IDEA

Innovations Deserving Exploratory Analysis Programs

High-Speed Rail IDEA Program

Prototype HSR Accurate Low-cost GPS Locomotive Location System

Final Report for High-Speed Rail IDEA Project 35

Prepared by:
K. Tysen Mueller
Seagull Technology, Inc.

September 2003

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS MANAGED BY THE TRANSPORTATION RESEARCH BOARD

This investigation was performed as part of the High-Speed Rail IDEA program supports innovative methods and technology in support of the Federal Railroad Administration's (FRA) next-generation high-speed rail technology development program.

The High-Speed Rail IDEA program is one of four IDEA programs managed by TRB. The other IDEA programs are listed below.

- NCHRP Highway IDEA focuses on advances in the design, construction, safety, and maintenance of highway systems, is part of the National Cooperative Highway Research Program.
- Transit IDEA focuses on development and testing of innovative concepts and methods for improving transit practice. The Transit IDEA Program is part of the Transit Cooperative Research Program, a cooperative effort of the Federal Transit Administration (FTA), the Transportation Research Board (TRB) and the Transit Development Corporation, a nonprofit educational and research organization of the American Public Transportation Association. The program is funded by the FTA and is managed by TRB.
- Safety IDEA focuses on innovative approaches to improving motor carrier, railroad, and highway safety. The program is supported by the Federal Motor Carrier Safety Administration and the FRA.

Management of the four IDEA programs is integrated to promote the development and testing of nontraditional and innovative concepts, methods, and technologies for surface transportation.

For information on the IDEA programs, contact the IDEA programs office by telephone (202-334-3310); by fax (202-334-3471); or on the Internet at http://www.trb.org/idea

IDEA Programs
Transportation Research Board
500 Fifth Street, NW
Washington, DC 20001

Prototype HSR Accurate Low-cost GPS Locomotive Location System
IDEA Program Final Report

for the period December 2001 through March 2003
Contract Number: HSR-35 / DTFH61-00-X-00005

Prepared for the IDEA Program
Transportation Research Board
National Research Council

K. Tysen Mueller
Seagull Technology, Inc.

September 2003

ACKNOWLEDGEMENTS

The author wishes to acknowledge the support of Fred Meek, Jeff Young, and the Union Pacific Railroad for providing the facilities, staff, and expertise to perform the field tests. Furthermore, the author wishes to acknowledge the members of the review board of this contract consisting of Chuck Taylor, TRB IDEA Program, Fred Meek and Jeff Young, Union Pacific Railroad, Jeff Baker, GE Transportation Systems, and Terry Tse, Federal Railroad Administration. In addition to the author, the staff at Seagull Technology, Inc. who contributed to the success of this program includes Richard Bortins, Jeff Brawner, Darren Dow, Paul Davis, Sharon Houck, and John Sorensen.

TABLE OF CONTENTS

1 EXECUTIVE SUMMARY

Under this contract, a prototype GPS Locomotive Location System (GLLS) was designed, built, and tested. The design focused on the heading signature of a train as it passes over a siding switch. This signature is exploited to precisely determine whether the locomotive has entered the siding or remains on the mainline track in support of a Positive Train Control (PTC) architecture.

This system is designed to satisfy the stringent parallel track resolution (PTR) specifications of a PTC architecture. These PTR specifications are interpreted to require that the passage of a train through a high speed switch (Type 33, with 1.7-degree frog angle) onto a siding (11.5 ft centerline separation with main track) can be established with a confidence level of 0.99999. These requirements are translated into a locomotive heading accuracy requirement of 0.20 degrees (1 sigma) or a lateral position accuracy of 1.3 feet (0.4 m, 1 sigma).

The prototype HSR GLLS is illustrated in Figure 1.

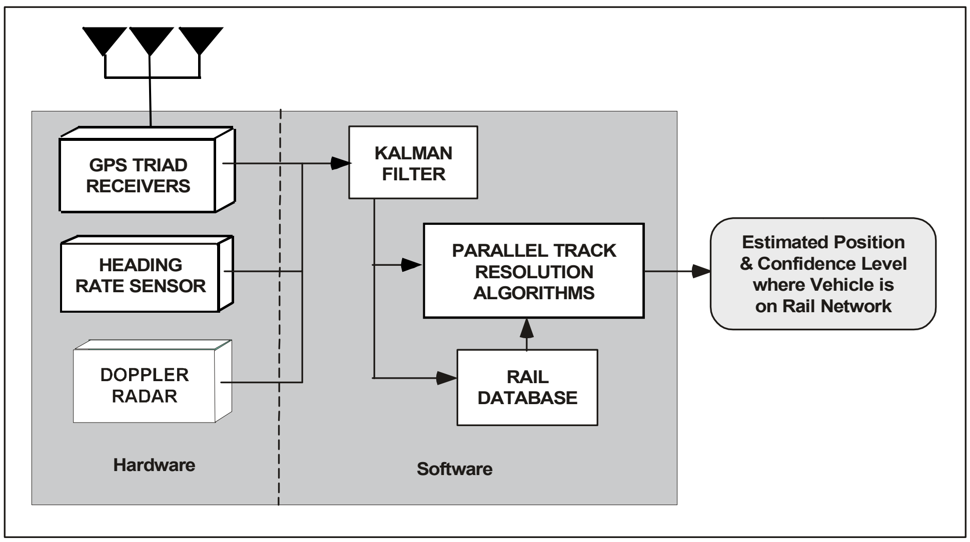

FIGURE 1 HSR GPS Locomotive Location System (GLLS)

Low-cost GPS receivers are used to determine the heading orientation of the locomotive in addition to the position and velocity. A low-cost heading rate sensor and Doppler radar provide dead reckoning heading, speed, and distance, when GPS is unavailable such as in a tunnel. All the sensor measurements are used by the Kalman filter software to dynamically calibrate the two dead reckoning sensors when GPS is available and also smoothes the heading and distance estimates. The current estimated location of the locomotive is then used to access the rail database to determine whether there are any sidings in the vicinity. When a siding is located in the database, the heading through the switch into the siding is compared with the estimated locomotive heading in the Parallel Track Resolution software. Based on this comparison, the train is assigned either to the siding or mainline track depending on the probability that it is on one or the other track.

Since the heading must be measured very precisely while using affordable sensors, the GLLS system focused on a multi-GPS receiver heading measurement system that is based on differential carrier phase measurements. This system is particularly attractive since it can be built with low-cost GPS receivers and is drift free, requiring only a sophisticated heading software algorithm. In addition, the desired accuracy can be controlled with the separation of the GPS antennas. Longer separations provide higher accuracy. The GPS receivers also provide position and velocity.

Under a prior concept feasibility contract [1], the GLLS architecture focused on the use of a low cost heading rate sensor and the locomotive odometer as the preferred dead reckoning sensors. While the use of a low cost, micro-machined rate sensor was incorporated into the current prototype, the use of the odometer presented a number of problems. The odometer problems revolved around the fact that most of the locomotives in use do not provide direction of motion (forward or backward). There are also a wide variety of different odometer models and vintages all of which would have to be accessed by a production GLLS. With feedback from the railroad, it was decided to select a low-cost Doppler radar that had been funded under another IDEA contract to provide advance warning of an approaching train for a highway crossing signal. This sensor also had the advantage in that it provided the direction of motion.

In developing the prototype design, the hardware and software requirements were identified, as summarized in Table 1. This table shows that the PTR heading requirements must be satisfied by the combined system of the GLLS and the rail database, even though the GLLS does not have any control over the database accuracy. In addition, the combined system must satisfy these requirements with/without GPS satellite coverage. The individual error components in Table 1 are combined by root-sum-squaring them to obtain the total GLLS error budget.

TABLE 1 Summary of Heading Accuracy Requirements

Data Sources	Equivalent Heading (1σ)	
	With GPS	**Without GPS**
Distance (for Database Access)	0.03 deg	0.03 deg
Speed (for Odometer Calibration)		0.05 deg
GPS Heading	0.15 deg	
Rate Sensor Noise		0.15 deg
Rail Database	0.11 deg	0.11 deg
TOTAL GLLS:	**0.19 deg**	**0.19 deg**
PTR REQUIREMENT:	**0.20 deg**	**0.20 deg**

In addition to laboratory and vehicle tests, the GLLS prototype was tested in the field. The first field test was performed to determine whether the newer alternating current (AC) locomotives produced a more severe electromagnetic interference (EMI) environment that could interfere with the reception of the GPS satellites. A one-day AC locomotive field test was performed in September 2001 in and north of the Oakland, CA, rail yard of the Union Pacific Railroad. During the tests, the locomotive was stressed by increasing the throttle while the brake was applied to simulate pulling a full load of cars. In addition, the locomotive was accelerated up to 70 mph and the dynamic (speed) brakes were applied, resulting in a large negative load. Under these test conditions, the signal to noise ratio (SNR) of the highest elevation angle GPS satellites remained nearly constant. This confirms that the AC locomotives do not pose any more of an EMI threat to GPS-based sensor systems than the older direct current (DC) locomotives.

A three day field test in and near Portland, OR was performed in late February 2003. The GLLS hardware performed well. The GPS heading algorithm and the heading and path distance Kalman filters operated under these real time conditions, as summarized in Table 2. The PTR algorithm could not be evaluated in real time due to a coordinate system conversion error that scaled the measured GPS latitude and longitude positions incorrectly. When the error was identified after the tests, the PTR algorithm was evaluated with recorded field data.

TABLE 2 Measured and Estimated Heading vs. Rail Database Heading

Parameter	**Accuracy (deg)**		**Comments**
	Mean	Sigma	
Heading with GPS Coverage			Based on heading filter estimation error
• Constant Heading Dynamics	-0.016	0.145	
• Variable Heading Dynamics	0	0.20	
• Required Heading Accuracy:	**0**	**0.15**	
Heading without GPS Coverage			Based on heading filter error covariance matrix
• Variable Heading Dynamics	0	0.20	
• Required Heading Accuracy	**0**	**0.15**	
Mainline Rail Database			Based on difference between filter heading (adjusted for estimation error) and database heading
• Measured Heading Accuracy	-0.01	0.73	
• Required Heading Accuracy	**0**	**0.11**	

In Table 2, the heading accuracy is shown under conditions when full GPS coverage was available and when it was not. In addition, estimates of the rail database accuracy are presented. When GPS coverage was available, the heading was measured while the train moved along a straight stretch of track and separately while it moved along a stretch of track with curves.

When the train is on a straight stretch of track, the mean and standard deviations can be combined to obtain a root-mean-square error (0.15 deg) which satisfies the heading requirement. Note that under the prior concept feasibility study [1], an accuracy of 0.16 deg was obtained for a similar stretch of straight track, however with a shorter antenna baseline.

For the variable stretch of track and GPS coverage, the heading accuracy was not satisfied. Similarly, for the variable stretch of track with no GPS coverage, the heading requirement also was not satisfied. Finally, based on an indirect method to estimate the rail database accuracy from the GLLS field data measurements, the rail database also did not satisfy the accuracy requirement that had been assigned to it in Table 1.

The GPS heading accuracy under variable stretches of track is due to the combined performance of the new GPS heading algorithm used under this contract and the performance of the Kalman filter that requires additional tuning. The current GPS heading algorithm is not as mature as the GPS heading algorithm that was used under the concept feasibility study. However, it has a greater performance potential than the previous software. This arises from the fact that the current algorithm not only uses carrier phase measurements from all visible satellites to compute heading, but can also compute a heading solution with measurements from a single satellite. This feature will provide a more robust and accurate heading solution when most of the GPS satellites are visible as well as when only a few are visible, such as in canyons, under bridges, under trees, or near tunnel entrances.

The rail database error estimate also includes a rail database position access error. This access error is due to the GPS position uncertainty. The GPS position error that was used to derive the rail database access error in Table 1 is 5 ft. It was determined that the actual GPS position error was as much as 80 ft, based on determining the position errors near several switches using a map match approach. Hence, the actual rail database access error might be as much as 0.5 deg rather than the 0.03 deg that was assigned to it in Table 1. If a 0.5 deg rail database access error is removed from the 0.73 deg rail database error in Table 2, the net rail database error is still 0.55 deg.

The rail database was not specifically surveyed for the field tests of this contract. Hence, the survey accuracy was sufficient to meet the needs of the railroad that hosted field test but not the needs of the GLLS prototype tests. Note that any locomotive-based location system will have to perform a tradeoff between onboard sensor errors and rail database errors, as outlined in Table 1. Based on the tentative rail database accuracies suggested by Table 2, the rail network will have to be resurveyed to a higher quality survey for all HSR locomotive location systems. This was done for the Illinois PTC tests, which were completed in 2003, using a commercial survey provider who claims to achieve the accuracy specified in Table 1 [2].

The PTR algorithm was evaluated with field-recorded data for two switches into a siding track. For each switch, two passes into the siding and two passes past the siding were evaluated. The PTR algorithm was able to correctly determine that the train had entered the siding or remained on the mainline track for all eight cases. These results were obtained for a Type 14 switch rather than a high speed Type 33 switch.

In evaluating these PTR results, it was noted that there were along track position errors that shifted the estimated GLLS heading relative to the database siding heading. The effect of these larger errors was that the PTR probability calculations did not always immediately rise to their maximum value near 1.0. Hence, to obtain a more robust PTR solution, map matching was evaluated to determine the position offsets prior to performing the PTR calculations. When this approach was used and the PTR calculations were recomputed the results of Figure 2 were obtained.

This figure shows the heading for two passes into a siding on the upper left-hand side and two passes past the siding on the upper right-hand side. The PTR probability that the train has entered the siding is computed for these for four passes in the bottom two panels. Also shown is the so-called PTR siding decision region. This region corresponds to the interval during which the mainline and siding headings are distinct. In Figure 2, the decision region was limited to the interval where the difference in the mainline and siding heading was at least 1 degree. In this region the PTR algorithm has to assess whether the train has entered the siding and with what level of confidence before assigning the train to the siding. As can be clearly, the correct assignment was made in all four cases.

One of the key features of GLLS is that it will provide the required accuracy at lower cost than other current locomotive location systems. For example, the system that was tested under the Illinois PTC relies on DGPS and expensive fiber optic gyros (FOGs) [3]. If a simple hardware cost comparison is made between the cost of three GLLS GPS receivers plus one low cost rate sensor with the cost of one DGPS receiver plus a single FOG of the competing system, the GLLS hardware costs are a factor of 4 smaller. If the competing system actually uses three FOGs as described in [3], the comparable GLLS hardware costs are a factor of 12 smaller.

