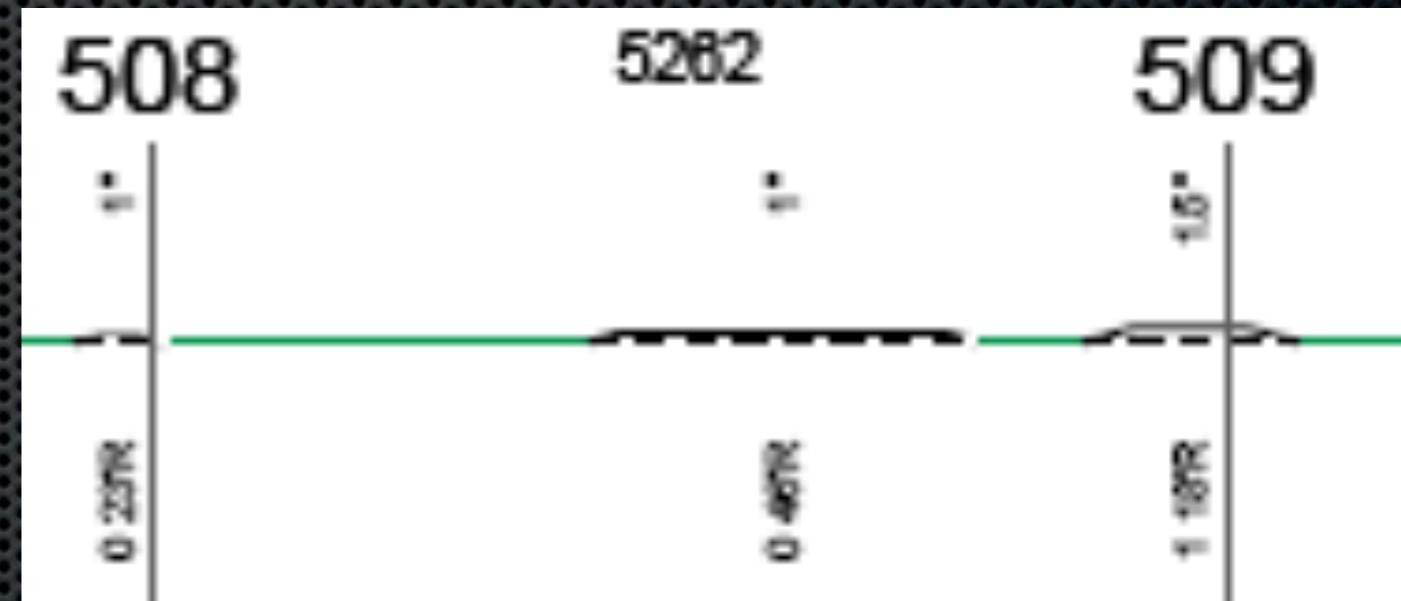


Model Discrepancies with Rail Company Track Charts



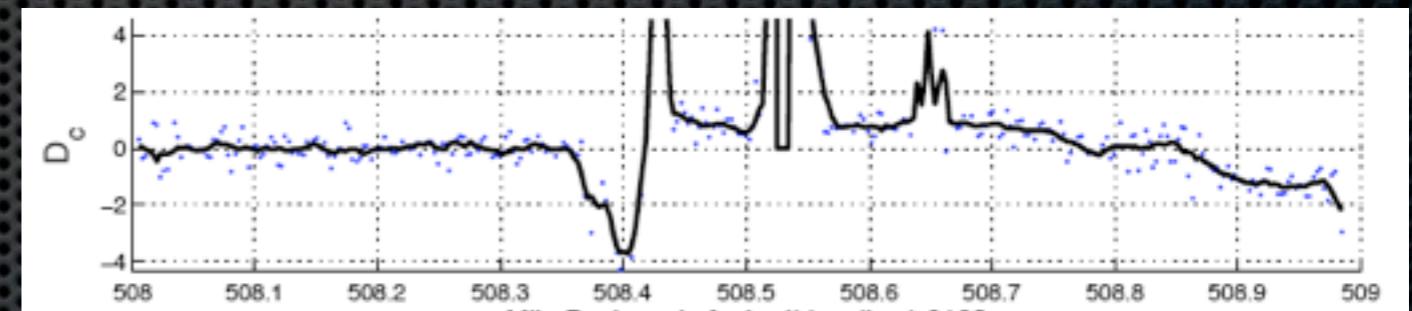
Model Discrepancies with Rail Company Track Charts

- MP 508.9 curve direction
 - TC: $1^{\circ}18'$ right



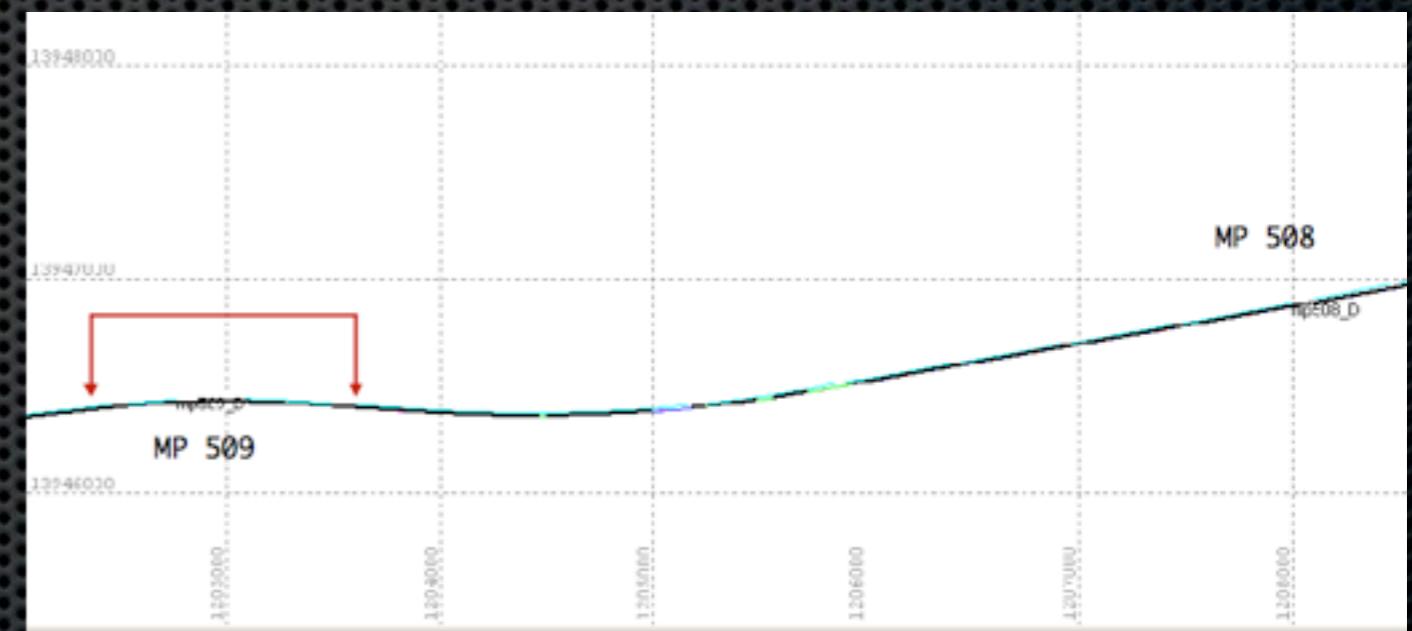
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 - TC: $1^\circ 18'$ right
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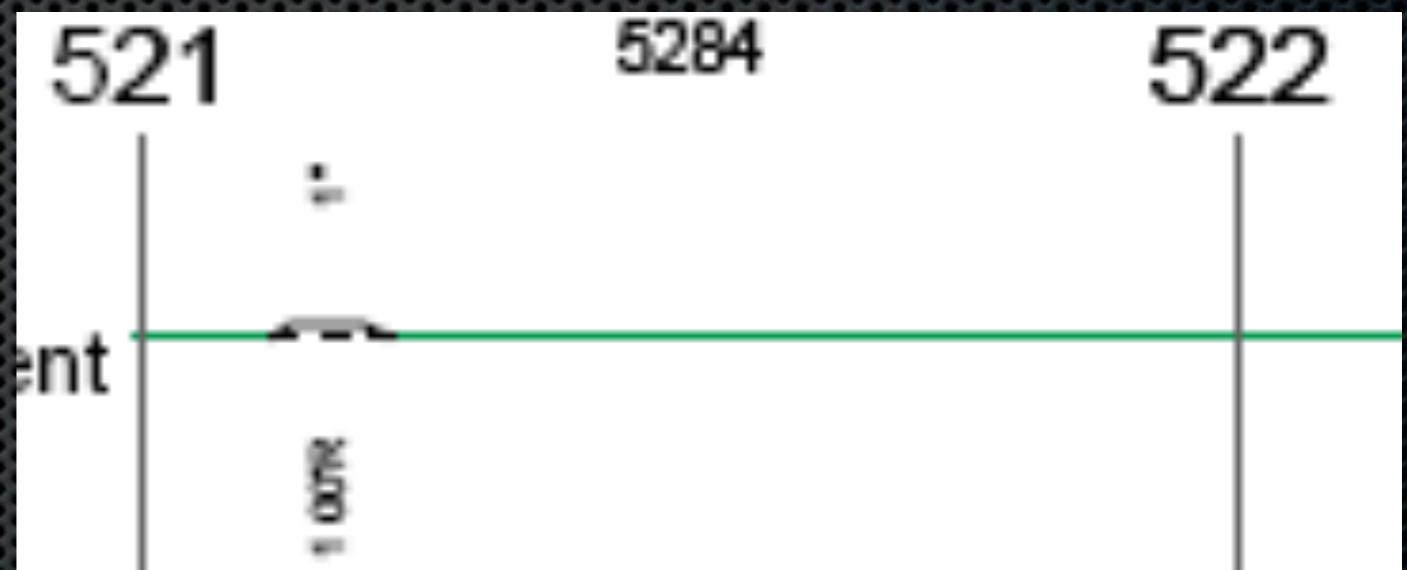
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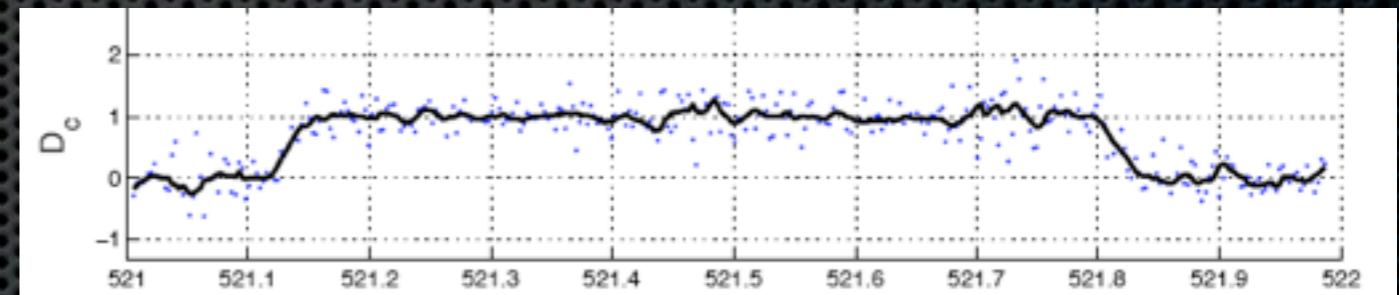
Model Discrepancies with Rail Company Track Charts

