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

- Loss of carload freight revenues relative to overall freight growth
  - Carload freight has quality of service issues (Moorman)
- Inspection of railway is critical and labor intensive
  - Labor intensive reliance on inspector skill and diligence
- Dependance 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 / $$$

CSX/NS SOA Track Measurement for Defect Detection

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

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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

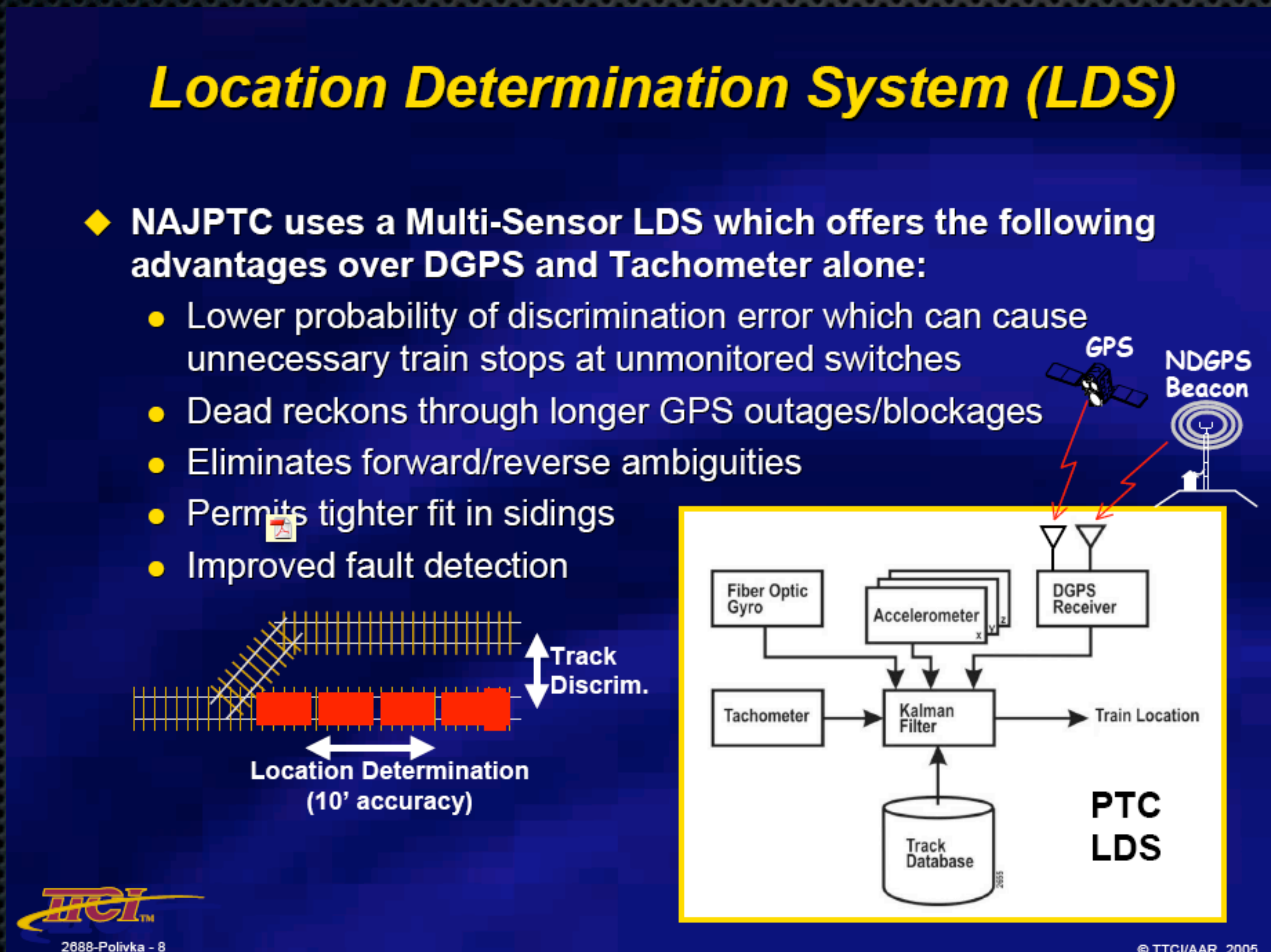
- CSX TGC-2
  - heavy / train / $$$
- NS TGC
  - heavy / train / $$$
- CSX GRMS-2
  - light / self-propelled / $$$
- CSX GRMS-1
  - light / self-propelled / $$$

RTK GPS Railway Measurement

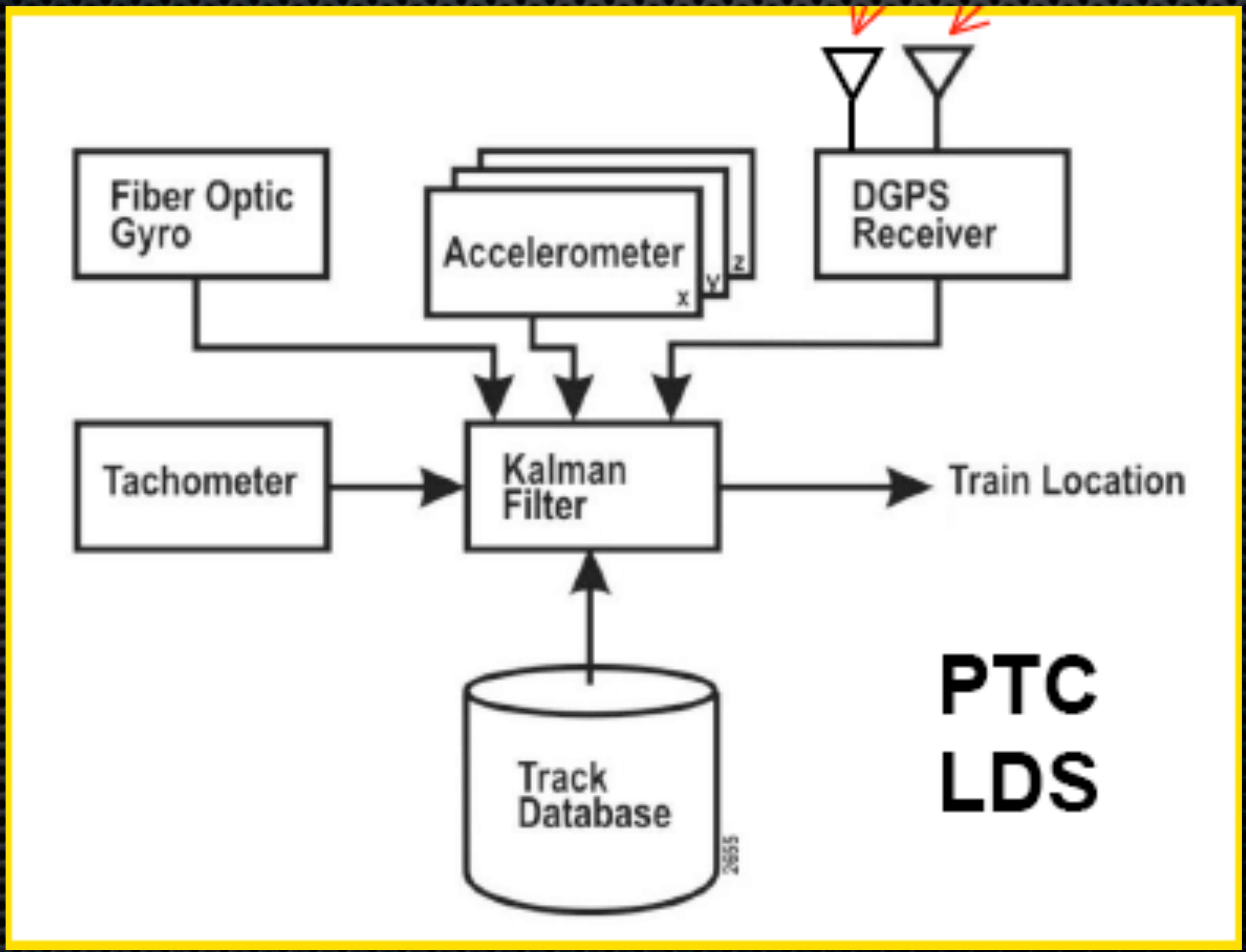
May 2010

The *Swiss Trolley* - Glauss

FRA LDS Concept 2005



FRA LDS Concept 2005



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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 the ability of RTK GPS to

1. Provide a method to improve yard profiles, affecting humpyard throughput resulting in increased service reliability
2. Bridge the gap in railway inspection methods between multi-million dollar track geometry cars and FRA mandated visual inspections
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 humpyard 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
- ‘Survey grade’ GPS/GNSS
- Existing VRS physical and IT infrastructure
  - Keep it simple - no auxiliary instrumentation to fill in expected data gaps

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 car 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 stall

Hump Yard Grades Affect Freight Service Quality

- Grade degradation and settlement due to
  - Railcar loading forces
  - Weather & geology
  - Outdated design grade
    - Railcar Journal to frictionless roller bearings
- Application of Lean Manufacturing principals
  - “Right train, right track” through improved control systems increased sensitivity to infrastructure defects

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

- Collect a data set by and RTK GPS equipped locomotive
- Minimize disruption to operations
- Maximize safety for surveyors
- Minimize impact on continuous car handling operation
  - Track closure and rail car reroutes
- Minimize demand for trained safety support personnel
- Determine the effects on GPS position due to signal distortion from multipath reflections

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Experiment 1
Hump Yard Survey

Experiment 1
Hump Yard Survey

- COTS RTK GPS Reference Station

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Experiment 1
Hump Yard Survey

- COTS RTK GPS Reference Station
- COTS RTK static instruments

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Experiment 1
Hump Yard Survey

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

Antenna Alignment

Tangent section of track used as a calibration area for alignment of the locomotive antenna with track centerline.

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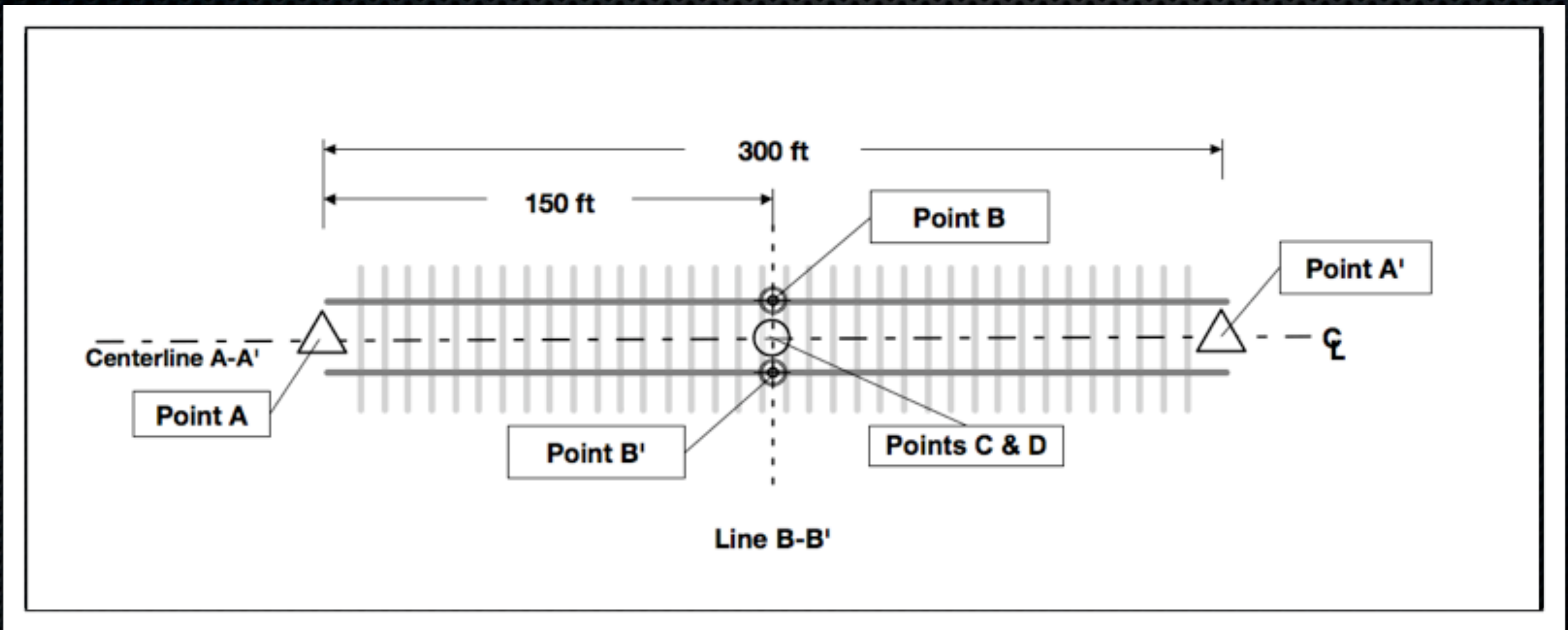
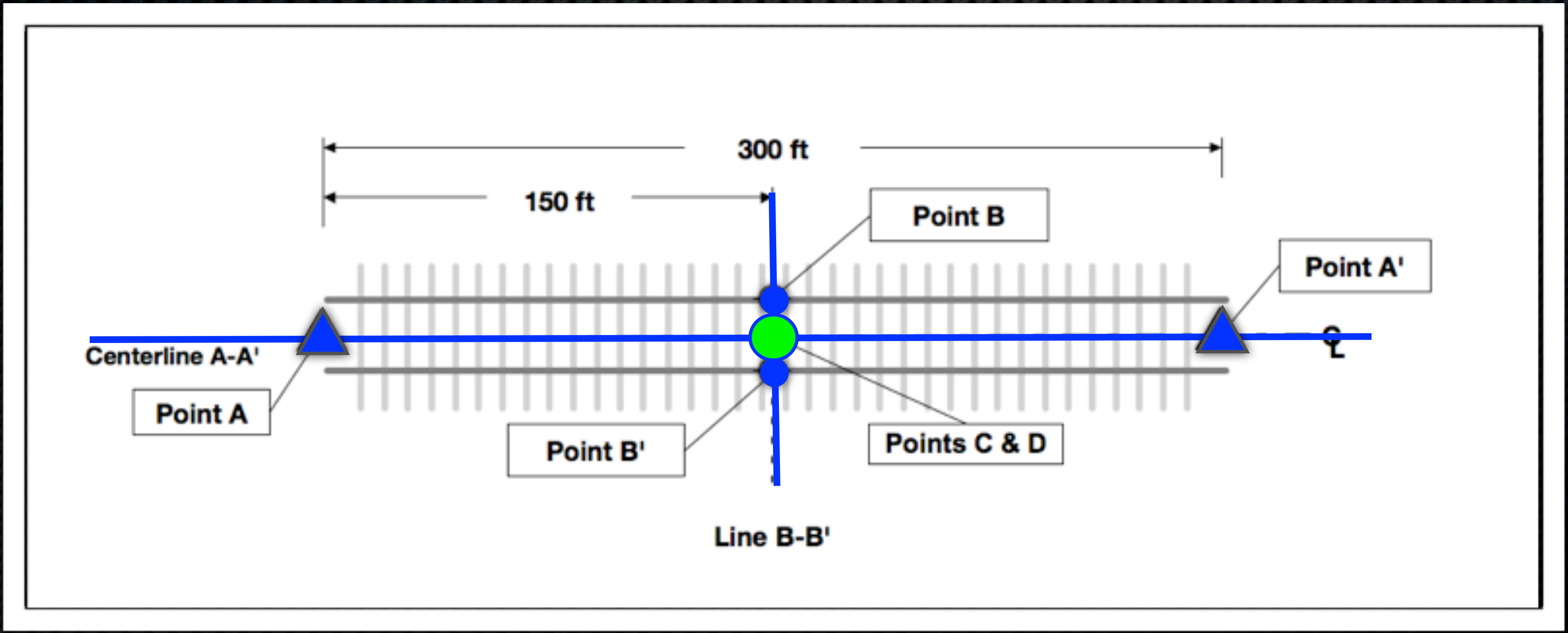
Antenna Alignment



