# A STUDY OF REAL TIME KINEMATIC GLOBAL NAVIGATION SATELLITE SYSTEMS IN RAILROAD TRANSPORTATION

by

Peter Joseph Dailey

A Proposal Presented In Partial Fulfillment

Of The Requirements For The Degree

DOCTOR OF PHILOSOPHY

IN CIVIL ENGINEERING

WEST VIRGINIA UNIVERSITY

December 11, 2009

# A STUDY OF REAL TIME KINEMATIC GLOBAL NAVIGATION SATELLITE SYSTEMS IN RAILROAD TRANSPORTATION

Peter Joseph Dailey

A Proposal Submitted to the Graduate
Faculty of West Virginia University
in Partial Fulfillment of the
Requirements for the Degree of
Doctor of Philosophy
Major Subject: Civil Engineering

PROPOSAL COMMITTEE

David R. Martinelli, PhD, chair

Darrell R. Dean, PhD

Robert N. Eli, PhD

Jim French, PhD

Andrew Nichols, PhD

# Contents

# List of Tables



# List of Figures

# Chapter 1

# Introduction

## Background

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

FRA[2] mandated bi-weekly 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 the the limited availability of these specialized measurement systems. The thesis of this research is that, given a sufficiently accurate and reliable augmentation system, railway infrastructure measurement can be performed quickly, with greater safety, and at less cost by determining absolute track position using global satellite positioning systems. Survey-grade track measurement using GNSS[3] instrumentation will remove ground-based surveyors from the hazards inherent to active rail yards; enable track monitoring of rail movement during routine visual inspections; and to determine the track occupancy of a train in parallel multi-track segments in dark territory or independent of wired track circuits.

[1] i.e., gage, profile, alinement, crosslevel, superelevation, and warp.
[2] Federal Railroad Administration
[3] Global Navigation Satellite Systems

The work proposed focuses on investigation into the use of Real Time Kinematic (RTK) augmentation to global satellite navigation systems to measure the absolute track position enabling solutions to rail measurement in yards and across wide areas of mainline track.

Space vehicles (SV) that comprise the GPS[4], as well as other global navigation satellite systems: GLONASS[5]; Galileo[6]; and CNSS[7], are orbiting reference beacons enabling autonomous geo-spatial positioning and timing across the globe. The geo-spatial positioning accuracy of these systems can be improved by augmenting the identifiable distortions to SV signal transmissions through the ionosphere and troposphere with corrections from ground based facilities.

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

## 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 exposure to railway hazards. Historically, North American railways use relative measurement methods for track inspection based on the idea that track curvature irregularity can be determined by the versine of a chord

The proposed research applies RTK augmented GNSS to measure track position within an absolute reference frame for use in addressing track profile measurement problems, determine relative horizontal alinement, and prove the ability to determine track occupancy in

[4]Sponsored by the United States Department of Defense (USDOD)
[5]GLObal'naya NAvigatsionnaya Sputnikovaya Sistema sponsored by the Russian Space Forces
[6]Sponsored by the European Union
[7]Compass Navigation Satellite System sponsored by the Peoples Republic of China

dark territory or independent of wired track circuits. These three railway problems will be investigated during the research.

1) An automatic classification yard uses the force of gravity to propel cars through a complex of tracks to the intended destination in the yard. Environmental factors[8] act on the motion of a railcar from its release through a transit of the yard bowl tracks to its rest position in the yard. Profile deviation from the design grade due to settlement occurs over time from railcar loading forces and the effects of weather [Szwilski et al., 2005]. Surveying a 60 track, thousand car per day yard places workers in a hazardous environment with yard production delays required to accommodate their safety. Production delays due to grade irregularities are difficult to quantify due to the limited availability of valid track profile information due to the difficulty and expense in conducting a yard survey [Barnes, 2007].

   The successful solution to hump yard grade surveys by RTK augmented GPS during yard production will result in the production of track profiles by removing surveyors from harms way, increasing the density of track observations and collect the observations in less time than ground-based differential level surveys.

2) Track superintendents[9] rely on biweekly visual inspections to identify track defects for directing maintenance resources. RTK augmented GNSS instrumentation will provide a record of horizontal track alinement during routine visual inspections by HiRail to aid in the identification of track shift or other compliance irregularities. Over time alinement records alinement records provide a history of track behavior attributable to car loading, weather, and geologic processes.

   The successful solution to augmenting visual track assessment with RTK augmented GNSS observations will result in the production of relative horizontal track alinements for use as an auxiliary component to track inspection practices [USC, 2009a; FRA, 2007; Bright, 2009].

3) Locating a train in parallel multi-track segments 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 a formidable task. Absolute track position using RTK augmented GNSS can locate track position with sufficient reliability to enable a subsequent traverse by a RTK-capable track vehicle to be correctly located in parallel, multi-track segments meeting the FRA location determination system (LDS) positioning requirements for positive train control

[8] Wind speed, direction, and ambient temperature

[9] Commonly referred to as Roadmasters.

(PTC) [FRA, 1995, pp.3].

The successful solution to locating position on the railway over wide areas will result in the ability to meet the FRA requirements for a wireless location determination system for positive train control.

## Research Objectives

The solution to many track measurement and rail vehicle location problems requires absolute track and vehicle position measurement over wide areas. The research will integrate RTK augmented GNSS 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 inspections. The research will employ locomotives and HiRail vehicles equipped with commercial off the shelf (COTS) GNSS survey equipment to evaluate the vertical precision, horizontal accuracy, and position reliability of RTK augmentation to meet the "...high integrity, and high reliability for safety-critical train control applications [Pruitt and Fly, 2008, pp.11]."

The primary objective of this research is to develop procedures and supporting models for assessment of RTK augmented GNSS integration within a Class I railroad environment. To achieve the primary objective, several secondary objectives will be established, as follows:

1) Use literature review, experimental data and intellectual property claims to investigate factors leading to the use of RTK augmented GNSS over railways.
2) Interview experts in the field of humpyard engineering and perform a review of the literature to identify methods of increasing humpyard the throughput. Study railcar motion through a humpyard to identify operational problems that may be related to profile degradation.
3) Develop and demonstrate a method for safely and precisely determining grades across the bowl area of an automatic classification yard, evaluating the use of COTS RTK GPS instruments aboard a locomotive during humping operations. Individual profiles for each bowl track in the yard will be produced.
4) Interview experts in the field of track inspection and wide area RTK augmentation delivery to identify methods for measuring rail position over wide areas of mainline track.
5) Develop and demonstrate a method for safely measuring track position across a wide

area.

6) Develop a model for horizontal track alinement analysis based on the string lining method using RTK augmented GNSS observations, and analyzing factors affecting GNSS measurement over mainline track.
7) Develop a methodology for assessing a location determination system suitable for supporting positive train control. The objective will determine if COTS RTK GNSS infrastructure and instrumentation are capable of demonstrating track position based on FRA stated tolerances [FRA, 1995, 4-5].

Development and demonstration of RTK augmented GNSS is significant to providing the rail industry with a practical and reliable standard of absolute rail position measurement over a wide area. Successful completion of this thesis will contribute modern tools that enable a variety of railway infrastructure measurement and monitoring not possible with US government provided augmentation. Existing and future 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 resulting 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 a 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 contrasted with the present use of dedicated track circuits[10], will lead to new practices in railway infrastructure management and track vehicle location. The economic benefit in reducing a rail company's dependance on hard-wired infrastructure[11] and attendant labor cost is significant.

Other cited benefits of accurate train location may include [FRA, 1995, pp.12-13]:

- 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).

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

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

- More efficient use of existing physical plant, increasing effective capacity while avoiding further outlays to build additional tracks or sidings.

## Research Approach

The research conducted in this investigation will be an analytical study supplemented by acquisition of RTK augmented GPS/GNSS track observations. The research will focus on 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 will be developed.