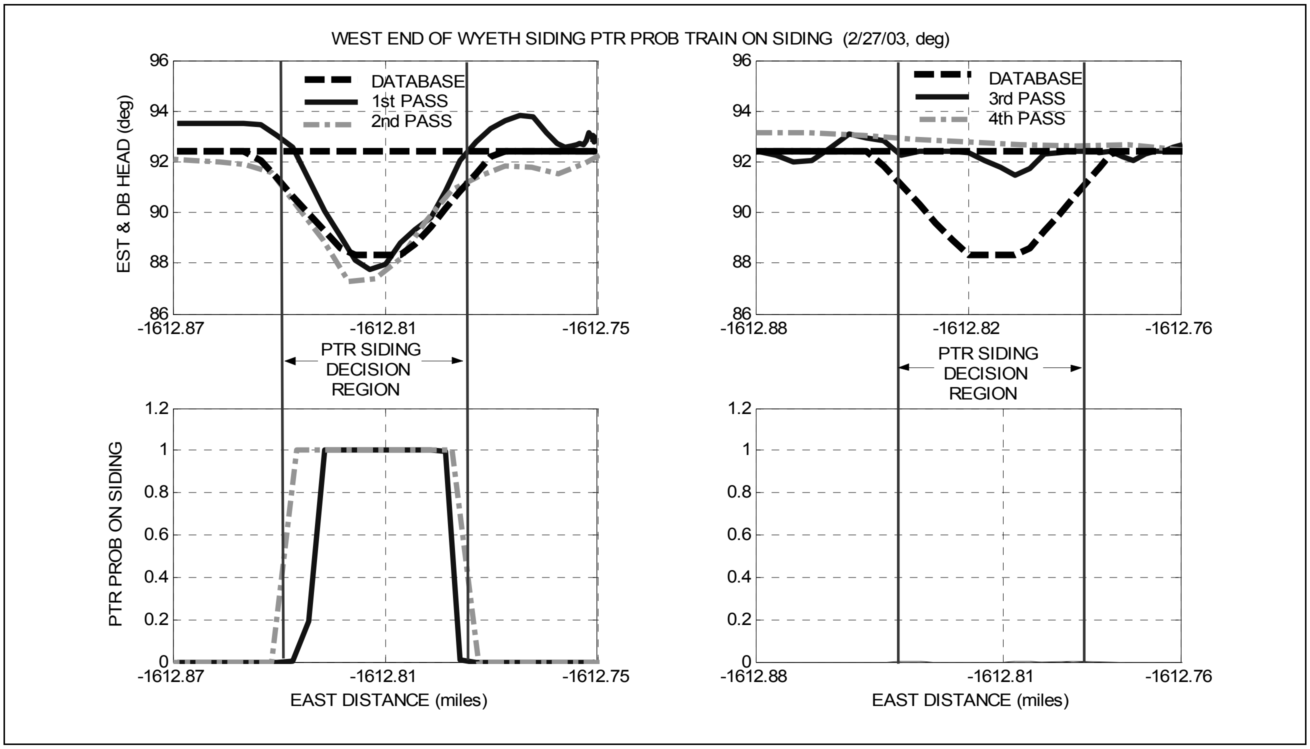

FIGURE 2 East End Wyeth Siding PTR Resolution Results Combined with Map Matching

In summary, the following accomplishments were achieved under this contract:

- Designed, build, integrated, and tested a prototype GLLS
- Incorporated Doppler radar directional speed sensor to replace odometer
- Selected a low cost rate sensor that meets required dead reckoning heading uncertainty over 90 sec period
- Incorporated a new GPS heading algorithm that includes option to determine heading with single satellite
- Developed sophisticated rail database access algorithm that models position and heading of three distinct track segments and switches
- Determined that GPS reception not affected by electromagnetic emissions from newer AC locomotives, based on one day field test with Union Pacific in Oakland, CA
- Performed 3-day field test with prototype GLLS in Portland, OR, and east in the Columbia River gorge with a Union Pacific DC locomotive
- GLLS hardware performed well during the Portland field tests, without any problems
- Field test PTR software performance limited by error in coordinate conversion used by PTR algorithm – PTR evaluated after tests with recorded field data
- Post-processed PTR results limited by large database uncertainty – determined with heading field data measurements
- Developed a map match algorithm and used it to correct along track GPS position errors at transition tracks into siding to improve the rail database accuracy and hence the PTR algorithm performance – DGPS position accuracy not required
- PTR results correctly identified when train had entered siding and when it remained on siding in eight out of eight cases for one siding that was analyzed extensively
- Demonstrated general functional capability of remaining GLLS software in field/with field measured data in lab
- Best achievable heading accuracy has not yet been realized under all dynamic conditions – GPS heading algorithm has not yet reached full maturity

2 IDEA PRODUCT

The objectives of this contract was to develop a prototype High-Speed Rail (HSR) GPS locomotive location system (GLLS) and to establish its feasibility. The prototype uses hardware that is low-cost, highly accurate, and robust. In addition, it exploits GPS heading technology that is drift-free and insensitive to magnetic disturbances.

This system is designed to satisfy the stringent PTR specifications. These PTR specifications are interpreted to require that the passage of a train through a high speed switch (Type 33, with 1.7-degree frog angle) onto a siding (11.5 ft centerline separation with main track) can be established with a confidence level of 0.99999. These requirements are translated into a locomotive heading accuracy requirement of 0.20 degrees (1 sigma) or a lateral position accuracy of 1.3 feet (0.4 m, 1 sigma).

The GLLS provides the sensor system and location algorithms that determine on which of several parallel tracks a locomotive is located. This information will be sent back automatically to the dispatch center using a communications link, under a Positive Train Control (PTC) architecture. The dispatch center then provides the authority to the locomotive to leave the siding when it is safe to return back to the mainline track. This product will also be flexible enough so that it can be used on maintenance-of-way vehicles to determine whether they are safely on a siding track when a train is heading toward them.

While the feasibility of the general GLLS design was demonstrated in a prior contract [1], the feasibility of the prototype GLLS hardware was demonstrated during this contract. The feasibility of the GLLS software was demonstrated under the restricted conditions of a train moving along straight stretches of track with full GPS coverage. For variable stretches of track or during periods without GPS coverage, the prototype software performance did not fully achieve the GLLS performance requirements.

The prototype Parallel Track Resolution (PTR) software was able to establish the location of a locomotive on a mainline or siding track with a high level of confidence while the locomotive passes over a switch connecting the mainline and siding tracks. The PTR software was augmented with a map match algorithm that reduces the rail database GPS along track position errors.

3 CONCEPT AND INNOVATION

The prototype GLLS is designed to satisfy these PTR specifications with GPS location system hardware and PTR software. As illustrated in Figure 1, the unique GLLS design incorporates heading measurements obtained with a low-cost multi-receiver GPS system using antennas mounted on the cab roof of the locomotive. These heading measurements are very accurate, drift-free, and independent of the locomotive speed.

The GPS heading is augmented with measurements from a highly robust, low-cost heading rate sensor. The multi-receiver GPS heading measurements are combined in a Kalman filter to improve the accuracy of the heading and dynamically calibrate the rate sensor bias when sufficient GPS satellites are in view.

GPS position and velocity measurements, available from any of the GPS heading receivers, are used to determine the distance traveled and the location of the locomotive on the rail network. The GPS position and velocity is also used to continuously calibrate the low cost radar velocity measurements. When GPS satellite coverage is temporarily interrupted, the calibrated low-cost sensors are used to determine the location of the locomotive with dead reckoning algorithms. Specifically, the heading rate sensor determines the orientation of the locomotive while the Doppler radar determines the distance traveled.

This location system incorporates sophisticated PTR software. This software determines the position and level of confidence with which the location of the locomotive is known, based on the position and heading. This software also incorporates the estimation error standard deviations of the measurements, as obtained from a Kalman filter. When the location of the locomotive is known with a confidence level of 99.999%, it is safe to allow another train to pass on the mainline.

Current onboard locomotive location systems under development are based on DGPS and inertial sensors coupled with a rail database. The low-cost location systems that rely only on the DGPS position do not provide sufficient position accuracy to establish PTR with a confidence level of 99.999% under all conditions. The high-end location systems appear to satisfy the PTR requirements; however they require an expensive heading gyro such as a fiber optic gyro (FOG). The prototype GLLS will satisfy the PTR requirements with an accurate low-cost modular design and sensors.

One of the key features of GLLS is that it will provide the required accuracy at lower cost than other current locomotive location systems. For example, the system that was tested under the Illinois PTC relies on DGPS and

expensive fiber optic gyros (FOGs) [3]. If a simple hardware cost comparison is made between the cost of three GLLS GPS receivers plus one low cost rate sensor with the cost of one DGPS receiver plus a single FOG of the competing system, the GLLS hardware costs are a factor of 4 smaller. If the competing system actually uses three FOGs as described in [3], the comparable GLLS hardware costs are a factor of 12 smaller.

Other approaches to the onboard PTR designs are to use an extensive network of rail occupancy transponders. Alternately, transponders may be used that allow the locomotive location system to remotely query the direction of a switch. While these individual transponders are much cheaper than an onboard PTR system, they require a huge infrastructure of sensors that must be installed, connected to a wayside communications system, and maintained.

4 INVESTIGATION

4.1 INTRODUCTION

Work under this project was performed in four stages:

- Stage 1: Work Plan, Specifications, and Field Test Plan
- Stage 2: Hardware and Software Development
- Stage 3: Hardware-Software Integration and Lab Tests
- Stage 4: Field Test, Analysis, and Final Report

The contract extended over a 15 month period starting in December 2001 and was completed in March 2003.

4.2 DESIGN REQUIREMENTS

This section summarizes the key GLLS system performance requirements. These system requirements are then are used to determine the sensor or software performance requirements.

4.2.1 Introduction

As stated in [*4*], "*The single most stressing requirement for the location determination system to support PTC [Positive Train Control] system is the ability to determine which of two tracks a given train is occupying with a high degree of assurance (an assurance that must be greater than 0.99999 or (09_5)). The minimum center-to-center spacing of parallel tracks is 11.5 feet. While GPS alone cannot meet the specified continuity of service and accuracy, NDGPS [National Differential GPS] in combination with map matching, inertial navigation systems, accelerometers, and other devices and techniques will provide both the continuity of service and accuracy required to meet the stringent requirements set forth for PTC.*"

The assurance of a navigation system is defined by [4] as the probability that the services will be sufficiently robust to meet the requirements of a user over both time and area. Based on this stated need, the GLLS must be able to determine on which of several parallel tracks a locomotive is located when the tracks are as little as 11.5 feet apart. The location must be established with a confidence level of 99.999%.

4.2.2 Scenarios

The parallel track resolution scenarios consist of parallel tracks that are separated by their minimum distance of 11.5 feet. A high-speed switch (Type 33) connects the mainline track with the siding track. This switch has a frog angle (angle between the outside and inside track at the point where the outside track crosses the inside track) of 1.7 deg [5].

For the dead reckoning requirements, two GPS outage scenarios are selected. The first corresponds to a locomotive passing under a 4-lane highway bridge at 10 mph. This leads to a short-term outage of around 5 seconds. The second dead reckoning scenario corresponds to a locomotive passing through a one-mile tunnel at 40 mph. The speed of 40 mph

is half the current maximum speed limit of 79 mph for most of the US rail traffic (The Northeast corridor Acela high speed train can exceed this speed limit). For this scenario, the GPS satellite coverage is lost for 90 seconds.

Another scenario consists of an extended period of partial masking of the GPS satellites. This might arise when the tracks are next to a hillside, just outside a tunnel, or in a culvert. The impact of this partial coverage is to degrade the GPS performance accuracy due to poor satellite geometry as measured by the horizontal dilution of precision (HDOP). The GLLS prototype addresses this scenario with a new GPS heading algorithm that can determine heading with only a limited number of satellites.

4.2.3 **Assumptions**

The Kalman filter can only calibrate a dead reckoning sensor random bias or scale factor error, but not the sensor noise errors. Hence, the dead reckoning accuracy of this system is limited by the dead reckoning sensor noise errors. When the GPS measurements are available, the impact of the dead reckoning sensor noise errors is mitigated for those sensor errors that can be measured directly or indirectly by the GPS measurements.

4.2.4 **Heading Requirements**

The heading and heading rate of the locomotive provide unique and useful signatures when the locomotive enters a turnout. This information can then be used, together with a rail database, to determine whether the train has entered a siding to permit another train to pass. The GLLS prototype currently only focuses on the heading signature.

The parallel track resolution (PTR) problem is illustrated in Figure 3. If there is uncertainty in the knowledge of the lateral position of a train and the measured position is to the left of the midpoint between the tracks, a parallel track resolution (PTR) algorithm will assign the train to the siding. Alternately, if the measured lateral position of the train is to the right of the midpoint, the PTR algorithm will assign the train to the mainline track.

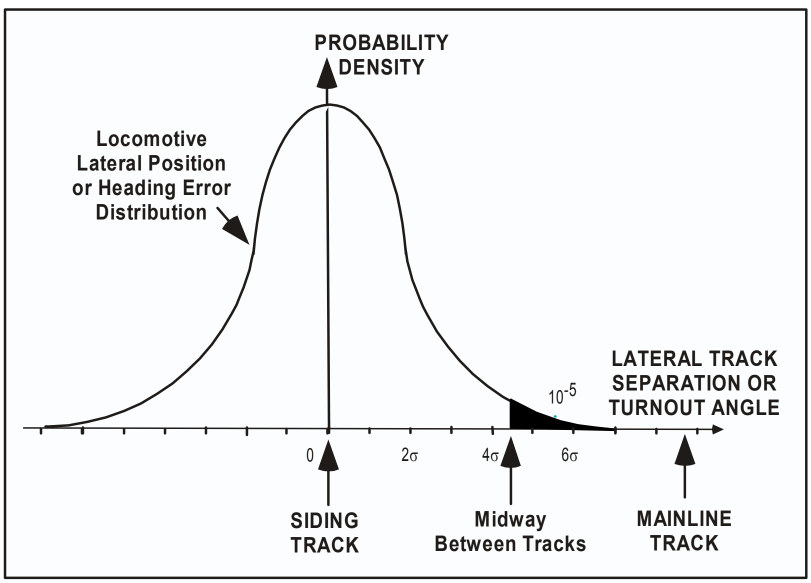

FIGURE 3 Parallel Track Resolution Problem

The errors contributing to the lateral position uncertainty of a train have statistics that may be described by a zero-mean Gaussian distribution. The 0.99999 confidence level requirement translates into a maximum positioning uncertainty of 4.3 standard deviations (4.3σ) that the lateral position of the train is to the right of the midpoint, when the train is actually on the siding. As shown in Table 3, this accuracy requirement translates into a maximum lateral position error of 0.41 meters (1σ).

This same approach is used to derive the heading accuracy requirement by focusing on the change in heading that occurs when a locomotive passes through a high-speed switch (turnout) unto a siding. The key switch-heading angle is the frog angle that is illustrated in Figure 4 and summarized in Table 4.