Antenna Alignment



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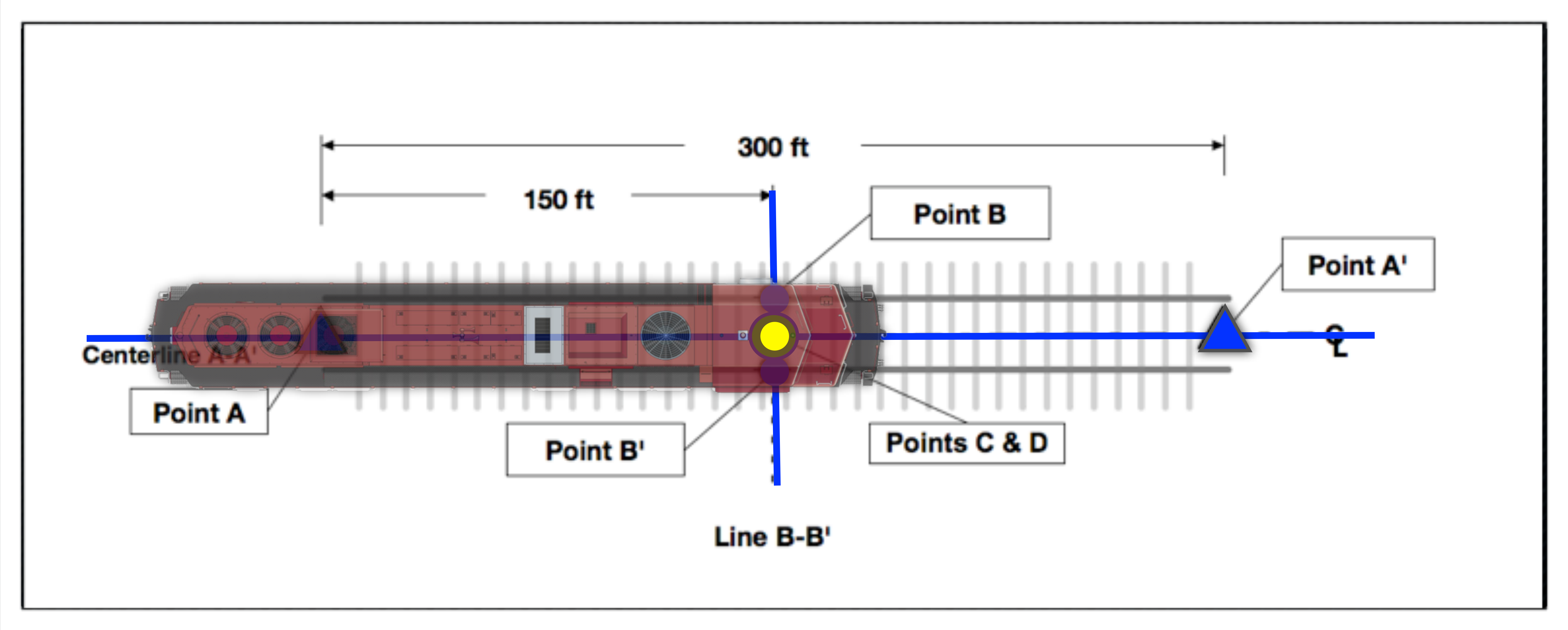
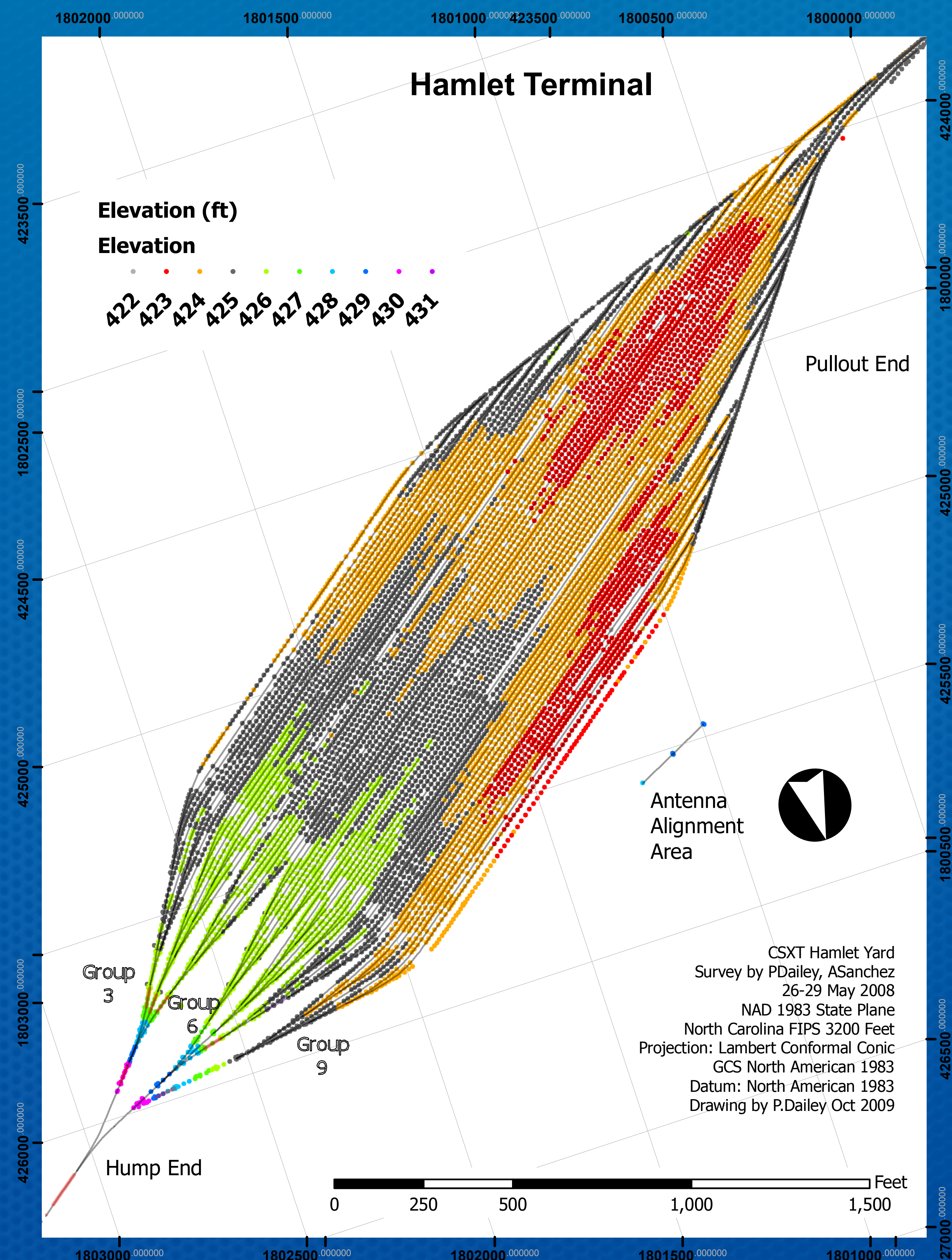
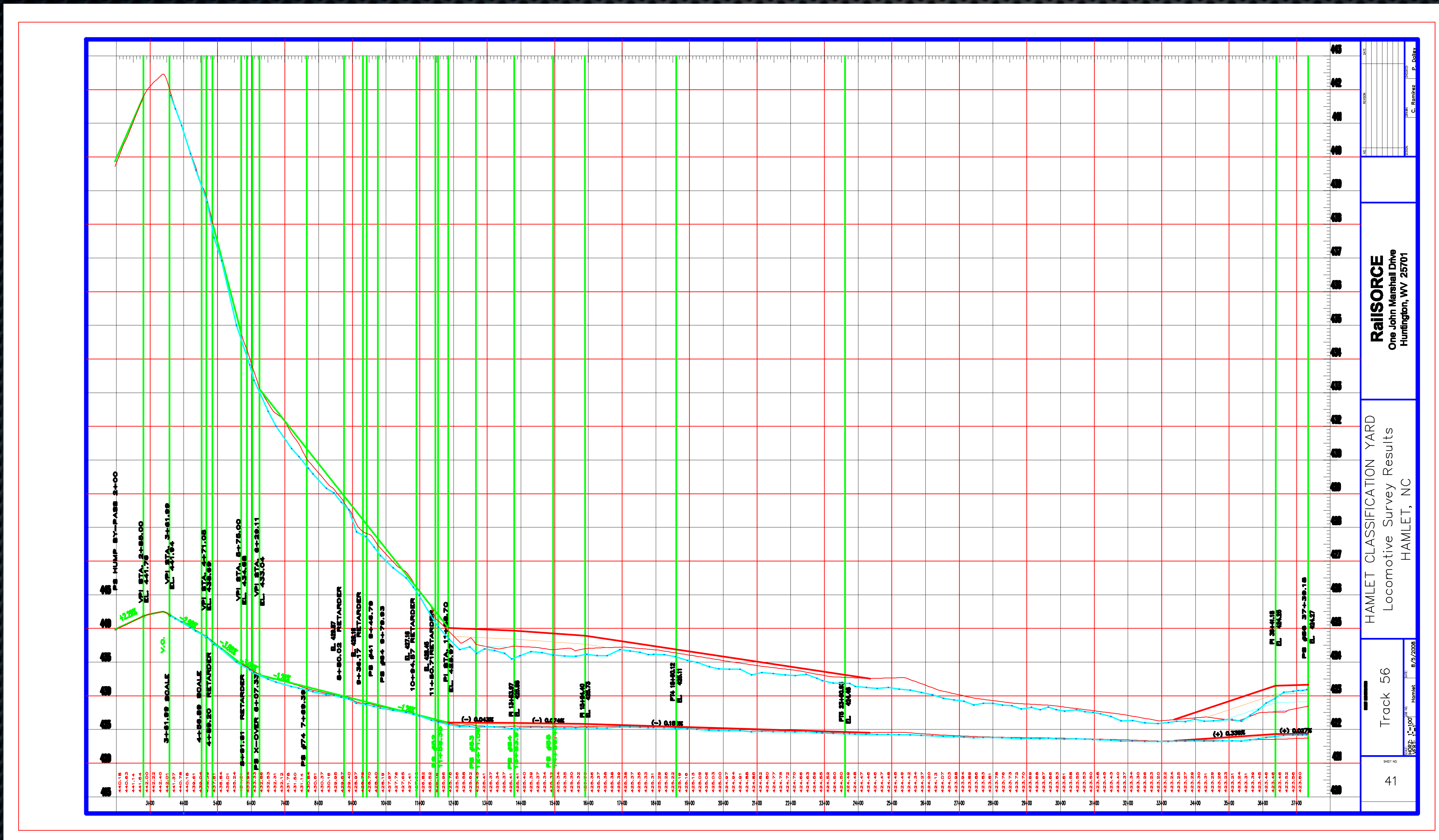
Antenna Alignment




Hamlet Terminal
Elevation (ft)
Elevation
422
423
424
425
426
427
428
429
430
431
Pullout End
Antenna
Alignment
Area
Group
3
Group
6
Group
9
Hump End
CSXT Hamlet Yard
Survey by PDailey, ASanchez
26-29 May 2008
NAD 1983 State Plane
North Carolina FIPS 3200 Feet
Projection: Lambert Conformal Conic
GCS North American 1983
Datum: North American 1983
Drawing by P.Dailey Oct 2009
0
250
500
1,000
1,500
Feet

Group 7, Track 56



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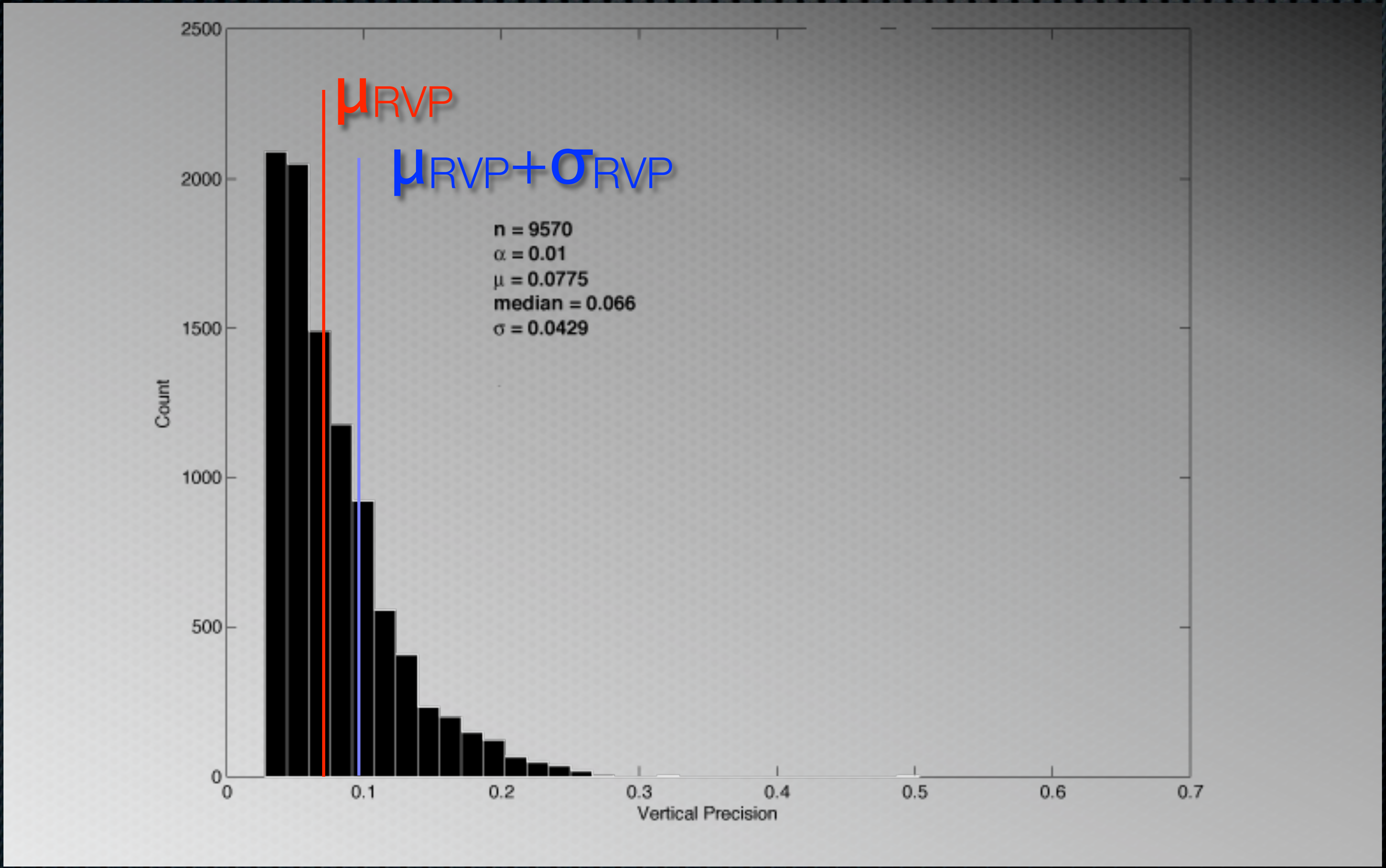
Multipath Analysis

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

Relative Vertical Precision



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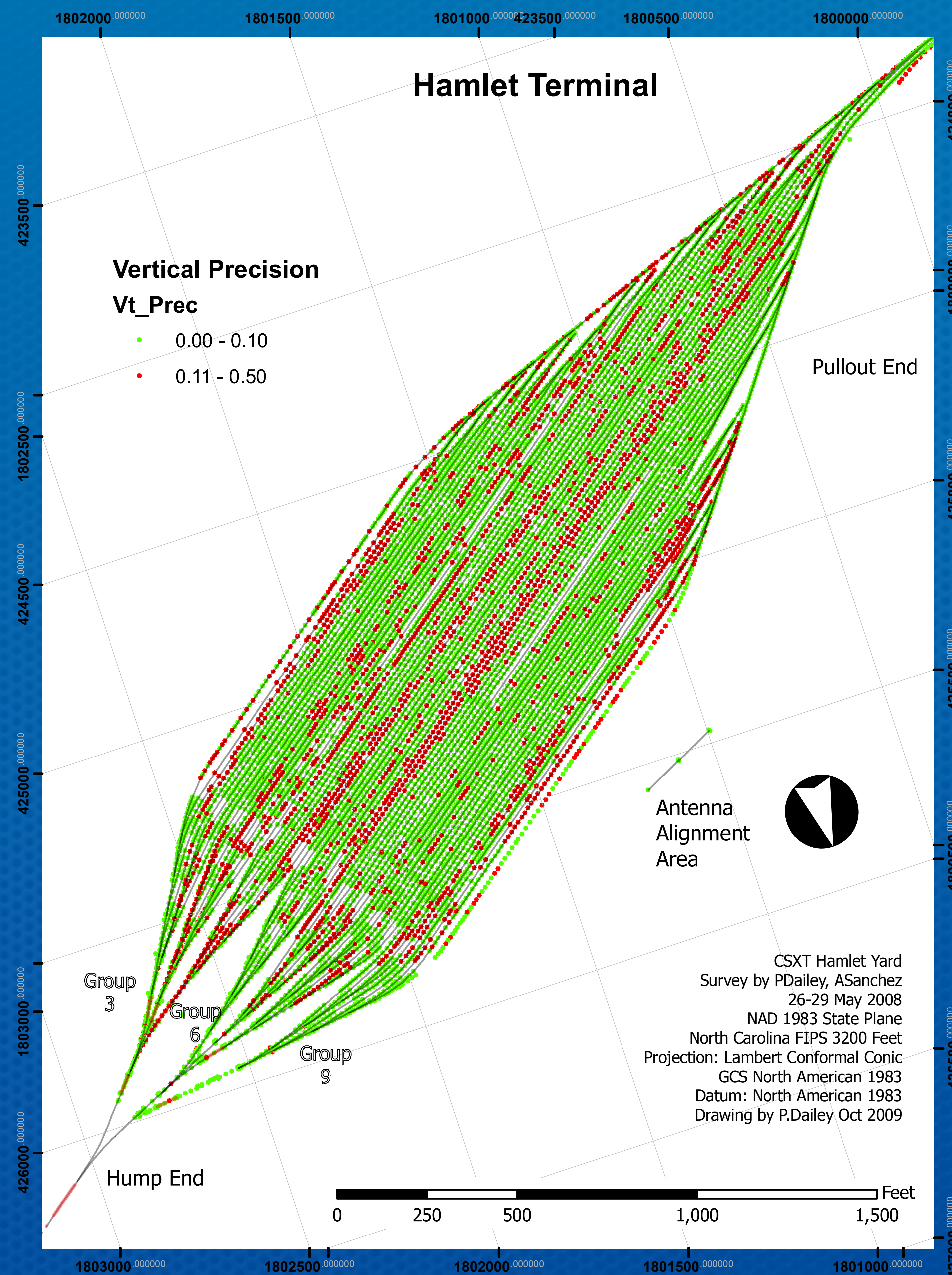

Hamlet Terminal
Vertical Precision
Vt_Prec
0.00 - 0.10
0.11 - 0.50
Pullout End
Antenna Alignment Area
Group 3
Group 6
Group 9
Hump End
CSXT Hamlet Yard
Survey by PDailey, ASanchez
26-29 May 2008
NAD 1983 State Plane
North Carolina FIPS 3200 Feet
Projection: Lambert Conformal Conic
GCS North American 1983
Datum: North American 1983
Drawing by P.Dailey Oct 2009
0 250 500 1,000 1,500 Feet

Research Result

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

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Conclusions

- Safer than differential level survey
  - 6 vs 500 exposure hours (est. Kerchoff & Szwilski)
- Greater data density than differential level survey
  - 10 ft vs 100 ft stations
- 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)

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 applications

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Experiment 2
Track Alinement

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

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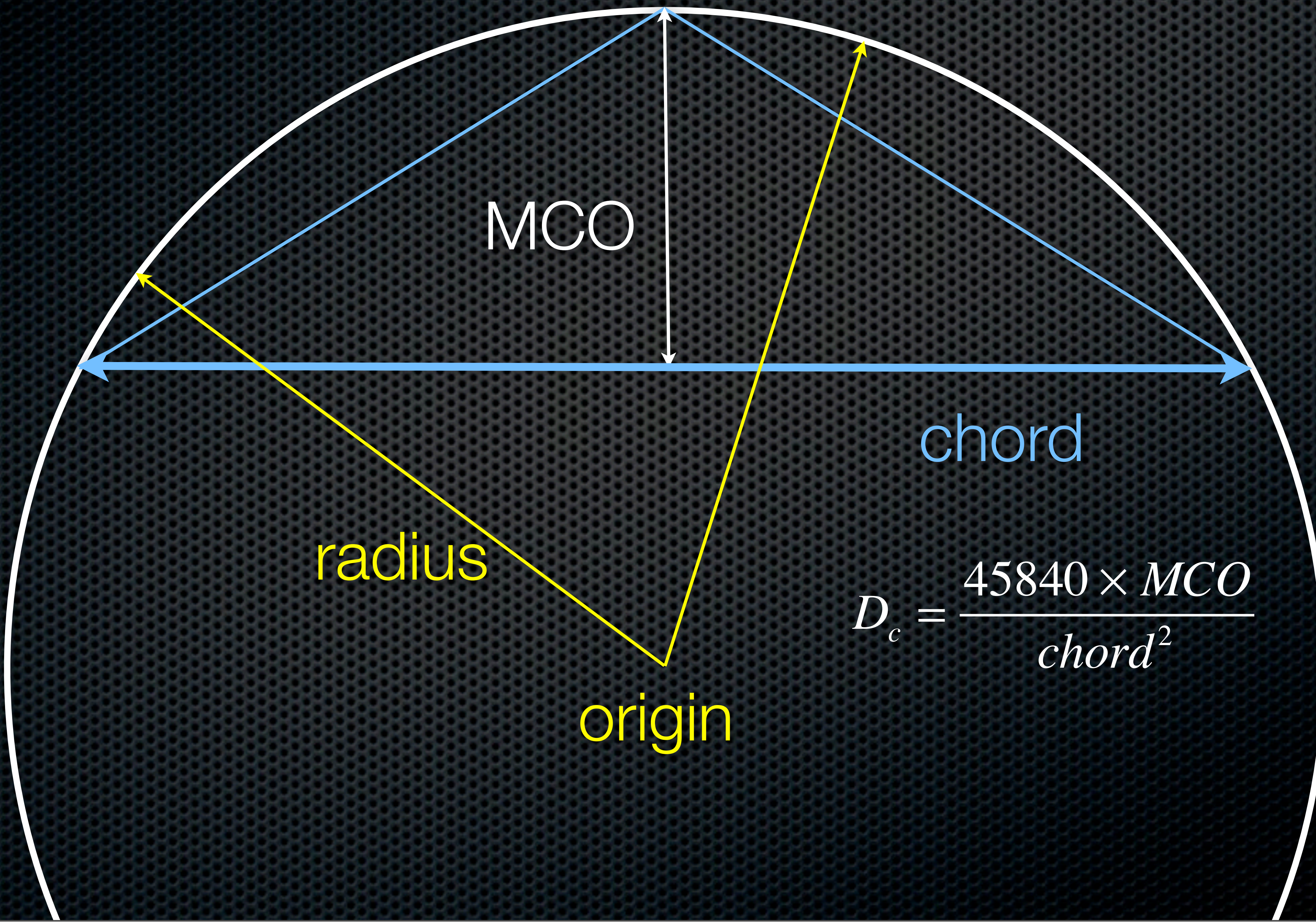
Degree of Curvature (D_C)