By solving the problems of determining absolute track location to a high degree of accuracy, the research will answer these questions:

1) *Vertical Precision:* Can a locomotive use RTK augmented GPS to measure the vertical profile of bowl tracks in an automatic classification yard during production activities?

2) *Horizontal Accuracy:* Can a common track vehicle use RTK augmented GPS/GNSS to determine the horizontal degree of curvature comparable with specialized track geometry vehicles?

3) *Reliability:* Can a common track vehicle use RTK augmented GPS/GNSS to meet the positioning requirements for track occupancy outlined by the FRA [FRA, 1995, pp.6-7] for a location determination system?

# Chapter 2

# Literature Review

## Background

Improving the USDOD[1] guarantee of 12.8 meter horizontal accuracy from the Global Positioning System Standard Positioning Service requires that positions calculated by a GPS receiver be augmented to correct for delays induced in the SV[2] signal's travel through the ionosphere and troposphere [USDOD, 2001]. Correctors transmitted to and processed by a capable receiver are able to compensate for a variety of SV signal transmission delays and instrument errors to improve the position determined at the receiver's antenna. Correctors are derived from the difference in 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. SV signal errors accumulate from an 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 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-

[1]United States Department of Defense
[2]Space vehicle

grade[3] position accuracy. The USDOT[4] was given presendential 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 effort [NSC Office of Science and Technology Policy, 1996]."

Federal government provided GPS[5] signal augmentation can be categorized by the augmenting signal transmitter location into Space Based Augmentation Systems (SBAS) and Ground Based Augmentation Systems (GBAS). SBAS use geosynchronous satellites to relay corrections from ground reference stations to the user, while GBAS send corrections from ground reference stations directly to the user.

## Space-Based Augmentation Systems

Government sponsored and privately funded SBAS are available to commercial users. FAA sponsors WAAS 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 the geostationary satellites and WAAS messages. The information is modulated on the GPS-like signal and broadcast to the users from geostationary satellites. WAAS corrections result in actual 95% horizontal accuracy ranging from 0.481 to 1.521 meters across the Continental United States (CONUS) [WAAS Test Team, 2009].

WAAS is limited to broadcasting differential corrections for GPS SVs only. As with SV signals, the reception of correctors broadcast from an SBAS can be adversely affected by

[3] Defined here and generally accepted as 1 to 3 meter horizontal accuracy
[4] United States Department of Transportation
[5] Non-GPS augmentation to GNSS systems is not provided by federal government systems

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. This characteristic as a primary objection by the FRA to the use of an SBAS as part of an LDS [Pruitt and Fly, 2008].

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

## 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 transmission of correctors to NDGPS capable receivers. A desirable aspect of long wavelength (1052-922 m) 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.

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

Even 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]."

## 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 main-line track in an asset mapping system demonstrated by Allen, Mason, and Stevens.

Allen, Mason, and Stevens developed a rail borne track-mapping system as a cost saving alternative to remote sensing from an aerial platform. Their survey platform consisted of a HiRail vehicle equipped to utilized publicly available real time correctors from the NDGPS in addition to post processed observations from a cooperative[6] Continuously Operating Reference Station (CORS). The GPS instrument was augmented with tachometer and inertial measurement unit (IMU) inputs. The IMU was tightly coupled with the GPS. 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. The results for cross-track and vertical error are referenced in table 2.1. 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 between 65 and 130 miles distant from the survey vehicle.

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

| Measurement System | Cross-Track Error(ft/95%) | Vertical Accuracy(ft/95%) |
|---|---|---|
| NDGPS | 5.2418 | 13.5308 |
| PPK $< 65$ | 1.5758 | 4.4049 |
| PPK $65-130$ | 2.9084 | 10.2528 |

The cross-track differences between the previously surveyed track locations and those measured by HiRail summarized in table 2.1. The results indicate that the PPK accuracies are insufficient for determining track alinement from NDGPS or observations post-processed with observations from individual CORS.

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

The cross-track accuracy determined from the experimental reaffirm the FRA report on NDGPS that track occupancy “When viewed as a two dimensional area problem, it is unlikely that any economically feasible [GPS] system could achieve this accuracy to the required $0.9_5$ probability [FRA, 1995, pp.6-7].”

Other track asset mapping systems exist for determining the location and type of of assets held by railroads. The Union Pacific Railroad has developed and markets a HiRail-based measurement vehicle built on a SUV chassis and referred to as the Precision Measurement Vehicle (PMV). The PMV is used to provide location and description of all assets that can be measured from the railway. While occupying active mainline track, PMV operators use several measurement technologies to determine asset location. Four independent encoded wheels provide linear referenced track position inputs by by accumulating the slope distance between wayside monuments. A differential GPS receiver provides mapping-grade absolute position, while a fiber optic gyroscope (OG) is used to measure grade. The OG also serves to dampen the elevation observations from the DGPS. 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 [UPRR, 2008].

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

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

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 | $\pm 15°$ |
| Asset location | Laser scanner | 180° |
| | | 1 mm @ 32 m |
| | | 10 mm @ 80 m |
| Gauge | Angular transducer/rail contact | 0-45° |

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 a Kalman filtering techniques to produces 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 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]. The tight instrument integration and slow survey speed make this approach impractical for track inspection survey over wide areas.

## Real Time Kinematic Technology

Augmentation technologies such as Real Time Kinematic (RTK), provide the capability of centimeter-level GPS positioning in real time while the receiver is in motion. RTK technology was assessed in the USDOT Final Report on NDGPS as poorly suited for positive train control. The reports states "As railroads continue to deploy CBTC[7] 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]." Transmitting RTK

[7] Communications Based Train Control

correctors to mobile users was characterized 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 disputes the 2008 USDOT assessment by 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 growing 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 ODOT's [2009]; MDOT [2009]; NCGS [2009]; KGS [2009]. Unlike federal systems, state and private systems are not limited to providing augmentation for only GPS SVs. Private investment in networked reference systems provides a market opportunity for firms to profit from the need for survey quality GNSS measurement. Delivering real time correctors to a mobile receiver is enabled by the increased capacity to transmit data by a number of means across wide areas. Wireless data transmission comes at a reasonable price and with data transmission rates several orders of magnitude greater than federal GBAS.

CORS networked to deliver observations as real time inputs to a virtual reference server adds the capability to continuously estimate the distortions of SV carrier phase observables while suppling correctors securely to mobile receivers. Mobile receivers use the VRS server supplied corrections to almost instantaneously refine local observations to within several centimeters. Mobile RTK users can expect to achieve position accuracies of 1-2 centimeters horizontal and 2-3 centimeters vertical across an entire VRS network with 95% confidence.

The proposed research seeks to bridge the cap between mapping-grade track asset surveys and complex track survey systems. This study will examine the ability of real time kinematic augmentation to enable selected railroad applications not achievable through current federal augmentation services.

## 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. Each transit through a terminal decreases the probability of an on-time delivery. Overall freight service reliability is the product of the probability-of-delay each time a car is handled along the way to its destination [Beshers et al., 2004].Rail freight carriers have difficulty in achieving acceptable carload service levels [Moorman, 2006].

Automated classification yards[8], 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.

Beshers notes that degradation of car-load service quality and movement away from boxcars to inter-model freight has resulted in a clear trend towards closing or repurposing hump yards rather than investment 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 [200, 2002].

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 waiting 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].

Profile deviation and settlement from design grade can be attributed to the effects of car loading forces and weather. Yard delays due to grade irregularities are difficult to identify due to the limited yard profile data available to the hump yard engineer. Limited data availability is due primarily to the difficulty in conducting a survey to profile track. [Barnes, 2007] [Szwilski et al., 2005].

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. Differential level point density is typically measured on 100' stations, resulting in the observation of approximately 3,000 points. The 480 to 720 man-hours of exposure in an active yard is evidence of the need to insure the 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.

[8] Commonly refered to as hump yards.

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 productivity from a yard track survey limit a manager's tolerance for obtaining bowl track profiles [Barnes, 2007].