TABLE 3 PTR Accuracy Requirements with 99.999% Confidence

Measured Parameter	Requirement	Required Accuracy (1 sigma)
Track Separation	11.5 ft (3.5 m)	1.34 ft (0.41 m)
Switch Frog Angle	Type 33 Switch: 1.7 deg	0.20 deg

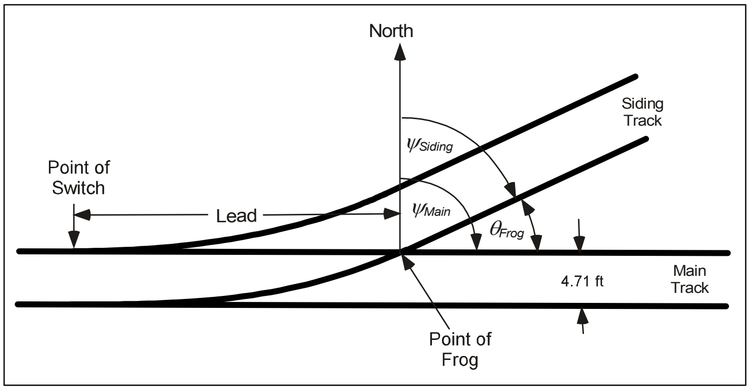

FIGURE 4 Switch Details (Left Switch Shown)

TABLE 4 Switch Parameters [5]

Switch Type	Lead (ft)	Frog Angle (deg)	Max Speed Lateral Switch (mph)	Max Speed Equilateral Switch (mph)
6	47.5	9.5	13	19
8	68.0	7.2	19	27
10	78.8	5.7	20	28
12	96.7	4.8	27	38
14	107.1	4.1	27	38
16	131.3	3.6	36	51
18	141.0	3.2	36	51
20	152.0	2.8	36	52
33	**253***	**1.7**		**120**

* Extrapolated from data within Table 4

The frog angle is the angle made between the outside and inside rail where they cross at the frog. For a high-speed switch such as a Type 33, the frog angle is 1/33 radians (1.7 deg).

In addition to the straight switch (one leg straight and one curved) illustrated in Figure 5, there are curved switches (both legs have curved tracks in same direction) and equilateral switches (curved switch in which one leg curves in one direction while the second in the other direction). For the curved switches the frog angle will still be the same as for the straight switch for the same Type of switch. However, for an equilateral the frog angle is split between the left and the right leg. If the PTR algorithm compares the solution for the left leg against the solution for the right leg of an equilateral, the total frog angle is still used. In other words, curved and equilateral switches do not provide any more stringent accuracy requirements to the GLLS prototype approach.

Hence, if the same approach is used to determine the PTR heading accuracy requirements, as was used to determine the PTR lateral position accuracy requirements, a required heading accuracy of 0.20 deg (1 sigma) is obtained. Since the GLLS uses a rail database to determine the location of the locomotive on a siding or a mainline track, the heading accuracy requirement has to be split between uncertainties in the database track heading and the GLLS locomotive

heading. The GLLS heading accuracy requirement is selected as 0.17 degrees (1σ) with a rail database accuracy of 0.11 degrees (1σ).

4.2.5 **Position Requirements**

While the lateral position requirements for PTR was defined in Table 3, the longitudinal position requirements that are required for the GLLS prototype are less stringent. This follows from the fact that the PTR algorithm will primarily use the heading estimate to determine the level of confidence with for the location of the locomotive. The PTR algorithm will, however, require knowledge of the linear distance traveled, or equivalent geodetic location, to determine in which part of the rail database the locomotive is currently located. Hence, the linear distance position accuracy has only a secondary affect on the PTR confidence level.

The relative position accuracy of a GPS receiver is shown in Figure 5. This figure illustrates the GPS position accuracy relative to the mean position, based on measurements collected for more than 24 hours from a stationary antenna on a roof using a CMC Superstar GPS receiver.

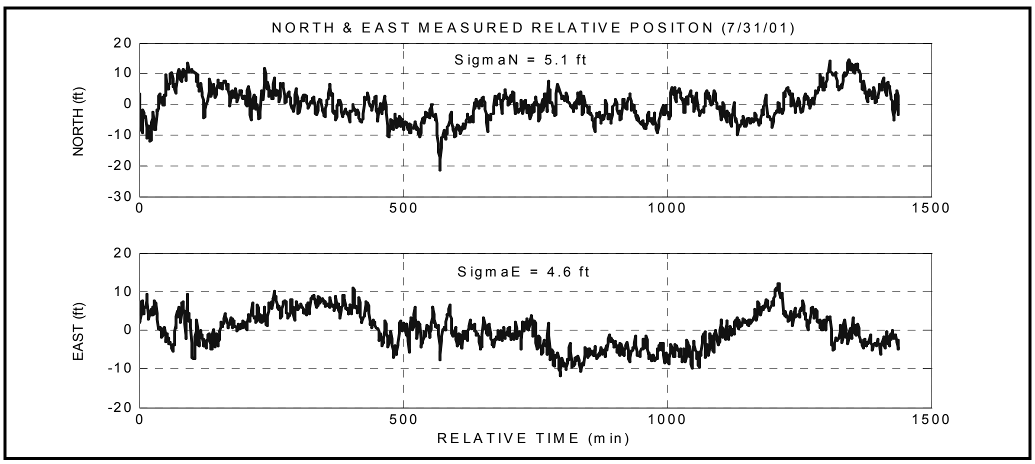

FIGURE 5 GPS Relative Position Errors (CMC Superstar, Rooftop Measurements)

It can be shown that for a Type 33 high-speed switch with an estimated lead of 253 ft and an average change in heading of 1.7^0, a path distance error of 5 ft, translates into a heading error of 0.03^0. Hence, if the absolute along tack position accuracy is 5 ft (1σ), the corresponding heading accuracy is 0.03^0 (1σ).

4.2.6 **Velocity Requirements**

GPS velocity is used primarily to calibrate the Doppler radar mounting pointing angle error that is similar to a scale factor error. Hence the accuracy of this radar calibration is limited by the GPS velocity accuracy. The GPS velocity can also be used as an additional source of heading information. Use of the velocity data for determining heading follows from the fact that the velocity vector must be aligned with the track since the locomotive is on the track.

Figure 6 illustrates the GPS velocity accuracy based on more than 24 hours of rooftop measurements using a CMC Superstar GPS receiver. If the radar is calibrated to within a velocity error of 0.08 ft/sec (1σ), this produces a 7-foot error over a 90-second period. This translates into a 0.05 deg (1σ) heading error for a Type 33 switch.

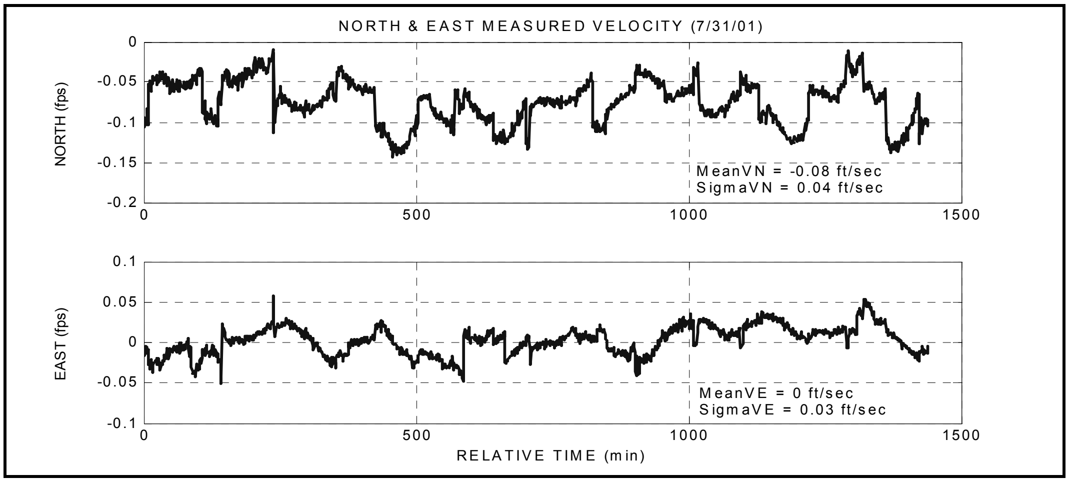

FIGURE 6 GPS Velocity Errors (CMC Superstar, Rooftop Measurements)

4.2.7 Heading Rate Sensor Requirements

Figure 7 illustrates the required heading rate sensor accuracy as a function of the dead reckoning time. For a required heading accuracy of 0.15 deg and a dead reckoning time of 90 seconds, a rate sensor noise accuracy of 0.016 $deg/\sqrt{sec}$ (0.95 $deg/\sqrt{hr}$) is required.

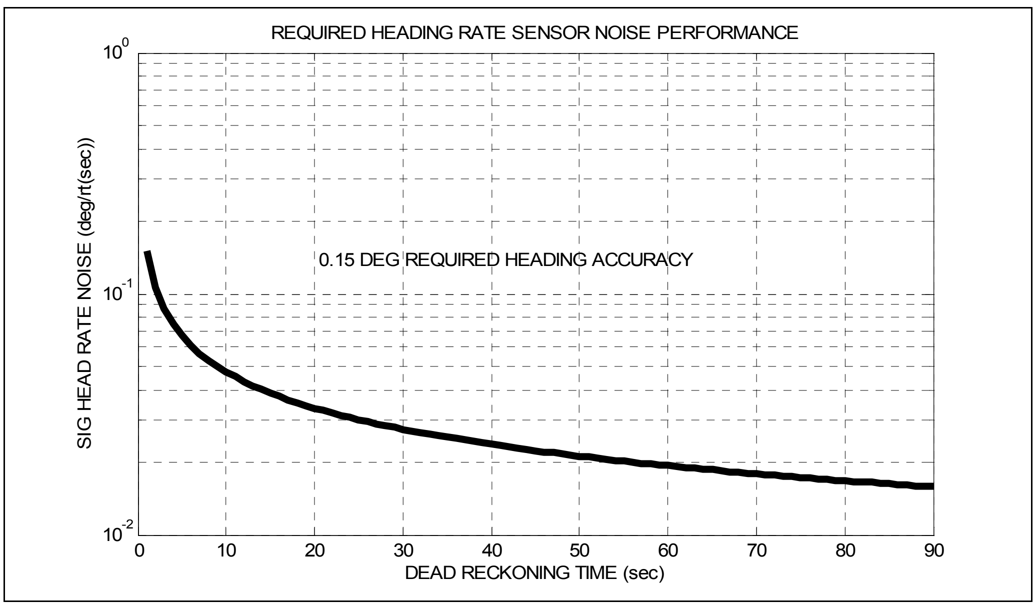

FIGURE 7 Required Heading Rate Sensor Noise Accuracy vs Dead Reckoning Time

4.2.8 Rail Database Accuracy Requirement

The key rail database measurements required for the GLLS are those associated with the switch. One approach is to precisely survey (map) the passage through both legs of the switch using DGPS and other means.

Another approach is to focus on the switch Type to determine the heading through a switch. In this case, the switch heading is determined, not by survey, but by the design and operational specifications for the switch. These specifications are required to assure that the switch does not lead to a derailment. In this application, the rail database would only have to identify the switch Type, as well as the precise location of the start and end of the switch. The PTR software would then determine the precise heading through both legs of the switch using a template or model for that Type switch.

Probably the latter approach will provide a more accurate knowledge of the heading through a switch. Hence, if the point of frog of a Type 33 switch is offset laterally by 6” (0.15 m) relative to the point of switch, then for the 253 ft lead, this results in an absolute heading error of 0.11 deg. A survey accuracy of 0.15 m is quoted by [2], the vendor that provided the rail survey for the stretch of tracks that were used in the Illinois PTC test program that was completed in 2003.

4.2.9 Summary Of Performance Requirements

The results of the above requirements are summarized in Table 5. All the errors are assumed to be zero mean and have standard deviations that are independent of each other. As a result the total heading error can be obtained by root sum squaring the individual heading error sources.

In Table 5, the distance and speed errors are measured along the track and are for a Type 33 switch with an estimated lead of 253 ft. The rail database position error leads to a cross track error that produces a much higher sensitivity to heading errors.

TABLE 5 Summary of Heading Accuracy Requirements (1 Sigma)

	Measured Value	**Equivalent Heading**	
	90 sec Outage	**With GPS**	**Without GPS**
Distance (Rail Database Access)	5 ft	0.03 deg	0.03 deg
Speed (Radar Sensor Calibration)	0.06 ft/sec		0.05 deg
GPS Heading	0.15 deg	0.15 deg	
Rate Sensor Noise	$0.016\ \text{deg}/\sqrt{\text{sec}}$		0.15 deg
Rail Database	0.5 ft	0.11 deg	0.11 deg
TOTAL GLLS:		**0.19 deg**	**0.19 deg**
PTR REQUIREMENT:		**0.20 deg**	**0.20 deg**

.

4.3 HARDWARE DESIGN

Figure 8 illustrates the major hardware components of the prototype GLLS and their interrelationships. The sensor system houses the GPS heading system, the heading rate sensor, microprocessor, and radar interface electronics. The software is hosted on a laptop computer in the right side of this figure. This laptop will also perform the data logging during the field tests.

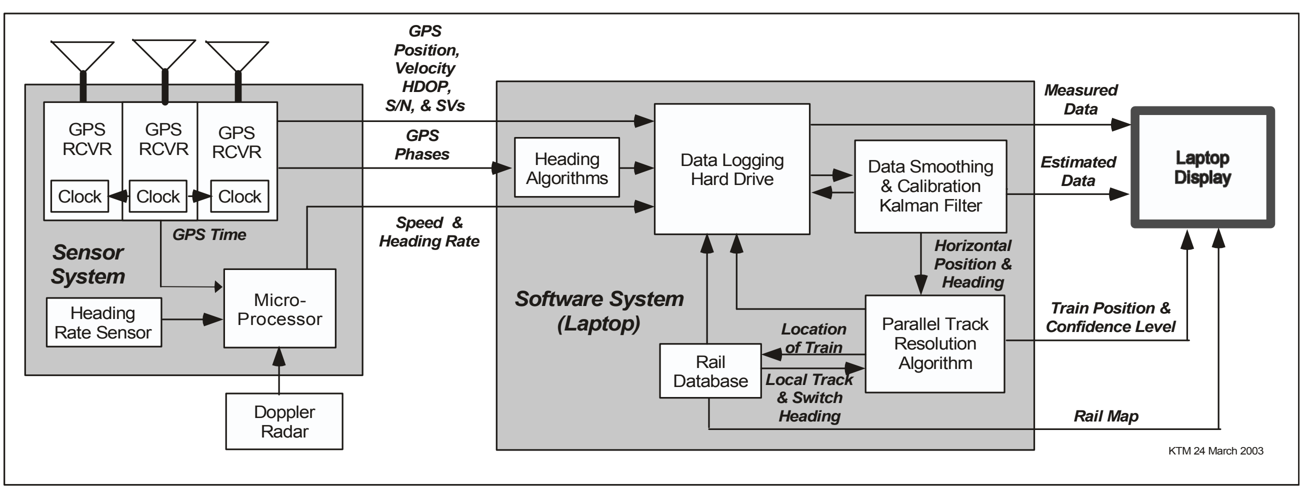

FIGURE 8 Prototype GLLS Hardware Architecture

4.3.1 GPS Receiver Selection

While the position requirements might be satisfied with a GPS receiver, the merits of using a more precise DGPS receiver were examined. The DGPS receivers can obtain their corrections from the US Coast Guard DGPS Marine Beacon network. This network is being expanded from the coastal sites to inland sites under the National DGPS (NDGPS) network program.