- MP 508.9 curve direction
 - TC: $1^{\circ}18'$ right
 - Model: ... left
- MP 521.15 curve length
 - TC: $1^{\circ}00' R @ 0.15$ mi



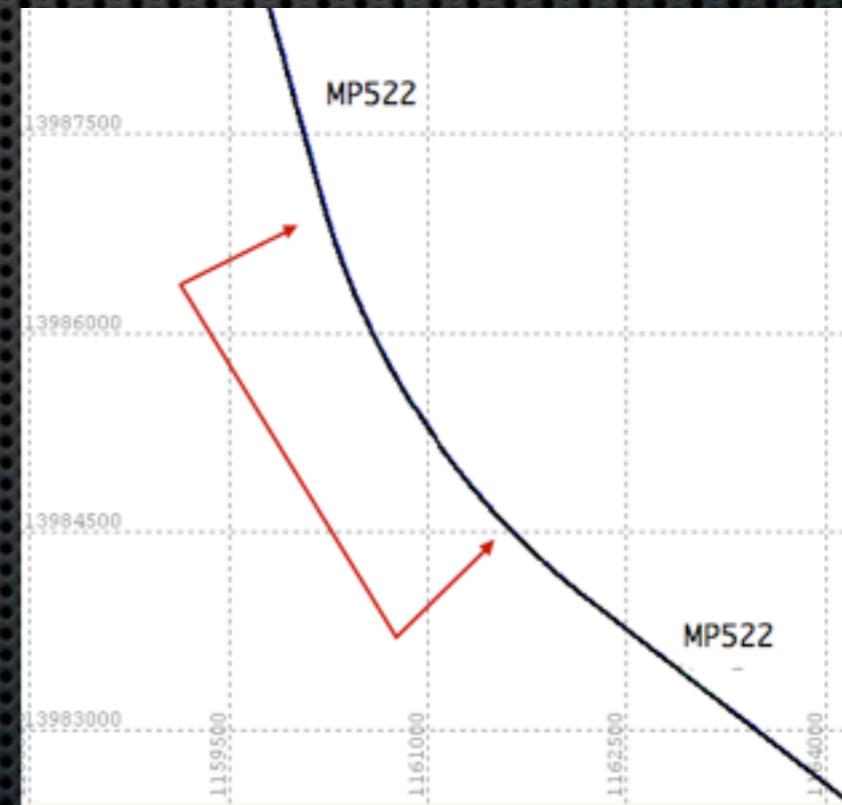
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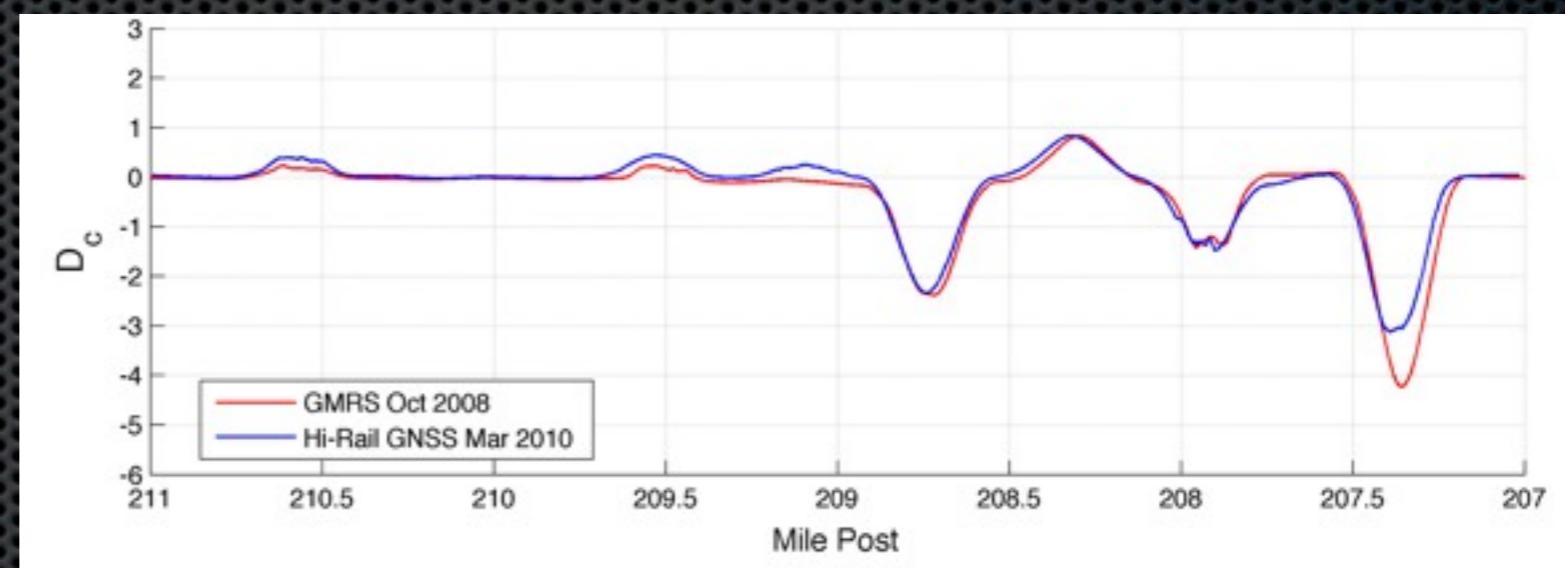


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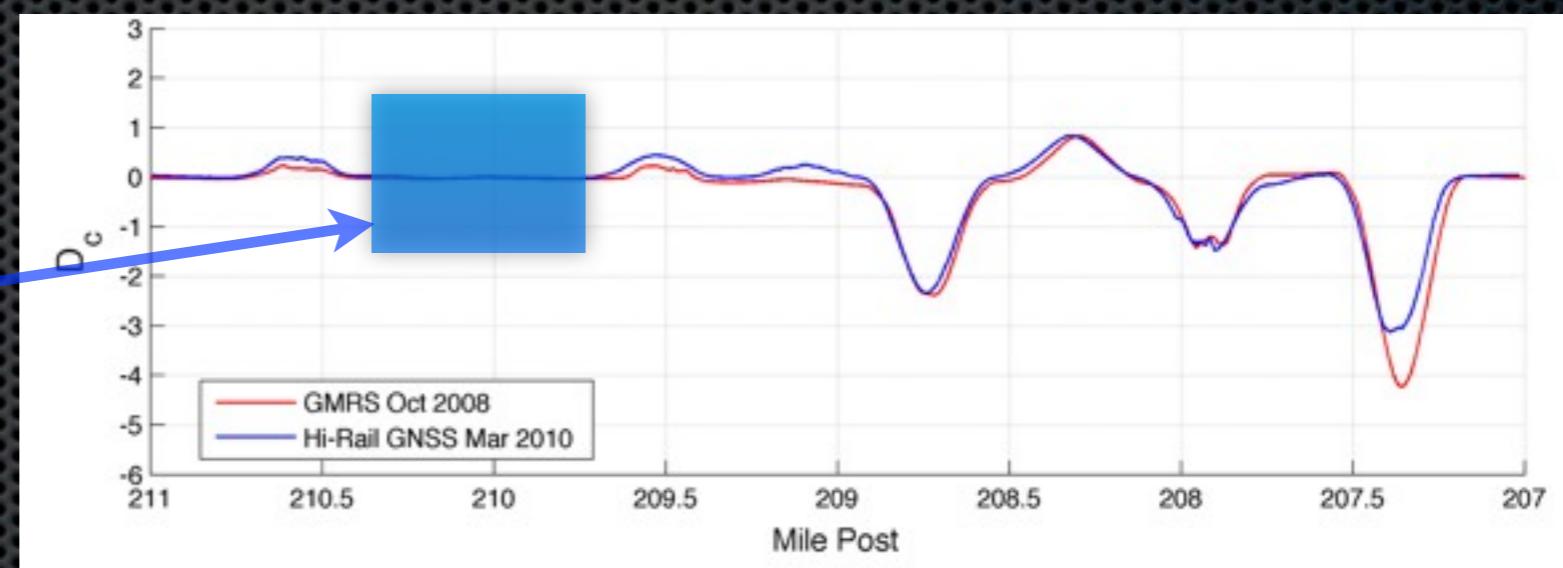


Comparison of Tangent D_c with CSX Geometry Car GMRS1



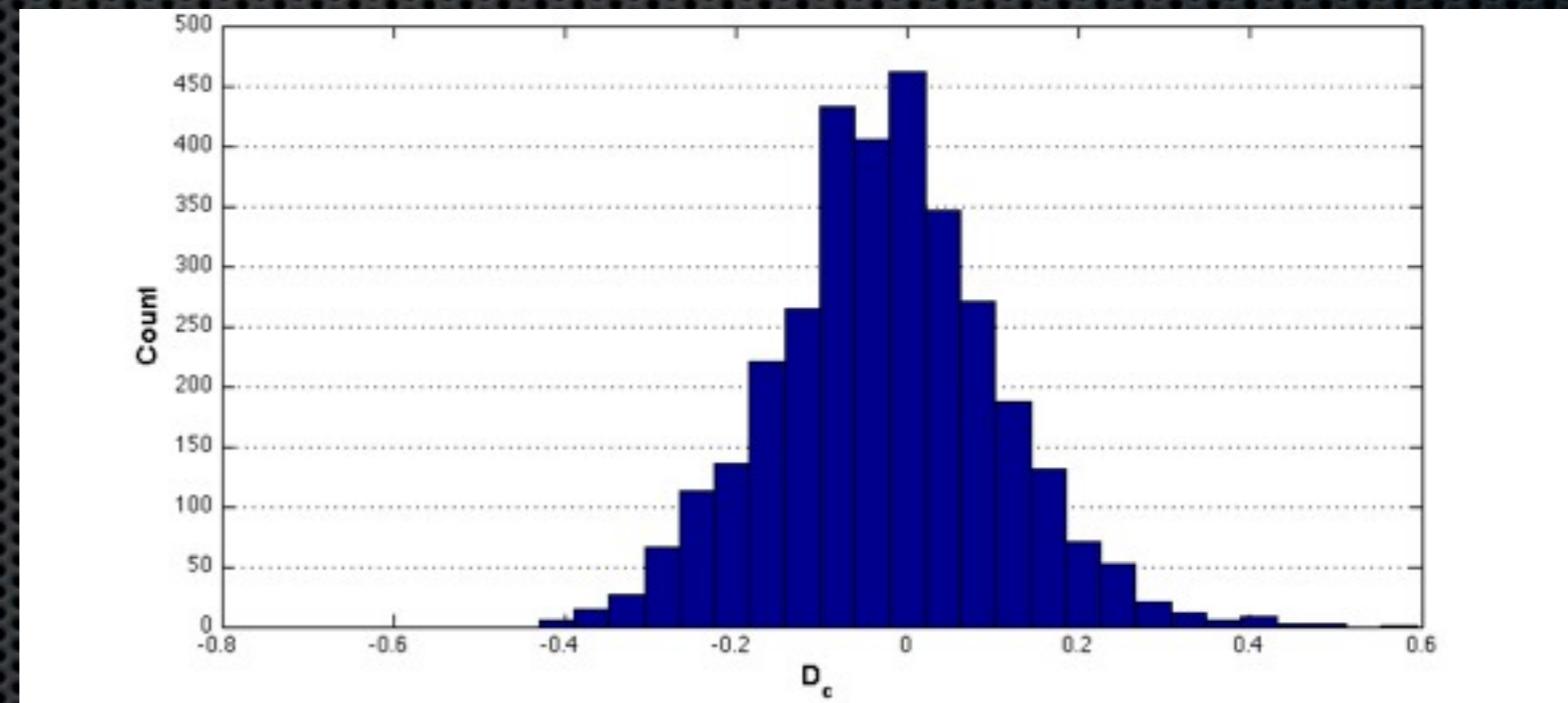
Comparison of Tangent D_c with CSX Geometry Car GMRS1