The the hump end of an automatic classification yard has a controlling effect on the motion of a railcar through the yard. Hump end yard operations are described in this video and provide an graphic understanding of railcar pacing, variety, and braking. 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. Requirements for additional personal protective equipment around hump yards is obvious on the audio track.

Anecdotal inference of yard infrastructure problems is the usual mechanism by which grade renewal is scheduled. The reaction of a car's motion through the yard can be observed by paying attention to the suspension. Modern hump yard control systems such as ProYard are able to count car transits through the yard network passing wheel detectors (magnetic proximity switches) linked to programable logic controllers (PLCs) programmed with timing logic. Misroutes and car stalls records are used as metrics to determine yard performance. This time lapse video shows a series of stalled flat railcars, in the first frames a flatcar strikes another stalled flatcar and rolls backwards, with the car's final rest position blocking the group switch. The blocked switch prevents any further railcars from classification into the blocked group. The stall then effectively shuts down the yard once the next car sequenced for the blocked group reaches the pin puller. The 21 minutes represented in the time-lapse video from stall to the trim locomotive kicking the cars into the alley is indicative of the type of delays affecting the on-time quality of car load service.

# 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 cars produce positions with odometers for track location within a linear reference system relative to wayside monuments. Wayside references commonly referred to as mile posts are typically a steel signpost inserted into the ballast beyond the field-site foul point. These markers are less than permanent, and are subject to destruction or displacement from routine track maintenance and vandalism. Resetting mile posts is a best guess effort. Track geometry car measurements are referenced to these moving marks, increasing the difficulty in comparing track geometry over time [Van Pelt, 2009].

The linear measurement system of a track geometry car produces accurate relative positions, but is unable to place the track location accurately within a global reference. Track geometry vehicles are limited in their inspection frequency, and are generally made across a given track segment quarterly [Bright, 2009].

With the successful completion of the research, absolute track position determined by RTK GNSS will be used to determine relative horizontal track alignment.

# Track Occupancy

The FRA has established that any location determination system suitable for supporting positive train control must establish track occupancy with a high degree of certainty. In a given parallel, multitrack segment, an LDS must be able to determine which track a given train is on with almost absolute certainty. The FRA therefore requires an 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].

# Literature Review Summary

Recent references to determining track position using satellite navigation systems to measure absolute track position in real time indicate a gap exists between the use of dedicated survey platforms. Allen showed that federally provided NDGPS augmentation closely coupled with an IMU does not provide the necessary precision for determining track alinement or occupancy, while Glauss's sophisticated multi-sensor array is incapable of deployment in wide area track inspection tasks. Review of patent claims indicates addition work exists in industry that seeks to integrate federally provided augmentation with IMUs, but these intellectual property claims are not yet evident in commercial products.

RTK infrastructure receivers networked to a VRS server form a relatively new technology that enable absolute position measurement to within a centimeter over wide areas. It is this unexplored capability that forms the basis for the proposed research.

## Contribution of the Study

By proving the value of RTK GNSS, this study will contribute methods by which track positions in an absolute reference frame can be performed with COTS instrumentation and common rail vehicles to:

1. Evaluate the ability of RTK augmentation to produce an accurate vertical profile performed by locomotive to measure bowl track profiles safely, rapidly, and accurately without disruption to yard production.
2. Evaluate the ability of RTK augmentation to accurately produce relative horizontal track alignment referenced to track mile posts in degree of curvature from absolute track position. The research will evaluate whether the use of RTK augmentation on a common track vehicle can accurately quantify horizontal alinement over a wide expance of miles of mainline track in a single day.
3. Act as a component of a location determination system suitable for supporting positive train control by establishing track occupancy with a high degree of certainty. In a given parallel, multitrack segment, an LDS must be able to determine which track a given train is on with near absolute certainty. The FRA therefore requires an 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].

# Chapter 3

# Methodology

The purpose of the research is to evaluate the capability of RTK augmented GPS/GNSS to safely, rapidly, and precisely measure track position employing common track vehicles such as HiRails and locomotives as a survey platform. Figure 3.1 describes the major goals and their relationship in meeting the research objectives. Rail transportation needs were identified from interviews with rail company experts, an assessment of current railroad process and capabilities, observation of yard operations in light of the expert interviews, and the identification of a statewide CORS network accessible to researchers. Additional interviews with subject matter experts has led to the design of experiments that can be performed within the safety and access constraints of a Class I railroad.

Three experiments were designed to examine the use of RTK augmented GPS/GNSS over yard and mainline railway to evaluate the vertical precision, horizontal accuracy, and the reliability of RTK augmentation to measure track position and determine track occupancy.

1) RTK GPS will be used in a automatic classification yard to produce track profiles.
2) RTK GPS/GNSS will used to produce horizontal track alinement information.
3) RTK GPS/GNSS will be evaluated for the ability to provide reliable indication of track occupancy.

The research will investigate the use of Real Time Kinematic (RTK) augmentation to the Global Positioning System (GPS) and Global Navigation Satellite Systems (GNSS) with three experiments. The experiments seek to determine if RTK GPS/GNSS augmentation can enable safe and rapid track observations for use in evaluating track infrastructure.

*Vertical Precision:* Can a locomotive use RTK augmented GPS to measure the vertical profile of bowl tracks in an automatic classification yard during production activity?

*Horizontal Accuracy:* Can a common track vehicle use RTK augmented GPS/GNSS to determine the horizontal degree of curvature comparable with specialized track geometry vehicles?
*Reliability:* Can a common track vehicle use RTK augmented GPS/GNSS to meet the positioning requirements for track occupancy outlined by the FRA for a location determination system?

# Research Design and Data Collection

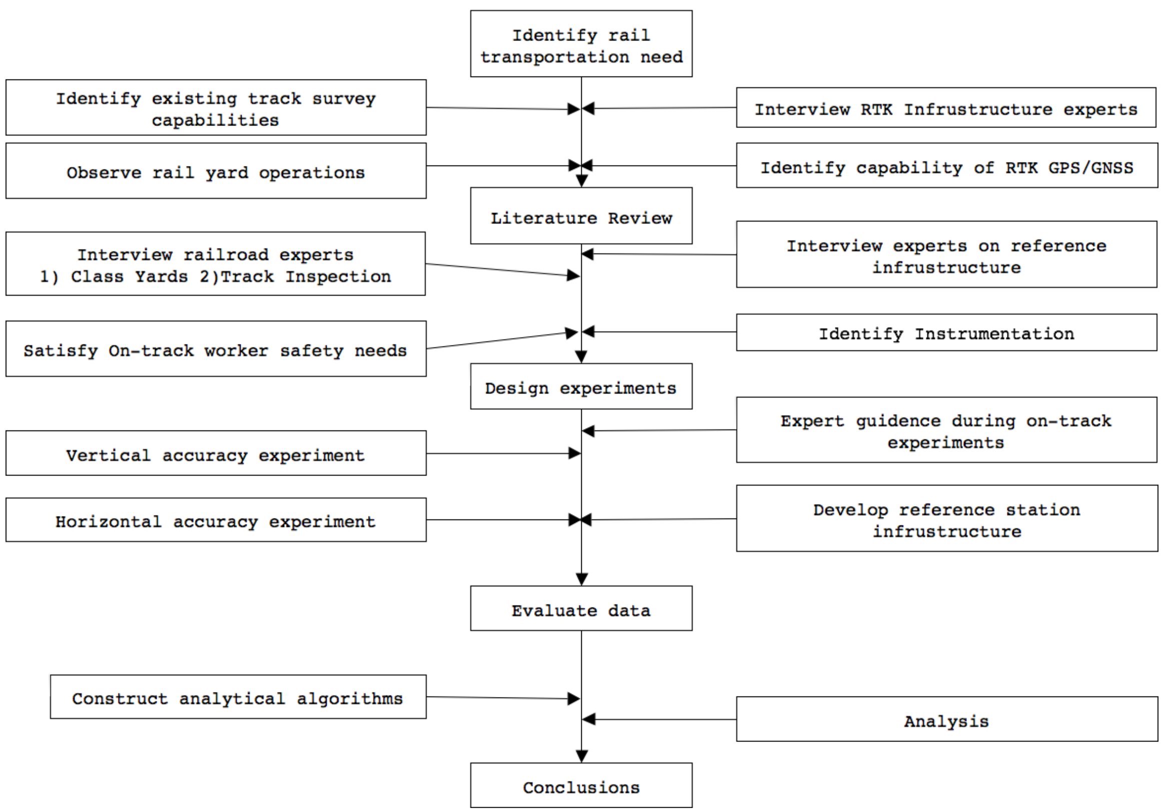


Figure 3.1: Research Plan

The research will investigate the capability of RTK GPS/GNSS augmentation over active track. Federal and private property laws restricts access to active track. Therefore all research activities will be performed in accordance with 49 CFR §214 railroad workplace safety regulations, subpart C *Roadway Worker Protection* [USC, 2009b] and subpart D *On*