The principal difficulty in using the US Coast Guard DGPS corrections is that they are broadcast at 300 kHz. Unfortunately, locomotives generate electromagnetic interference (EMI) at this frequency. As a result, during the Seattle field tests performed under the previous contract, the DGPS corrections could only be received about half of the time on a DC locomotive.

Alternately, the corrections can be obtained from the FAA Wide Area Augmentation System (WAAS). WAAS transmits corrections from geo-synchronous communications satellites that are at stationary (with respect to the earth) locations above the equator. The principal difficulty in using the WAAS corrections is the geo-synchronous equatorial location of the satellites. As a result, there is greater likelihood that the WAAS signals will be masked by local terrain, particularly at the northern latitudes.

In addition to the coverage limitations of both the US Coast Guard DGPS corrections and the WAAS corrections, DGPS receivers will be more expensive than the comparable GPS receivers. Based on all of these factors, the GPS receiver is considered to be sufficient for the GLLS.

4.3.2 GPS Antenna Baseline Requirements

Figure 9 shows how the heading accuracy varies as a function of antenna baseline for a two-antenna GPS heading system. This curve is based on roof top measurements with the GPS attitude system used under the previous feasibility contract.

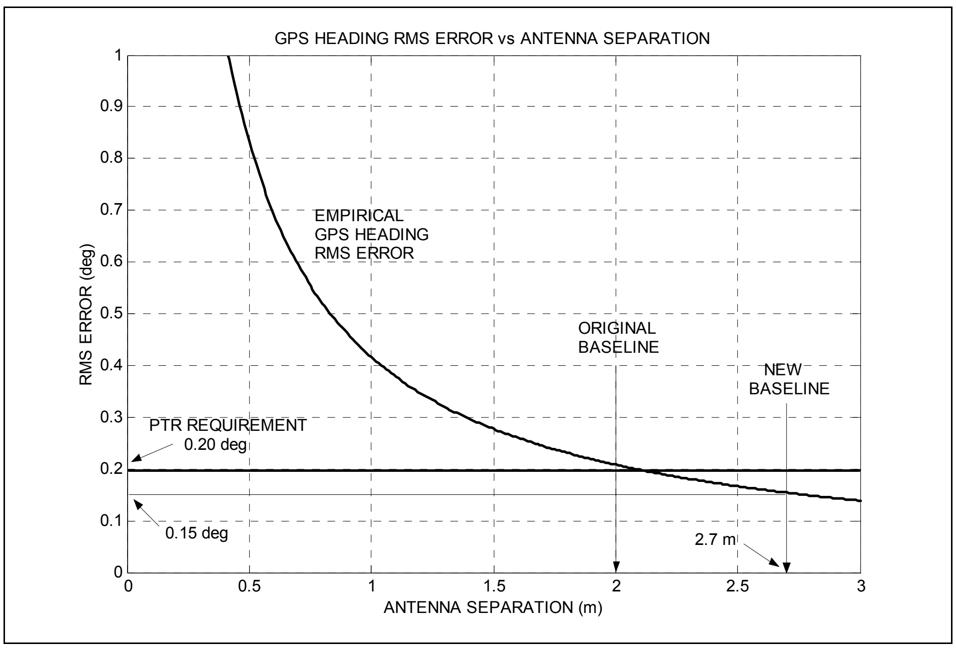

FIGURE 9 GPS Heading Accuracy as a Function of Antenna Baseline

This figure shows that the 0.15 deg heading accuracy requirement assigned to the GLLS can be satisfied with an antenna baseline of approximately 2.7 meters (9 feet). The preferred orientation of the antennas on the locomotive cab roof is horizontal and aligned along the direction of motion. In this orientation, the antennas are insensitive to any roll orientation, whether from the orientation of the rails or the lateral sway of the locomotive. If this axial orientation of the GPS heading antennas is not feasible, any horizontal orientation of the antennas can be used. This option may be the only solution for the Portland field tests on a Union Pacific DC locomotive.

4.3.3 GPS Heading Reference System Recommendation

It is recommended that the CMC Electronics Superstar or Allstar GPS receivers be used for determining the position, velocity, and multi-receiver heading of the locomotive. This is a good, low-cost, phase-capable GPS receiver that will be available, even in small quantities, for the foreseeable future. Seagull personnel have several years' experience in using these receivers in real-time instruments (GMA-2100) and projects (GPR Camcopter and NOAA Ship Motion Measurement System).

A minimum of two GPS receivers with separated antennas is required to determine the GPS heading. If a third GPS receiver is used, with the antenna placed halfway between the first two, this configuration provides additional redundancy in case one of the receivers fails. However, if a failure of any of the two outer antenna receivers occurs, the heading accuracy will be reduced by approximately fifty percent. Alternately (if space permits) an equilateral triangular pattern of the three antennas can be selected, the failure of one receiver can be tolerated, without reducing the heading accuracy obtained with the remaining receivers.

4.3.4 Heading Rate Sensor Recommendation

Table 6 shows generic unit prices and noise performance specifications for 12 angular rate sensors supplied by 4 manufacturers. The cost estimates have been arbitrarily scaled to protect proprietary information. However these generic costs can be used to determine which sensors provide the best cost-performance tradeoff. The table lists the sensors in order of increasing noise (decreasing accuracy). Comparison of the requirement in Table 5 with the noise performance in Table 6 indicates that all but the last 3 sensors will meet this requirement. The most cost-effective sensor of those that meet this requirement is the Silicon Sensing CRS-03. This is the rate sensor that was recommended for the GLLS prototype.

TABLE 6 Angular Rate Sensor Generic Prices and Noise Specifications

Manufacturer	Model	Type*	Generic Unit Prices			Noise
			per 1	per 10	per 100	$deg/\sqrt{sec}$
Fizoptika	VG910F	FOG	312	248	248	0.0010
KVH	Ecore 2000 analog	FOG	724	724	624	0.0014
KVH	Ecore 2000 RS232	FOG	749	749	649	0.0014
Fizoptika	VG910	FOG	222	211	211	0.0020
Fizoptika	VG910C	FOG	212	211	211	0.0020
KVH	Ecore 1000 analog	FOG	474	474	412	0.0056
KVH	Ecore 1000 RS232	FOG	499	499	424	0.0056
BEI Systron Donner	QRS11-00100-100	SSRS	612	534	411	0.0100
Silicon Sensing	**CRS-03**	SSRS	**88**	**62**	**50**	**0.0158**
BEI Systron Donner	QRS14-00100-XXX	SSRS	336	294	228	0.0200
BEI Systron Donner	**HZ-90-100A**	SSRS	81	68	44	0.0250
Silicon Sensing	RRS-01	SSRS	500	300	200	0.0495

* FOG -- Fiber optic gyro; SSRS -- Solid state rate sensor

4.4 SOFTWARE DESIGN

The software design includes the sensor measurement processing, sensor calibration, and the PTR algorithms. In addition, it also includes the field data collection and display software. These elements are illustrated in the software architecture of Figure 10.

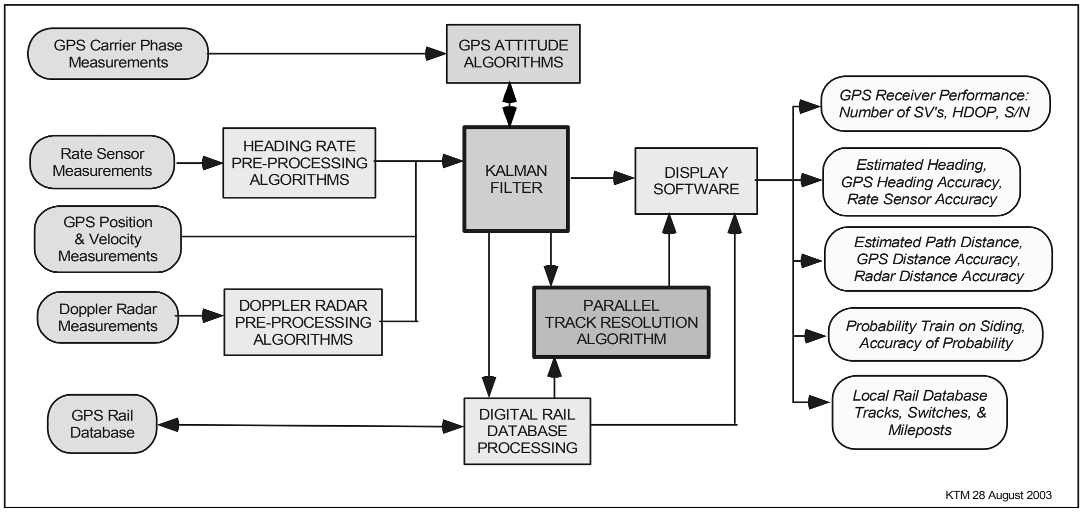

FIGURE 10 Software Architecture

4.4.1 Kalman Filter

The Kalman filter uses a set of redundant measurements available to the GLLS to produce smooth estimates of the heading and distance traveled as well as estimates of the sensor errors. The latter are used to calibrate or correct the raw sensor measurements. The measurements consist of the GPS receiver measurements and the dead reckoning sensor (rate sensor and radar) measurements. The dead reckoning sensor measurements are used to define the state dynamics. Periodic GPS receiver measurements, in turn, are used to provide corrections to these state measurements.

The data flow diagram for the Kalman filter is presented in Figure 11.

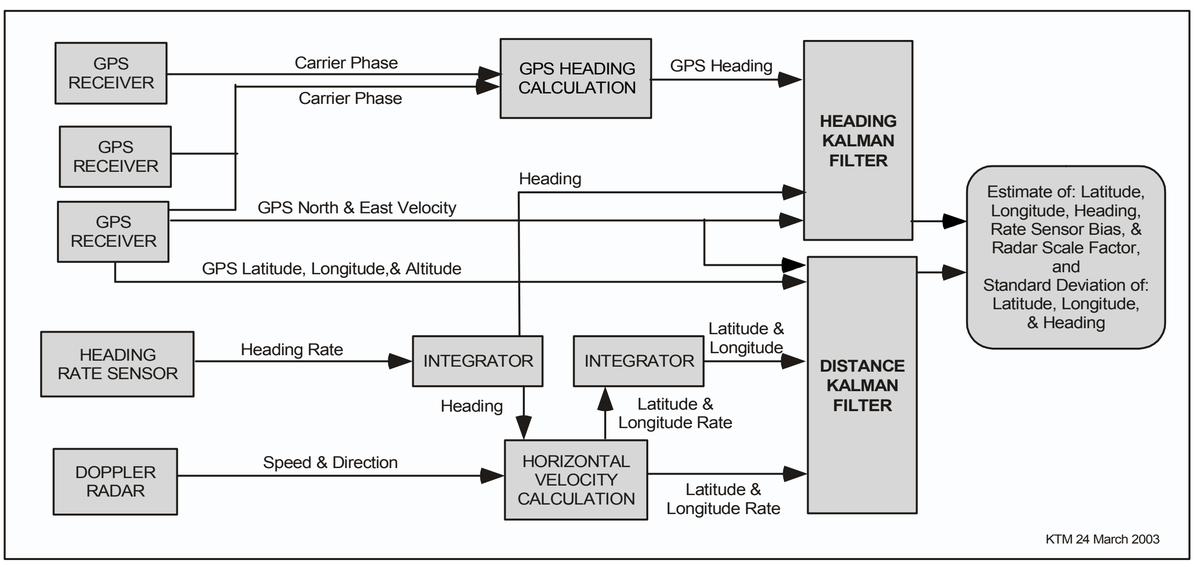

FIGURE 11 Kalman Filter Architecture

4.4.2 Rail Database

Since the GLLS prototype field tests were to take place in the Portland area and east along the Columbia River Gorge, the Union Pacific rail database was obtained for this area. This database consisted of mainline tracks and sidings as illustrated in Figures 12 and 13.

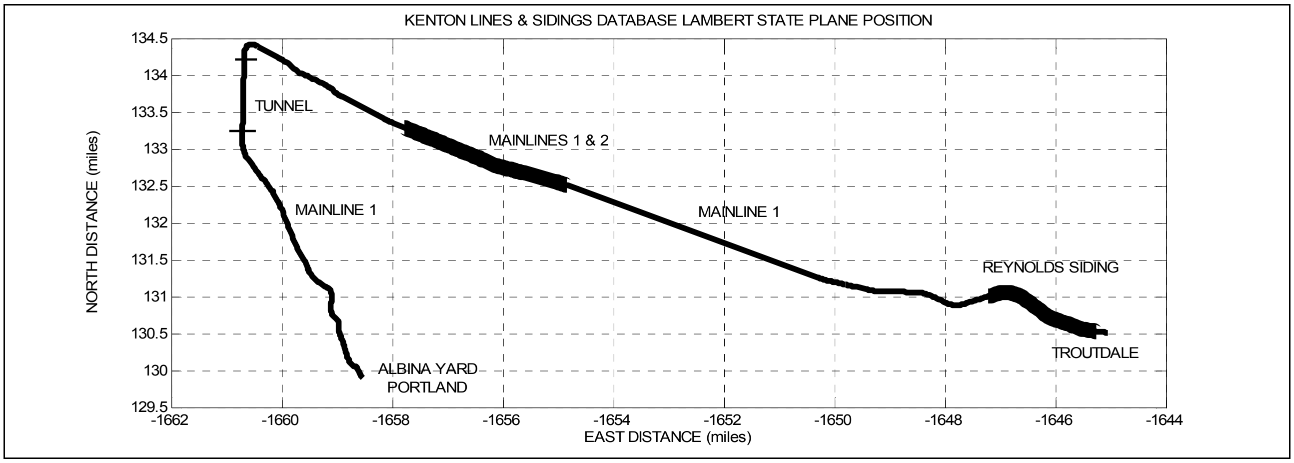

FIGURE 12 Kenton Line on Union Pacific Portland Subdivision

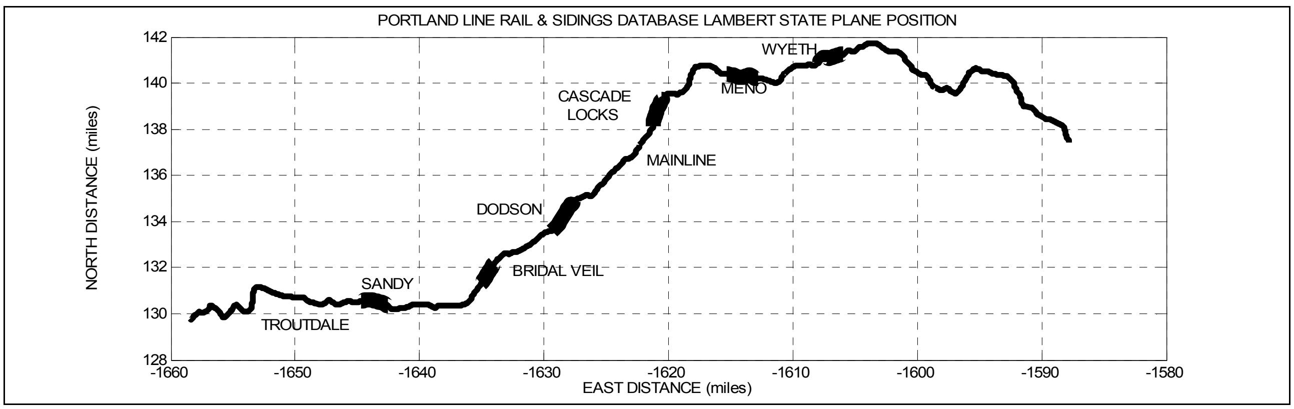

FIGURE 13 Portland Subdivision, East of Kenton Line

4.4.3 **UP Rail Database Algorithms**

Unlike the BNSF rail database, the UP rail database uses a sparse set of geodetic nodes. These nodes are used to indicate the beginning or end of three different types of track segments. The three track segments are the straight, Talbot transition spiral, and the circular track. These three track segments are illustrated in Figure 14.