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

- Using a 62 foot chord results in
  - MCO measurement in inches closely approximating D_C

Degree of Curvature (D_c)



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

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Visual Track Inspection

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

Research Question

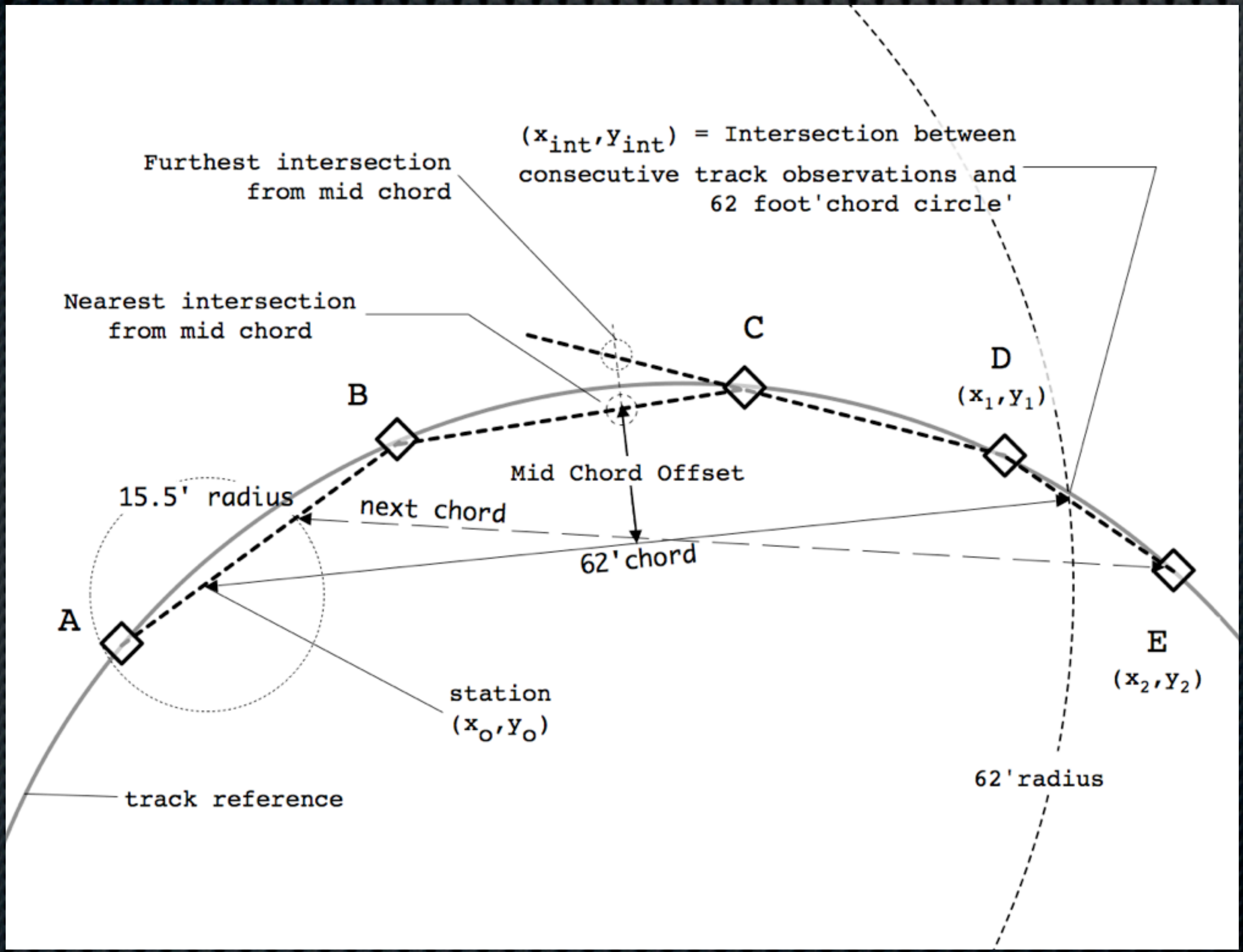
Can RTK GNSS instrumentations mounted to a track inspector's Hi-Rail be used to determine the degree of curvature (D_C) across mainline track comparable with specialized track geometry cars?

Mainline Track Alinement 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
- Observe track position continuously across an inspector's 29 mile area of responsibility at track speed between 10 and 40 mph
- Model the FRA sting line method for determining D_C
  - Verify model output against rail company track charts
- Compare D_C with track geometry car D_C measurement

Modeling D_C from XYZ



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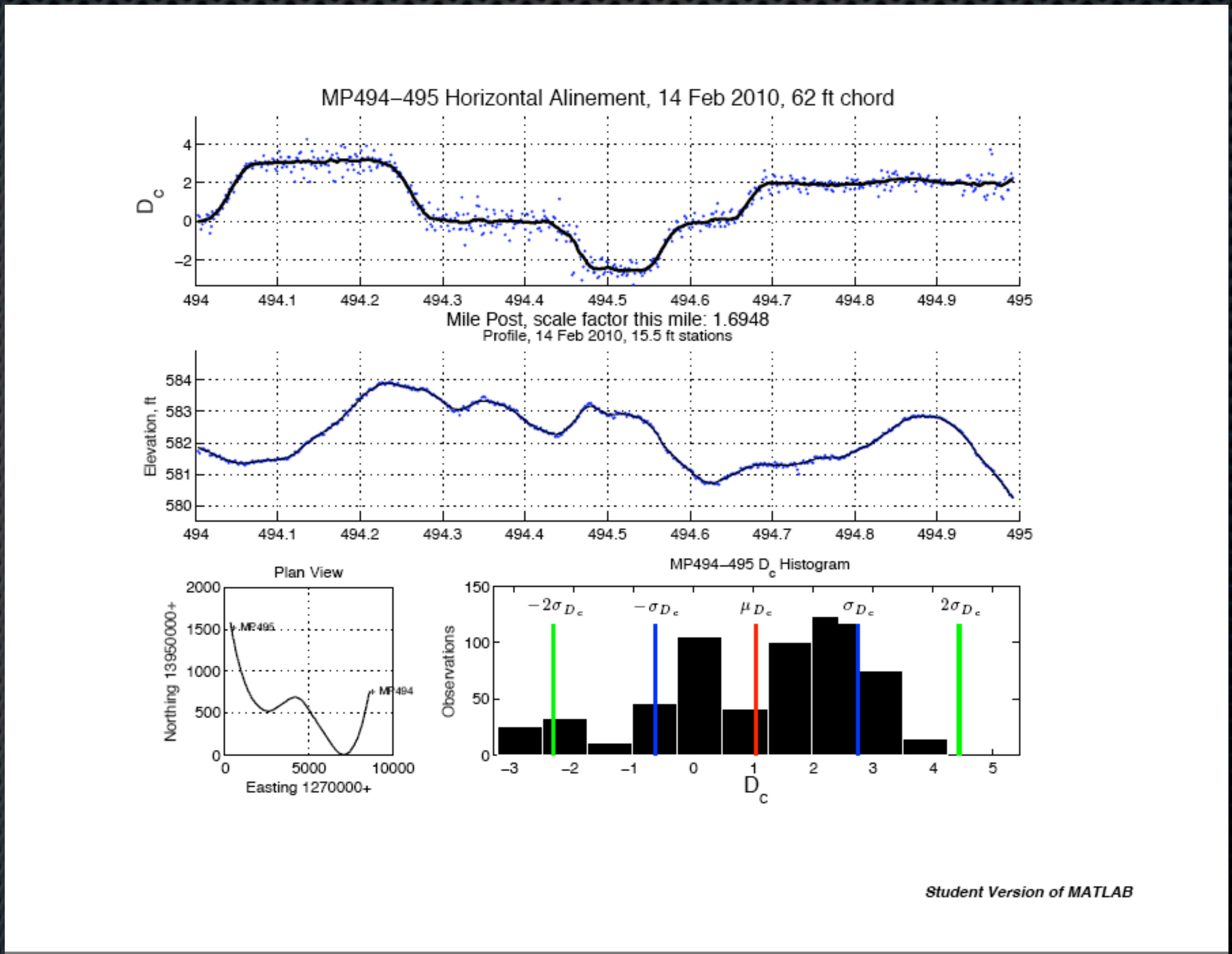
Experiment 2 Results

- 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

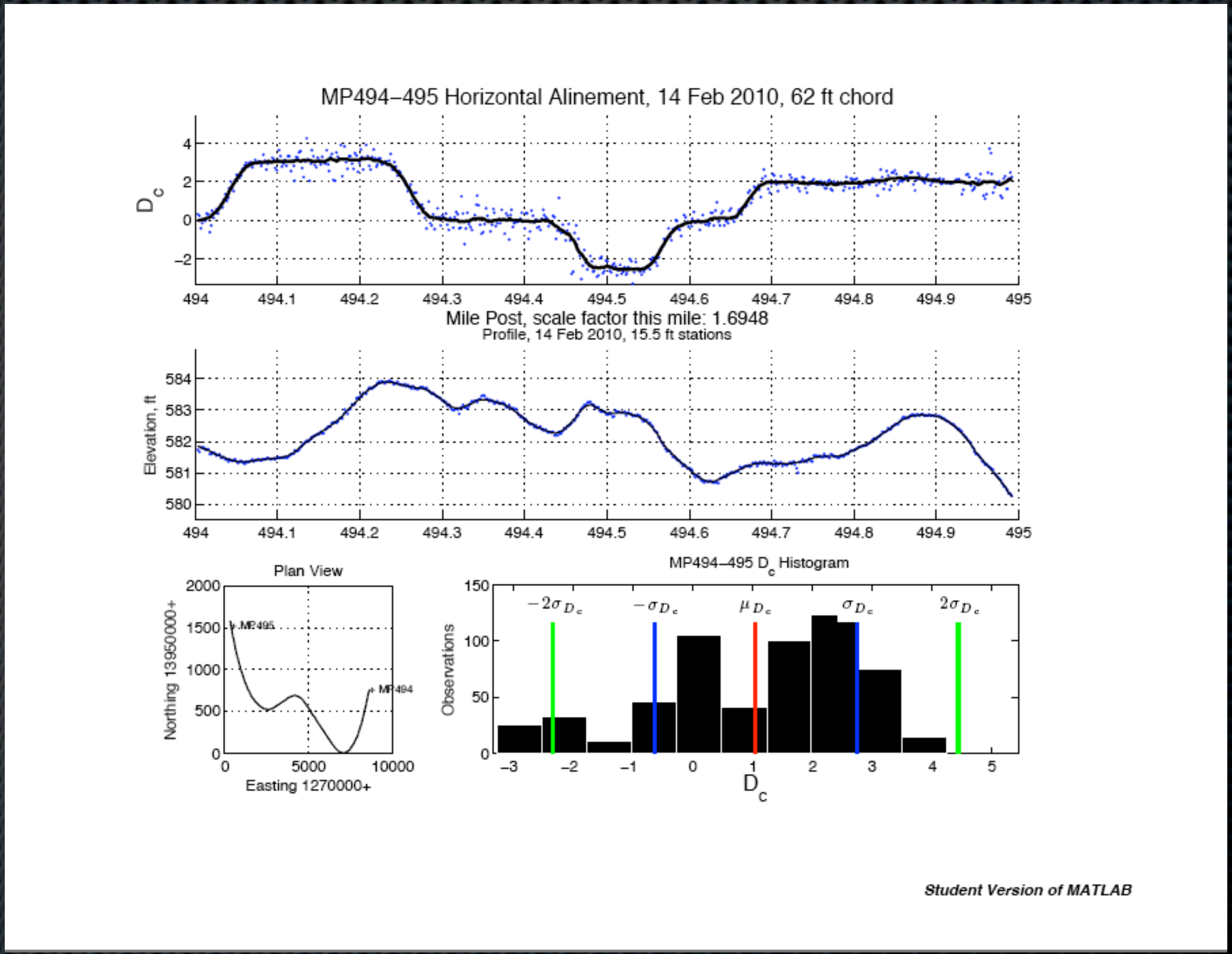
Survey	Observations
A	18,095
B	15,225
C	22,866
D	19,993
E	21,001