*Track Roadway Maintenance Machines and HiRail Vehicles* [USC, 2009c] as well as rail company rules and procedures specific the the research location.

An evaluation of RTK augmented vertical measurement will be made by single epoch observations of track position by locomotive across an active hump yard. The track positions will be used to produce profiles for each bowl track.

An evaluation of RTK augmented horizontal performance will be made using single epoch observations of track position by a common track vehicle over active mainline track. Horizontal track alinement will be evaluated by determining the degree of curvature from track observation.

An evaluation of RTK augmented position reliability will be made by a common track vehicle over active mainline track. Multiple track positions over identical segments will evaluated against previously produced track geometry. Track positions will be evaluated for RTK's likelihood of determining track occupancy.

A scope of work with the anticipated timeline for completion of the plan objectives is referenced in figure 3.4.

Horizontal coordinates will reference the World Geodetic System 1984 (WGS84) ellipsoid. Vertical coordinates will reference the North American Vertical Datum of 1988(NAVD88). An East, North, Up (ENU) Cartesian coordinate projection will be used for deriving track alinement and position, with coordinate and distance units reported in decimal feet.

The electrical point of reference for a GPS/GNSS antenna is the phase center. The phase center is offset some distance from a physical reference location on the antenna housing. The physical antenna reference for each of these experiments will be the antenna mounting point. The survey controller will contain a table of offset distances between phase center and mounting point for the antennas used during each experiment. A procedure to align the antenna mounting point on the track vehicle with a track reference location (i.e. centerline, left or right rail) will be performed as part of the mobile track vehicle setup.

Estimates for the horizontal and vertical precision are calculated by the GPS/GNSS receiver. This estimate is the product of the geometric dilution of precision (GDOP) and the user-equivalent range error (UERE). The GDOP is determined by the geometry of the SV constellation in view, while the UERE is considered the statistical sum of the contribution from each of the error sources associated with a visible space vehicle [Leick, 2004; Leva et al., 1996].

The observation procedure for these experiments progress from setup of the reference station or reference network; establishing a means of communication between the reference station/network and the track vehicle; aligning the antenna and configuring the mobile receiver onboard the track vehicle.

## Experiment One: Vertical Precision

Can a locomotive use RTK augmented GPS to measure the vertical profile of bowl tracks in an automatic classification yard without the need for track closures?

The objective of experiment one is to use a locomotive to survey an active hump yard to produce track profiles from RTK augmented track observations. The hump yard survey will use a single RTK reference station transmitting correctors via UHF radio to a mobile receiver onboard a locomotive. The reference station components for this experiment will consist of a reference station receiver, reference station antenna, and a UHF data radio. A fixed-height tripod to support the GPS and UHF antennas will be set up on the highest point available at the yard to provide minimal obstructing SV signals and maximize height above average terrain (HAAT) for UHF data reception by the roving receiver. The reference station will record observations during several four to eight hour sessions. The compressed observations will be converted to the Receiver INdependent EXchange (RINEX) format and processed through the National Geodetic Survey Online Position User Service (NGS OPUS) to adjust the position of the reference station position.

RTK correctors broadcast from the reference station by UHF data radio will augment the GPS receiver position aboard the locomotive. A survey controller connected to the receiver will manage automated data collection and record single epoch observations with a nominal horizontal separation of ten feet. Track profiles will originate at a common reference point at the hump end terminating at the pullout-end switch for a particular track.

Points of interest such as switches, wheel detectors, and retarder inlet and outlets locations will be surveyed using the static survey instrument on the ground using watchman-lookout protection during the brief period.

Aggregate track observations will be deconstructed to individual track segments and be assigned a linear reference location.

Experiment one will:

1. Collect continuous single epoch observations on a nominal 10 foot horizontal spacing with RTK augmented GPS onboard a locomotive in an active hump yard.
2. Produce a plan view color mapped elevation drawing for the bowl area of the yard.
3. Produce a plan view color mapped vertical precision drawing for the bowl area of the yard.

4. Produce two-dimensional profile drawings for each track.
5. Determine the descriptive statistics for the performance of RTK augmented GPS vertical elevation as measured by a locomotive.

*Variables of analysis*: A three dimensional (ENU) coordinate will consist of:

- Northing
- Easting
- Elevation
- Vertical precision estimate
- Time and date of observation
- A count of the SVs in view of the mobile receiver
- Vertical Dilution of Precision (VDOP), a measurement of the geometry of the SVs in view

## Experiment Two: Horizontal Accuracy

Can a common track vehicle use RTK augmented GPS/GNSS to determine the horizontal degree of curvature comparable with specialized track geometry vehicles? The objective of experiment two is to perform a mainline track survey to produce horizontal track alinement from RTK augmented track observations. The track alinement survey will use a network of CORS RTK reference stations located along the survey route to stream observations to a central Virtual Reference Station (VRS) server. A public cellular data service will transmit correctors from the VRS to a mobile receiver onboard a track vehicle. A survey controller connected to the mobile receiver will record single epoch observations with a nominal horizontal separation of ten feet.

The track observation data will be used to find the degree of curvature using a software modeling the standard string lining method for railways. Experiment two will:

1. Collect continuous single epoch observations on a nominal 10 foot horizontal spacing with RTK augmented GPS/GNSS on board a track vehicle over at least 30 miles of mainline track.
2. Develop a software model for calculating the radius of curvature from RTK augmented GPS/GNSS track vehicle observations. The software will model the string lining method described in the FRA *Track Safety Standards Compliance Manual* [FRA, 2007, pp.26-30] using a 62 foot chord length on 15.5 foot stations.
3. Graphically correlate RTK augmented GPS/GNSS alinement determined from the software model plotted with track geometry car degree of curvature over identical

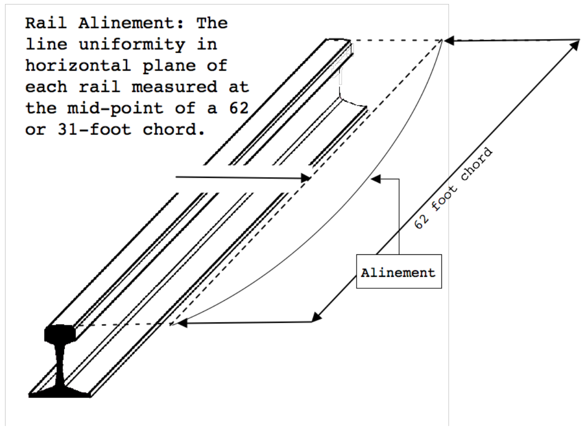


Figure 3.2: Horizontal Alinement

track sections.

4. Determine the horizontal alinement variability of the horizontal alinement found from RTK augmented GPS/GNSS observations in select tangent segments.