This figure shows that in moving from a straight stretch of track to a circular curved stretch of track, or vice versa, a transition spiral segment is used. The specific spiral used by the Union Pacific is the Talbot transition spiral. This spiral is characterized by a variable degree of curvature that is dependent on the square of the distance traveled.

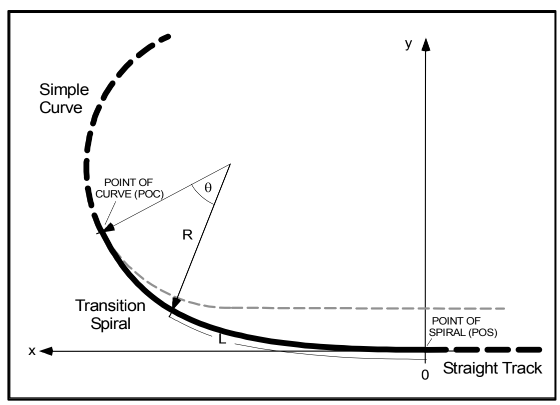

FIGURE 14 Basic Track Segments in Rail Database

When the rail database for the Portland subdivision was obtained from the Union Pacific, it included a number of sidings, in addition to the mainline tracks. While the mainline track description was complete, the siding data was incomplete. As a result a model for the switch transition track into or out of siding had to be developed. This model, which is illustrated in Figure 15, shows that the transition track can be approximated with a circular track segment, a straight track segment, and another circular track segment. This model was used to assure a smooth transition into or out of the siding track.

In addition to the equations for the track segment position history, equations for the azimuth history had to be developed. These equations permitted an analytical azimuth distance history to be computed.

The calculations required to extract and use the database are summarized in the data flow diagram of Figure 16. To convert the GPS receiver and rail database geodetic locations to a State Plane local horizontal coordinate system requires either a Transverse Mercator or Lambert Conformal Map transformation. For the State of Oregon in which the field test was performed, the latter is the required transformation.

The local rail database coordinates are then fed into one of the three track algorithms: circular, spiral, or straight track. The rail database in all cases provides the distance, L, for which this track segment is valid. These algorithms can also compute the track segment tangent heading in Lambert State Plane coordinates.

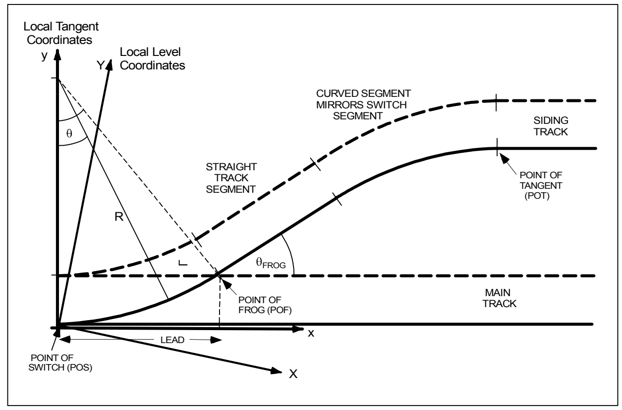

FIGURE 15 Switch Transition Track Model

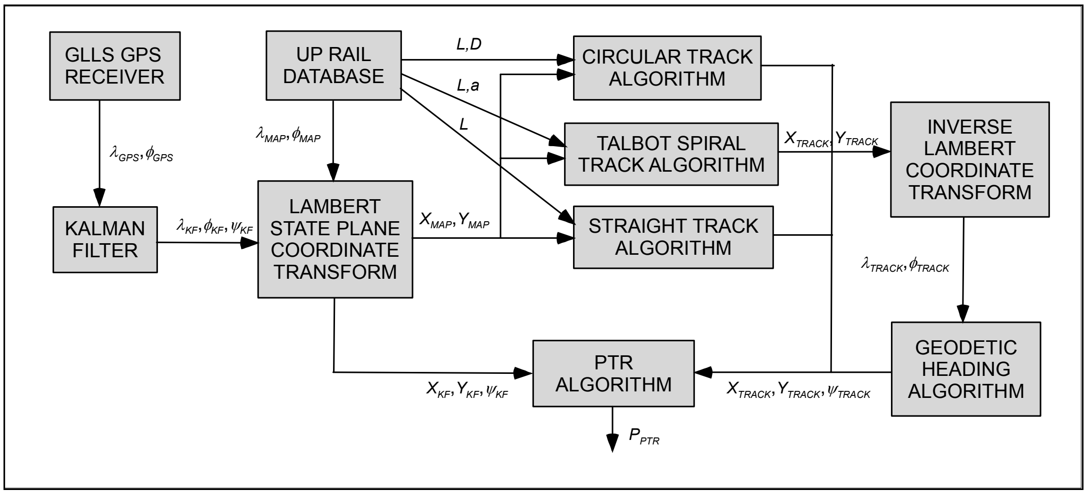

FIGURE 16 UP Rail Database Related Calculations

When the database location and heading is to be compared with the GPS heading, a heading conversion is required. This follows from the fact that the GPS heading is in geodetic (ellipsoidal earth coordinates) while the database heading is in the State Plane coordinates. The option that was selected and illustrated in Figure 16 is to convert the rail database State Plane coordinate positions back into geodetic coordinates. The database geodetic heading is then computed numerically by using consecutive geodetic positions from the database.

In addition for the circular track, the database provides the degree of curve, D. The degree of curve is the number of degrees subtended by a circular arc when traversing 100 ft along the circumference of the circular arc. For the spiral there is an equivalent parameter, a, that is the rate of change of the spiral during the first 100 ft along the spiral.

With these track calculations, any point along the rail database can be found in addition to the points at the beginning or end of these track segments. Not shown above are the rail database input/output algorithms for locating the nearest switch to the current location of the GPS receiver.

To check the accuracy of the Lambert transformation, the beginning and end of a long stretch of track from the UP Portland rail database was obtained and converted to State Plane coordinates. The distance obtained from the UP database and that obtained with the Lambert transformation agreed to within 3 parts per million. This validates the accuracy of the Lambert transformation algorithm.

Figure 17 shows a view of the one of the sidings, the west end of the Sandy Siding. Figure 18 shows the Portland mainline and Wyeth siding track north and east positions that were computed with the database algorithms. Likewise, Figure 19 shows the corresponding geodetic azimuth history for the mainline and Wyeth siding as a function of the east distance. Note the switch signatures at the beginning and end of the siding in Figure 19. The field data collected from the Wyeth siding will be discussed later.

FIGURE 17 West End of Sandy Siding

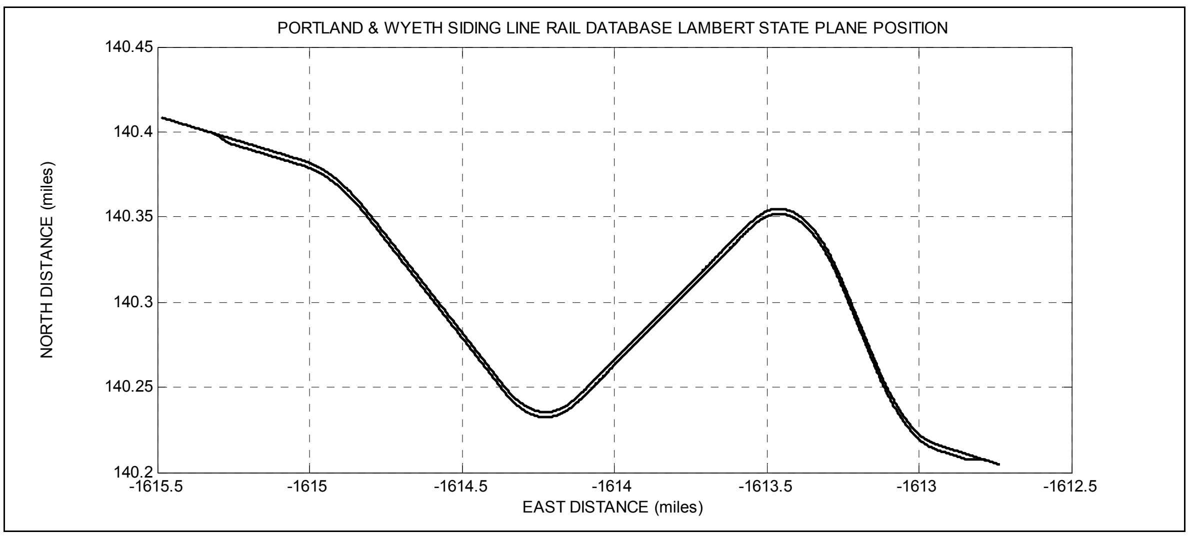

FIGURE 18 Portland Rail Database Positions (Portland Mainline and Wyeth Siding)

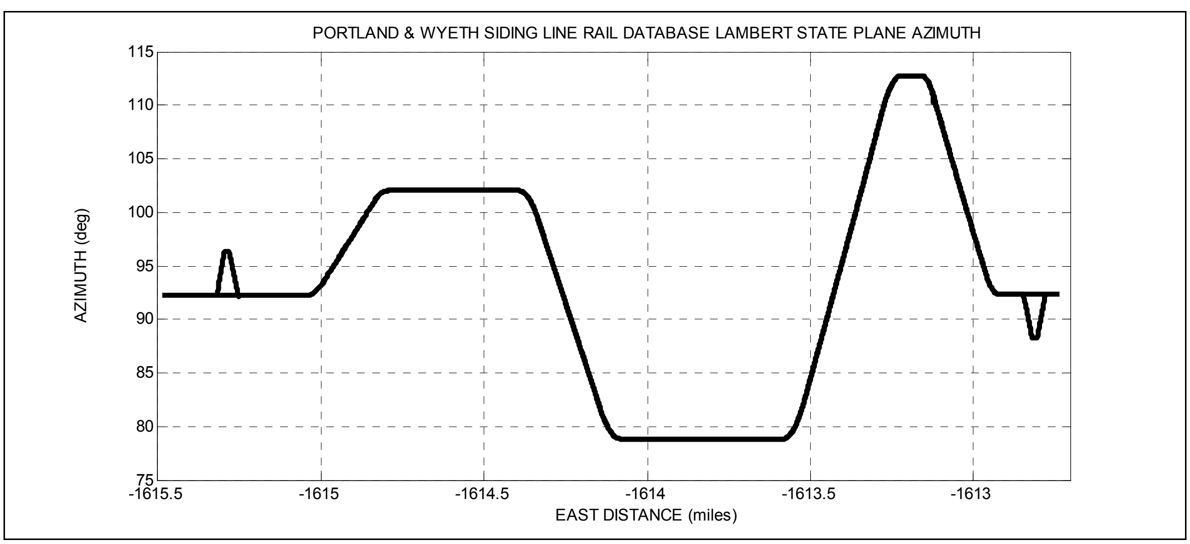

FIGURE 19 Mainline and Wyeth Siding Geodetic Azimuth History

4.4.4 Parallel Track Resolution Software

The mechanization of the PTR algorithm is summarized in Figure 20. This software architecture has been amended to include a position map match algorithm prior to the PTR algorithm. The motivation for this addition is based on the field test results that will be discussed in Section 4.9.5. This figure shows that the path distance and heading Kalman filters provide estimates of the locomotive location and heading.

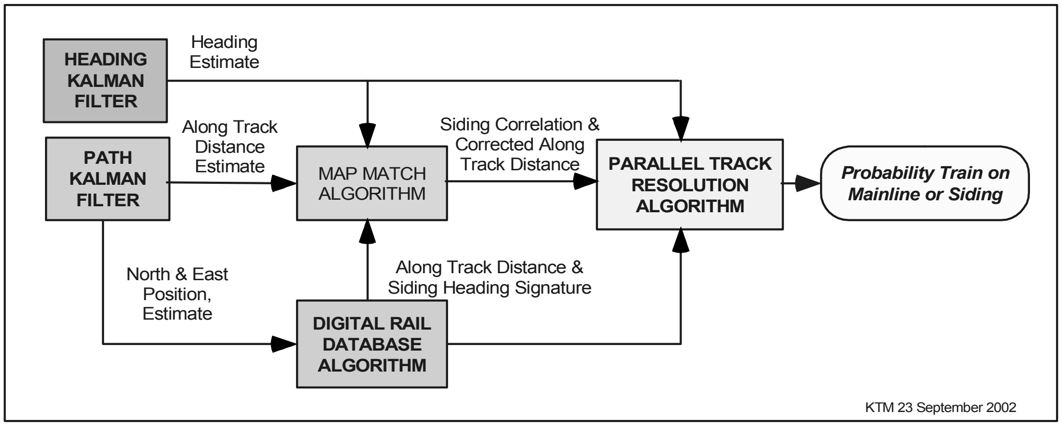

FIGURE 20 Summary of Parallel Track Resolution Algorithm Interface

Since the GPS position was found not to be accurate enough to accurately determine the location of the switch in the database, a map match algorithm was used to determine the along track position offset using the estimated locomotive heading and the siding heading. This offset is used to correct the along track position error of the locomotive. In addition to determining the along track position error of the locomotive, the map match algorithm also determines the correlation between the database siding signature and the locomotive signature. This correlation is used as a preliminary screen to determine whether the locomotive has entered the siding.

To isolate the actual track on which the locomotive is located, the locomotive estimated heading is compared to the mainline and siding track headings from the rail database as the locomotive moves over a switch. Then by incorporating the uncertainty in the Kalman filter estimates, the most likely track location (whether mainline or siding) is established by the PTR algorithm.

4.4.5 Data Logging

All data logging will be performed on the laptop computer. Logged data will be used for post-test analysis of the GLLS. Data logging will be enabled or disabled via the user interface. There are three categories of logged data:

- Raw measurements,
- Processed data, and
- User selected events.