Results
XYZ to D_c Model Output



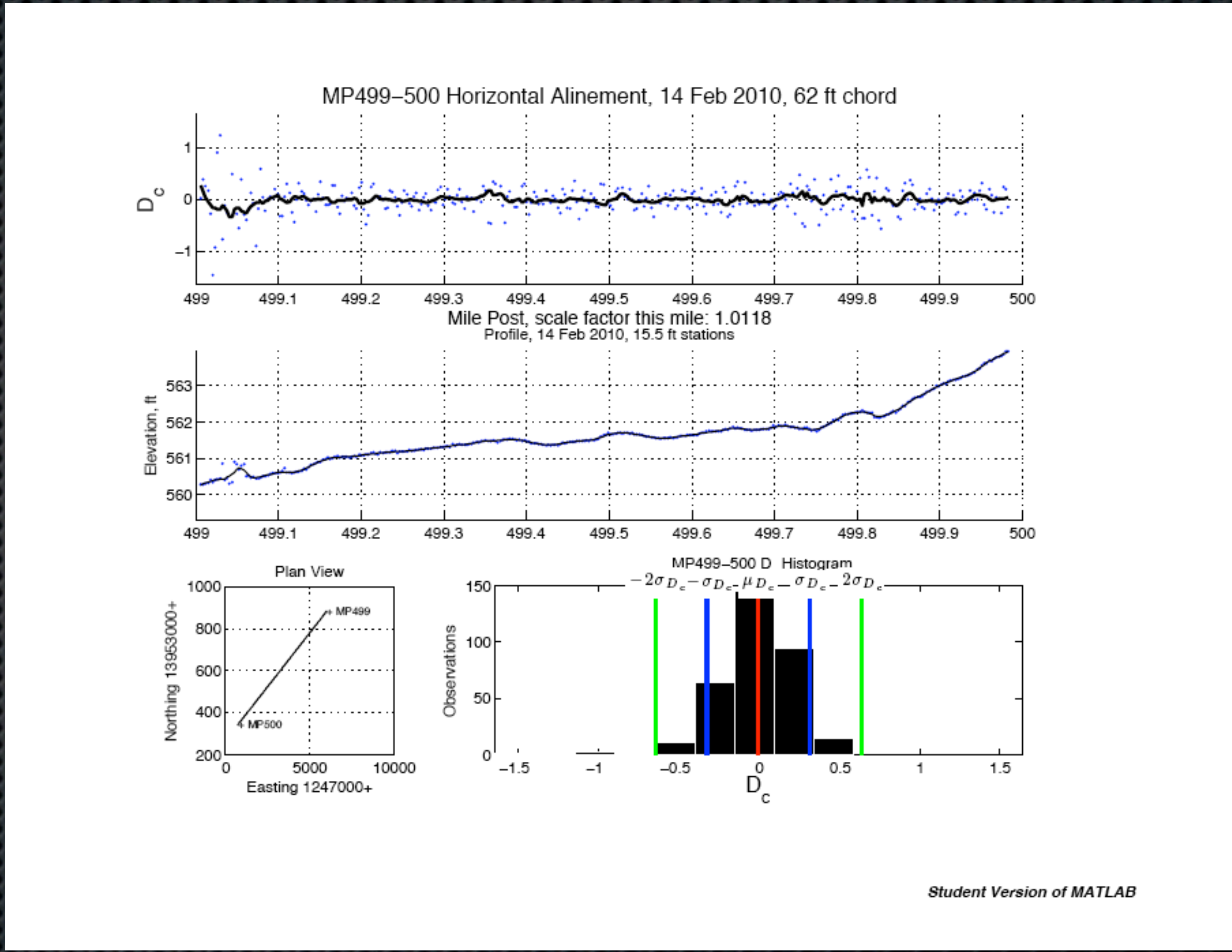
Results
XYZ to D_c Model Output

- MP 494-495
  - verify curves



Results XYZ to D_c Model Output

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



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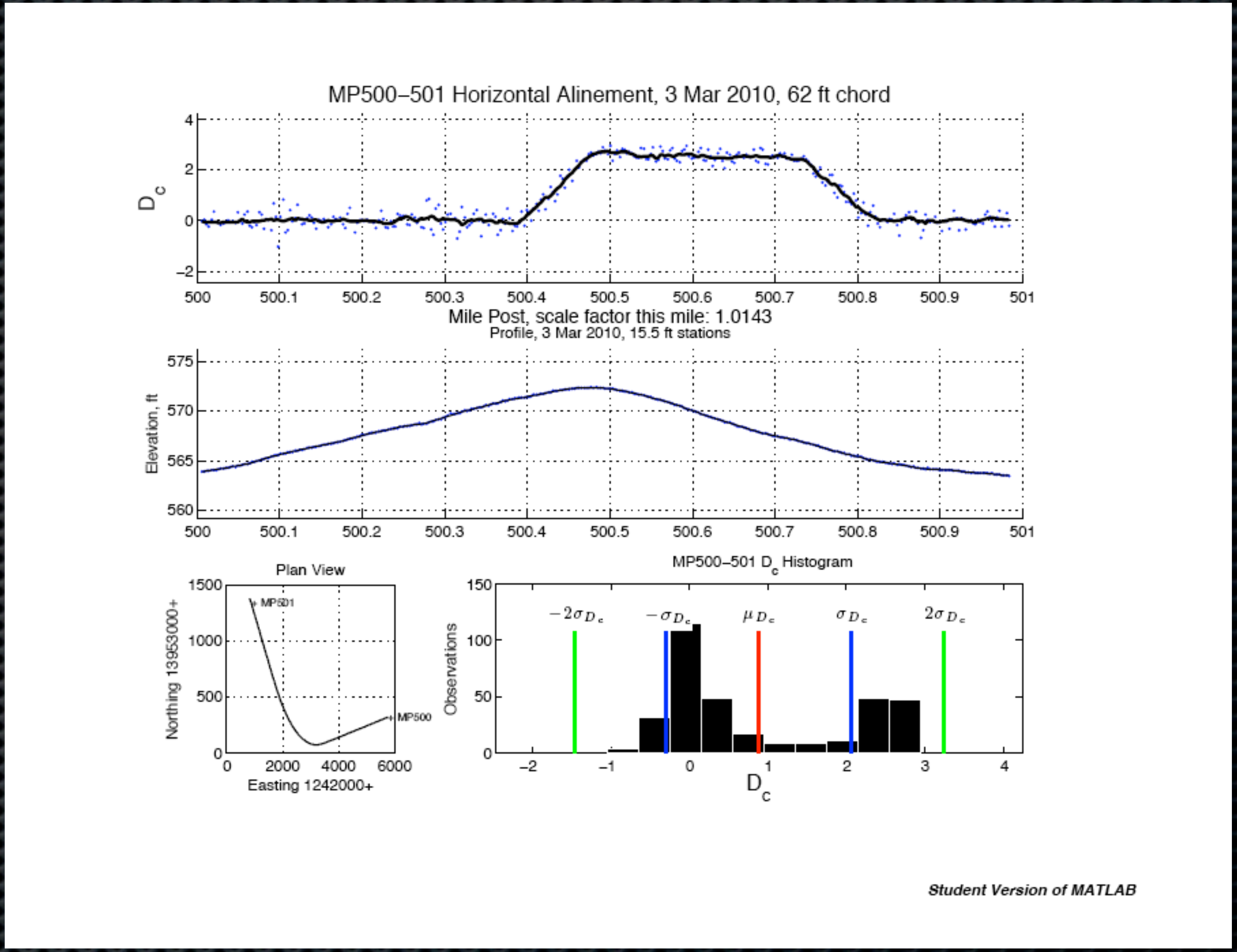
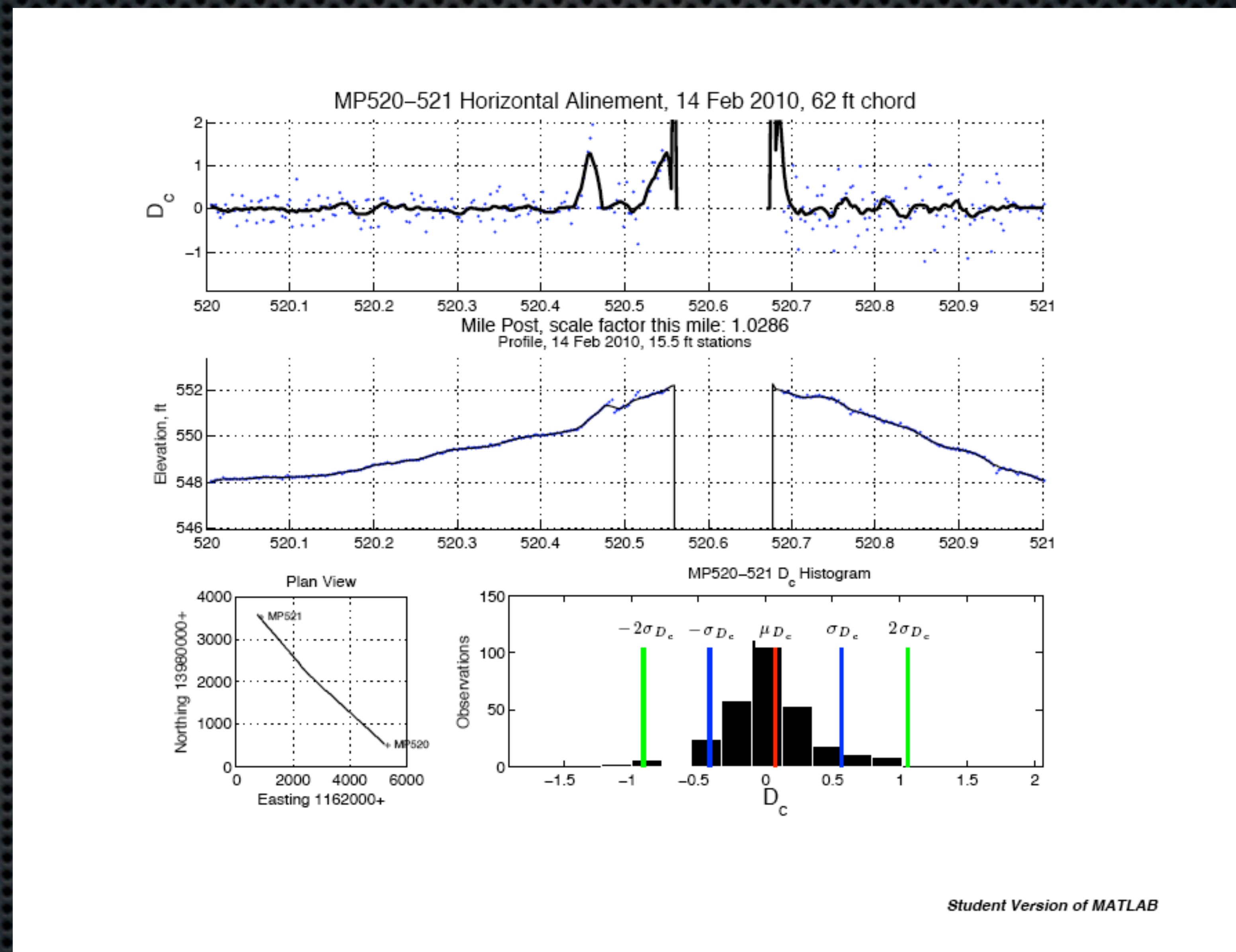
Results
XYZ to D_c Model Output

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

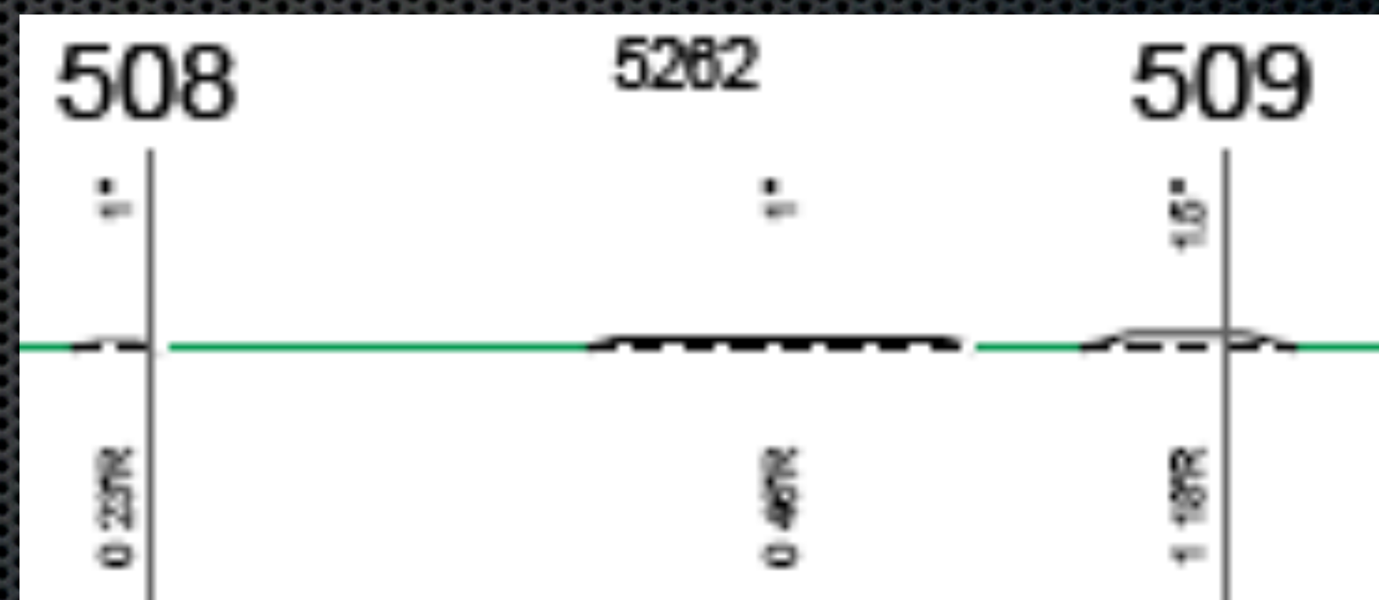


Results
XYZ to D_c Model Output

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



Model Discrepancies with Rail Company Track Charts



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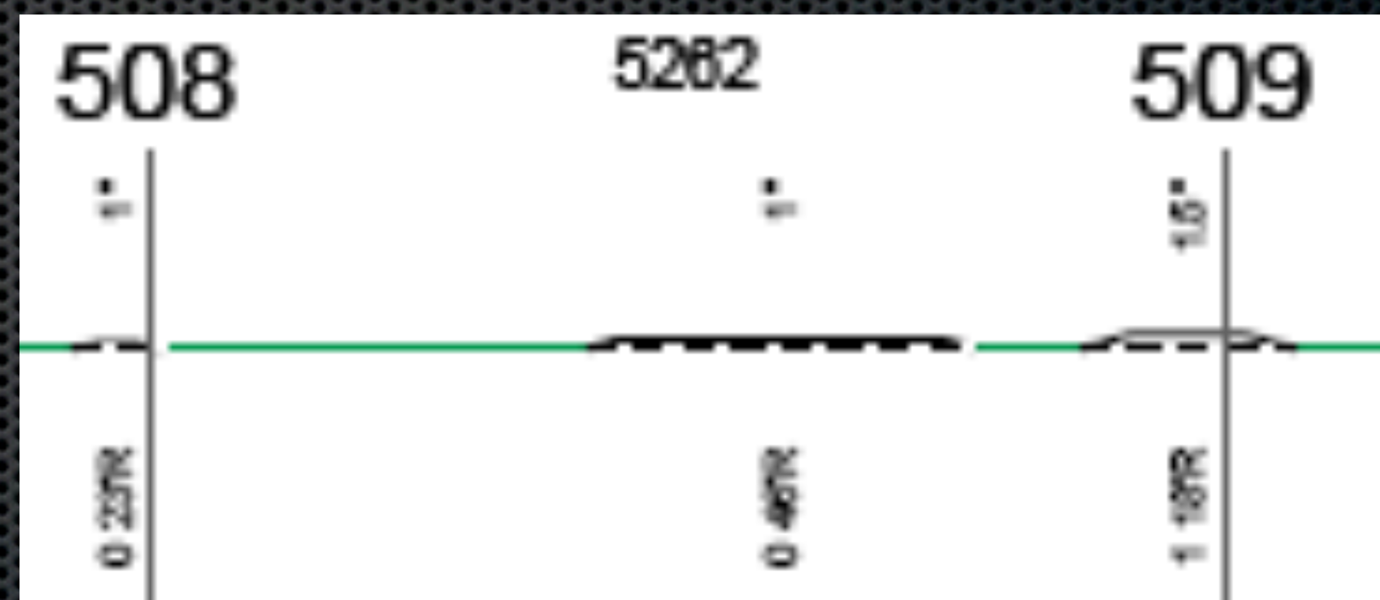
Model Discrepancies with Rail Company Track Charts

- MP 508.9 curve direction
  - TC: 1°18’ right



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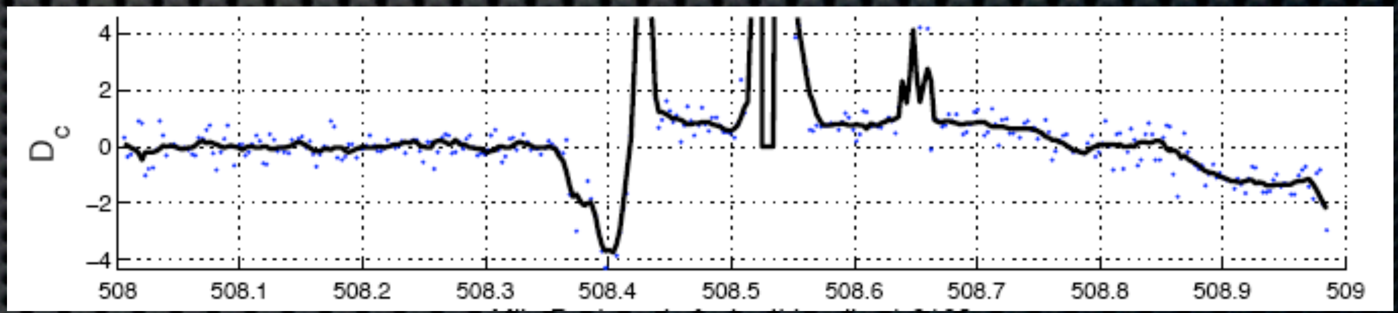
Model Discrepancies with Rail Company Track Charts

- MP 508.9 curve direction
  - TC: 1°18’ right
  - Model: ... left



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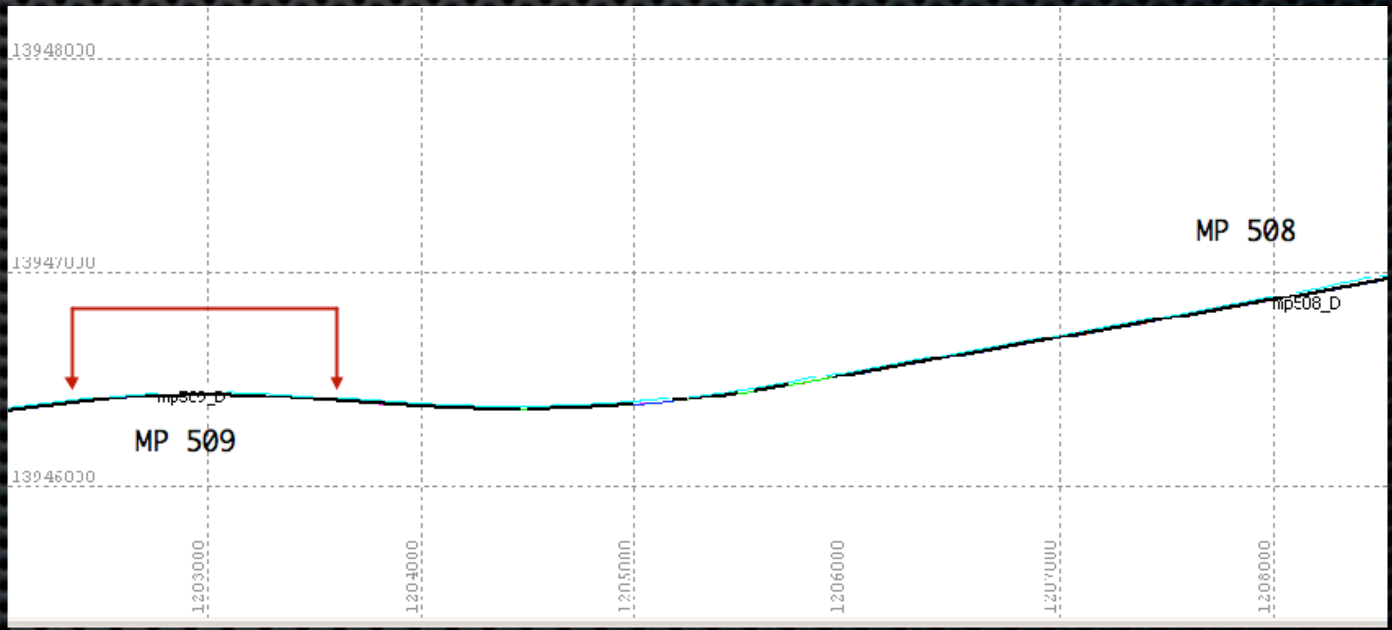
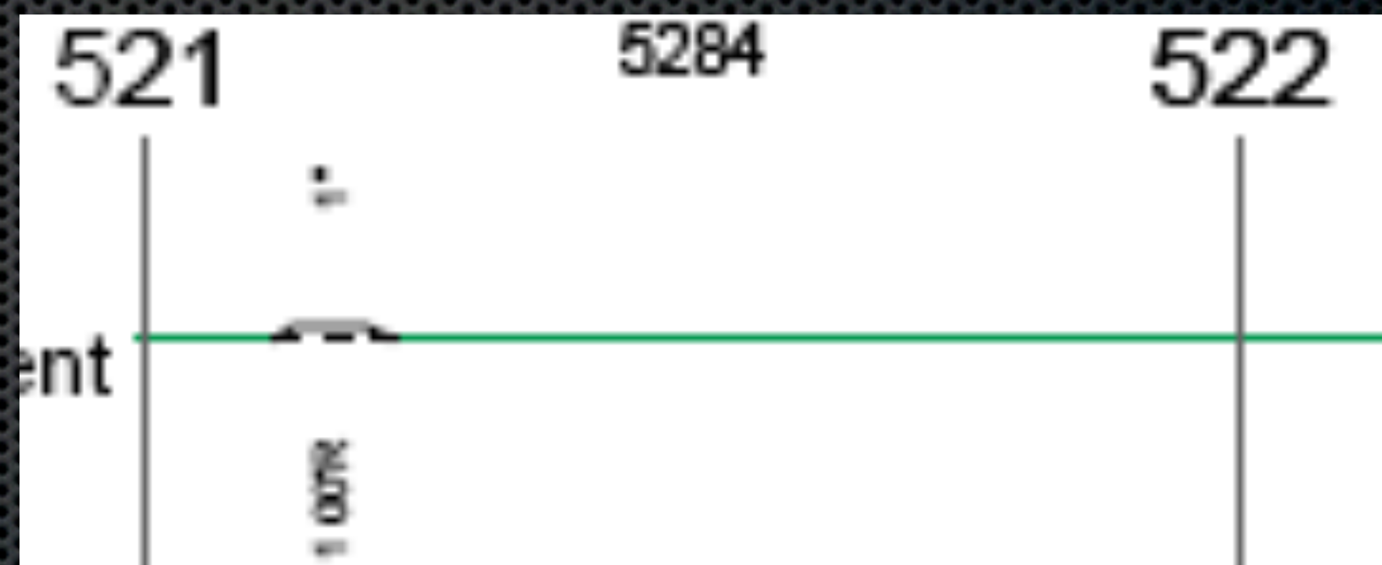


Model Discrepancies with Rail Company Track Charts

- MP 508.9 curve direction
  - TC: 1º18’ right
  - Model: ... left
- MP 521.15 curve length
  - TC: 1º00’R @ 0.15 mi



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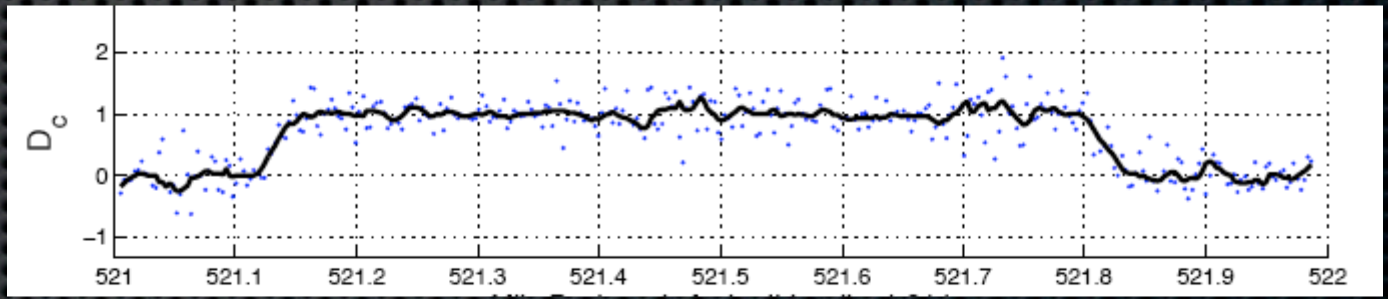