*Variables of Analysis*: Three dimensional (ENU) coordinates will consist of:

- Northing
- Easting
- Elevation

## Experiment Three: Reliability

Can a common track vehicle use RTK augmented GPS/GNSS to meet the positioning requirements for track occupancy outlined by the FRA for a location determination system?

The objective of experiment three is to determine how reliably RTK augmentation can reproduce the position of track vehicle as an aid to determining track occupancy. The track occupancy experiment will use a network of CORS streaming observations to a central server farm. A mobile receiver onboard a track vehicle will use a public cellular data service to securely access correctors transmitted to the receiver by the VRS. A survey controller connected to the receiver will record single epoch observations with a nominal horizontal separation of ten feet.

Multiple sets of mainline track observations will be used to find a mean location of tangent and circular track geometries by least-squares linear regression. The distance between individual observations from a each traverse of the track geometry determined by regression will be used to determine if RTK augmented GPS/GNSS can reproduce track position with sufficient statistical significance to meet the FRA requirement for a location determination system.

Experiment three will:

1. Collect continuous single epoch observations on a nominal 10 foot horizontal spacing with RTK augmented GPS on board a track vehicle over at least 30 miles of mainline track.
2. Determine an average track position for selected tangent and circular curve segments from continuous track vehicle observations.
3. Determine the distance from subsequent observations by track vehicle to the reference tangent and curve geometry.
4. Determine if statistical evidence exists to indicate if RTK augmentation of GPS/GNSS is capable of determining the track occupancy of a vehicle meeting FRA performance standards of a location determination system.

*Variables of Analysis*: Three dimensional (ENU) coordinates will consist of:

- Northing
- Easting
- Elevation

# Instrumentation

Instruments to be used in the research are summarized in table 3.1.

- An ad hoc reference station (AhRS) as listed in table 3.1 uses a stationary reference antenna to receive SV signals for manipulation by a GPS receiver to produce correctors for transmission over UHF data radio to a capable mobile GPS receiver.
- A continuously operating reference station (CORS) provides continuous data for RTK surveying applications.
- Virtual Reference System (VRS) is a network of CORS that enable RTK augmented GPS/GNSS positioning over a wide area, eliminating the need to position ad hoc reference stations along the survey route. A VRS network is made up of GPS/GNSS CORS hardware, modeling and networking software, plus a communications interface. RTK mobile receivers are able to securely access a VRS real-time network modeled correction with system integrity monitoring that warns of any data problems.
- A static survey unit is an RTK enabled GPS/GNSS receiver used by a surveyor to determine the coordinate of a position by recording an average of multiple-epoch observations while occupying the point of interest.

Table 3.1: GPS/GNSS Instrumentation

| Unit | Instrument | Description | Experiment |
|---|---|---|---|
| Ad hoc<br>Reference<br>Station | Trimble 5700<br>Zephyr Geodetic<br>Trimmark III UHF radio | 24 ch. GPS rcvr<br>GPS antenna w/GP<br>450Mhz band | 1 |
| CORS | NetRS/NetR5<br>Trimble Zephyr Geodetic | 24/72 ch. GPS<br>GPS/GNSS antennas | <br>2, 3 |
| VRS | Trimble Network Infrastructure | Server software | 2, 3 |
| Static Module | Trimble R8<br>Trimble TSC2 | 24 ch. GPS w/int. radio<br>Survey Controller | 1 |
| Mobile#1<br><br>Mobile#2 | Trimble 5700<br>Trimble TSC2<br>Trimble R7<br>Trimble TSC2 | 24 ch. GPS w/int. radio<br>Survey Controller<br>72-ch. GNSS receiver<br>Survey Controller | 1<br><br>2, 3 |

- A mobile survey unit is an RTK enabled GPS/GNSS receiver used to determine the coordinates of a position while in motion by recording single epoch observations.

## Data Validity and Integrity

The number of observations generated during each experiment can estimated by simply dividing the length of track to be surveyed in feet by the nominal distance between observations. Table 3.2 provides an estimate for the number of observations expected from each experiment.

Table 3.2: Data Estimate by Experiment

| Experiment | Est. Length | Est. Observations |
|---|---|---|
| 1 | Hump yard, 58 tracks x 2,000 ft | 11,6000 |
| 2 | Single mainline traverse of 30 miles | 15,800 |
| 3 | Three mainline traverses of 30 miles | 47,400 |

*Validity*

Insuring the the validity of these data will rely on the quality control performed by the data collector software. A field notebook will be kept to record values (i.e., antenna height from top of rail, locomotive number, track reference point) found during antenna alinement. The recorded values will be programmed in the controller as a specific survey style to insure using identical calibration values between observation files during multi-day surveys. The TSC2 survey controller will be programmed to reject observations that fall outside threshold values for horizontal and vertical precision. Threshold values will be selected that balance the continuous recording of all data with observation precision. In this way the survey controller software will act as a filter to eliminate outliers.

Plotting experiment one observations using ESRI ArcMap software allows a three-dimensional examination for groups that have consistent higher or lower elevations than other observations. This information will be examined for indications that a blunder may have occurred as the result of incorrectly entered antenna elevation offset.

Experiment two observations will be checked to insure the observations are continuous by using the software to flag a change in bearing between any two observations that approaches 180°, indicating the track vehicle backed up while recording observations. Observations generated by inadvertent recording in this manner will be deleted.

*Integrity*

The elevation integrity of observations will be maintained by using NAVD83 and avoiding 'mixing' datums within or between experiments [NGS, 2009].

During experiment one, several hundred points of interest (i.e., track switch points, retarder inlet and outlet, wheel detectors) will be surveyed on the ground. This data will be adjusted such that the POI is perpendicular to the rail and coincident with the track reference point. Maintaining the integrity of the adjusted observations will be performed graphically by plotting the adjusted points with the track vehicle observations to verify the adjusted POI is properly located.

Management of some data will use a web-based spreadsheet to provide collaboration between researchers. Data integrity will be enhanced due to the 'change logging' and 'previous version rollback' features of the web-based spreadsheet.

# Data Analysis

The analytical objectives referenced in figure 3.1 will combine quantitative measurement with a qualitative evaluation of track observations produced by mobile track vehicle equipped with RTK augmented GPS/GNSS instrumentation. Observations are collected by a survey controller and are transferred to *Trimble Geomatic Office* (TGO) software where any reference station location adjustments will be propagated to each observation.

The adjusted observations will be exported from the TGO software in a format that includes each observation name (coded by track segment), feature code (i.e., centerline, switch point, wheel detector, retarder inlet), northing, easting, elevation, horizontal and vertical precision, time and date, and number of SVs. The variables of analysis used in a particular experiment will be extracted from the export file.

Mainline track locations are reported as a linear reference from a wayside mile post monument. A track reference uses the mile post number plus the offset from the monument in decimal miles. Mile post references are typically measured by odometer, therefore the offset distance from the mile post is the accumulated slope distance. In addition, the slope distances between mile posts over railways in the United States is not a constant measure. To determine a mile post reference location, the number of feet offset from a mile post monument to the desired location is divided by distance between mile posts in feet plus the mile post number[1].

## Experiment 1: Vertical Precision

Hump yard track observations collected from onboard a locomotive will be exported from the survey controller to TGO. Observation coordinates will be adjusted by using the ad hoc reference station location determined from observing sessions processed by the National Geodetic Survey (NGS) *Online Position User Service* (OPUS). Observation sessions will be a minimum of four hours in length.

The OPUS-derived position will be substituted for the reference station initial autonomous position, with the track observations recalculated from the observation vectors by TGO. The reference station observations will be concatenated and converted to the Receiver INdependent EXchange (RINEX) format. The resulting observation and and navigation files will be processed using UNAVCO TECQ (translation, editing, quality check) software. The TEQC report will be examined for anomalous site or receiver influences, such loss of L1 and/or L2 signal, ionospheric and multi-path phase slip, receiver clock slip, and blocked SV signals in relation to poor vertical precision observations.