All of the raw measurements that are produced by the GPS heading system and provided to the laptop running the PTR software shall be logged. During the field tests performed under the previous contract, a field-test engineer had to keep a written log of events (e.g.: time that milepost N was passed). To automate field event data logging, the user-entered time-stamped events shall be logged. The user can elect to record one of the pre-specified events and the system shall log the type of event and the current GPS time.

The user interface will allow the human operator to:

- Configure the system;
- Enable or disable data logging;
- Monitor the system health;
- Record user selected events; and
- Graphically monitor the current track location of the train and the results of the PTR algorithms.

4.5 LOCOMOTIVE SPEED AND DIRECTION MEASUREMENT

The Seagull GLLS prototype requires a sensor that can operate at a speed up to 80 mph and determine the direction of motion independent of the GPS receiver. This provides the capability of determining position during periods of intermittent GPS signal reception such as in tunnels, underpasses and heavy foliage.

In the Stage 2 report, it was agreed that the Union Pacific would mount a second axle alternator and its associated power supplies onto the locomotive that Seagull will use during the Portland Subdivision field tests. This was considered the best solution to get an odometer for the field test that provides an output consisting of distance of travel as well as direction.

Upon additional research, the Union Pacific recommended that Seagull procure a speed and direction sensor that could operate on any locomotive with minimal installation effort. They also suggested that this is a key requirement for the GLLS as a commercial product. This suggestion was also motivated by the fact that most Class 1 railroads in the United States have a locomotive fleet that is probably as diverse as the UP fleet.

To satisfy this speed and direction requirement Seagull explored a variety of alternate dead reckoning speed sensors. It was decided that a Doppler radar speed sensor manufactured by O'Conner Engineering, Inc., shown in Figure 21, was probably the best choice. As a result, one of these sensors was acquired by Seagull to support the Portland field tests. This sensor is a low cost microwave sensor that uses the Doppler Effect to measure the speed and direction of movement over both rough and smooth terrain from 1 to 100 mph with a resolution of 0.05 mph. It provides an RS232 output containing speed and direction data.

This sensor passed preliminary functional tests performed by Seagull in the laboratory and the output data was recorded successfully.

FIGURE 21 O'Conner Radar Speed Sensor

This ground speed sensor must be installed on the locomotive about 2-3 ft above the ground at an angle of approximately 45 deg. A candidate location for this sensor for the field test is on a 2" pipe that fits into one of the air hose ends next to the locomotive coupler, as illustrated with the radar mockup in Figure 22. This location is probably not a viable long-term (product) solution. However, another manufacturer has developed a Doppler radar that fits underneath the locomotive and is currently being used on the German railroad.

4.6 RATE SENSOR LAB TESTS

The candidate rate sensor selected for the GLLS was the Silicon Sensing System CRS-03 sensor. This is a low-cost micro-machined solid state inertial sensor. The decision to use this sensor was made during Stage 1 by comparing the specifications of candidate sensors that would satisfy the minimum dead reckoning requirements. The comparison also focused on the sensor that would meet these requirements at the lowest cost.

After a single CRS-03 sensor was obtained from the manufacturer and tested in the lab, the performance was found to be much less than the manufacturer's specifications. Based on discussions with the manufacturer, a set of anti-aliasing band pass filters were obtained to filter the output noise and improve the performance of this sensor. For reference, the rate sensor that had been used during the previous contract was also available. This is the Systron-Donner Horizon low-cost micro-machined rate sensor. The bias noise errors for both sensors are shown in Figure 23. It can be seen that with the analog filters, the CRS-03 bias noise error is reduced by a factor of four.

FIGURE 22 Proposed Location of Radar

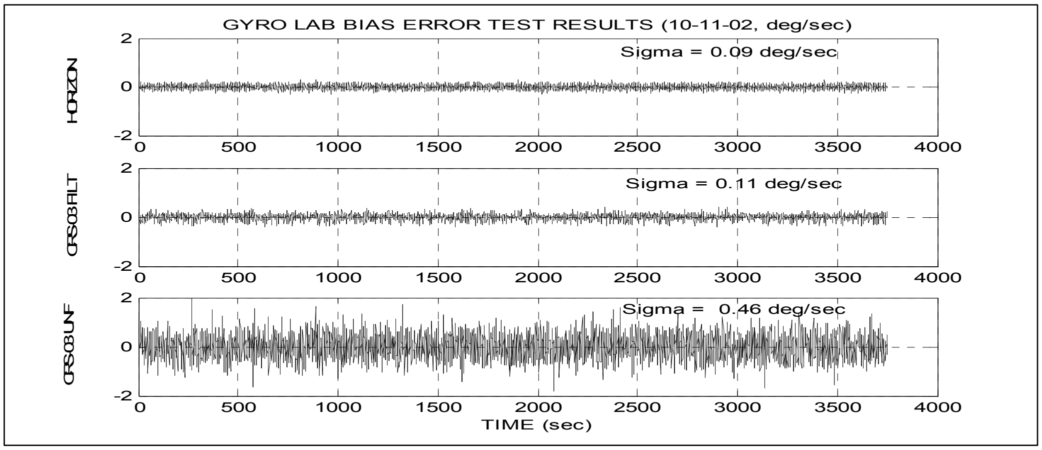

FIGURE 23 Comparison Rate Sensor Bias Error Statistics

To determine the bias noise sigma, the noise error rates of Figure 23 were integrated. The results are summarized in Figure 24 for the CRS-03 and in Figure 25 for Horizon, with both rate sensors using the analog filters. These results show that if a maximum angular error of 0.15 deg is required, the best that can be achieved with the filtered CRS-03 is a dead reckoning time of 45 sec when the sensor is sampled at 100 Hz. The filtered Horizon rate sensor, however, is able to satisfy the 0.15 deg error after 90 seconds with a 100 Hz sampling rate and nearly so with the 50 Hz rate. Hence, the filtered Horizon rate sensor sampled at 50 Hz was selected as the preferred dead reckoning rate sensor. One reason for the improvement in the accuracy of both sensors with the higher sample rate is the fact that more samples of the noise from the sensor are obtained and these are minimized by integrating the noisy rate measurement.

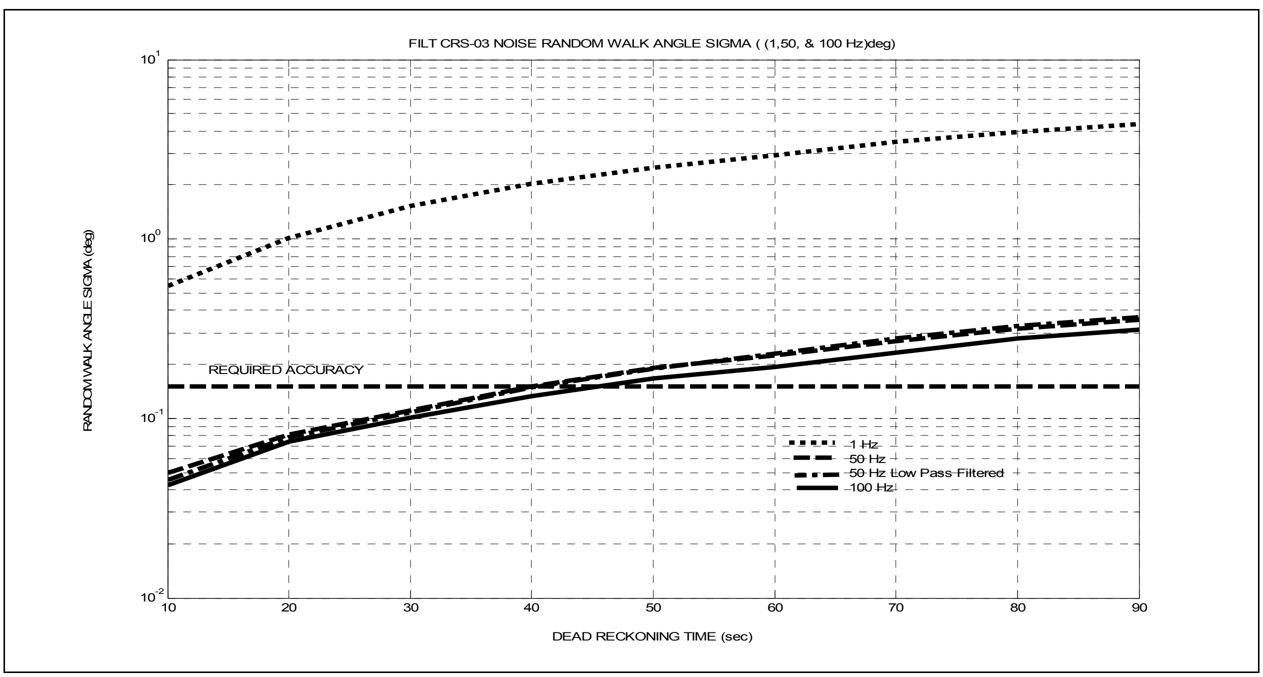

FIGURE 24 Filtered CRS-03 Angular Error vs. Dead Reckoning Time

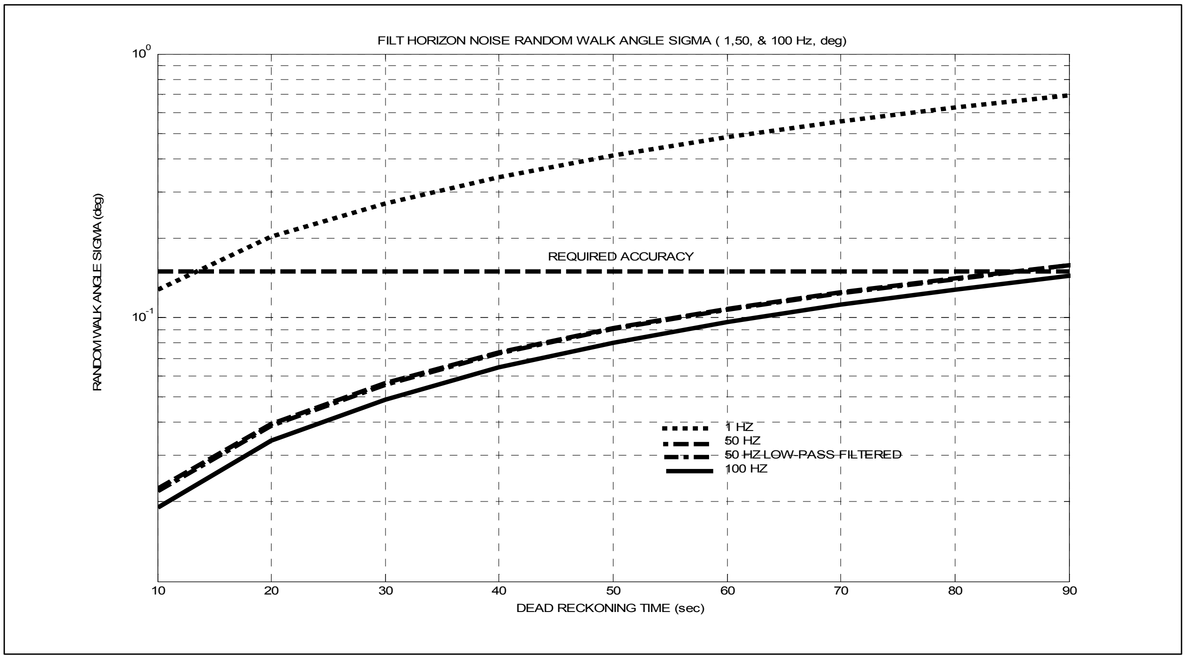

FIGURE 25 Filtered Horizon Angular Error vs. Dead Reckoning Time

4.7 SOFTWARE INTEGRATION

The current Kalman filter architecture was illustrated in Figure 11. This architecture is a change from the integrated position-heading architecture presented in the Stage 1 report. The issues that led to this decision are the following. When all the measurements are combined into a single Kalman filter, the maximum amount of information is available and hence the best accuracy can be obtained. However, the more complex the Kalman filter, the harder it is to tune and the less stable it is in the presence of unexpected disturbances. Conversely, with the dual Kalman filter approach a lower accuracy is achieved; however, the two filters are more stable.

Considerable effort was expended over the first three stages of this contract to tune a single composite 11-state Kalman filter, using field data that was collected under the previous contract. Considerable difficulty was encountered in achieving a single stable Kalman filter. This led to the decision to use two separate filters -- a 3-state heading Kalman filter and a 1-state distance scale factor Kalman filter. It was expected that the difference in accuracy between the two approaches would be overshadowed by the additional stability that is obtained.

Another change that was made was to replace the odometer output with a Doppler radar sensor. The latter provides both speed and direction. Another benefit in switching from the odometer to the Doppler radar sensor is the fact that the principal error source in both sensors is the scale factor error. In the odometer, uncertainties in the scale factor are dependent on the true circumference of the locomotive wheel to which the odometer is attached. For the Doppler radar, the true line of sight angle along which the radar is performing its measurement is unknown. Hence the unknown misalignment error can be treated as an unknown speed scale factor error.

The same Kalman filter algorithm developed for the heading filter is generic, and hence, can be used for any Kalman filter application. The distance filter is a simple single variable (scale factor) filter. The filter was developed in Matlab and then translated into C++.

4.8 OAKLAND GPS RECEIVER FIELD TEST RESULTS

4.8.1 Field Test Description

Seagull performed the AC locomotive field test on 25 September 2002 with the help of the Union Pacific Railroad on a Union Pacific GE C44 AC locomotive (No. 5752). The tests were conducted during the morning and afternoon at the

Union Pacific rail yard in Oakland, California, as well as on a stretch of track north of Oakland past Richmond, California. The purpose of these tests was to determine whether the newer AC locomotives might introduce electromagnetic interference (EMI) to the GPS receivers that are the key sensors used by the GLLS. Figure 26 shows the two-locomotive test train that was used in the test with the AC locomotive, No. 5752 in the lead.

The test instrumentation consisted of a single GPS receiver with antenna, a laptop to record the receiver measurements, and a power converter. The power converter tapped into the locomotive 74 VDC line on the locomotive and was used to power both the GPS receiver and the laptop.

FIGURE 26 25 Two-Engine Test Train (GE C44 AC Locomotive)

To determine how hard the locomotive was working and hence generating potential EMI, the engineer's console was monitored. The engineer's console is shown in Figure 27.

As indicated in the upper right hand side of this figure, both the load in terms of amps generated as well as the effort (force) in terms of 1000 lbs (Klbs) were shown. The former used a light bar display while the latter provided a direct numerical output. The observed relationship between Loads in amps and Effort in Klbs appears to be approximately: 150 amps ~ 16 Klbs. Note that the load scale ranges up to positive loads up to 1,800 Amps down to negative loads of -1,200 Amps. The latter loads are generated when the locomotive brakes.

Since the locomotive would not be pulling a full train, other tests had to be performed to increase the loading on the locomotive Three general approaches were used. The first test consisted of increasing the power exerted by the locomotive while the brake was applied. This could be done while the locomotive was stationary or moving.