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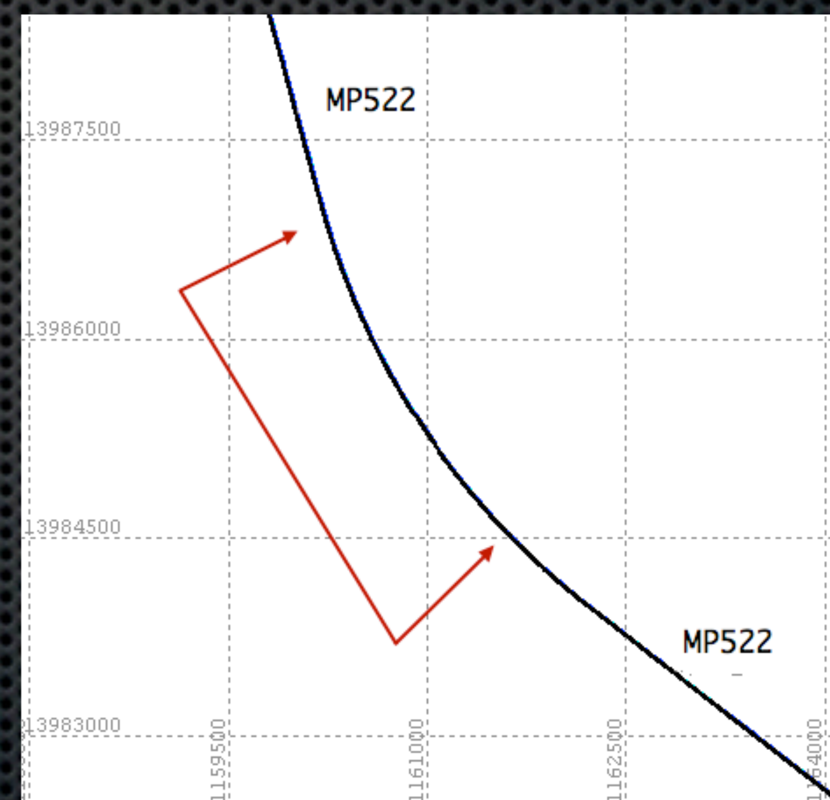
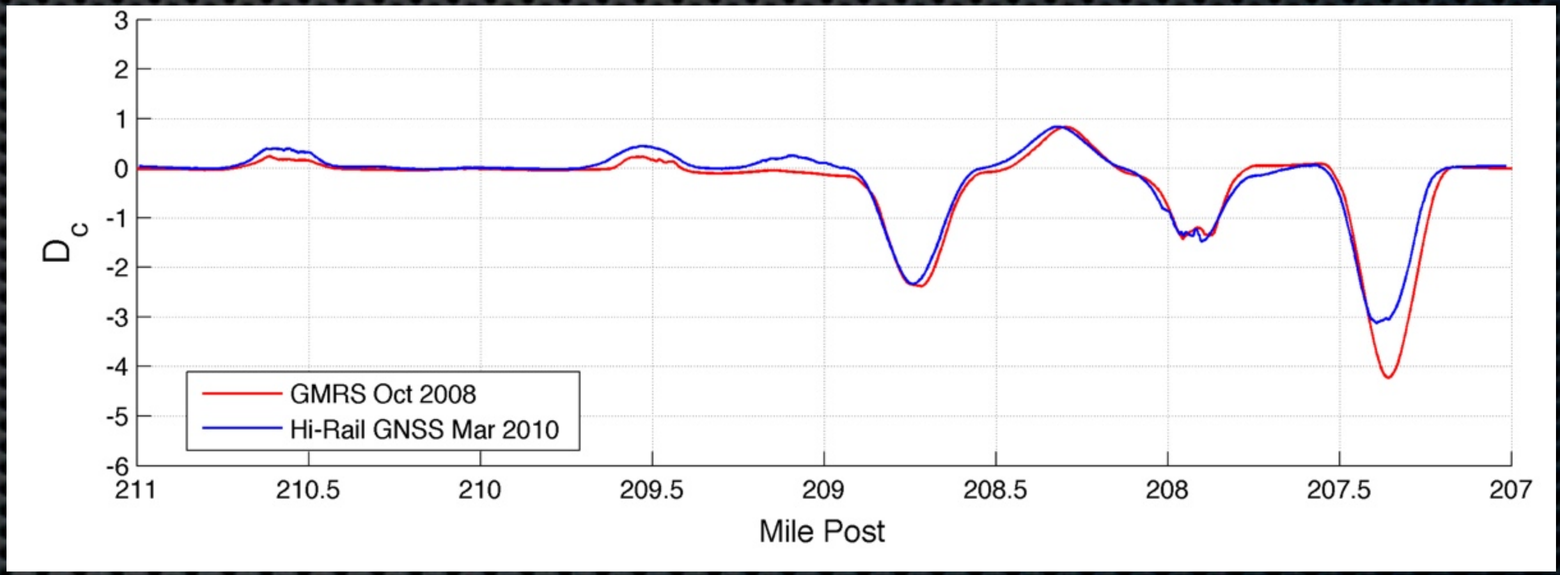


Comparison of Tangent D_C

with CSX Geometry Car GMRS1



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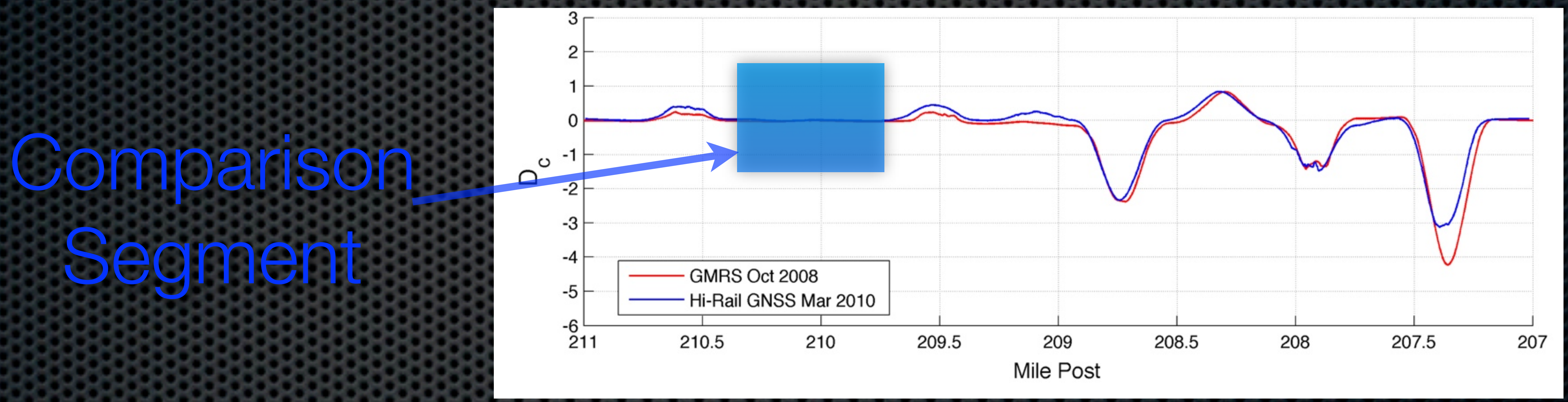

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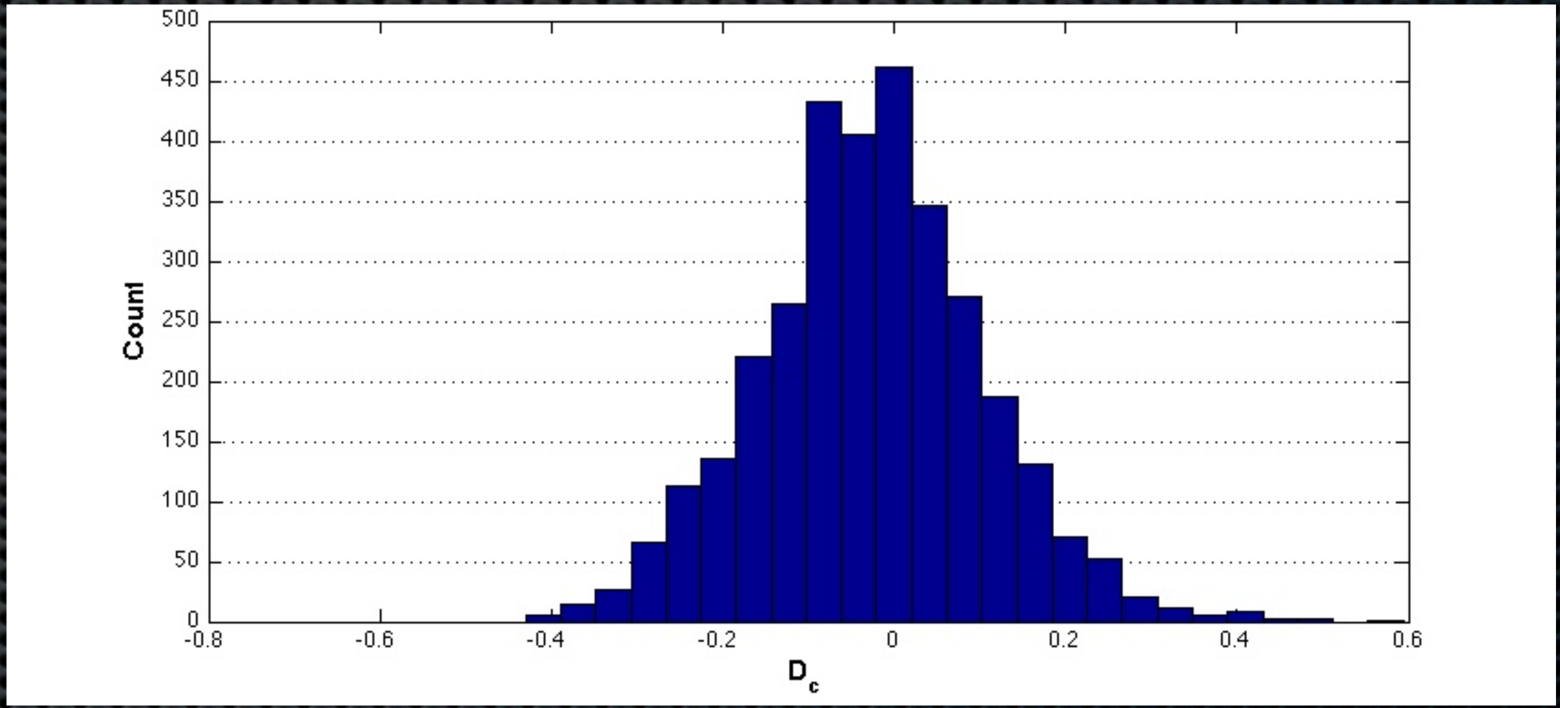
Comparison of Tangent D_C

with CSX Geometry Car GMRS1

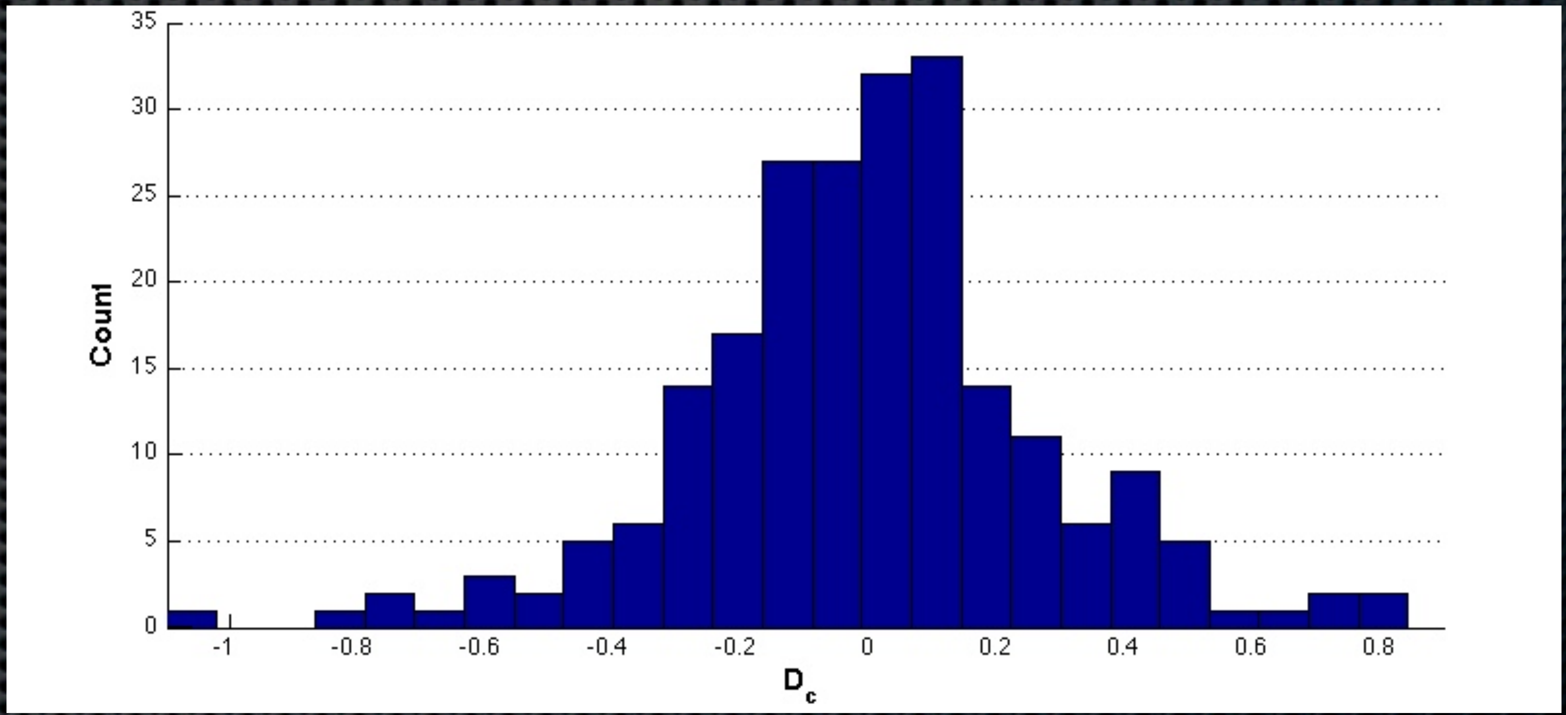
- CSX GMRS-1
  - N = 3,253
  - μ_{DC} = -0.0264
  - σ_{DC} = 0.131