Further adjustment to track elevations will made by observing any survey monuments found proximal to the yard. Monuments will observed for at least 180 epochs. The current

[1] Assumes increasing mile post numbers, subtract if decreasing.

NGS Permanent Identification (PID) datasheet value will used to adjust the AhRS elevation.

The yard observations will be separated into layers organized by lead, group, and track. Deconstructing the aggregate observations enables individual tracks to be configured from a continuous series of points from the hump lead through the main, intermediate and group retarders, group, lead, and bowl tracks by activating the correct layers in TGO. A properly configured track will be apparent as a continuous series of points extending from the hump to the pullout end.

Locations of track points of interest (i.e., track switch points, retarder inlet and outlet, wheel detectors) are associated with a position nearest a particular rail. The POI will be observed at the center top-of-rail nearest the POI physical location using the static survey instrument. The position of the points of interest will be adjusted in the office to be perpendicular with the center top-of-rail observation and coincident with the track centerline.

Continuous track observation names will be renumbered in series from hump to pull out. Feature coded definitions will enable separation by point type and automatic line work created for the centerline points. The line work and observation data will be exported from TGO in the ESRI[2] shapefile format. The point data will also be exported exported as a comma delimited (CSV) file.

The CSV file will be imported to a spreadsheet program, where a linear reference will be found for each point. The elevation and linear reference coordinate will be scaled in the spreadsheet and added to a CAD drawing containing the track design grade[3].

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

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

Acceptable elevation quality will be apparent as a smooth track profile. Poor quality observations will appear with greater variation between points, resulting in a jagged or

[2]Environmental Systems Research Institute, Inc.
[3]Provided by the rail company sponsor.

sawtooth profile. Poor quality elevations will be identified and correlated with: observation time; vertical precision estimated by the receiver; and reference station observations during the period.

The vertical precision calculated by the receiver will be used to determine descriptive statistics and to plot a histogram for the yard profile survey.

## Experiment 2: Horizontal Accuracy

Mainline track observations collected onboard a track vehicle will be exported from the survey controller into *Trimble Geomatic Office* software, examined for blunders, and exported as described previously. Analysis of variables will be processed to determine the degree of curvature, following the string lining method described in Federal Railroad Administration *Track Safety Standards Compliance Manual for track classes 1-5* per 49CFR§213.55. This method follows the historical use of string lining for determining the degree of curvature on railways [Hickerson, 1964].

The software model will use RTK augmented GPS/GNSS ENU observations to find the degree of curvature at points linearly referenced to wayside monuments. The model will determine the coordinates of stations spaced at 15.5 foot intervals. For each station, a 62 foot chord intersecting a line segment defined by sequential RTK observations will be used to determine the middle ordinate offset for that chord.

Equivalent linear mile post references will be determined from sequential RTK observations by accumulating the slope distance between observations. Since the distance between mile post reference monuments over a railway in the United States varies, it will be necessary to evaluate each mile length independently. A mile post reference location will be determined by adding the mile reference number to the the ratio of the accumulated distance offset from a mile marker and the total distance accumulated between mile markers.

The string lining method as practiced by track inspectors and superintendents determines points of greatest alinement deviation by moving a 62 foot string along the track in increments until the point with maximum deviation is found. The software model will use a similar approach in moving the chord in 15.5 foot stations along lines defined by a series of RTK track observations. The distance from the chord middle ordinate to a line segment defined from RTK track observations will produce the mid-chord offset (MCO). The software model will determine MCO from RTK augmented GPS/GNSS as represented in figure 3.3.

Coordinates for the chord end point are determined by extending a 62 foot radius circle originating from the station coordinates, figure 3.3 station $(x_o, y_o)$. The 'chord circle' intersection with a line segment defined from the farthest point inside the chord circle and the nearest point outside the circle determines the chord terminal coordinate. The intersection is indicated at point $(x_{int}, y_{int})$ in figure 3.3, lying between points D and E. The MCO is

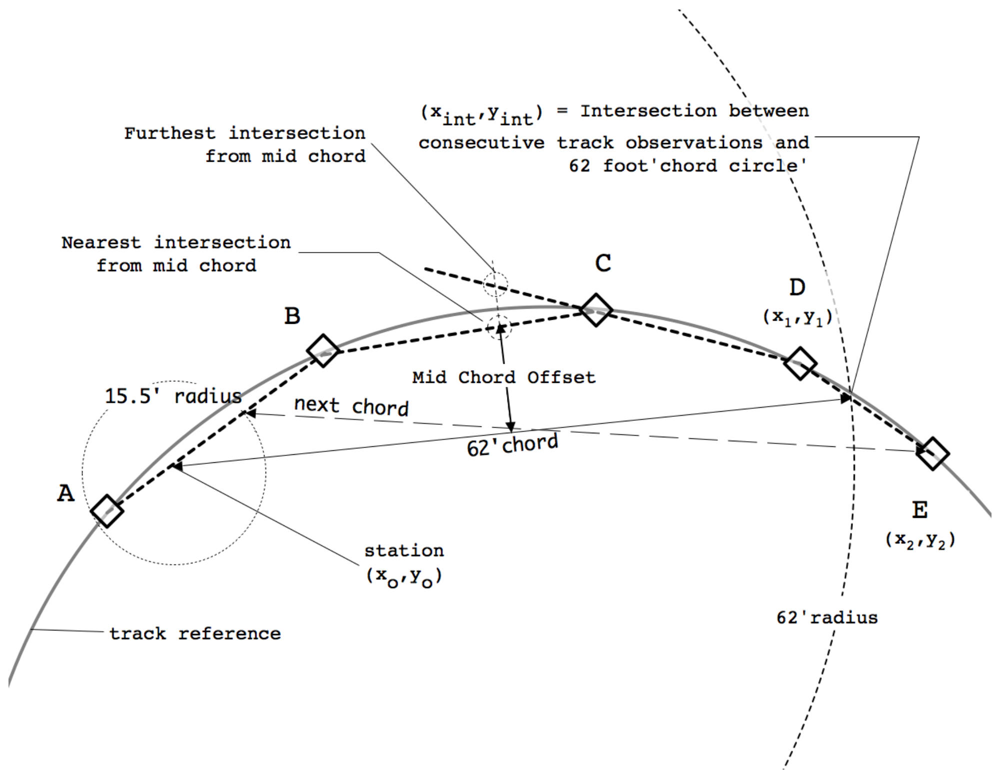


Figure 3.3: Modeling the String Lining Method from RTK Track Observations

determined from an line orthogonal with the chord at the middle coordinate. The the mean distance between the nearest and farthest of two line intersections projected from the three RTK observations nearest the middle ordinate (figure 3.3 points B, C, and D) and the middle ordinate orthogonal to the chord determines the MCO. The degree of curvature (chord definition) is found from the MCO and chord length in feet by the relationship [Hickerson, 1964].

$$D_c = \frac{45840 \times MCO}{chord^2} \tag{3.1}$$

The model will assign a mile post reference to the degree of curvature. The coordinates of the next station will be found by intersecting a 15.5 foot radius curve originating at the current station with a line between observations similar to the procedure for determining the chord terminal coordinates as indicated in figure 3.3.

A railway can be described as a smooth, continuous shape. Therefore, as an aid to exploring track alinement, a smoothing algorithm will be applied to the degree of curvature verses mile post information to filter and reduce the effect of outliers. A local regression smoothing method using a weighted linear least-squares regression will be employed. The optimal span of neighboring data points that produces a smoothed data set that most closely resembles the degree of curvature data from a specialized track geometry vehicle will be found through trial and error.

RTK derived track alinements from different traverses recorded over a time period will be plotted and evaluated for:

- Horizontal alinement correlation between track geometry vehicle degree of curvature vs. mile post reference and the degree of curvature found from RTK augmented GPS/GNSS track observations.
- Correlate between the horizontal alinement of RTK augmented GPS and augmented GNSS transits across the same track segment.
- Determine and compare the degree of curvature variability in select tangent track segments for RTK augmented GPS/GNSS instrumentation and a rail company provided track geometry vehicle data.