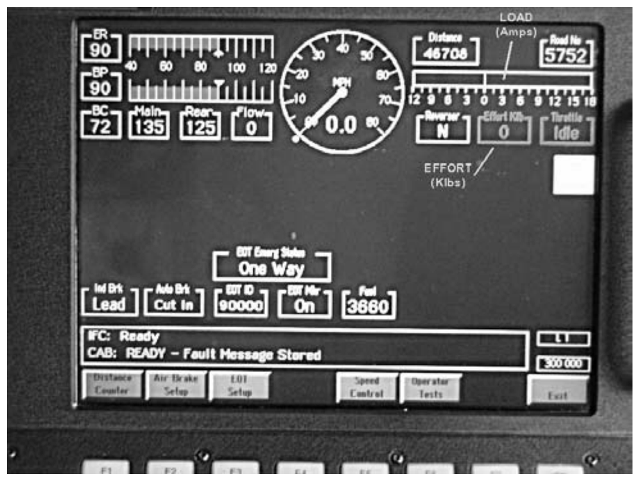

FIGURE 27 Close-up of Digital Display at Engineers Console

The second approach was to accelerate the locomotive up to the speed limit as fast as possible. Finally, the third approach was to dynamically brake the locomotive while it was moving with a high enough speed to permit this option.

To monitor the sensitivity of the GPS receiver to any potential EMI, the signal-to-noise ratio (SNR) was recorded for each satellite. In addition, the loss of satellites was monitored to determine whether this was due to satellite masking or severe EMI.

4.8.2 Field Test Results

As shown in Figure 28, the train was stationary for nearly 1 hour while the engine was idling, except for a brief move forward approximately 75 meters at 2,100 sec. The first panel in Figure 28 shows the SNR values for satellites with PRN 4, 6, 7, and 10. The second panel shows the corresponding satellite line of sight elevation angles. Finally, the last panel shows the speed of the locomotive.

There are brief periods near 300 sec and 1,000-1,200 sec where some of the satellites were lost. During this period, the rooftop antenna was examined or photographed several times which might have briefly blocked out some of the satellites. Near 3,000 secs, the engine load was increased from 0 to 1,100 amps while the brake was applied, as shown in this figure. However, no change in the SNR or loss of satellite lock was observed.

Figure 29 presents the results for the second hour of this test. Again, only the highest four elevation satellites are shown corresponding to PRN 1, 4, 7, and 10. During this period, the work train moved out of the yard to head north

towards Richmond, CA. As can be seen from the locomotive speed history in the bottom panel, there were still a considerable number of periods when the train had to wait for another train to pass or a signal to change.

The frequent, but brief, periods during which satellite coverage was lost occurred when the trains passed under bridges or near a stand of trees along the track. This correlation can be seen in that during this hour the only satellite losses occurred for these high elevation satellites while the train was in motion.

Figure 29 shows some of the key tests that were performed. These consisted of applying the brakes near 5,200 and 5,500 secs. Also, the dynamic brakes were used near 6,500 secs. The initial load test, with loads up to 900 amps, clearly indicates no degradation or loss of satellite lock. The remaining load tests are ambiguous due to the loss of satellite coverage.

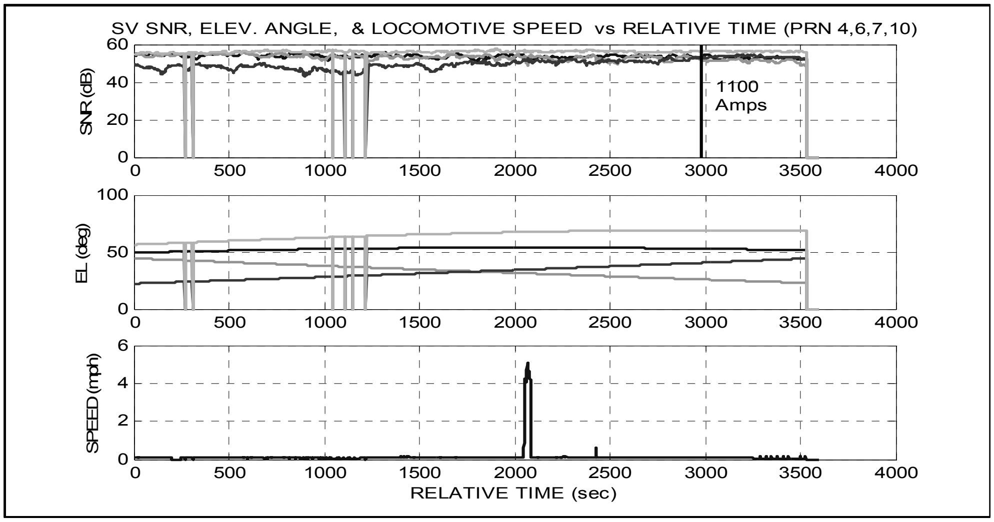

FIGURE 28 Satellites SNR and Elevation Angle, Locomotive Speed vs. Time

The final hour of the tests focused primarily on returning the train back to the Oakland yard. Hence, no significant additional tests were performed during this period. Based on these tests, it is concluded that there does not appear to be any EMI interference to GPS receivers. Since commercial GPS receivers operate at a frequency of 1.575 GHz, this conclusion was anticipated.

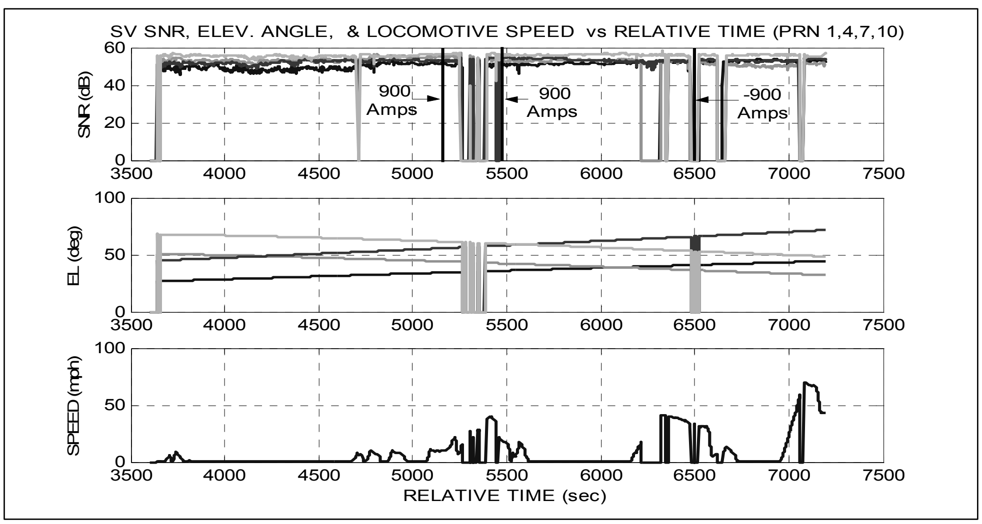

FIGURE 29 Satellite SNR and Elevation Angle, Locomotive Speed vs. Time

4.9 PORTLAND FIELD TEST RESULTS

The Portland field tests were performed on a Union Pacific SD70M locomotive during the last week in February, 2003 over a 3 day period. This test schedule is a compromise solution, given the costs that are involved for the Union Pacific in providing the locomotive and railroad staff in support of these tests. All of these costs were donated to this contract by the Union Pacific.

Installation of the equipment was performed at the Union Pacific Albina Yard, as shown in Figure 30. The first day was used to install the GLLS prototype equipment on the locomotive as well as travel through a 1 mile long tunnel. Also the Kenton mainline tracks and Reynolds siding were measured.

The next two days were mainline tests from Portland east along the Columbia River with cliffs partially masking part of the sky. Within 35 miles east of Portland on the Portland Subdivision Line, there is only a single mainline track with 6 sidings that are contained in the rail database. These sidings provided a convenient scenario to test the PTR algorithm by making several passes around and through these sidings. The numbers of passes were achieved despite mainline traffic that had a higher priority than the test train.

FIGURE 30 Installation of GLLS Equipment onto Locomotive in Albina Yard

4.9.1 **Test Setup**

Installation of the GPS receiver antennas were made using the pattern shown in Figure 31. This was the best pattern that could be selected while taking advantage of the horizontal part of the cab roof. Installation of the Doppler radar is shown in Figure 32 on a pipe that was attached to an air hose opening near the front coupler.

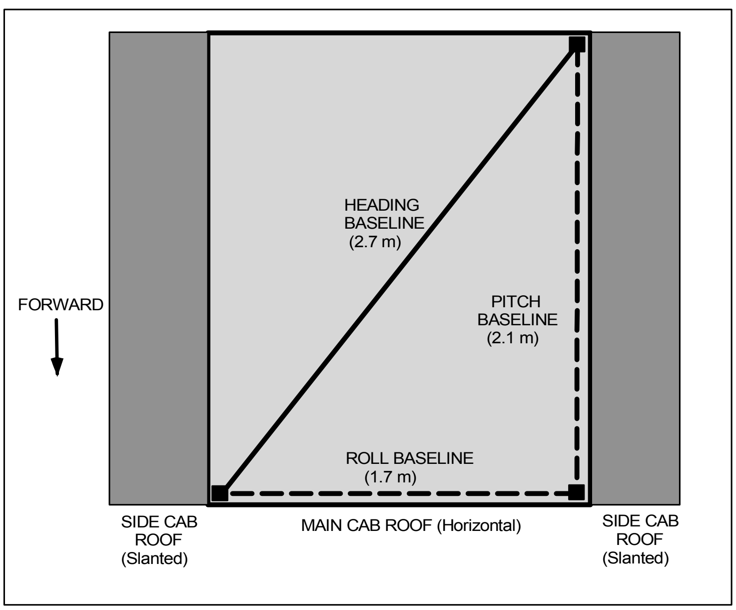

FIGURE 31 GPS Antenna Configuration

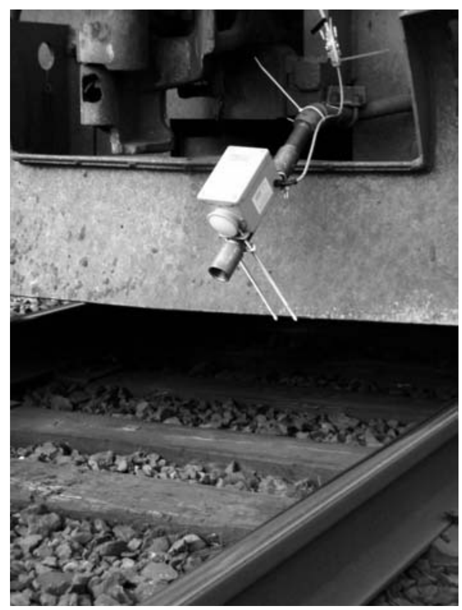

FIGURE 32 Doppler Radar Mounting

4.9.2 **Heading Results**

Heading measurements were made during various phases of the field tests. The measurements included GPS heading and GPS velocity heading when GPS satellite coverage was available and when the train was in motion. The measurements also included direct measurement of the heading rate sensor bias during periods when the locomotive was stationary.

Figure 33 shows the heading accuracy during a 350 second period of full GPS coverage while the locomotive is moving along straight stretch of track. Hence, both GPS and velocity heading measurements are available.

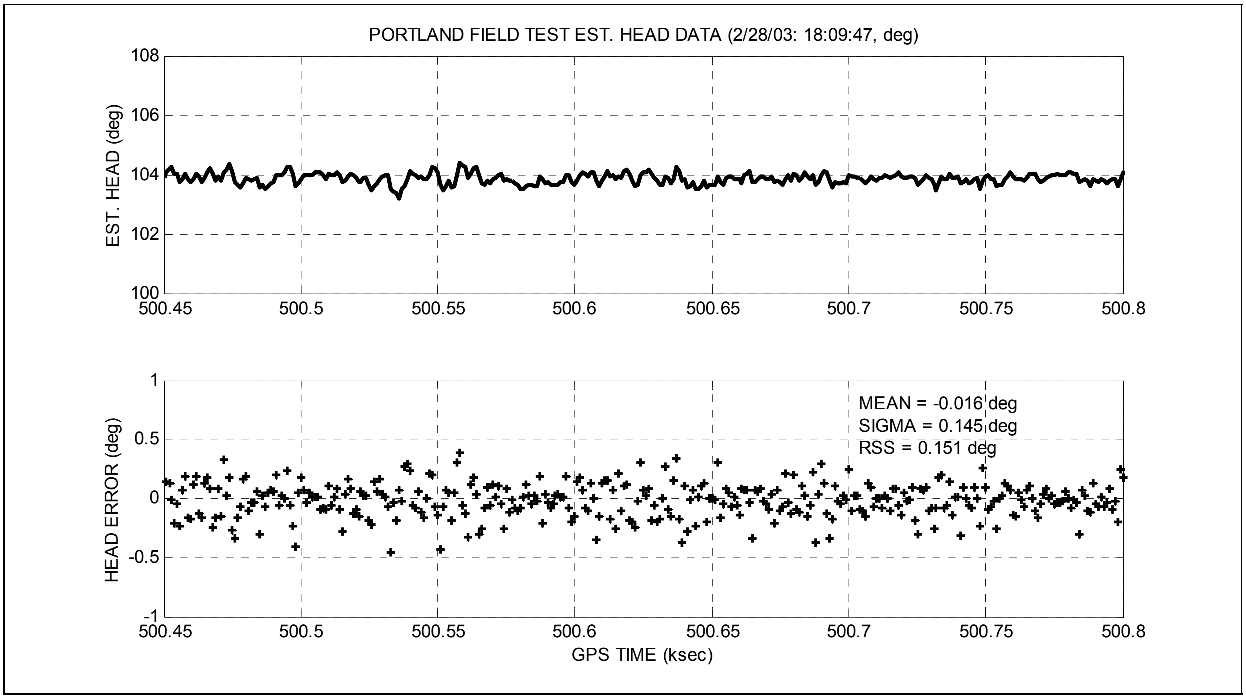

FIGURE 33 Estimated Heading Accuracy while Train Moving on Straight Stretch of Track

The mean heading estimation error is -0.02 deg while the standard deviation is 0.14 deg. When the error mean and standard deviation are combined in a root-sum-square sense, the combined accuracy is 0.15 deg -- the heading accuracy goal.

To determine the database accuracy, the results of Figure 34 were used. The requirements during this 350 sec period, covering approximately 5 miles along the mainline tracks, were that there is continuous satellite coverage, the locomotive is in motion, and that not sidings are traversed. The first requirement assured that the filter heading would include GPS heading. The second requirement assured that multiple points along the rail database would be measured. Finally, the last requirement assured that the possibly lower accuracy of the sidings would not influence the mainline database accuracy results.

