

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 geometry¹ must be identified and maintenance resources brought to bear to insure safe operation at the design track speed.

FRA² 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 GNSS³ 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 territory⁴, 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 GPS⁵, as well as other global navigation satellite systems:

¹i.e., gage, profile, alinement, crosslevel, superelevation, and warp.

²Federal Railroad Administration

³Global Navigation Satellite Systems

⁴No signal control

⁵Sponsored by the United States Department of Defense (USDOD)

GLONASS⁶; Galileo⁷; and the future CNSS⁸, 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 States Department of Transportation (USDOT) has selected the National Differential GPS (NDGPS) augmentation system to increase accuracy in transportation applications. NDKPS has been promoted by the FRA as a means to achieve reliable track occupancy, however no NDKPS 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 0.95⁹ 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 versine¹⁰ [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 factors¹¹ 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

⁶GLObal’naya NAvigatsionnaya Sputnikovaya Sistema sponsored by the Russian Space Forces

⁷Sponsored by the European Union

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

⁹0.99999 or 99.999%

¹⁰In 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 $\lim_{L \rightarrow 0} 8 \frac{v}{L^2}$

¹¹Wind 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 were compared. Subsequent track positions met the researcher’s interpretation of the FRA positioning guidelines 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 circuits¹², provides an 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 dependence on existing hard-wired infrastructure¹³ 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 (Barboursville, 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.

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

¹³Estimated replacement mainline cost of \$125,000 per mile \times 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 yards¹, 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.

¹Commonly 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 PLCs³ 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 and 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 utilize publicly available real time correctors from the NDGPS in addition to post processed observations from a cooperative⁵ Continuously Operating Reference Station (CORS). The

³Programable Logic Controllers

⁴[http : //www.youtube.com/watch?v = yglx9RER70](http://www.youtube.com/watch?v=yglx9RER70)

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.

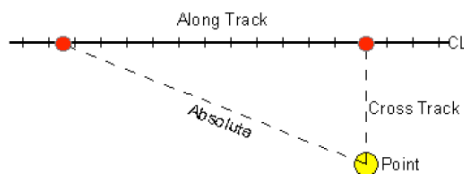


Figure 2.1: Track Centerline Accuracy Parameters [Allen et al., 2006]

Other track asset mapping systems exist for determining the location and type of 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 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 axis⁶ 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	$\pm 15^\circ$
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

⁶Referred 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 USDOD⁷ 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 SV⁸ 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 receiver. 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-grade⁹ position accuracy. The USDOT¹⁰ 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

⁷United States Department of Defense

⁸Space vehicle

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

¹⁰United States Department of Transportation

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

Federal government provided GPS¹¹ 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 FAA¹² sponsors WAAS¹³ 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 side¹⁴ 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 wavelength¹⁵ 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.

¹¹Non-GPS augmentation to GNSS systems is not provided by federal government systems

¹²Federal Aviation Administration

¹³Wide Area Augmentation System

¹⁴SV orbits viewed from the ground, are not present in northern segments.

¹⁵ $\lambda=922$ 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 receiver¹⁶ [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 multi-path 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
Measurement 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	×	✓	✓	×

¹⁶At 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 [USDOTFHHA 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 alignment, 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 CBTC¹⁷ 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 signals¹⁸, 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-

¹⁷Communications Based Train Control

¹⁸L2C 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 gap 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.