Tangent segments will be selected from the beginning, middle, and end of the study area. The degree of curvature variance will be determined from selected tangent in those tangent segments. A threshold of $\pm$one-half degree of curvature will be used to determine if statistical evidence is present to indicate comparable performance with a track geometry vehicle.

## Experiment 3: Reliability

The reliability of RTK augmented GNSS observations to reproduce track position will be determined from track observations during an initial traverse of mainline track with a track vehicle and subsequent traverses. Track observations from sample tangent and circular curve segments will define the tangent and circular geometries by the method of linear least-squares regression. The geometric coefficients defining the tangent and circular track location and the limit of the tangent and curve coordinates will be used as the track reference location.

An objective for a linear regression model is to determine the equation coefficients for tangent and and circular curve geometries through ‘center of mass’ of the track observations.

In the case of tangent segments, RTK track vehicle coordinates will be treated as a point on a line parallel with the tangent segment. The distance between the reference tangent and observed point will be determined by finding the distance between the two parallel lines.

In the case of circular segments, subsequent observation coordinates will be treated as a point on a circle parallel to the reference circular segment and sharing the same origin. The distance between the reference curve and the observed point will be determined by finding the difference between the curve radius and vehicle coordinate distance from the curve origin.

The mean distances between traverses over for selected geometry segments will be evaluated for conformity with the FRA specification for a LDS used in PTC.

## Summary

The research will explore the use of RTK augmented GPS/GNSS in dynamic track measurement experiments. Each experiment will examine the value of RTK augmentation to provide track measurements in the vertical and horizontal plane and well as examining the reliability of single epoch RTK enabled observations to act as a component of a location determination system.

Experiment 1 will evaluate the vertical precision of RTK augmented GPS by setting up a locomotive with mobile survey-grade GPS instrumentation to record a track position every ten feet across an active automatic classification yard. The recorded positions will be used to produce a profile for each track. The mean vertical precision for the bowl area of the yard will be determined from the mobile receiver's precision estimate. A threshold of 0.1 feet will be used as a gage of acceptable RTK vertical precision in this experiment.

Experiment 2 will evaluate the horizontal accuracy of RTK augmented GPS/GNSS performance by setting up a mobile track vehicle to record track position every ten feet on active mainline track across a wide area. Horizontal track alinement will be evaluated by finding the degree of curvature from track observations. The degree of curvature variation across selected tangent track segments will be found and compared with the variation of a specialized track geometry vehicle. A mean variation of ± one-half degree of curvature will be used as a threshold to gage acceptable RTK horizontal accuracy in this experiment.

Experiment 3 will evaluate RTK augmented GPS/GNSS position reliability by observing track position by a common track vehicle over active mainline track, and using the track coordinates to determine coefficients for straight and circular geometries over selected track segments. A subsequent traverse recording RTK positions will be evaluated against the straight and circular geometries to determine the mean distance between traverses. The distances will be used to provide an estimate of the likelihood of determining track occupancy using RTK augmented GPS/GNSS meeting FRA guidelines for a location determination system in positive train control applications.

The research timeline represented in figure 3.4 was developed from the research plan in figure 3.1.

| # | Name | Duration | Start | Finish | Cost |
|---|---|---|---|---|---|
| 1 | Literature Review | 239.0 d | 3/5/07 | 1/31/08 | $ 0.00 |
| 2 | Hump yard video | 2.0 d | 3/27/08 | 3/28/08 | $ 0.00 |
| 3 | **Reference Infrustructure** | **210.0 d** | **2/26/07** | **12/14/07** | **$ 0.00** |
| 4 | Interview Networked CORS Experts | 5.0 d | 2/26/07 | 3/2/07 | $ 0.00 |
| 5 | Install and add CORS to VRS | 60.0 d | 9/24/07 | 12/14/07 | $ 0.00 |
| 6 | **Experiment 1** | **471.0 d** | **5/16/07** | **3/4/09** | **$ 0.00** |
| 7 | Interview Humpyard Expert | 1.0 d | 5/16/07 | 5/16/07 | $ 0.00 |
| 8 | Hump yard survey | 5.0 d | 5/27/08 | 6/2/08 | $ 0.00 |
| 9 | Observation adjustment | 15.0 d | 6/6/08 | 6/26/08 | $ 0.00 |
| 10 | Profile Drawings | 30.0 d | 6/26/08 | 8/6/08 | $ 0.00 |
| 11 | GIS Mapping | 5.0 d | 10/27/08 | 10/31/08 | $ 0.00 |
| 12 | Vertical analysis | 3.0 d | 3/2/09 | 3/4/09 | $ 0.00 |
| 13 | Statistical analysis | 3.0 d | 5/18/09 | 5/20/09 | $ 0.00 |
| 14 | **Experiment 2** | **217.0 d** | **2/26/09** | **12/25/09** | **$ 0.00** |
| 15 | Interview Track Maintenance | 1.0 d | 11/2/09 | 11/2/09 | $ 0.00 |
| 16 | Interview Track Inspection Expert | 1.0 d | 5/19/09 | 5/19/09 | $ 0.00 |
| 17 | Mainline Survey 1 | 3.0 d | 2/26/09 | 3/2/09 | $ 0.00 |
| 18 | Mainline Survey 2 | 2.0 d | 9/28/09 | 9/29/09 | $ 0.00 |
| 19 | Mainline Survey 3 | 2.0 d | 11/2/09 | 11/3/09 | $ 0.00 |
| 20 | Develop String Lining algorithm | 80.0 d | 4/27/09 | 8/14/09 | $ 0.00 |
| 21 | Process data with SL model | 5.0 d | 11/26/09 | 12/2/09 | $ 0.00 |
| 22 | Statistical Analysis | 15.0 d | 12/7/09 | 12/25/09 | $ 0.00 |
| 23 | **Experiment 3** | **58.0 d** | **11/26/09** | **2/15/10** | **$ 0.00** |
| 24 | Develop algorithms | 30.0 d | 11/26/09 | 1/6/10 | $ 0.00 |
| 25 | Apply model to data | 15.0 d | 11/26/09 | 12/16/09 | $ 0.00 |
| 26 | Statistical analysis | 15.0 d | 1/26/10 | 2/15/10 | $ 0.00 |
| 27 | Conclusions | 30.0 d | 2/15/10 | 3/26/10 | $ 0.00 |

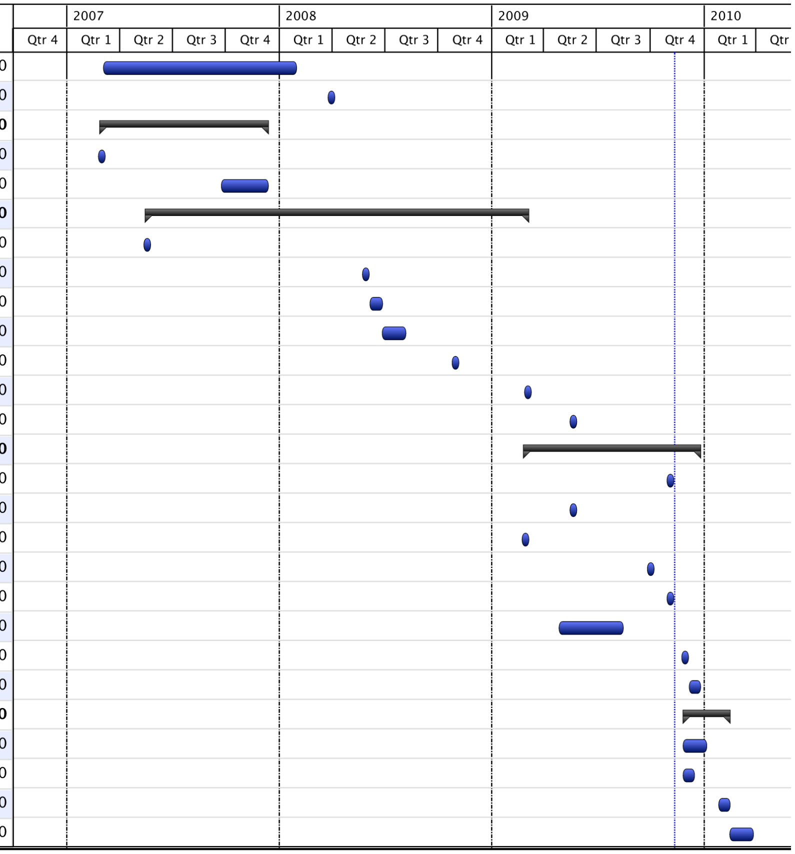


Figure 3.4: Research Timeline

# Bibliography


Leonard Allen, J. Brent Mason, and Jeff Stevens. Rail Borne Track Asset Mapping. In *Proceedings of the AREMA 2006 Annual Conferences*. American Railway Engineering and Maintenance-of-Way Association, June 2006. [vi, 2, 10]