Comparison
Segment



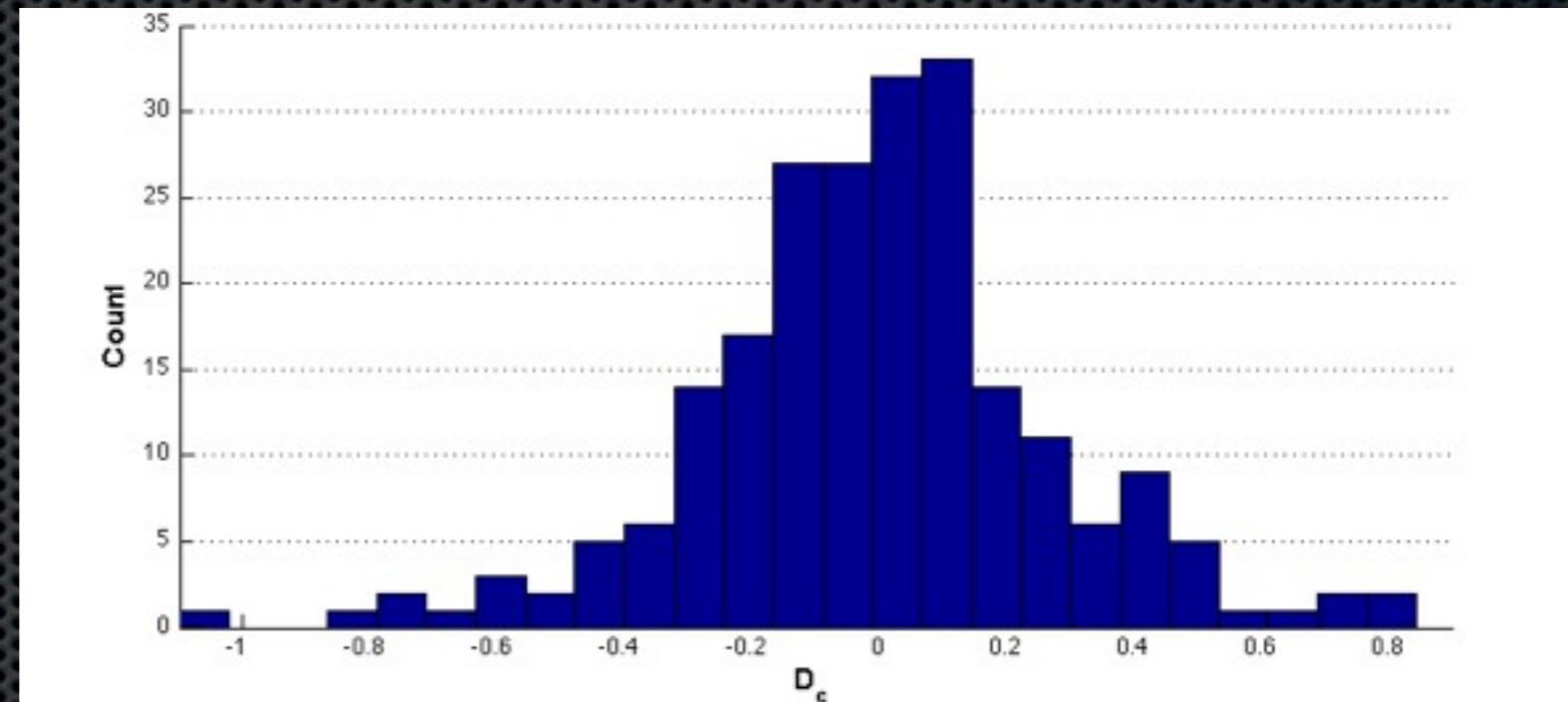
Comparison of Tangent D_c with CSX Geometry Car GMRS1

- CSX GMRS-1
 - $N = 3,253$
 - $\mu_{D_c} = -0.0264$
 - $\sigma_{D_c} = 0.131$

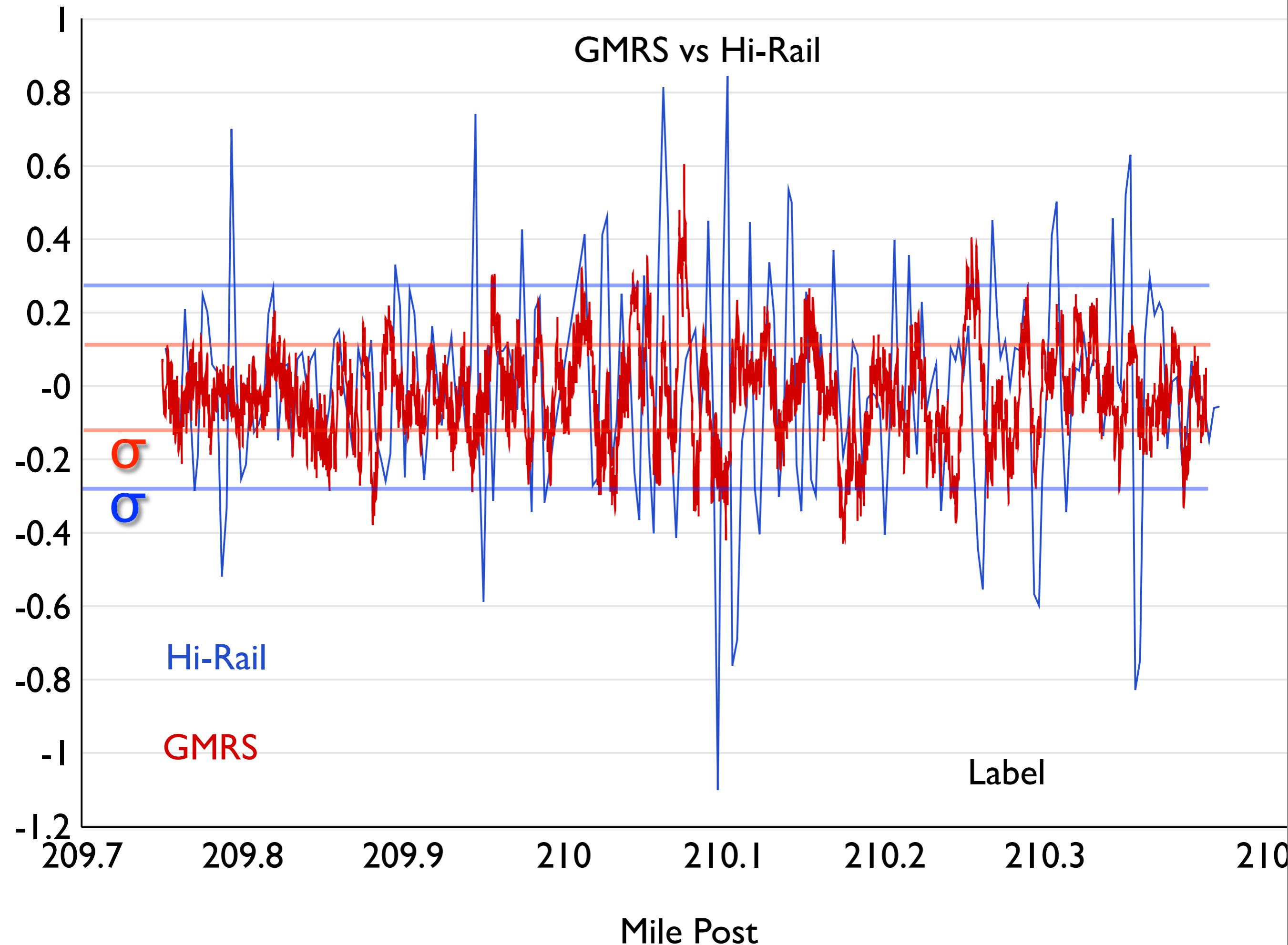


Comparison of Tangent D_c with CSX Geometry Car GMRS1

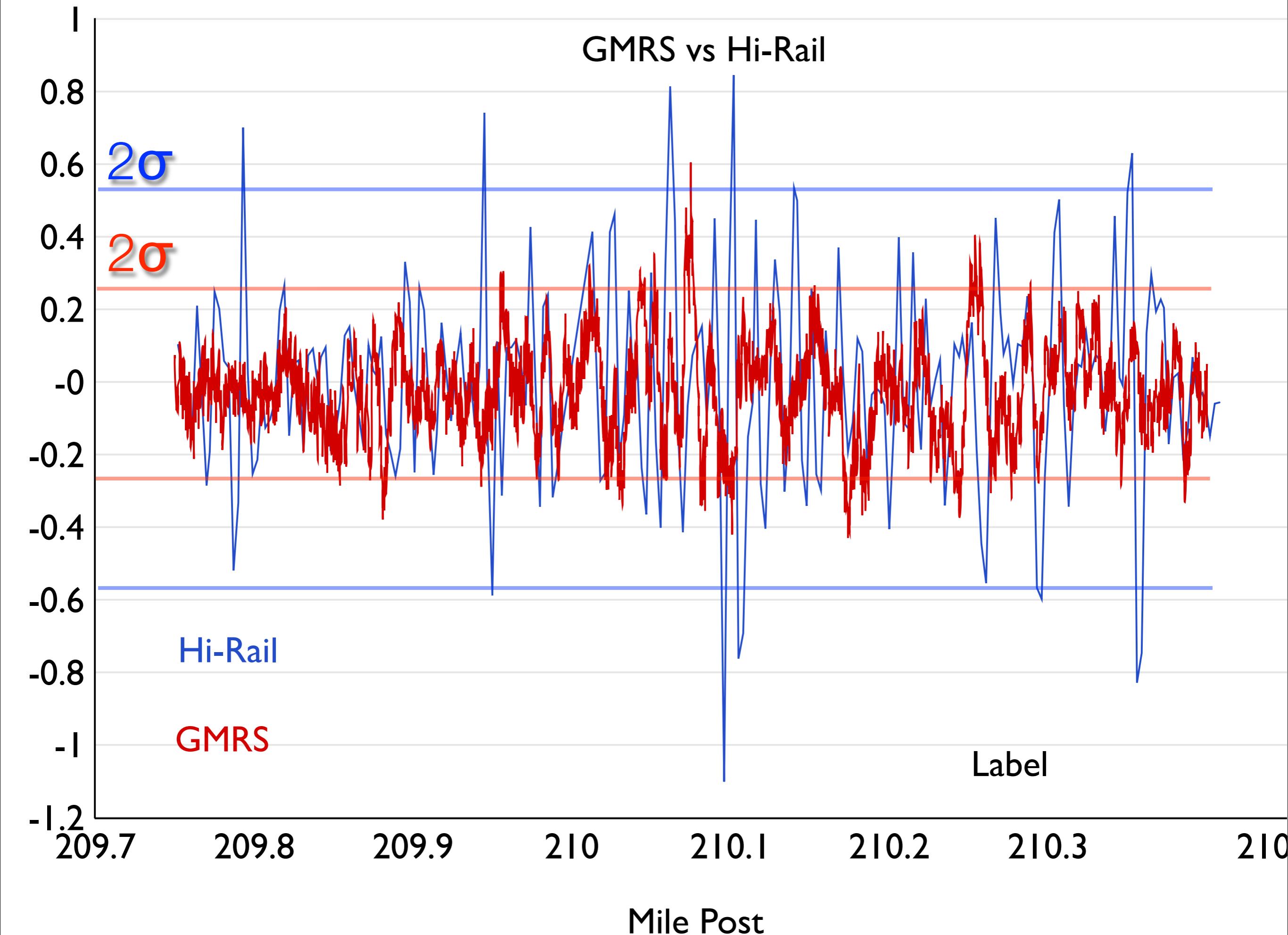
- CSX GMRS-1
 - $N = 3,253$
 - $\mu_{D_c} = -0.0264$
 - $\sigma_{D_c} = 0.131$
- Hi-Rail
 - $N = 222$
 - $\mu_{D_c} = -0.0042$
 - $\sigma_{D_c} = 0.279$