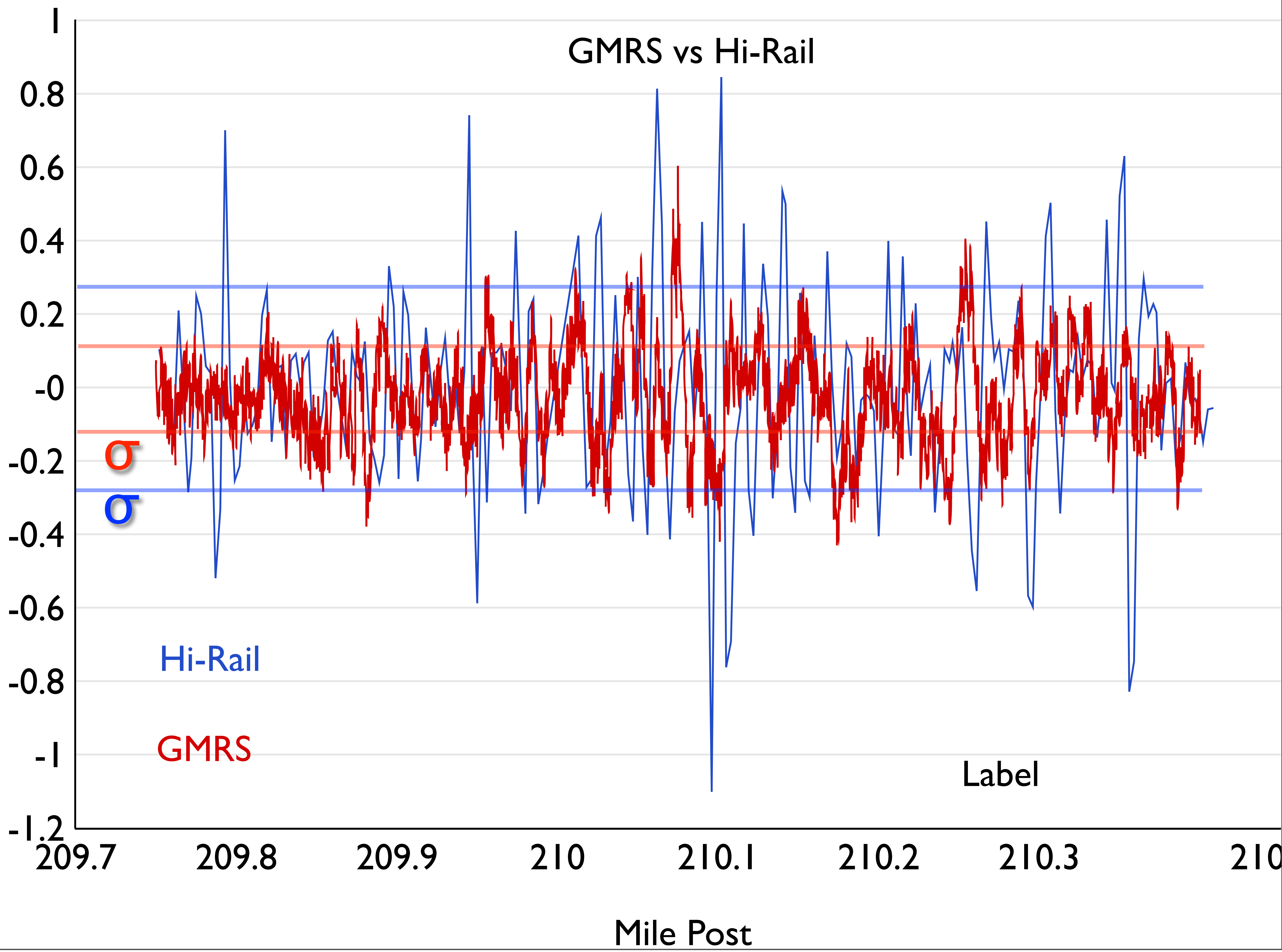


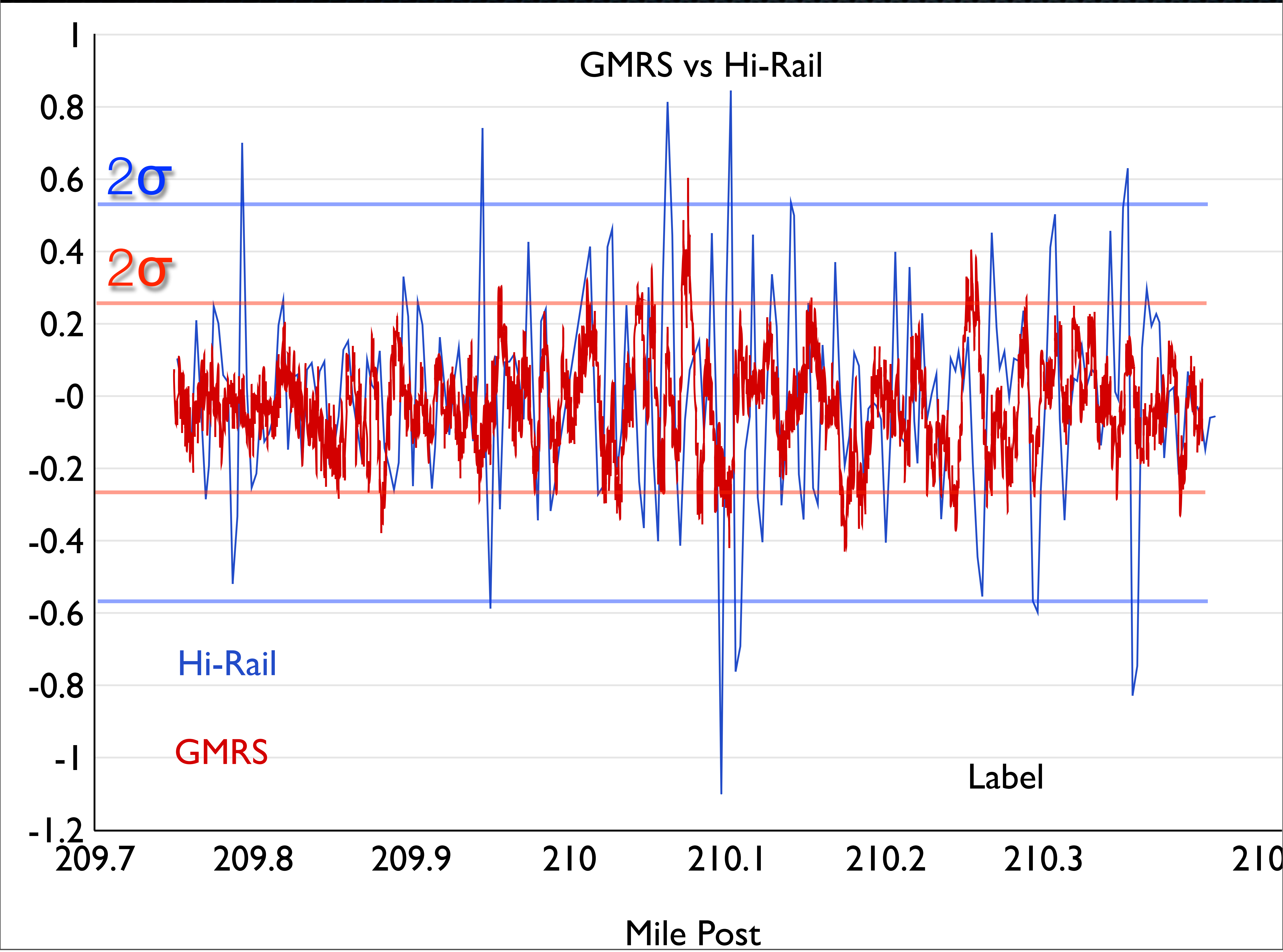
Comparison of Tangent D_C

with CSX Geometry Car GMRS1

- CSX GMRS-1
  - N = 3,253
  - μ_{Dc} = -0.0264
  - σ_{Dc} = 0.131
- Hi-Rail
  - N = 222
  - μ_{Dc} = -0.0042
  - σ_{Dc} = 0.279




GMRS vs Hi-Rail
1
0.8
0.6
0.4
0.2
-0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
σ
σ
Hi-Rail
GMRS
Label
209.7
209.8
209.9
210
210.1
210.2
210.3
Mile Post



GMRS vs Hi-Rail
2σ
2σ
Hi-Rail
GMRS
Label
1
0.8
0.6
0.4
0.2
-0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
209.7
209.8
209.9
210
210.1
210.2
210.3
210
Mile Post

Conclusions

- XYZ to D_C model verified by rail company information
- Hi-Rail not equivalent to track geometry car
- Hi-Rail & XYZ to D_C of present model near the limit of the instrumentation
    - ±1 cm (0.39 in) @ 95% CI
- Present GNSS signals for continuous track observations impeded by LOS from overhead obstructions

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Alinement 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

Alinement Defects

§213.55 Alinement

Alinement 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	1¾"	1¼"	1¾"
4	1½"	1"	1½"
5	¾"	½"	⅝"

[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 study & improved model may produce actionable track alinement information
- Capable of detecting track class 1-4 actionable defects
- 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.

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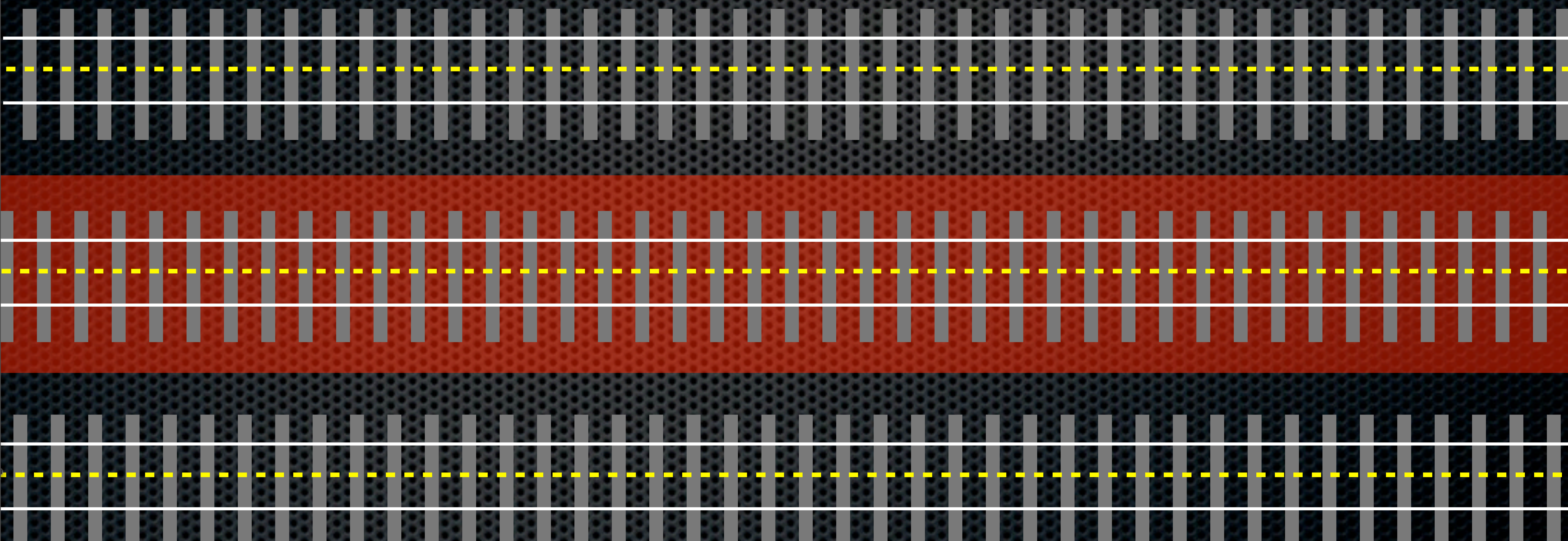
FRA Wireless Track Occupancy



1995 Federal Railway Administration Report

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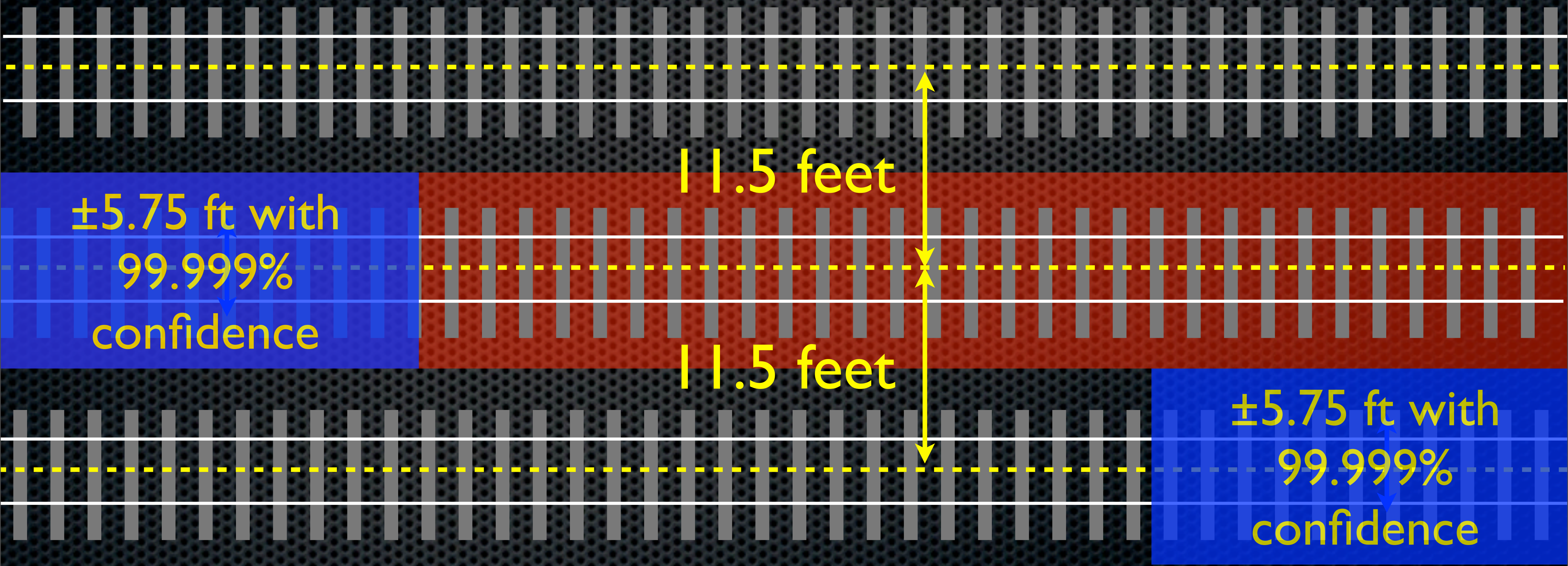
FRA Wireless Track Occupancy



1995 Federal Railway Administration Report

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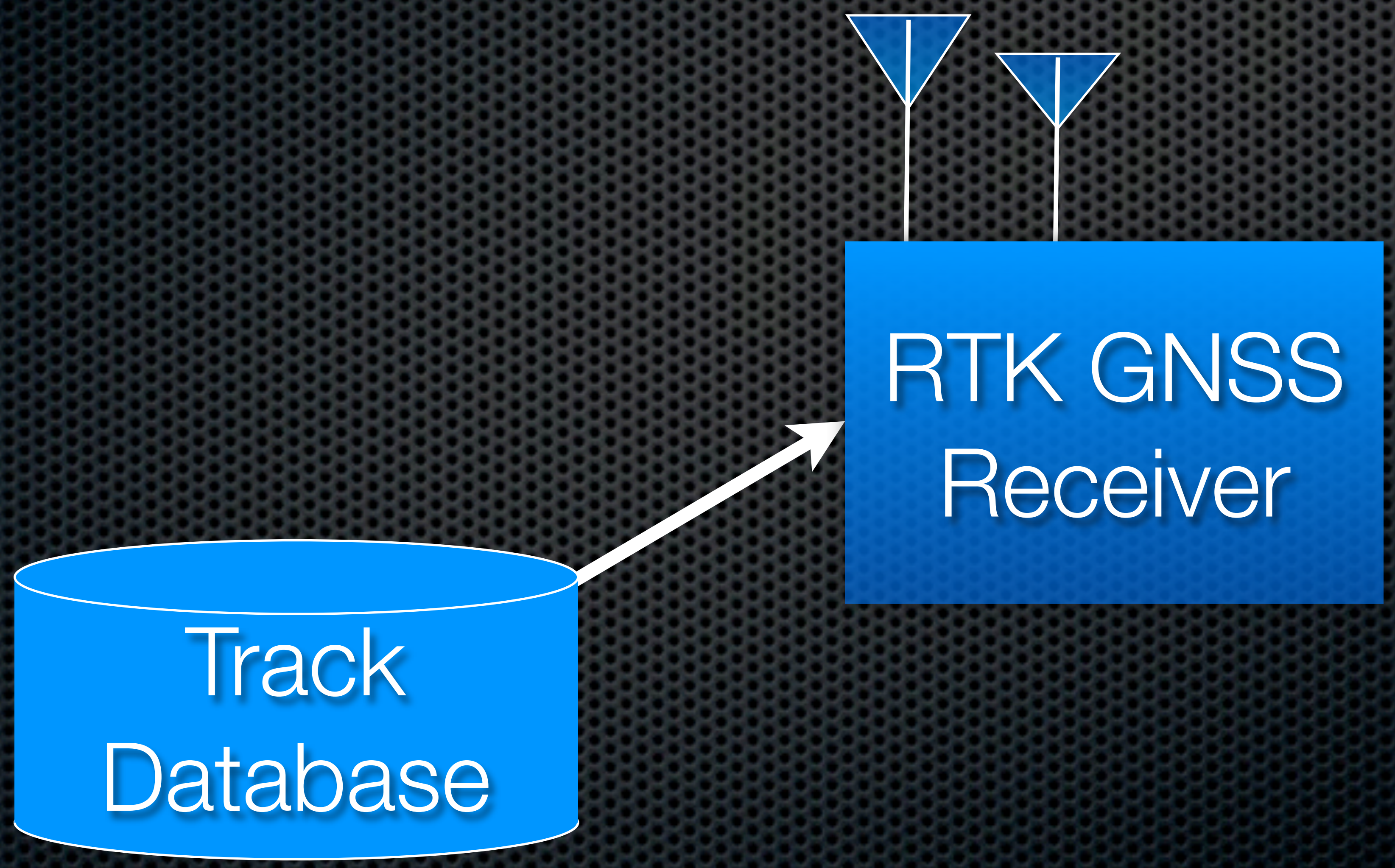
Motivation

- 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”

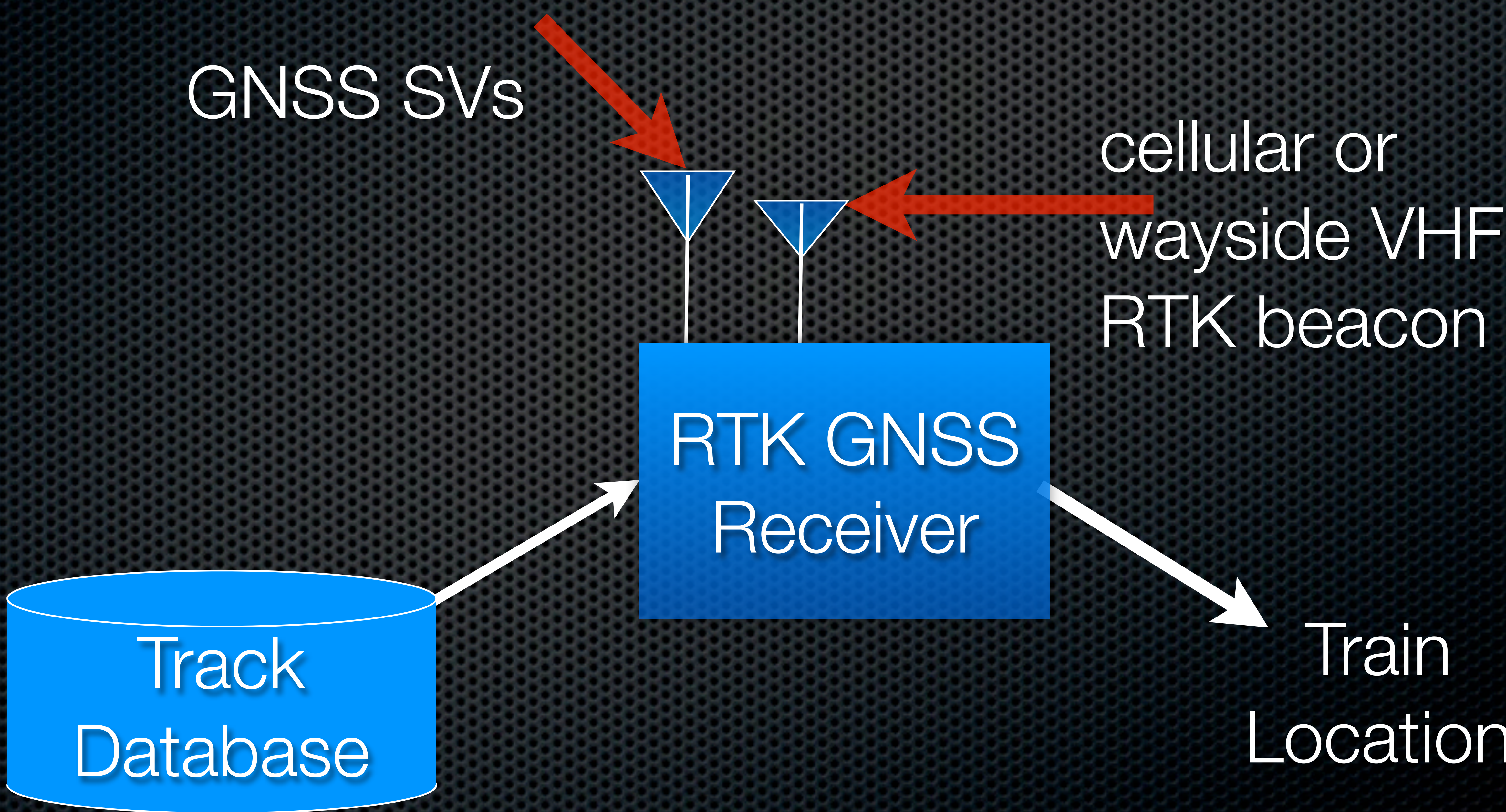
Motivation

- 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



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Research Question

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

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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
    - Tangent segment
    - Circular curve segment