Ralph Glaus. *Kinematic Track Surveying by Means of a Multi-Sensor Platform*. PhD thesis, Swiss Federal Institute Of Technology, 2006. [vi, 11, 12]

USDOT. National Transportation Statistics, Annual Publication, 2008. URL http://www.bts.gov/publications/national_transportation_statistics. [1]

FRA. Differential GPS: An Aid to Positive Train Control. Technical report, Federal Railroad Administration, 1995. URL www.navcen.uscg.gov/dgps/dgeninfo/traincontrol/dgps4a.pdf. [2, 3, 5, 6, 9, 10, 16, 17]

Anthony B. Szwilski, W. Brad Kerchof, John Tomlin, Peter J. Dailey, Zhibin Sheng, and Richard Begley. Rapid Surveying Of A Classification Yard Employing High-Accuracy DGPS (RTK). In *Proceedings of the AREMA 2005 Annual Conferences*. The American Railway Engineering and Maintenance of Way Association, September 25-28 2005. URL http://www.arema.org/eseries/scriptcontent/custom/e_arema/library/2005_Conference_Proceedings/00048.pdf. [3, 14]

Gil Barnes. Head of CSX Hump Yard Engineering. Personal interview, May 16 2007. [3, 14]

USC. United States Code, Title 49, Part 213, Subpart C - Track Geometry, 2009a. URL http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr;sid=a92f8f8c60b5a4769b34869f7324af63;rgn=div5;view=text;node=494.1.1.1.8.3. [3, 15]

FRA. *Track Safety Standards Compliance Manual*. Federal Railroad Administration, Office of Safety Assurance and Compliance Track and Structures Division, Washington, D.C., April 2007. URL http://www.fra.dot.gov/downloads/safety/track_compliance_manual/TCMTOC.PDF. [3, 24]

Ron Bright. Head of CSX Track Inspection. Personal interview, May 19 2009. [3, 15]

Gary Pruitt and Carl Eric Fly. NDGPS Assessment Final Report. Technical Report DTFH61-04-D-00002, United States Department of Transportation, March 2008. URL http://www.navcen.uscg.gov/ndgps/ndgps. [4, 7, 9, 12, 13]

Randolph R. Resor, Michail E. Smith, and Pradee Patel. Positive Train Control (PTC): Calculating Benefits and Cost of a New Railroad Control Technology. *Journal of the Transportation Research Forum*, 44(2):77–98, 2005. [5]

USDOD. Global Positioning System Standard Postitioning Service Performance Standard. Technical report, US Department Of Defense, 2001. URL http://www.navcen.uscg.gov/GPS/geninfo/2001SPSPerformanceStandardFINAL.pdf. [7]

Alfred Leick. *GPS Satellite Surveying*. John Wiley and Sons, Hoboken, NY, 3rd edition, 2004. [7, 21]

NSC Office of Science and Technology Policy. NSTC-6 U.S. Global Positioning System Policy. Presidential Directive, March 1996. URL http://www.hq.nasa.gov/office/codez/new/policy/pddnstc_6.htm. [8]

WAAS Test Team. Wide Area Augmentation System Performance Analysis Report. Quarterly Report 29, FAA/William J. Hughes Technical Center, Atlantic City International Airport, NJ 08405, July 2009. URL http://www.nstb.tc.faa.gov/reports/waaspan29.pdf. [8]

Fugro N.V. OmniSTAR Worldwide DGPS Service, September 2009. URL http://www.fugro.com/survey/satellite/omnistar.asp. [9]

FRA. Analysis of Antennas to Improve Differential Global Positioning System (DGPS) Reception on Locomotives. Research result, Federal Railroad Administration, August 2000. URL http://www.fra.dot.gov/downloads/Research/rr00_03.pdf. [9]

Thomas J. Meyer and Thomas R. Metzger. Locomotive Location System and Method. USPTO patent 7,209,810, April 24, 2007. [9]

UPRR. Union Pacific Railroad Precision Measurement Vehicle Operations, 2008. URL http://www.uprr.com/aboutup/telecom/groups.shtml#2. [11]

ODOT's. Ohio Department of Transportation Aerial Engineering Virtual Rreference System Real Time Kinematic Network, September 2009. URL http://www.dot.state.oh.us/Divisions/ProdMgt/Aerial/Pages/VRSRTK.aspx. [13]

MDOT. Michigan Department Of Transporation CORS, September 2009. URL http://www.mdotcors.org/. [13]

NCGS. North Carolina Geodetic Survey, October 2009. URL http://www.ncgs.state.nc.us/. [13]

KGS. Kentucky Geodetic Survey's Geodetic Control in Kentucky, October 2009. URL http://ngs.ky.gov/index.html. [13]

Eric W. Beshers, James R. Blaze, and Randolph R. Resor. Scheduled Railroading and The Viability of Carload Service. Technical report, Office of Policy, Federal Railroad Administration, March 16 2004. URL http://www.fra.dot.gov/downloads/policy/policy_carload_study_2004.pdf. [14]

Charles W. Moorman. Freight Rail Perspectives on Capacity Issues: Summary of Remarks. In *Workshop to Support FRA Railroad Research and Development*. Transportation Research Board, April 5-6 2006. [14]

North America's Hump Yards. *TRAINS Magazine*, June and July 2002. URL http://www.trains.com/trn/default.aspx?c=a&id=537. [14]

Edwin R. Kraft. Patent 6,418,854: Priority car sorting in railroad classification yards using a continuous multi-stage method. United States Patent Office, July 16, 2002. [14]

Rodney Van Pelt. CSX Roadmaster. Personal interview, November 5, 2009. [15]

USC. United States Code, Title 49 Part 214, Subpart C, Roadway Worker Protection, 2009b. URL http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=e1e054ac618be974227886aec39b5522&rgn=div6&view=text&node=49:4.1.1.1.9.3&idno=49. [20]

USC. United States Code, Title 49, Part 214, Subpart D, On-Track Roadway Maintenance Machines and Hi-Rail Vehicles, 2009c. URL http://ecfr.gpoaccess.gov/cgi/t/

text/text-idx?c=ecfr&sid=e1e054ac618be974227886aec39b5522&rgn=div6&view=text&node=49:4.1.1.1.9.4&idno=49. [21]

Joseph L. Leva, Maarten Uijt de Haag, and Karen Van Syke. Performance of Standalone GPS. In Elliott D. Kaplan, editor, *Understanding GPS Principles and Applications*. Artech House Publishers, Boston, MA, USA, 1996. [21]

The Digital Survey Data (DSDATA) Format, NGS Bluebook. dsdata.txt, March 2009. URL http://www.ngs.noaa.gov/cgi-bin/ds_lookup.prl?Item=DSDATA.TXT. [27]

Thomas F. Hickerson. *Route Location and Design*. McGraw-Hill Book Company, New York, New York, fifth edition, 1964. [30, 31]