GMRS vs Hi-Rail



GMRS vs Hi-Rail



Conclusions

- XYZ to D_c model verified by rail company track charts
- Hi-Rail not equivalent to track geometry car
- Present GNSS signals for continuous track observations impeded by LOS from overhead obstructions

Implications for Measuring Alignment Defects

§213.9 Classes of track: operating speed limits

9(a) Except as provided in paragraph (b) of this section and [§213.57\(b\)](#), [213.59\(a\)](#), [213.113\(a\)](#), and [213.137\(b\) and \(c\)](#), the following maximum allowable operating speeds apply:

Over track that meets all of the requirements prescribed in this part for	The maximum allowable speed for freight trains is	The maximum allowable speed for passenger trains is
Excepted	10	N/A
1	10	15
2	25	30
3	40	60
4	60	80
5	80	90

Table 1

Implications for Measuring Alignment Defects

§213.55 Alignment

Alignment may not deviate from uniformity more than the amount prescribed in the following table:

Class of Track	Tangent Track	Curved Track	
	The deviation of the mid-offset from a 62-foot line [1] may not be more than—	The deviation of the mid-ordinate from a 31-foot chord [2] may not be more than—	The deviation of the mid-ordinate from a 62-foot chord [2] may not be more than—
1	5"	N/A ³	5"
2	3"	N/A ³	3"
3	1 $\frac{3}{4}$ "	1 $\frac{1}{4}$ "	1 $\frac{3}{4}$ "
4	1 $\frac{1}{2}$ "	1"	1 $\frac{1}{2}$ "
5	$\frac{3}{4}$ "	$\frac{1}{2}$ "	$\frac{5}{8}$ "

[1] The ends of the line must be at points on the gage side of the line rail, five-eighths of an inch below the top of the railhead. Either rail may be used as the line rail, however, the same rail must be used for the full length of that tangential segment of track.

[2] The ends of the chord must be at points on the gage side of the outer rail, five-eighths of an inch below the top of the railhead.

[3] N/A - Not Applicable.

Table 4

Implications

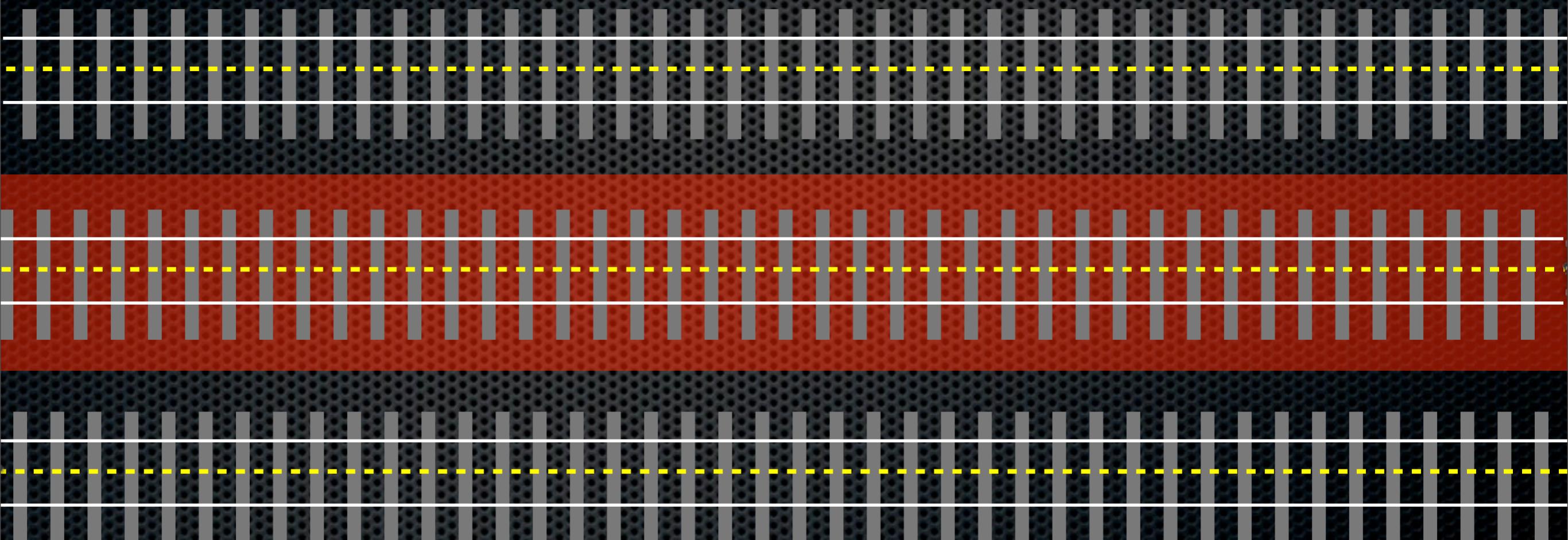
- Further modeling will enable track class 1-4 alignment defect detection
- Additional GNSS sensor(s) will expand determination of
 - Superelevation (roll axis)
 - Grade (pitch axis)
 - Twist (roll axis change over a distance)

Experiment 3

Determining Track Occupancy

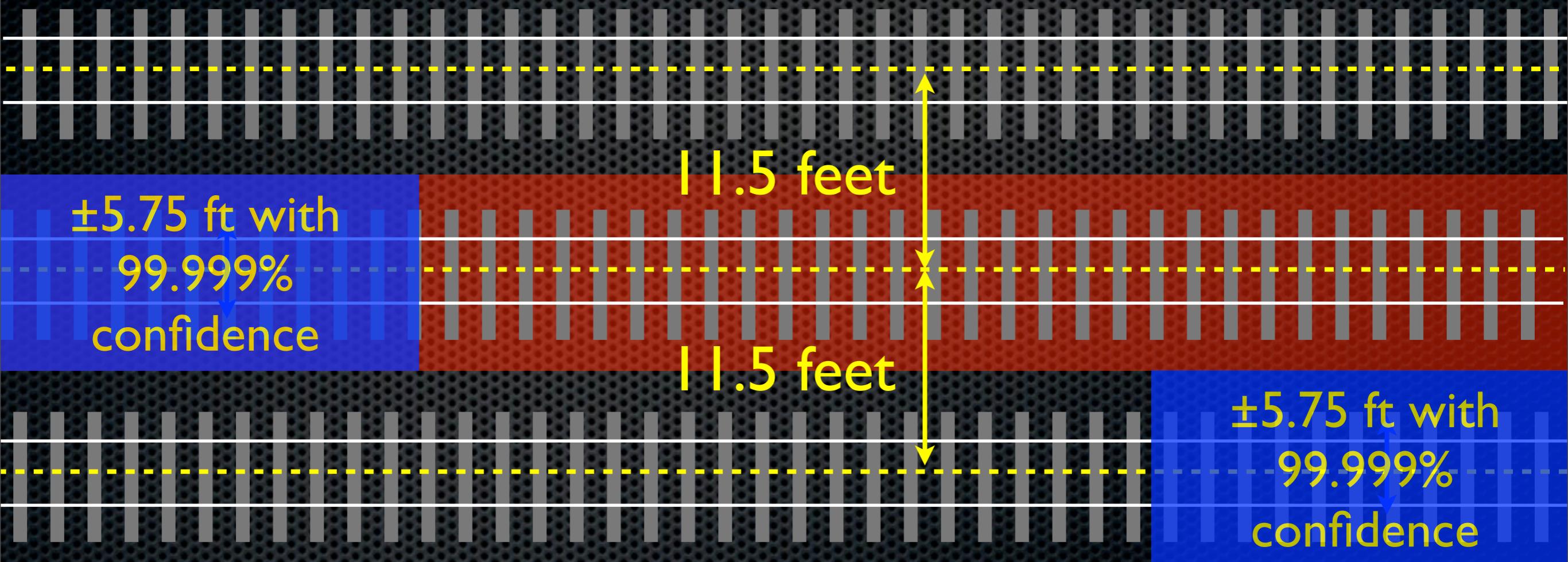
Assess the ability of RTK GNSS to determine the track occupancy of a track vehicle meeting the definition of a location determination system.