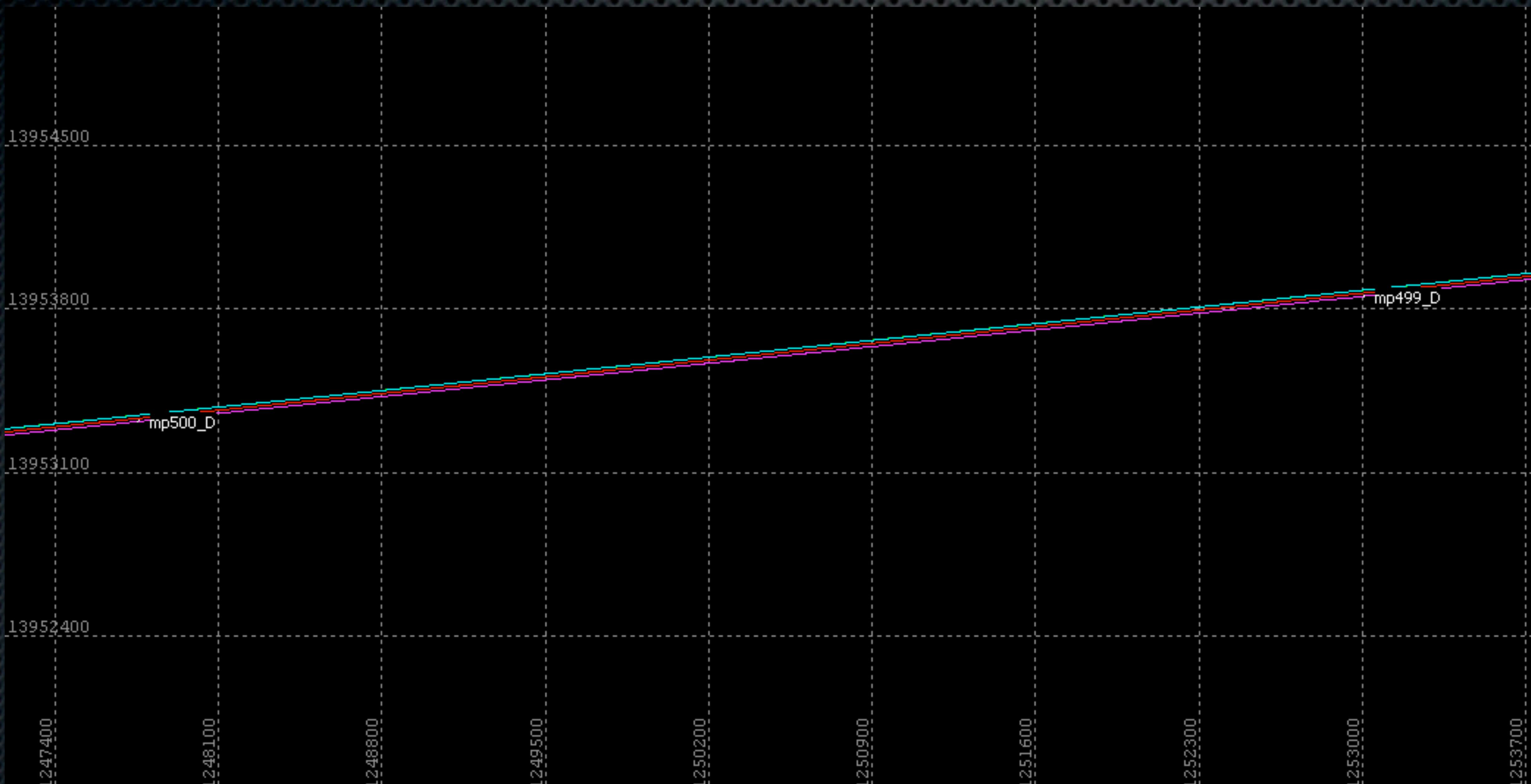
Observation Data

- 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



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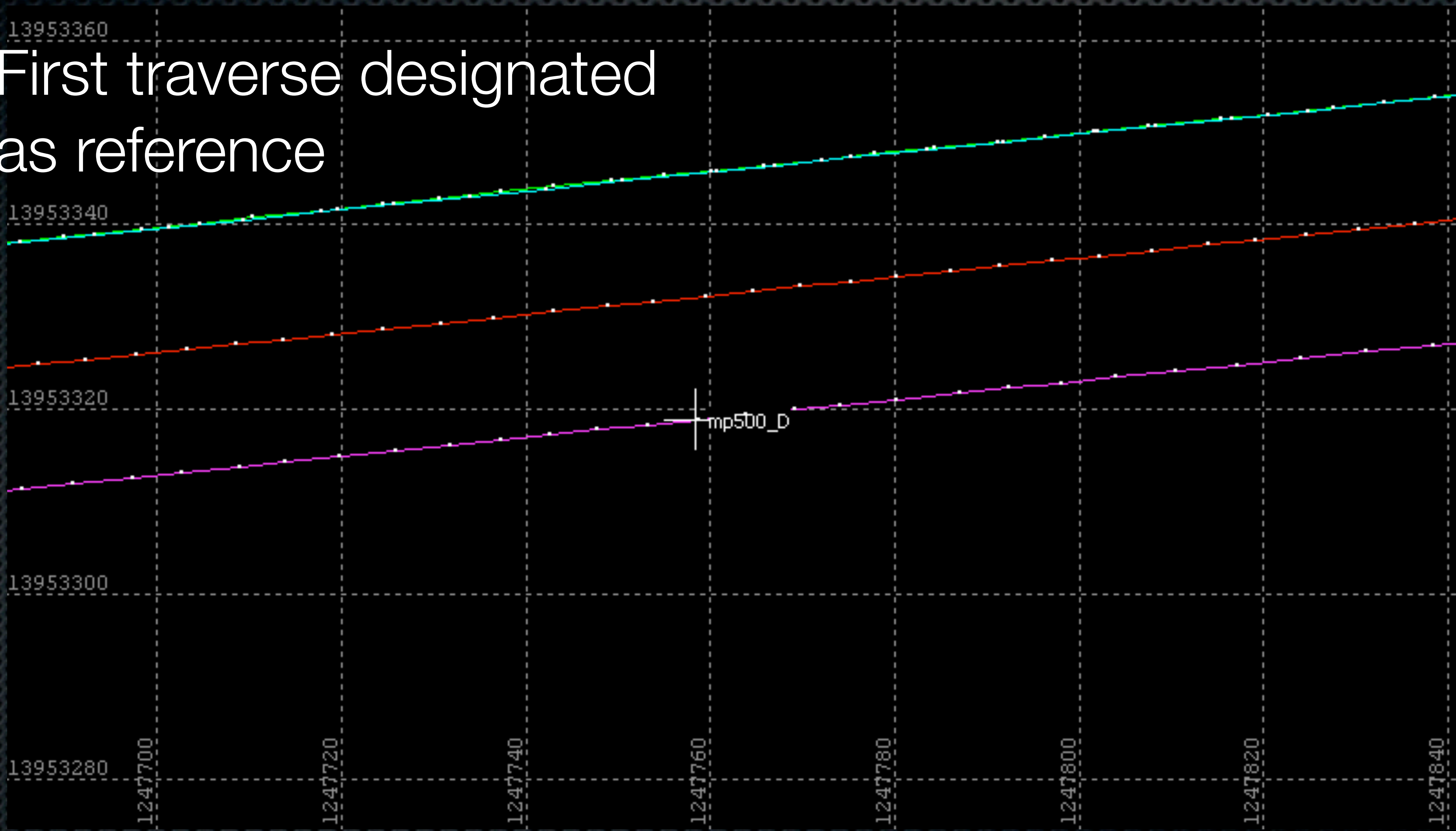
Tangent Segment

- First traverse designated as reference



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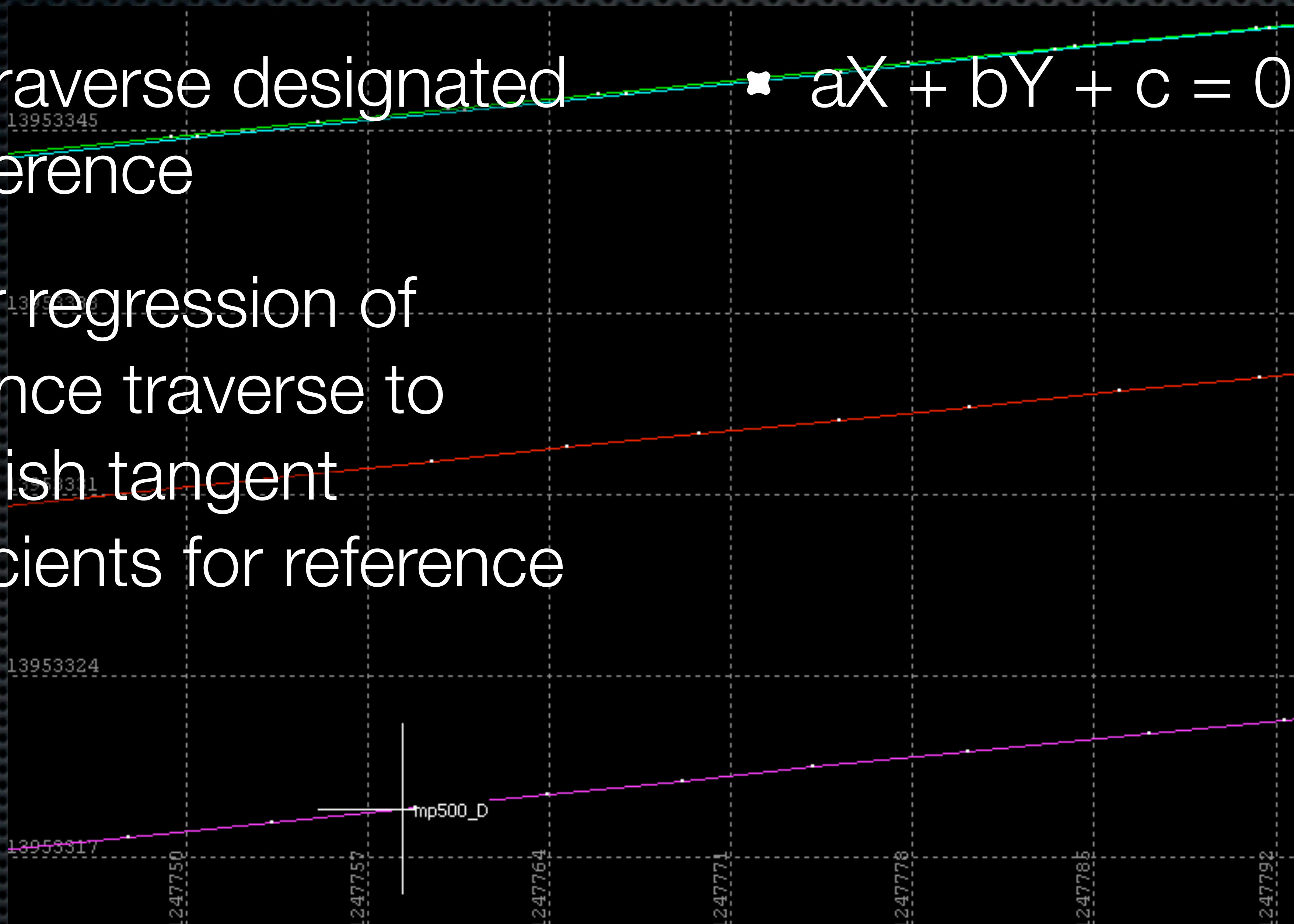
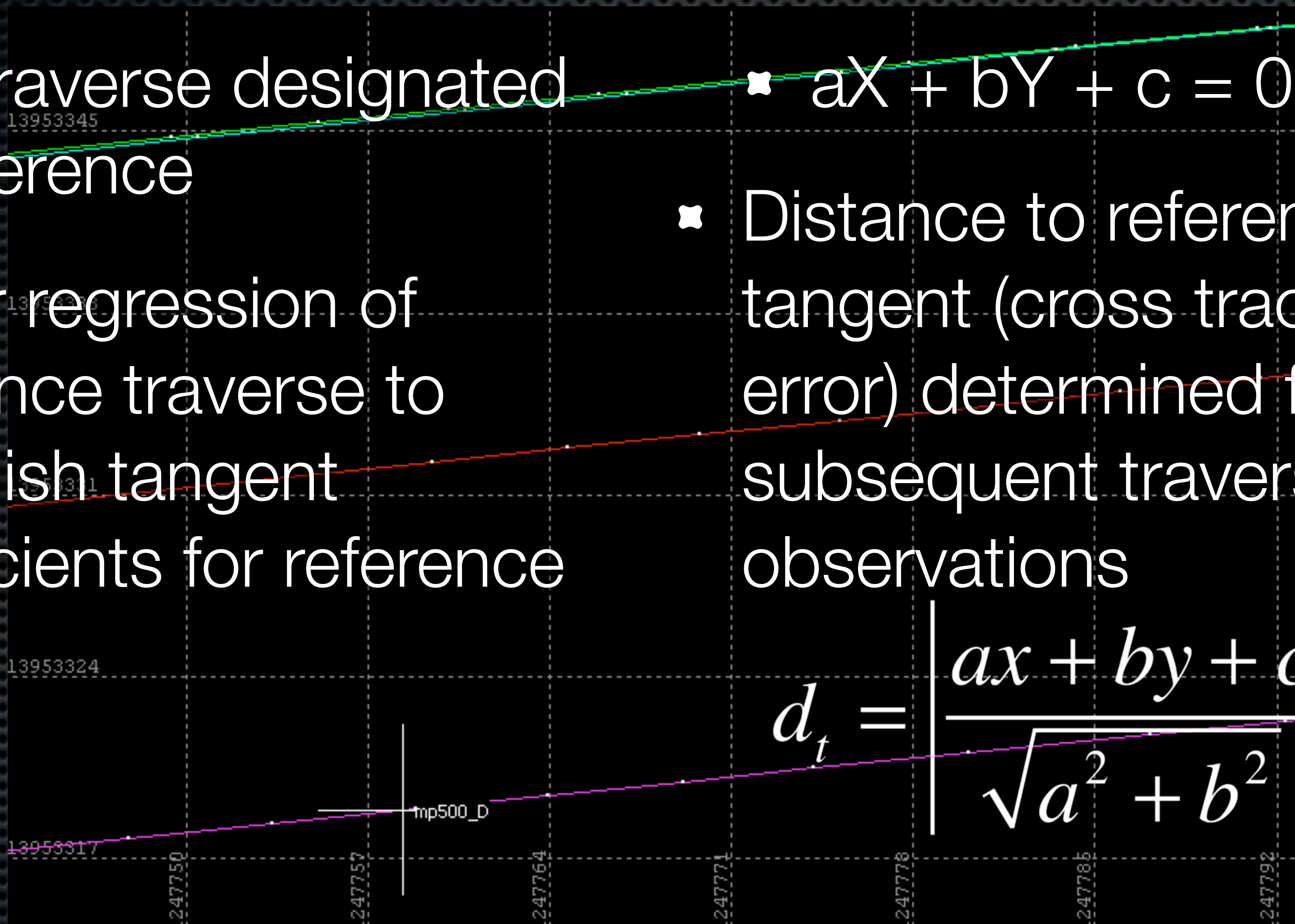
Tangent Segment



- First traverse designated as reference
- Linear regression of reference traverse to establish tangent coefficients for reference line

- $aX + bY + c = 0$

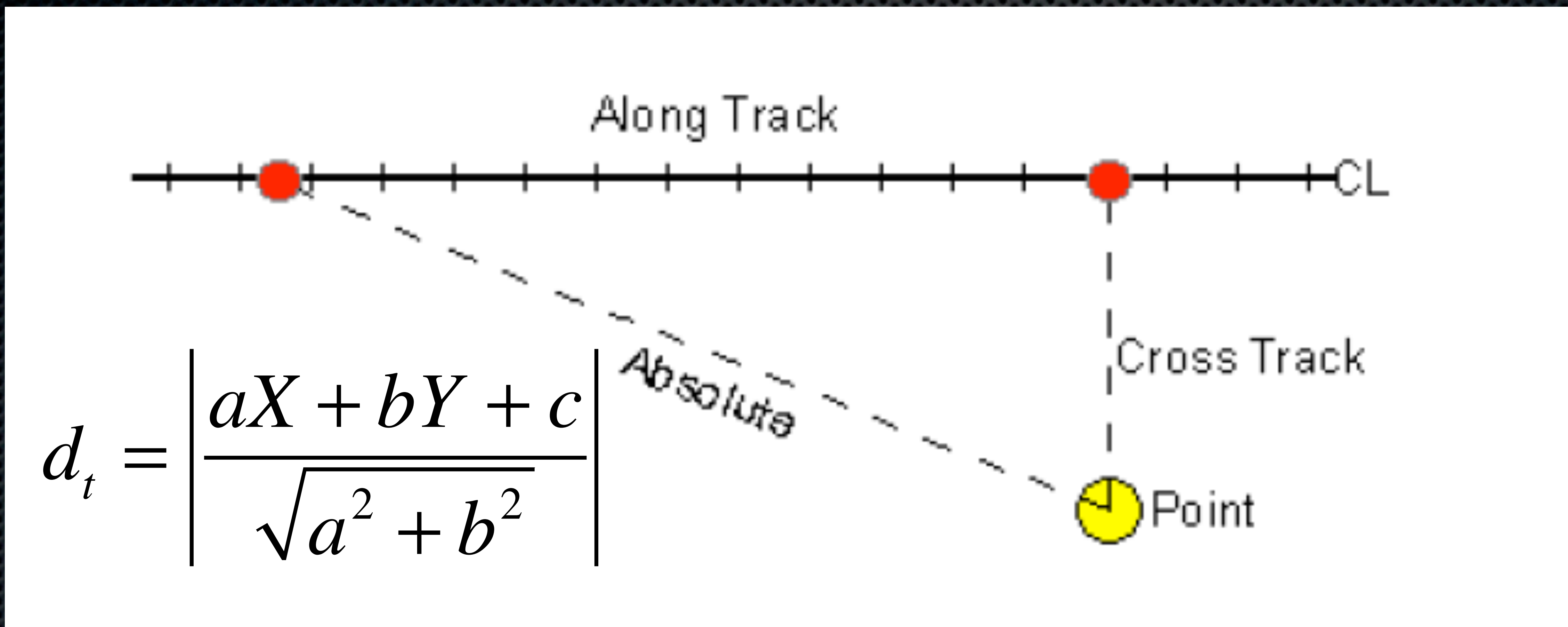
Tangent Segment



- First traverse designated as reference
- Linear regression 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

$$d_t = \left| \frac{ax + by + c}{\sqrt{a^2 + b^2}} \right|$$

Tangent Segment



$$d_t = \left| \frac{aX + bY + c}{\sqrt{a^2 + b^2}} \right|$$

Distance to reference centerline is cross track error

(Allen, et.al.)