FRA Wireless Track Occupancy



1995 Federal Railway Administration Report

FRA Wireless Track Occupancy



1995 Federal Railway Administration Report

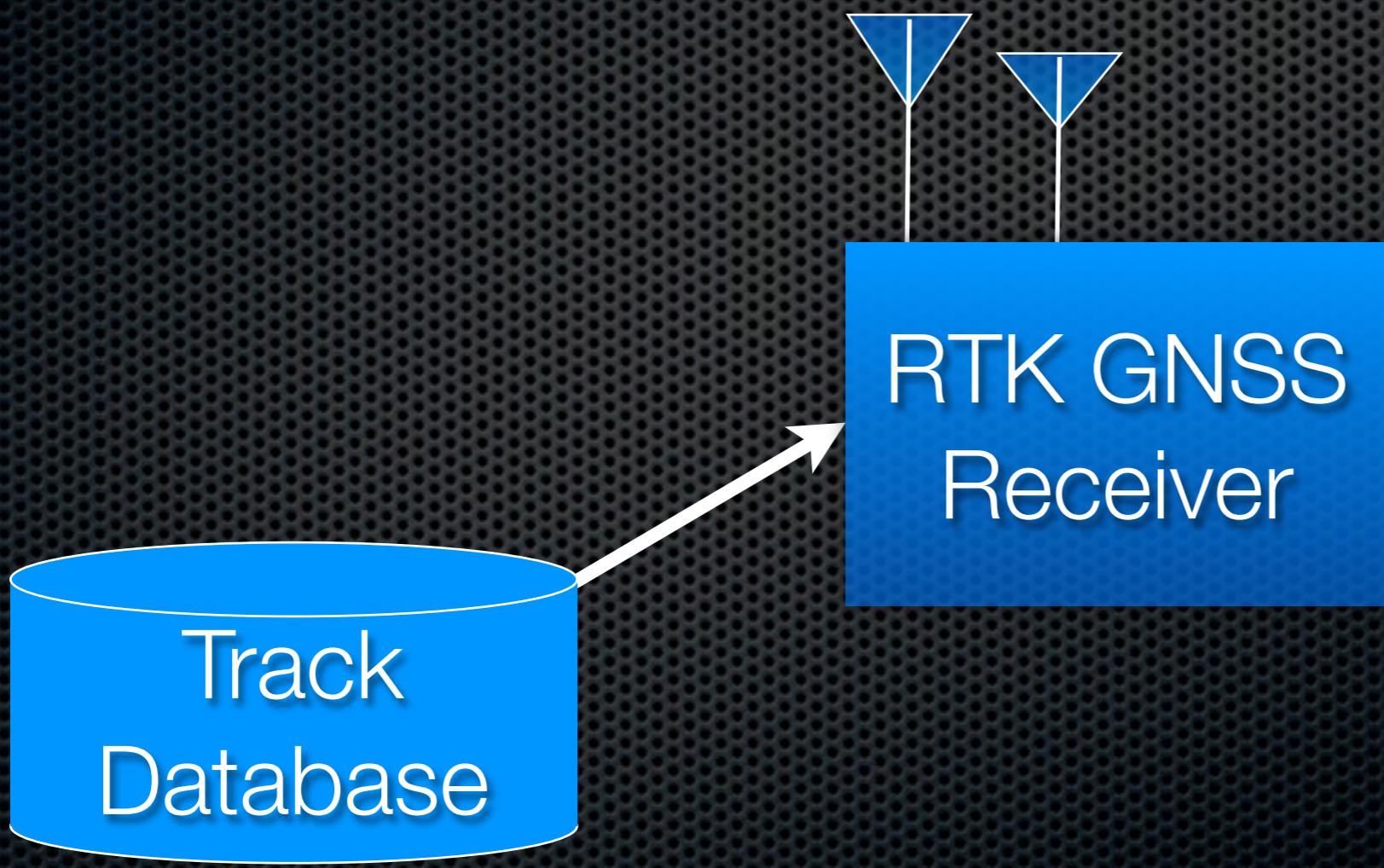
Motivation

- Track occupancy presently determined by wired track circuits
 - Insulated joints between CWR segments
 - Axle completes low voltage circuit across rails
 - Proximity switches (magnetic)
 - Loop detectors
- Replacement value for signals: \$125,000 / mile (Moorman)
- No wired circuits or signals = “Dark Territory”

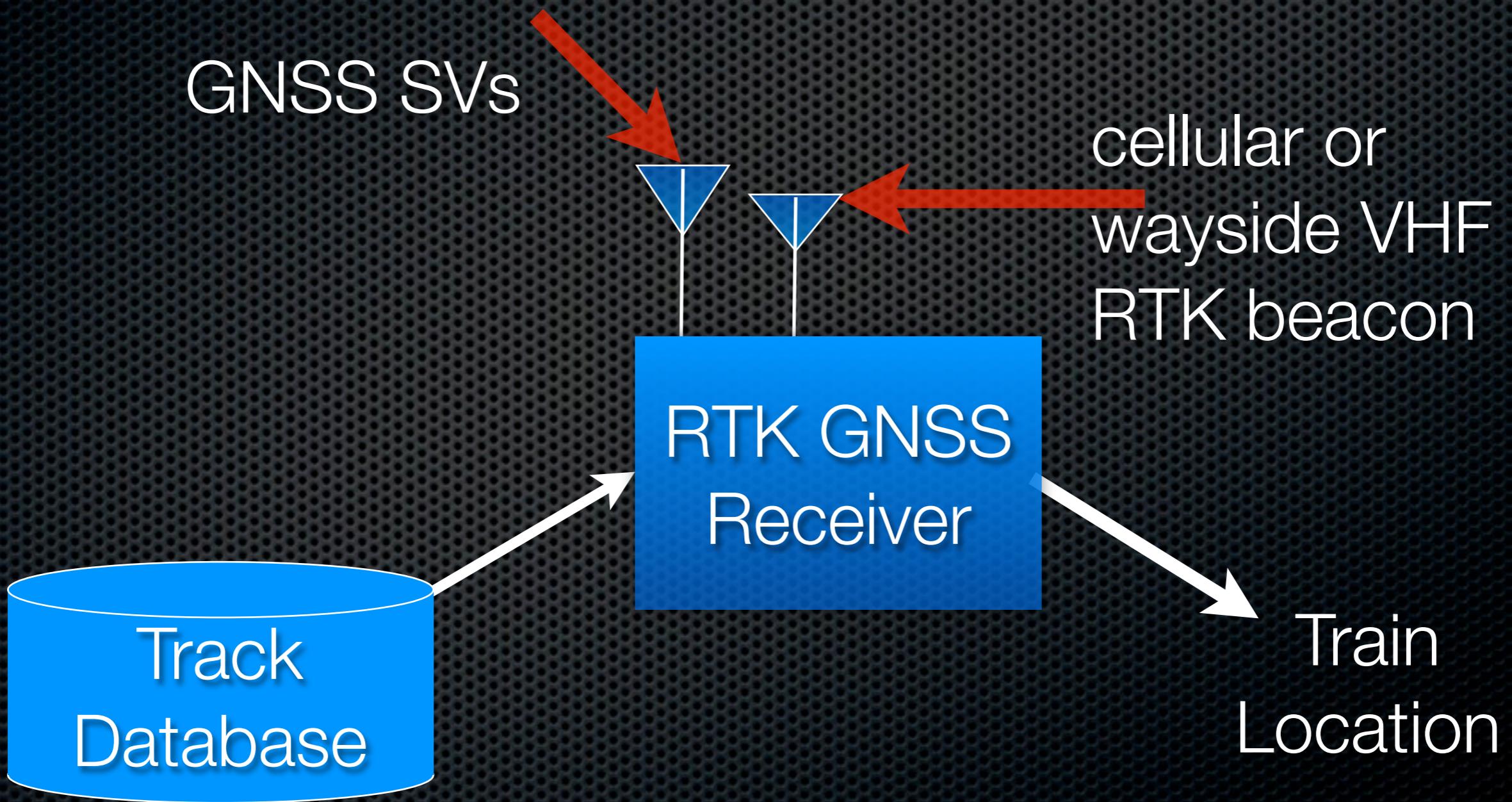
Motivation

- Railroad Safety Improvement Act of 2008
 - Class I railroads, as well as intercity passenger and commuter railroads, must install PTC on main line tracks by Dec. 31, 2015.
 - Act defines mainline as > 5 MGT/Y

Research Postulates that RTK GNSS will simplify LDS



Research Postulates that RTK GNSS will simplify LDS



Research Question

Can RTK GNSS determine track occupancy meeting
the FRA specifications for a location determination
system?

Track Occupancy Purpose & Objectives

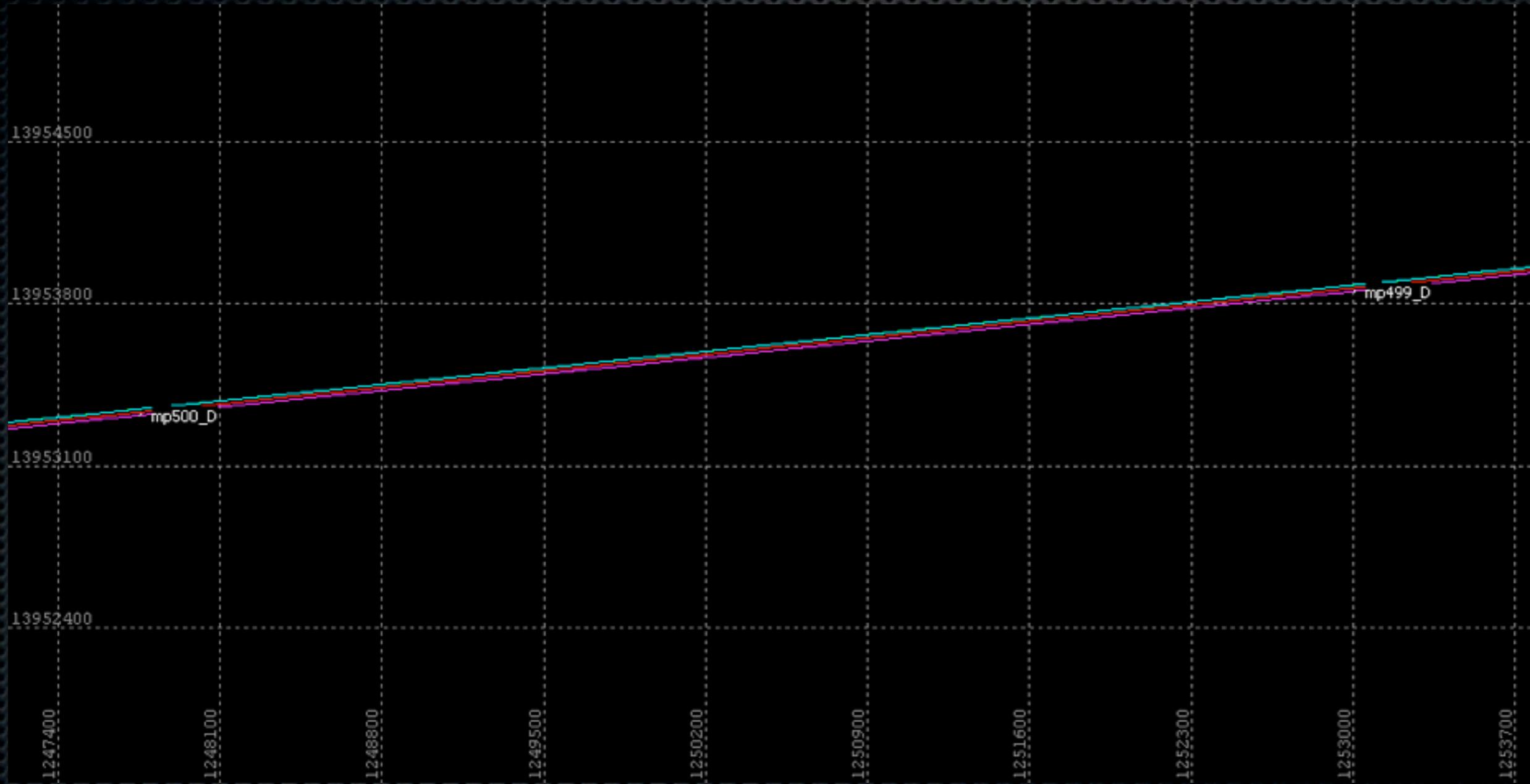
Determine if RTK GNSS track measurement can meet the definition of a LDS

- Develop a test for determining track occupancy on multiple parallel track from RTK observations for
 - A tangent track segment
 - A circular curve track segment

Observation Data

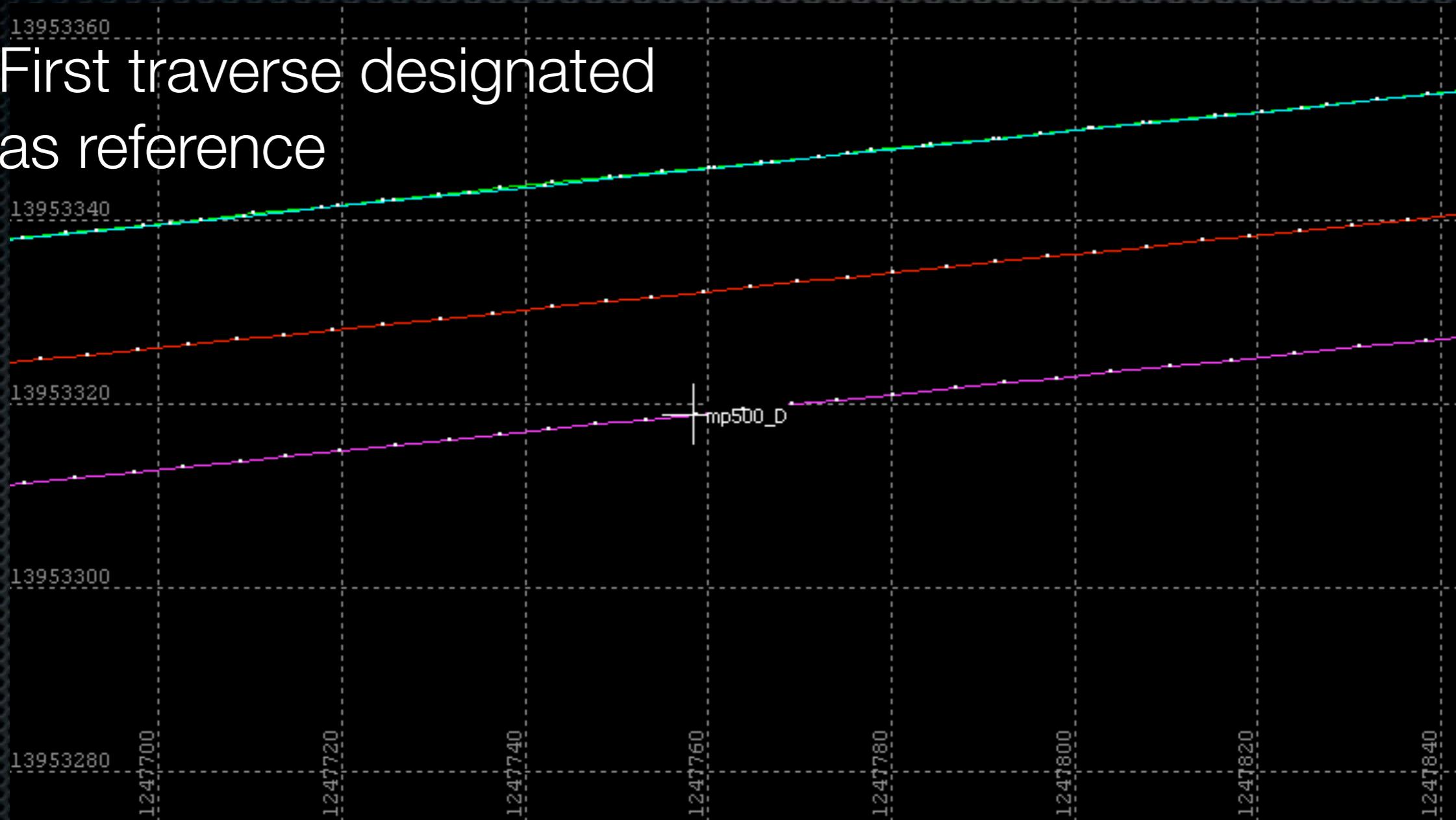
- Mainline tangent and circular track segments
 - Three parallel tracks
 - Five traverses
- Tangent: CSX Kanawha Subdivision
MP 498.9 to 500.2
- Curve: Kanawha Subdivision
MP 500.2 to 500.7

Tangent Segment



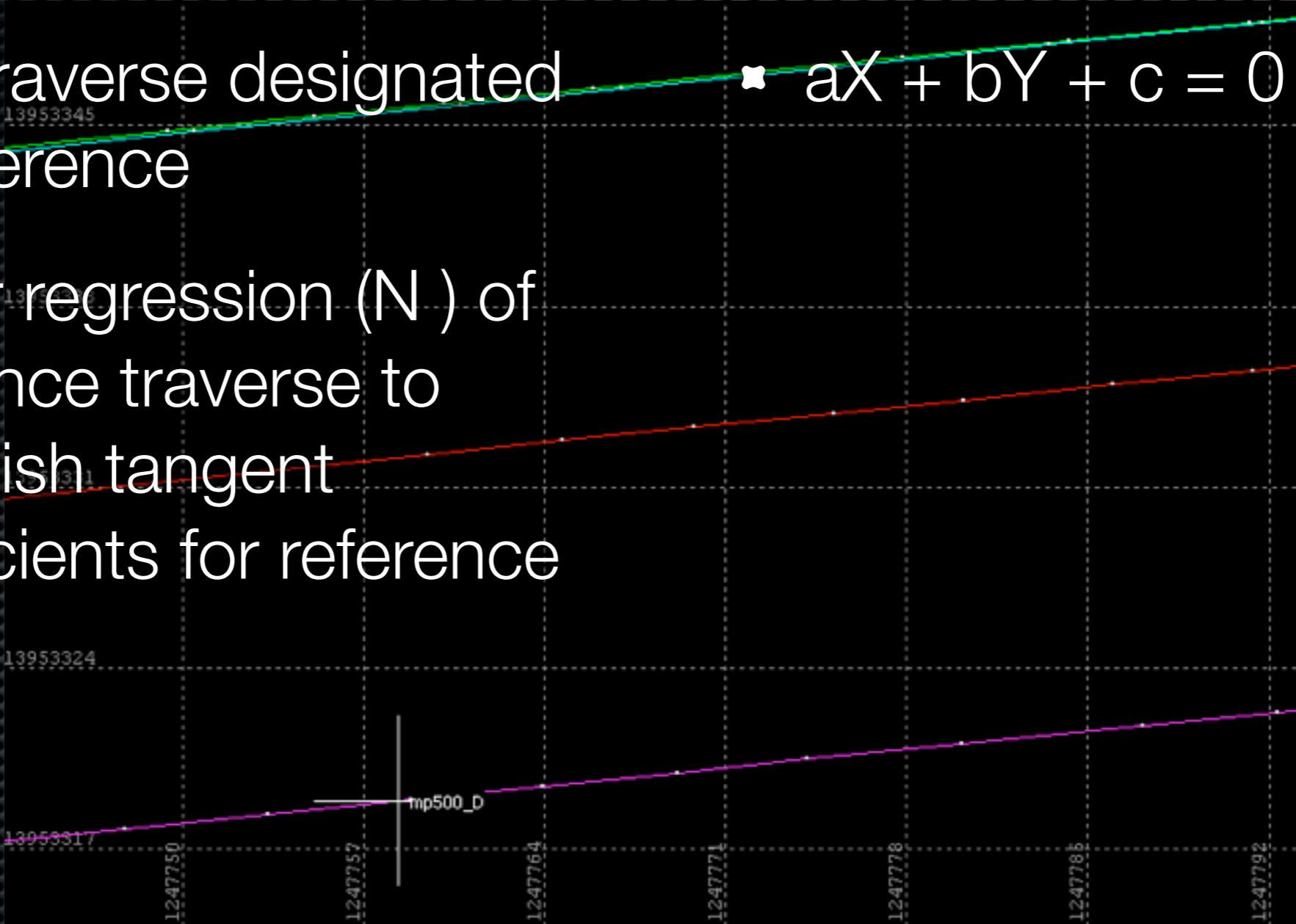
Tangent Segment

- First traverse designated as reference



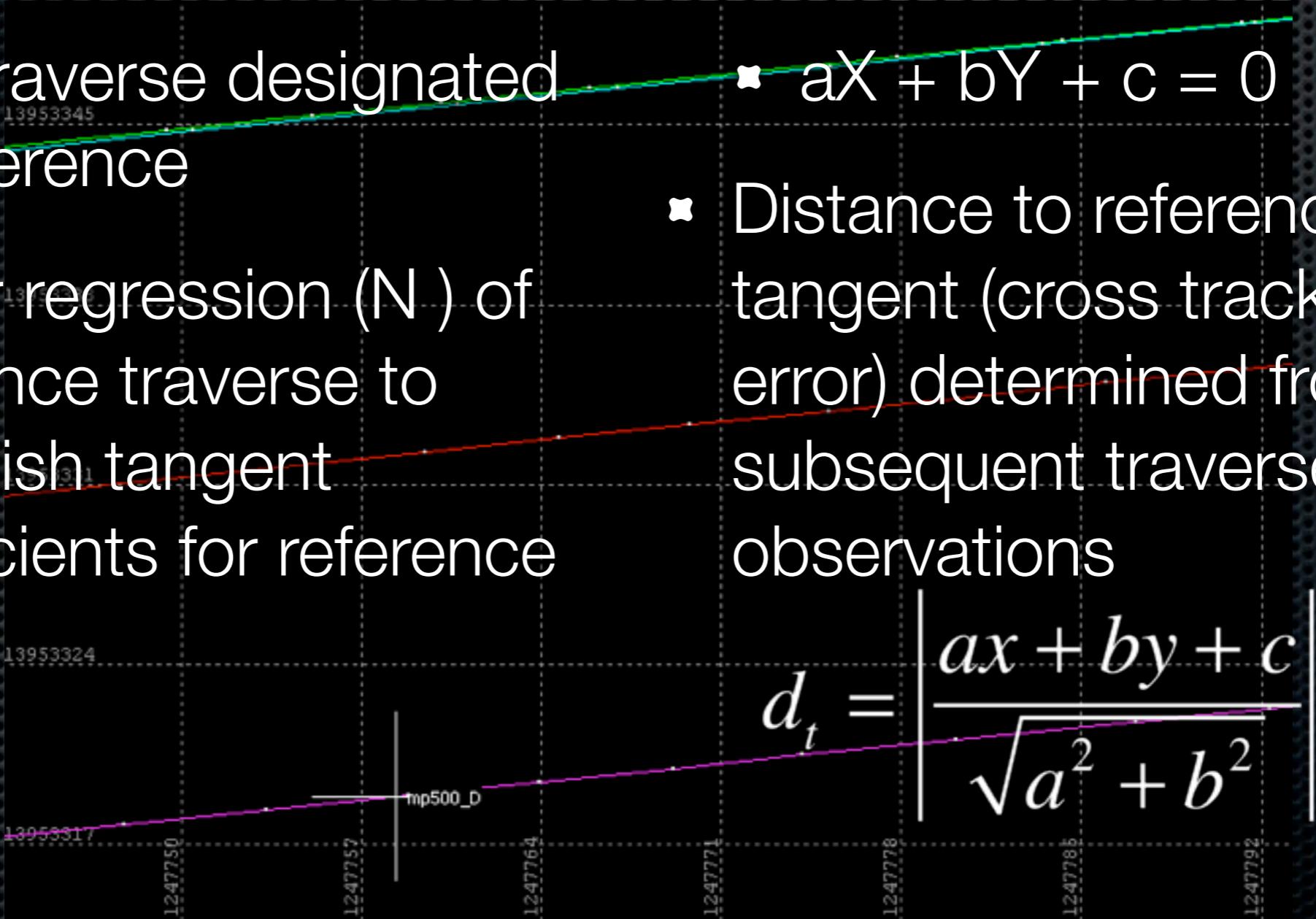
Tangent Segment

- First traverse designated as reference
- Linear regression (N) of reference traverse to establish tangent coefficients for reference line
- $aX + bY + c = 0$