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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-α)
  - α=0.00001

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

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

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Hypothesis Test Result
Tangent Track

Track	N	μ_d	σ_d	Reject h_0?
2_A-2_A	1,189	0.13’	0.08’	no
2_B-2_A	1,244	0.13’	0.08’	no
3_C-2_A	1,152	13.10’	0.35’	yes
1_D-2_A	1,158	13.51’	0.20’	yes
3_E-2_A	1,156	13.05’	0.31’	yes

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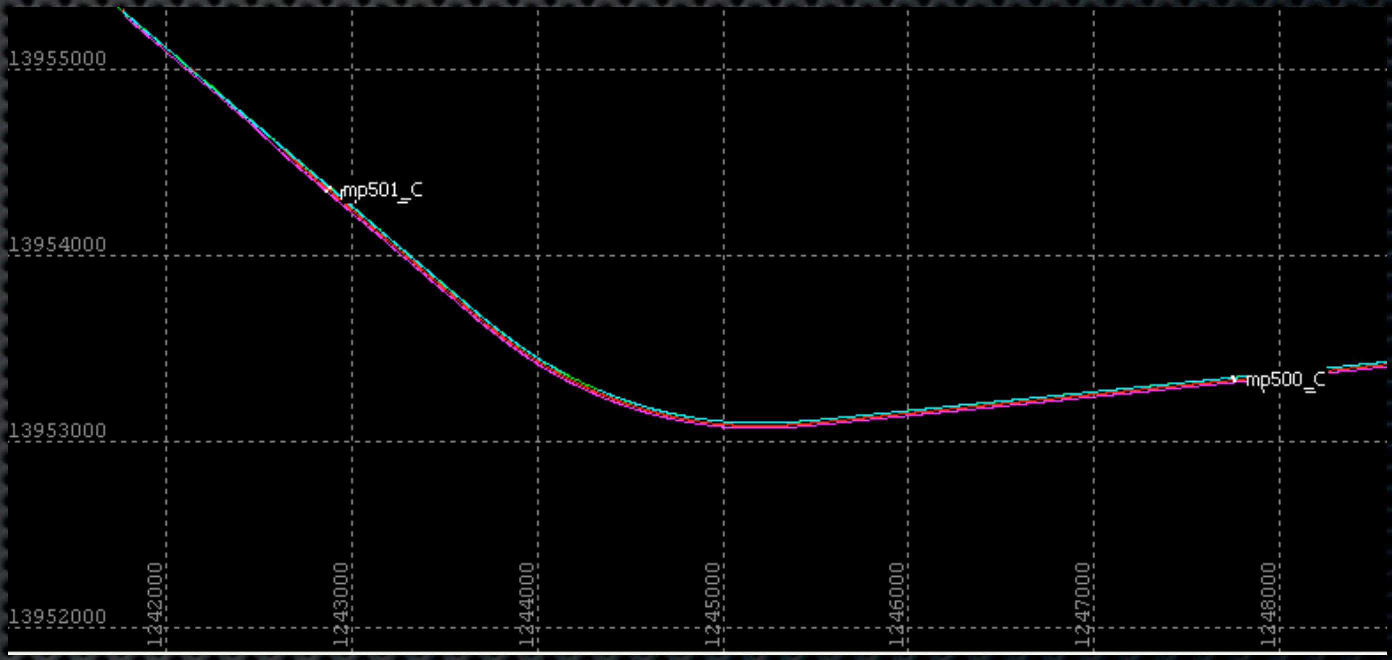
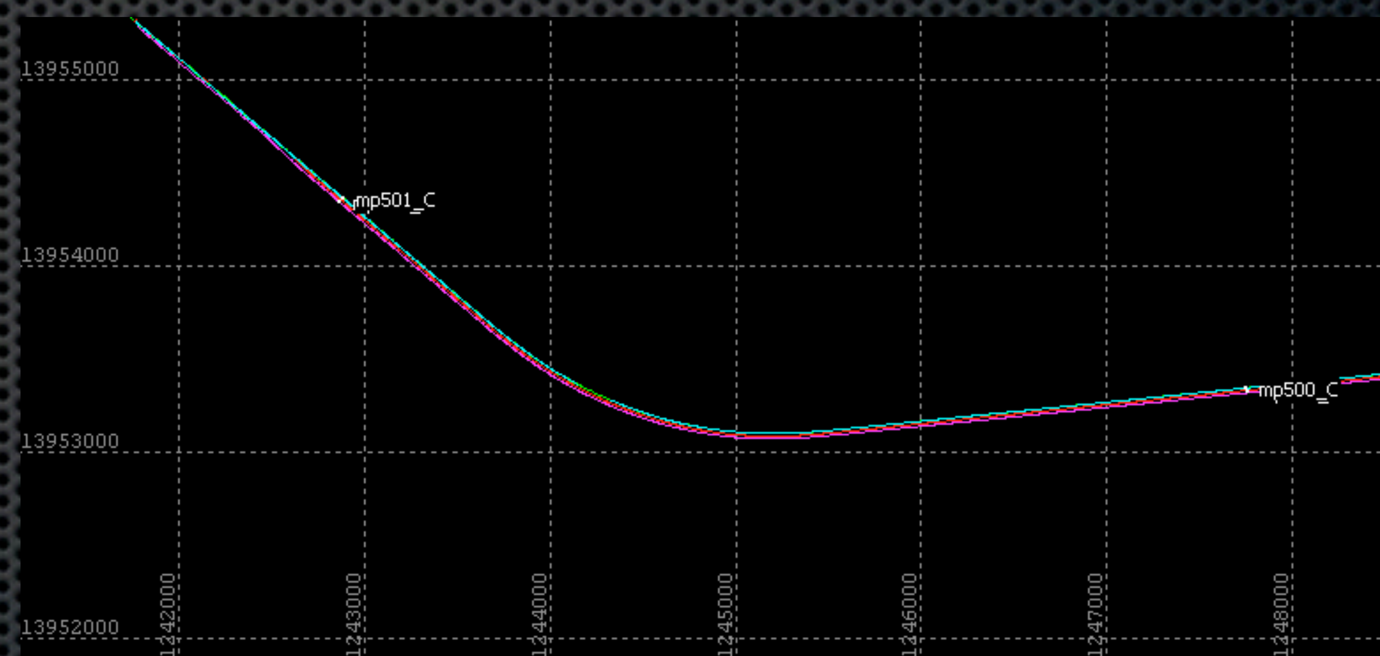
Curve Segment



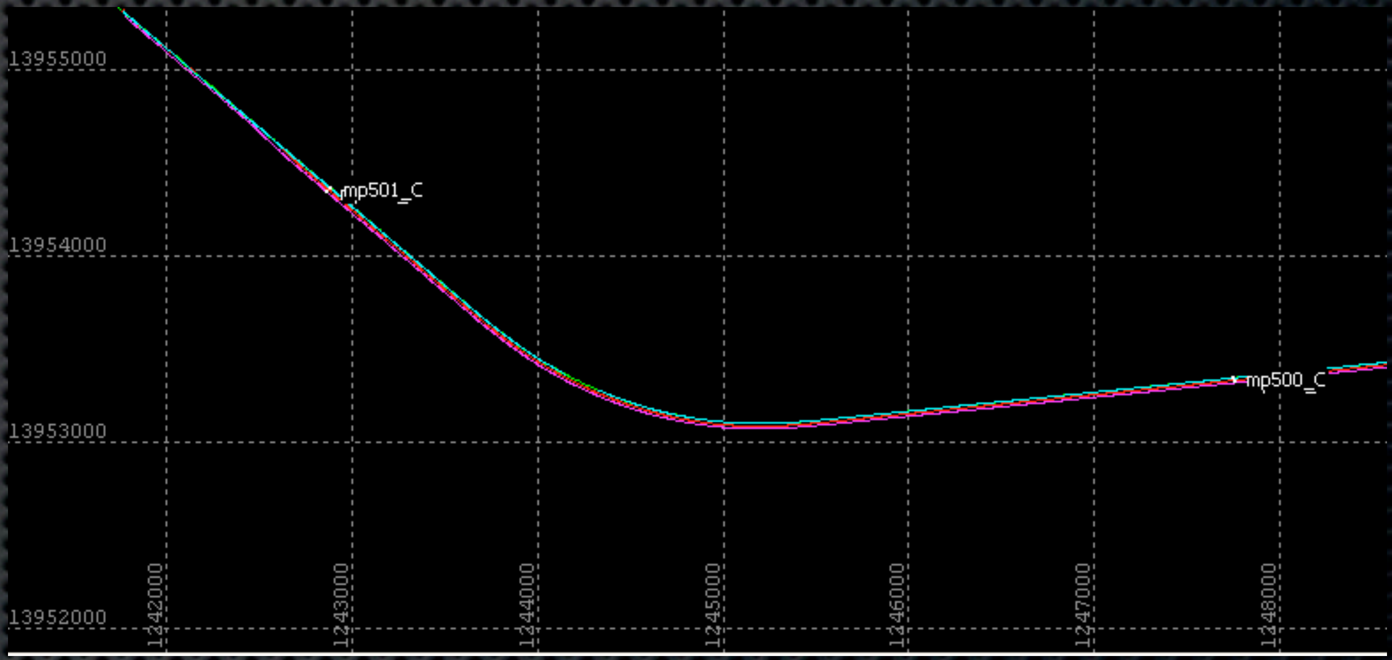
Curve Segment

- Circular portion (full body) of curve



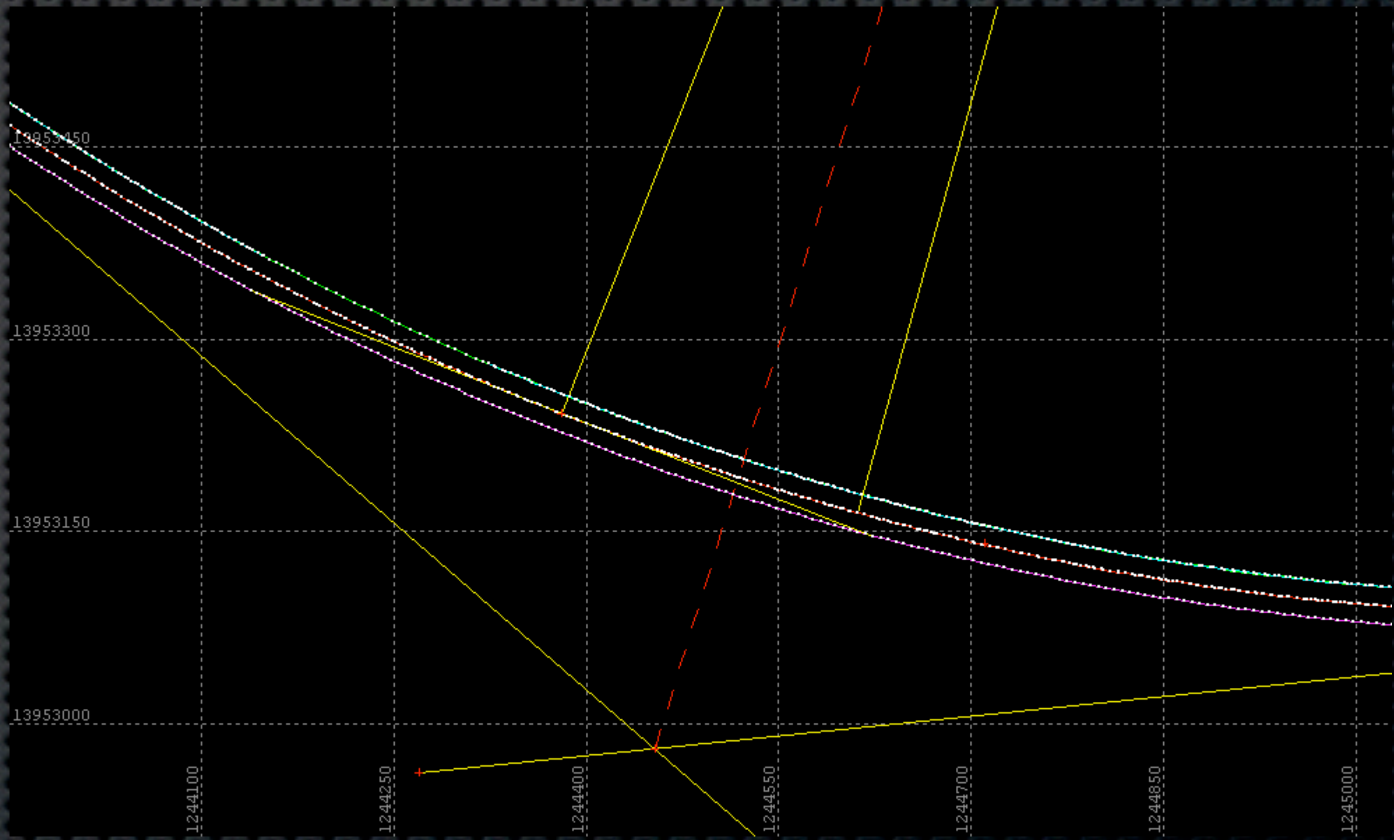
Curve Segment

- 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
  - Origin & radius



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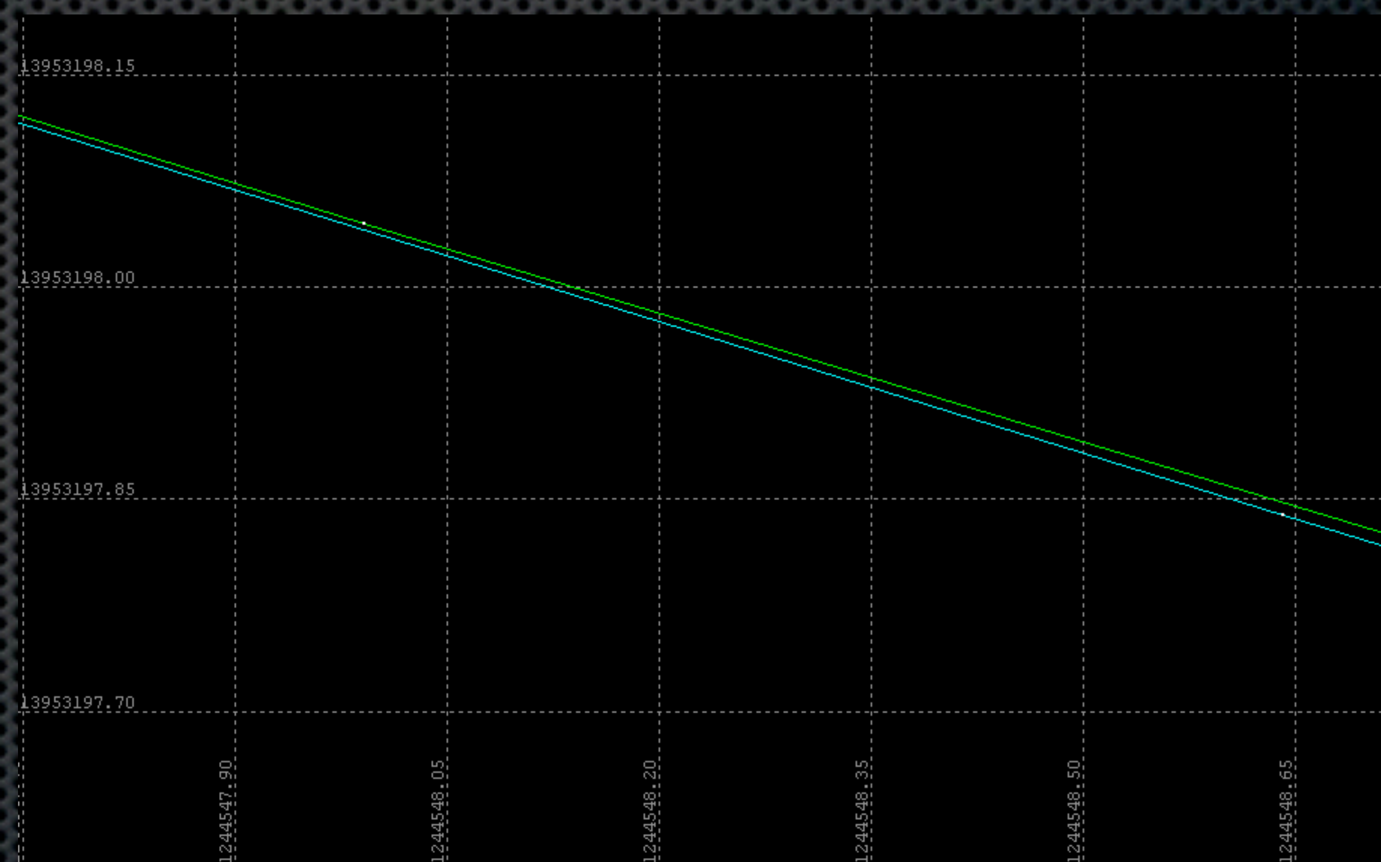
Curve Segment

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



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Hypothesis Test Result
Circular Curve Track

$Track_{traverse}$	N	μ_r	σ_r	Reject h_0?
2_A-2_A	85	0.00’	0.03’	no
2_B-2_A	98	0.03’	0.04’	no
3_C-2_A	98	-14.53’	0.16’	yes
1_D-2_A	97	13.93’	0.10’	yes
3_E-2_A	92	-14.57’	0.14’	yes

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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
- Can be applied to any ~~track~~ vehicle
- Applicable to individual on-track workers

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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
- Pipelines: Above ground monitoring for seasonal/abnormal effects

Civil & Mining Engineering

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

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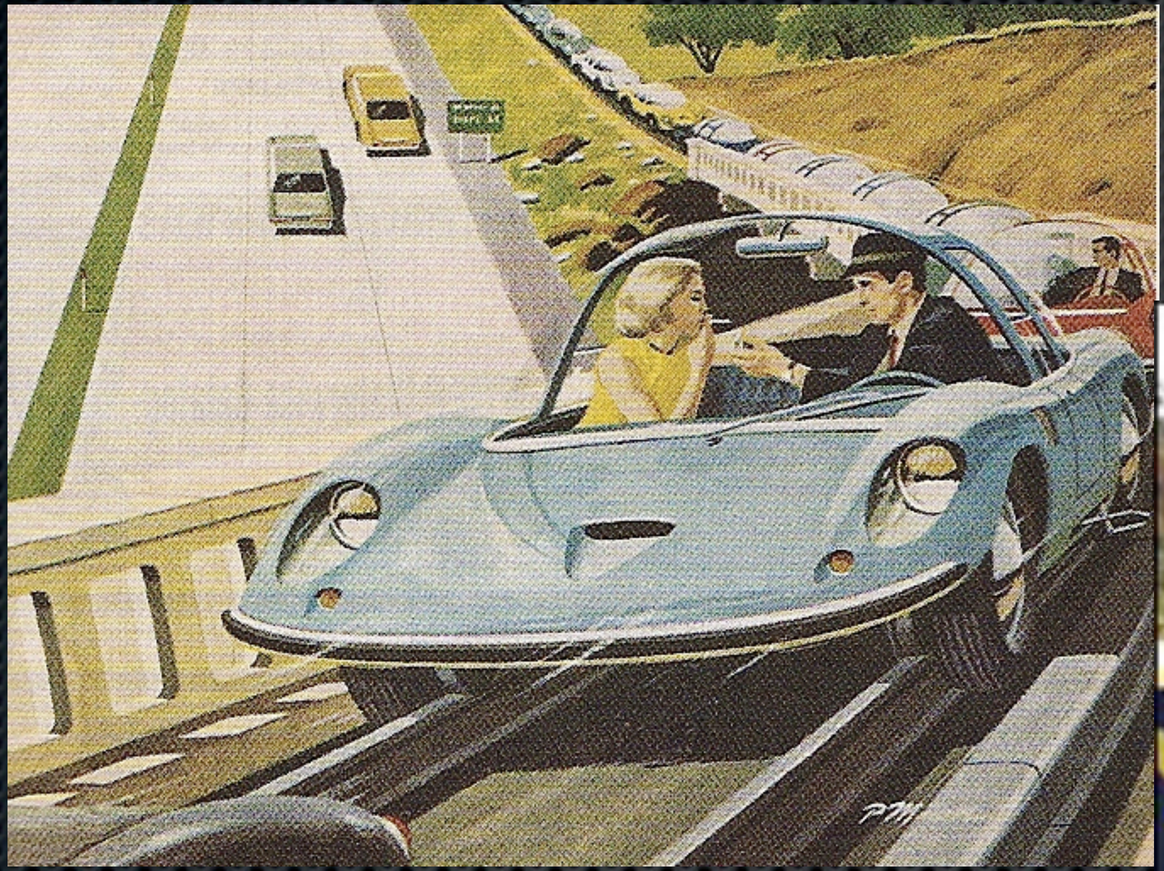
Self-guided Vehicles



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