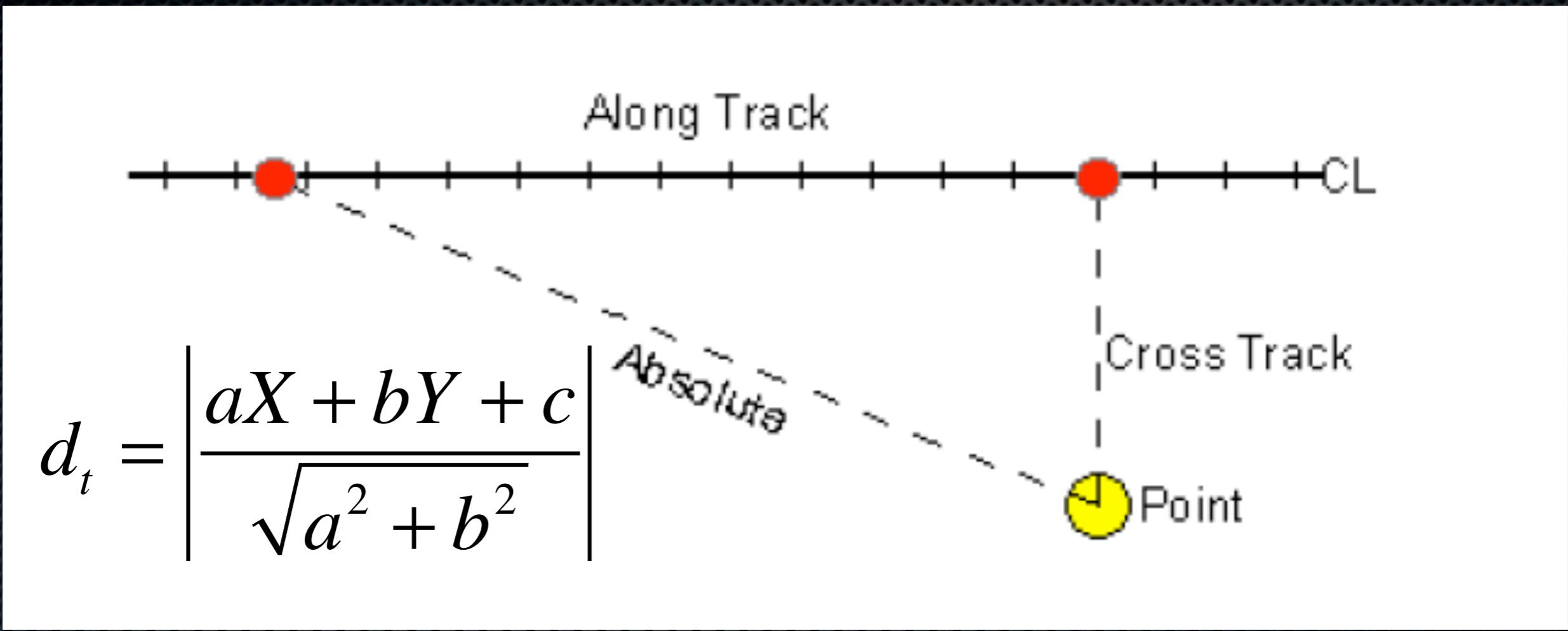


Tangent Segment

- First traverse designated as reference
- Linear regression (N) of reference traverse to establish tangent coefficients for reference line
- $aX + bY + c = 0$
- Distance to reference tangent (cross track error) determined from subsequent traverse observations



Tangent Segment



Distance to reference centerline is cross track error
(Allen, et.al.)

Track Occupancy

Null Hypothesis - Tangent

- Z-test uses standard deviation of X-track distances from reference tangent dataset
 - Eliminate track roughness from test tracks
- Test that the mean is a random sample from a normal population with a cross track error less than half a centerline to centerline distance of 11.5 feet
- CI = $100(1-\alpha)$
- $\alpha=0.00001$

$$h_0 : \mu_d \leq \frac{11.5}{2}$$

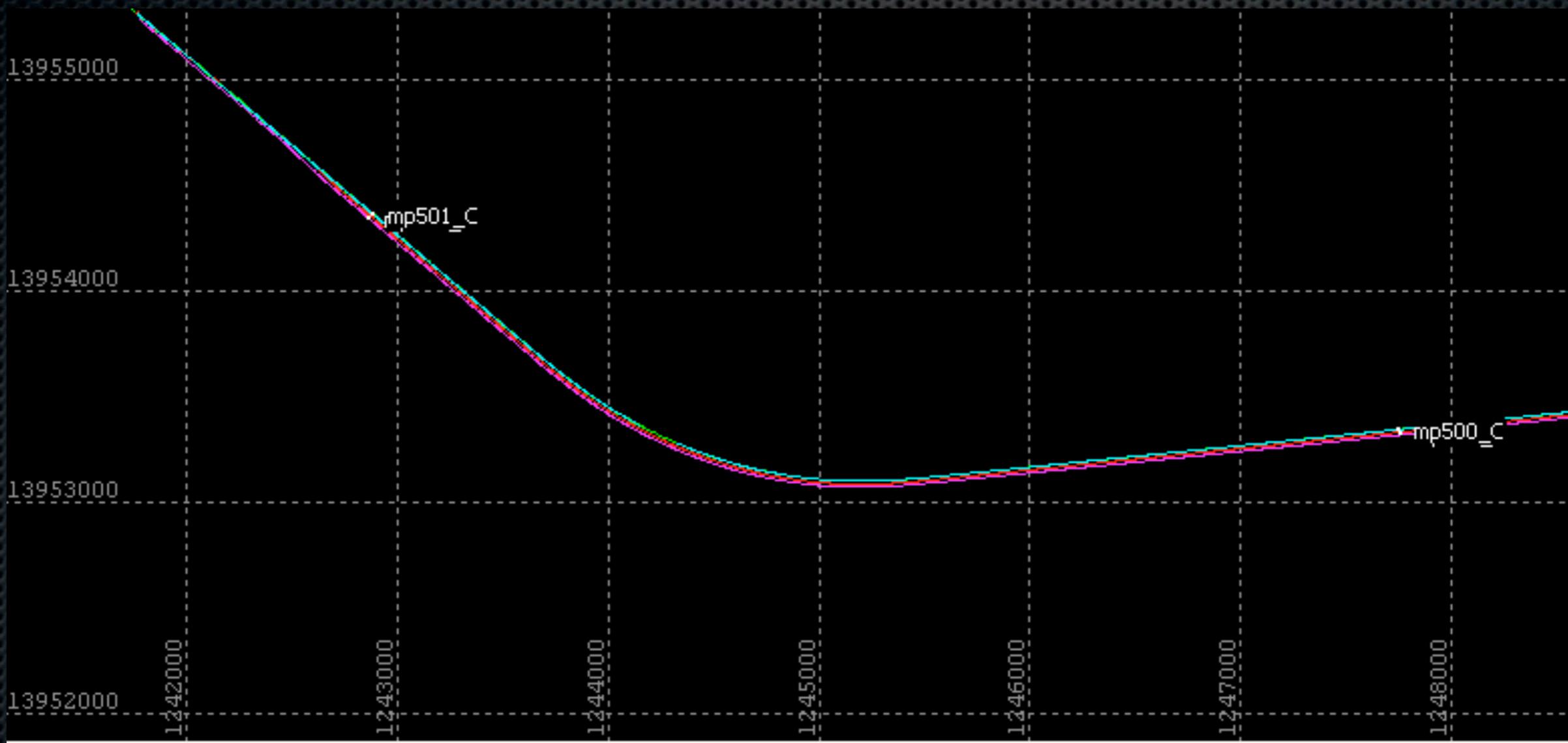
$$h_1 : \mu_d > \frac{11.5}{2}$$

Hypothesis Test Result

Tangent Track

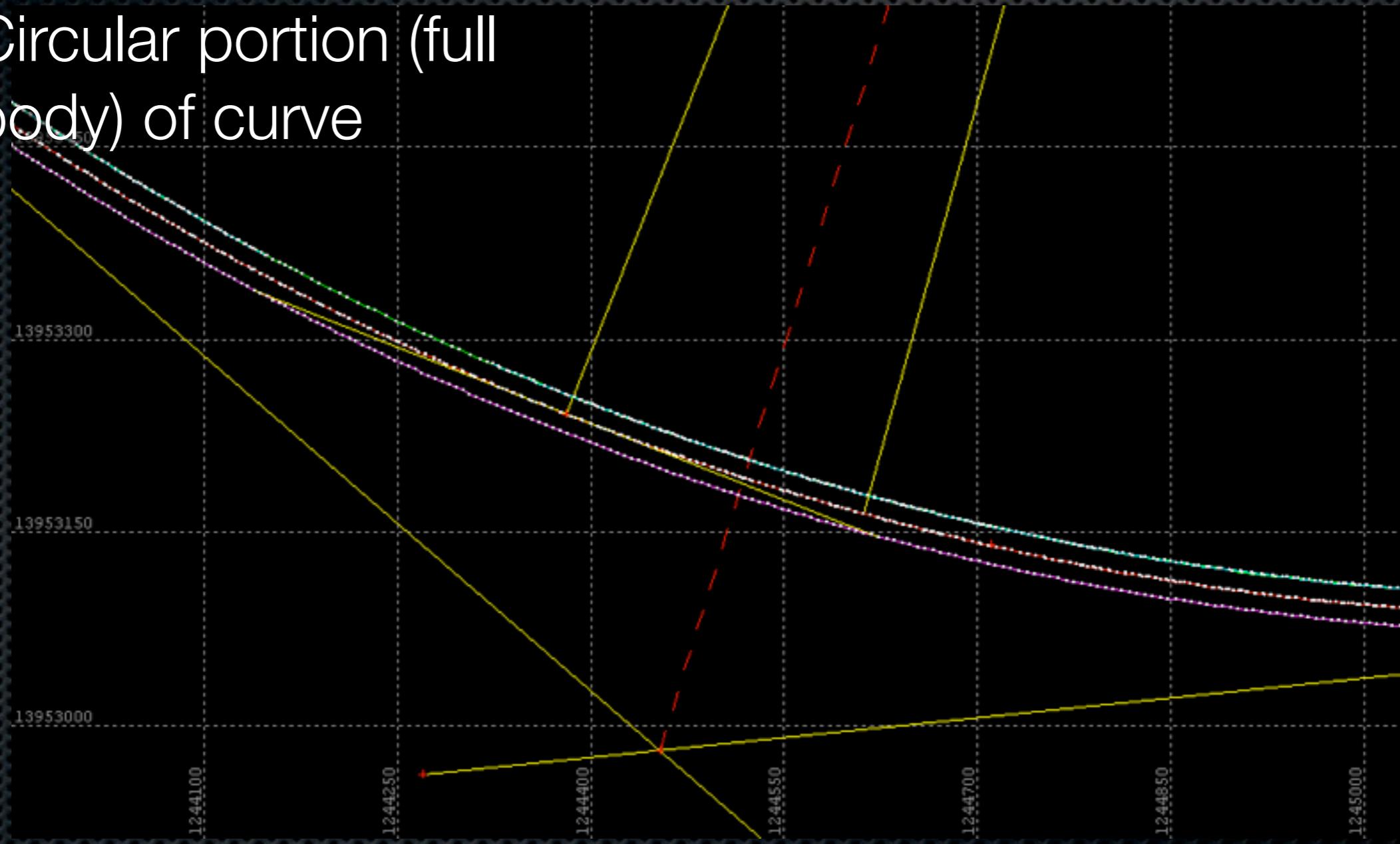
Track	N	μ_d	σ_d	Reject h_0 ?
2A-2A	1,189	0.13'	0.08'	no
2B-2A	1,244	0.13'	0.08'	no
3C-2A	1,152	13.10'	0.35'	yes
1D-2A	1,158	13.51'	0.20'	yes
3E-2A	1,156	13.05'	0.31'	yes

Curve Segment



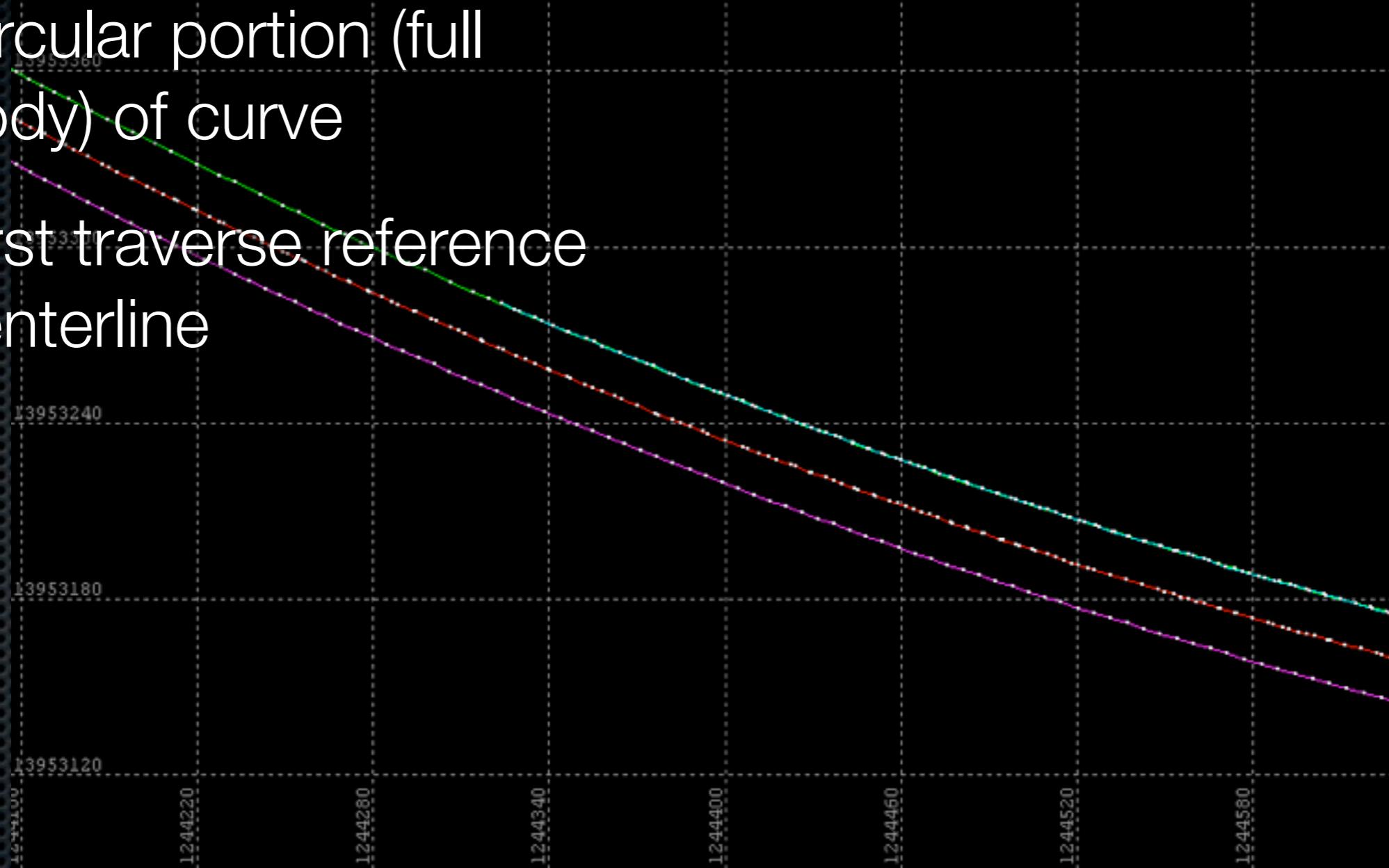
Curve Segment

- Circular portion (full body) of curve



Curve Segment

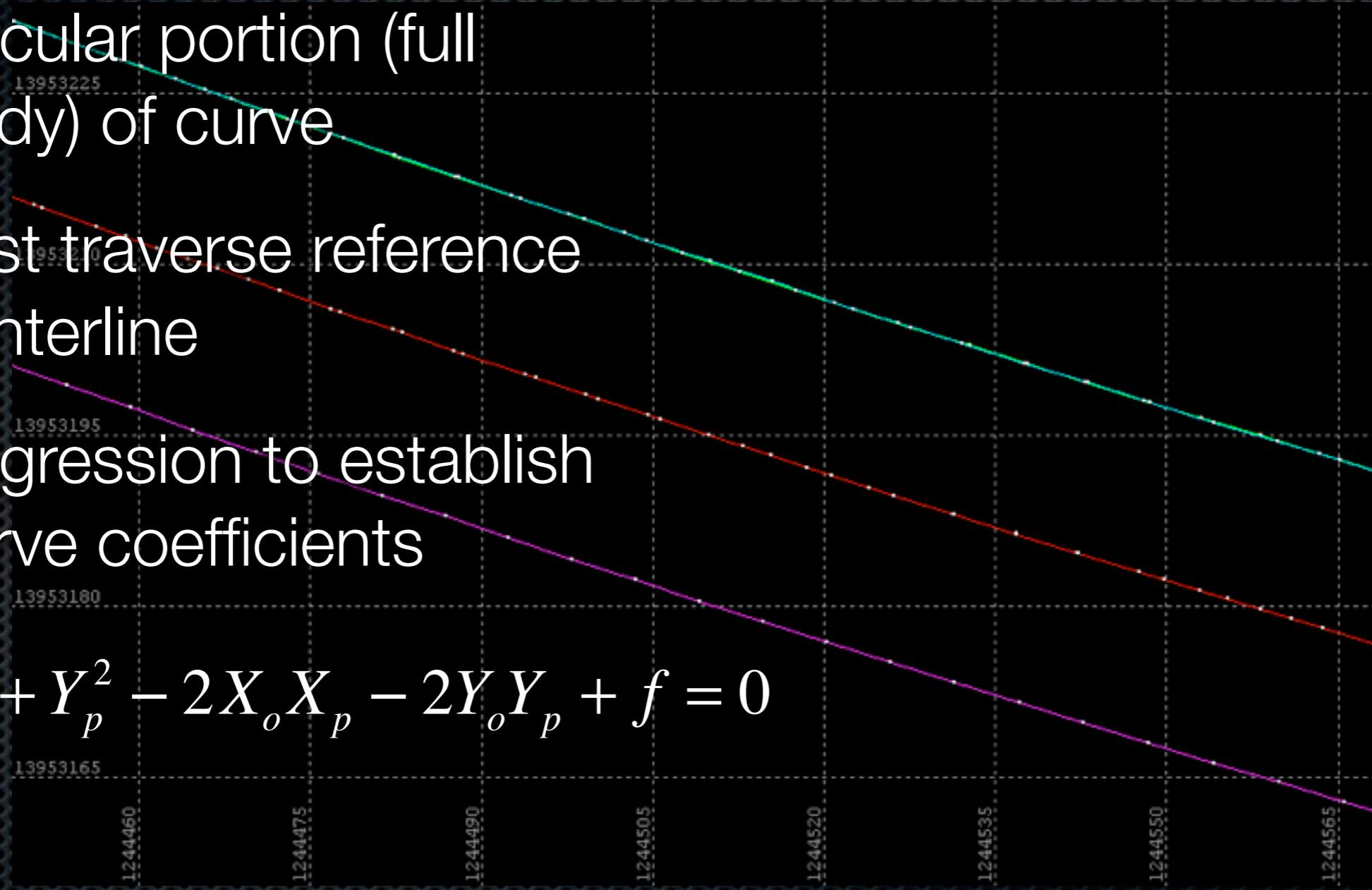
- Circular portion (full body) of curve
- First traverse reference centerline



Curve Segment

- Circular portion (full body) of curve
- First traverse reference centerline
- Regression to establish curve coefficients

$$X_p^2 + Y_p^2 - 2X_o X_p - 2Y_o Y_p + f = 0$$



Curve Segment

- Circular portion (full body) of curve
- First traverse reference centerline
- Regression to establish curve coefficients
- Distance to reference curve centerline determined from subsequent traverse observations

$$d_c = r - \sqrt{(x_p - X_o)^2 + (y_p - Y_o)^2}$$

$$X_p^2 + Y_p^2 - 2X_oX_p - 2Y_oY_p + f = 0$$



Hypothesis Test Result

Circular Curve Track

Track _{traverse}	N	μ_r	σ_r	Reject h_0 ?
2A-2A	85	0.00'	0.03'	no
2B-2A	98	0.03'	0.04'	no
3C-2A	98	-14.53'	0.16'	yes
1D-2A	97	13.93'	0.10'	yes
3E-2A	92	-14.57'	0.14'	yes

Conclusions

- Given a priori track centerline locations and a network RTK VRS server, track occupancy can be determined by single epoch RTK observations over a wide area meeting the accuracy requirement for an LDS.

Implications

- Simplified occupancy determination local to an LDS onboard a locomotive, Hi-Rail, or other track vehicle
 - RTK receiver, communication with VRS, database, processor
- Self-determined RTK positions transmitted through wayside voice repeater enable real time tracking or track occupancy determination external to track vehicle
- Applicable to any ~~track~~ vehicle
- Applicable to individual on-track workers

Transportation Implications

- Highway: vehicle/human interaction
 - Lane deviation alerts driver
- Air: Precision approach and landing
 - To any airfield w/o barometric altimeter
- Waterway: River bed profile mapping & water level for bridge clearance

Civil & Mining Engineering

- RTK VRS Networks enable
- Structure monitoring (further study: diurnal, seasonal)
 - Bridge
 - Dam
 - Coal slurry impoundment

Self-guided Vehicles