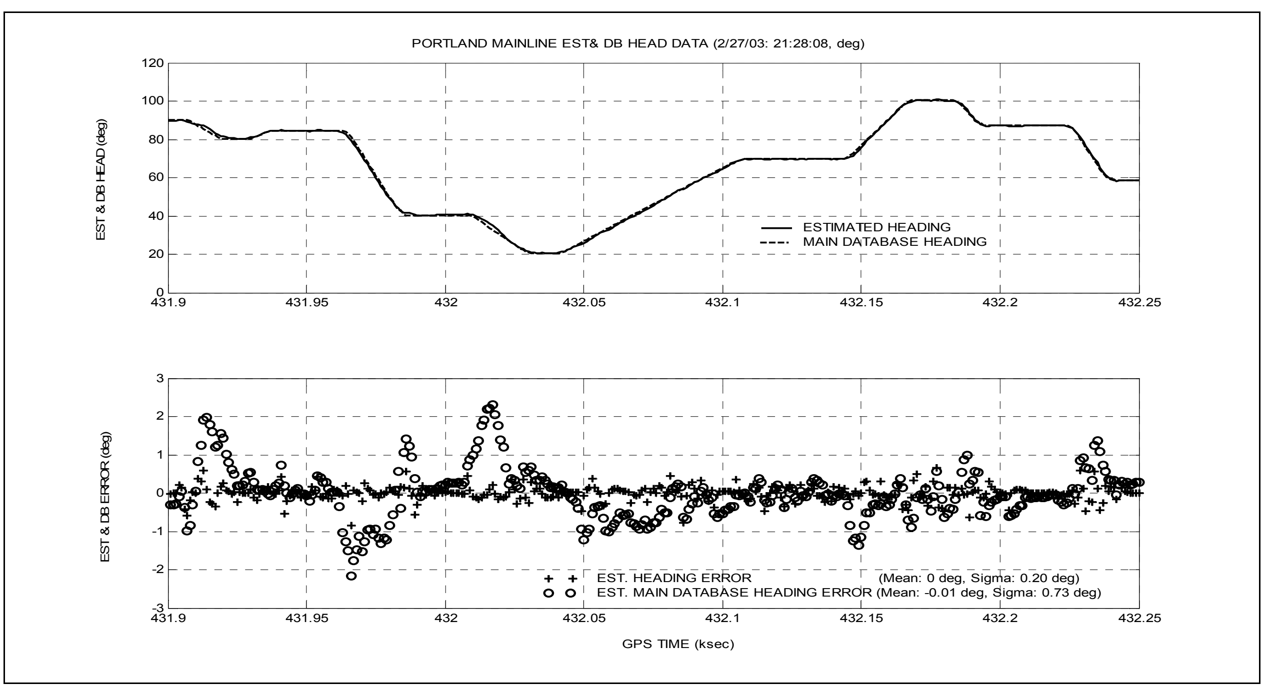

FIGURE 34 GPS Filtered vs. Rail Database Heading while Train Moving along Variable Stretch of Track

The top panel shows both the filter estimated heading superimposed on the mainline rail database heading. The bottom panel shows both the filter estimation and estimated database heading errors. In particular for this variable heading scenario, the filter mean error was 0 deg and the standard deviation was 0.20 deg. The latter error is larger than the required heading standard deviation of 0.15 deg.

The rail database heading mean error was -0.01 deg while the standard deviation was 0.73 deg. This rail database error is much larger than the specified value of 0.11 deg one sigma. This error also includes any rail database access errors. These access errors include the locomotive position errors that are due to the GPS position error uncertainty. As will be illustrated in a later section, this position error appears to be as much as 80 ft rather than the 5 ft one sigma that was part of the specifications. If this position error is 16 times larger, then the corresponding database access heading error will also be 16 times larger, leading to a 0.48 deg access error. When 0.48 deg is removed from the 0.73 deg total rail database error in a root-difference-square sense, a net rail database error of 0.55 deg is left.

To put the database heading accuracy into proper context, the rail database was surveyed to the position accuracy required by the Union Pacific. There was no heading accuracy requirement imposed on the survey. The rail database field survey measurements where fit to the three distinct track segment types: straight, spiral, or circular. Hence, while the track segment was straight and the straight-line fit was made to the measurements, it is possible that the fit was skewed by a fraction of a degree.

4.9.3 **Dead Reckoning Accuracy**

The fields test provided the perfect dead reckoning scenario in the form of a 1.01 mile long tunnel just north of the Albina yards where the field tests originated. Multiple passes were made through this tunnel during the three day field tests. However, several problems were encountered. The original 90 second dead reckoning scenario assumed passage through a one mile long tunnel while traveling at 40 mph. The maximum speed permitted through the Portland tunnel was 25 mph, leading to a minimum dead reckoning period of 144 sec.

Problems were also encountered with the heading filter while entering or exiting the tunnel in that the filter heading became very erratic. As a result, the dead reckoning heading estimates that depend on the last measured heading combined with the output of the integrated calibrated heading rate sensor were thrown off completely. The source of this Kalman filter problem is still under investigation. One possible source is GPS multipath errors while another possible source is the rapidly changing GPS satellite geometry (and hence heading accuracy) as more satellites become masked.

However, during the field tests, intermittent loss of satellite coverage occurred, particular on the Portland subdivision line east of Portland. Figure 35 shows two periods of satellite coverage loss lasting 106 sec and 58 sec.

The top panel shows the GPS heading and GPS velocity heading measurements together with the estimated heading obtained from these measurements. As can be seen, the heading measurements are interrupted during the loss of satellite coverage, shown in the second panel from the top. However, the filter is able to continue providing heading estimates primarily by integrating the calibrated heading rate sensor. Finally, the bottom panel provides two different estimates of the estimated heading accuracy. The first one is the heading estimation error that is available and non-zero when there are heading measurements available. The second one is the heading estimation error standard deviation. This latter error indicator is not as precise as the former. As shown in the bottom two panels, while the filter is able to dead reckon through a period of varying heading, the accuracy is degraded to a standard deviation of 0.20 deg.

The primary source of the poor dead reckoning heading accuracy is due to the lower GPS heading accuracy prior to the dead reckoning periods. This is suggested by the larger scatter in the heading estimation error prior to the two dead reckoning periods.

4.9.4 **Parallel Track Resolution Results**

This section discusses the PTR results that were obtained with the field data measurements. One of the problems that occurred with the rail database access algorithm in the field was that a code error lead to an incorrect scaling of the Lambert state plane positions computed using the measured GPS latitude and longitudes. The presence of an error was noted in the field, since no sidings could be obtained from the database with the GLLS position estimates. However, the solution was not identified till after the tests. After the scaling error was corrected, the field measurements were played back through the field real time PTR software – so far as the software was concerned, the measurements were obtained in real time.

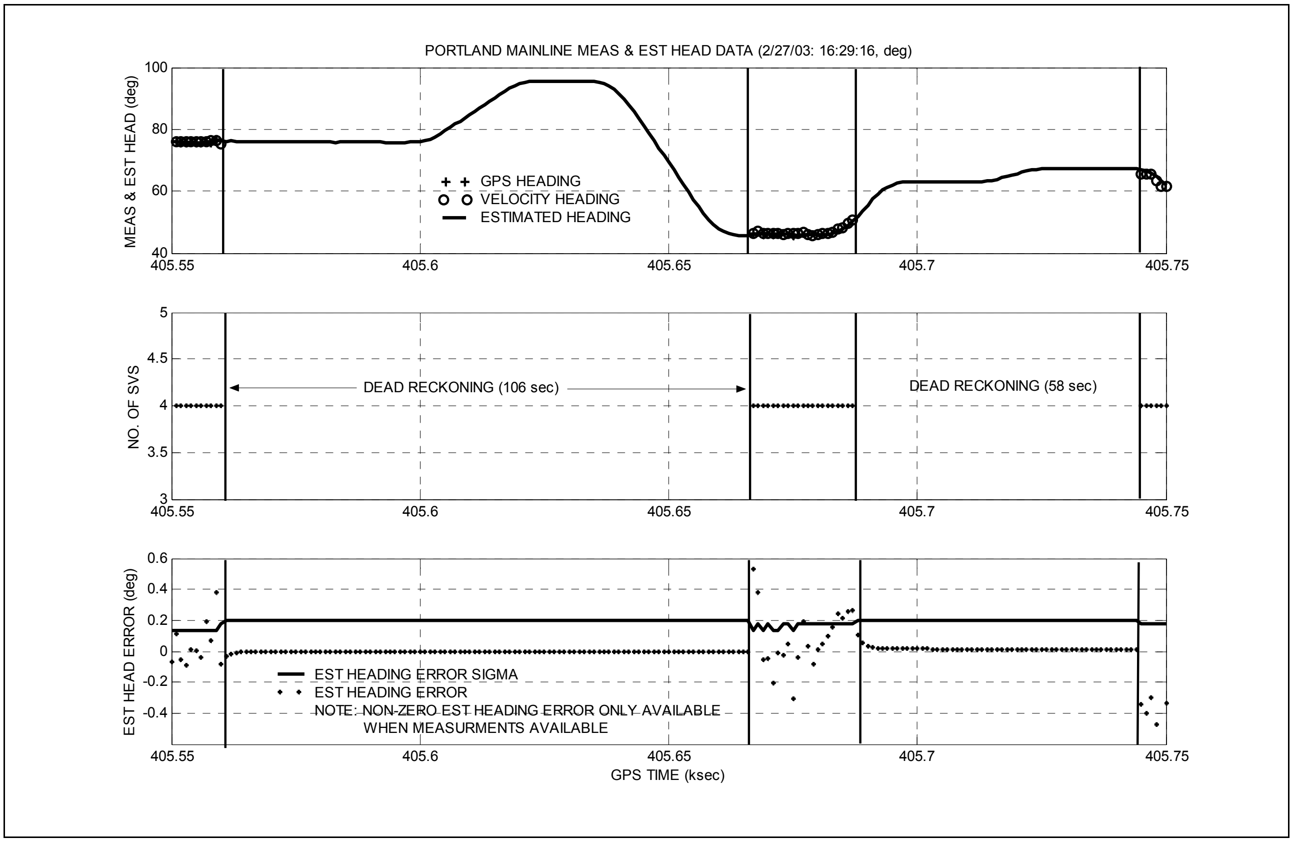

FIGURE 35 Dead Reckoning Heading Results

While a significant number of siding passes were recorded, this section will focus on one particular siding to illustrate the performance that was obtained. Specifically the Wyeth siding that was previously illustrated in Figures 18 and 19 was used. The heading histories of four passes over the switch on the west end of that siding are illustrated in the top two panels of Figure 36 while the four passes over the switch on the east end of the siding are shown in top two panels of Figure 37. The bottom two panels of both figures present the PTR probabilities that the train has entered the siding.

The lateral shift in the estimated heading for the top left panels of Figures 36 and 37 arise from the GPS position errors that produce a the rail database access error. The vertical fluctuations primarily reflect heading estimation uncertainties in addition to database heading errors.

In both figures, two of the passes were into the siding (1^{st} and 2^{nd} Pass) while two of the passes were past the siding (3^{rd} and 4^{th} Pass). Passes 1, 3, and 4 were made in the early morning while the Pass 2 was made in the early afternoon. A likely reason for the large east position differences between Passes 1 and 2 is that the second one occurs during the time of day (2 PM local time) when the ionosphere delay is largest.

When the position specifications were developed and selected as 5 ft one sigma, 24 hours of roof top position measurements were used. To derive these rooftop statistics, the standard deviation was computed relative to the mean position error. If the ionosphere error over a 24 hour was zero mean, then the relative position rooftop measurements would have been sufficient to specify the position accuracy. Unfortunately, the ionosphere delay error is always positive and just becomes negligible during the night. In other words, the ionospheric delay is a slowly varying positive bias error that various only noticeably over a period of an hour or longer.

In both figures is also shown a so-called ‘PTR siding decision region.’ This is the position interval where the mainline and siding heading signatures are distinct around the siding switch. In these figures, the additional requirement was imposed that the difference between the mainline and siding database heading must be at least one degree before the PTR calculations are initiated. This requirement minimizes errors in the PTR probability calculations due to errors in the estimated heading and rail database heading.

The PTR probabilities for Passes 1 and 2 in both Figures 36 and 37 are very distinct and show that that this algorithm clearly determines that the train has entered the siding. Once the PTR algorithm has determined that the train has entered the siding the algorithm saves this information and assigns the train to the siding.

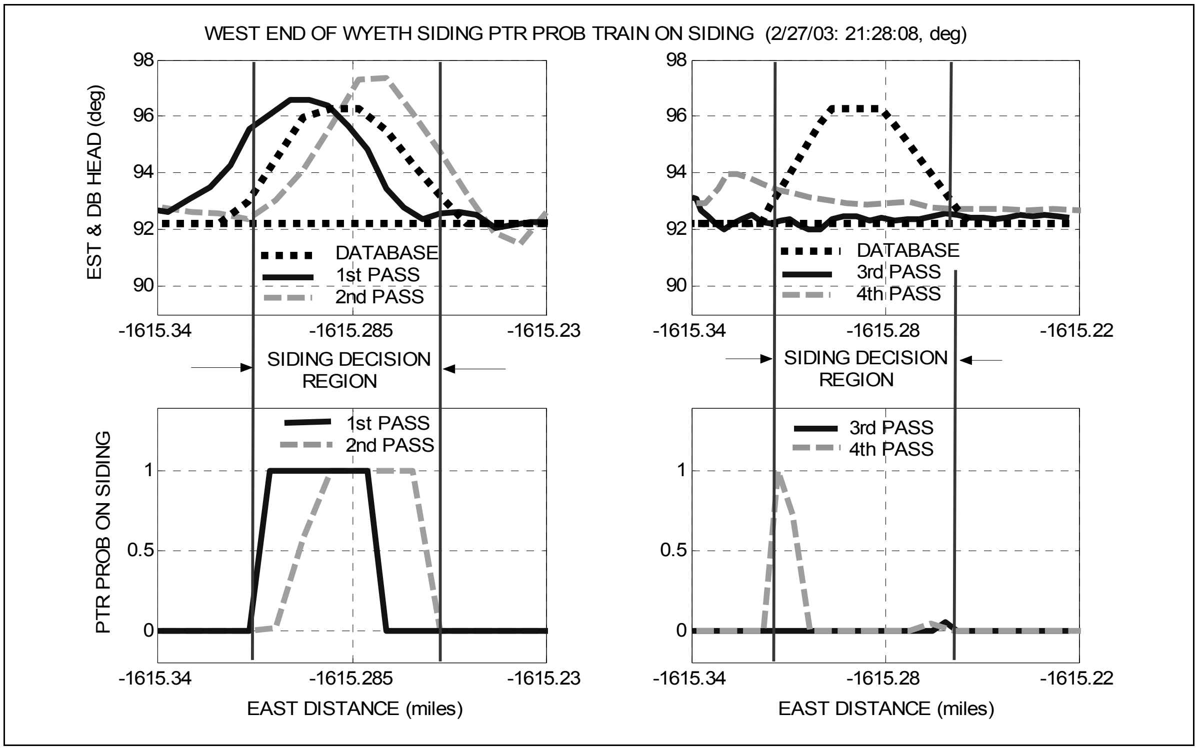

FIGURE 36 Heading and Probability Train has moved into Siding for West End of Wyeth Siding

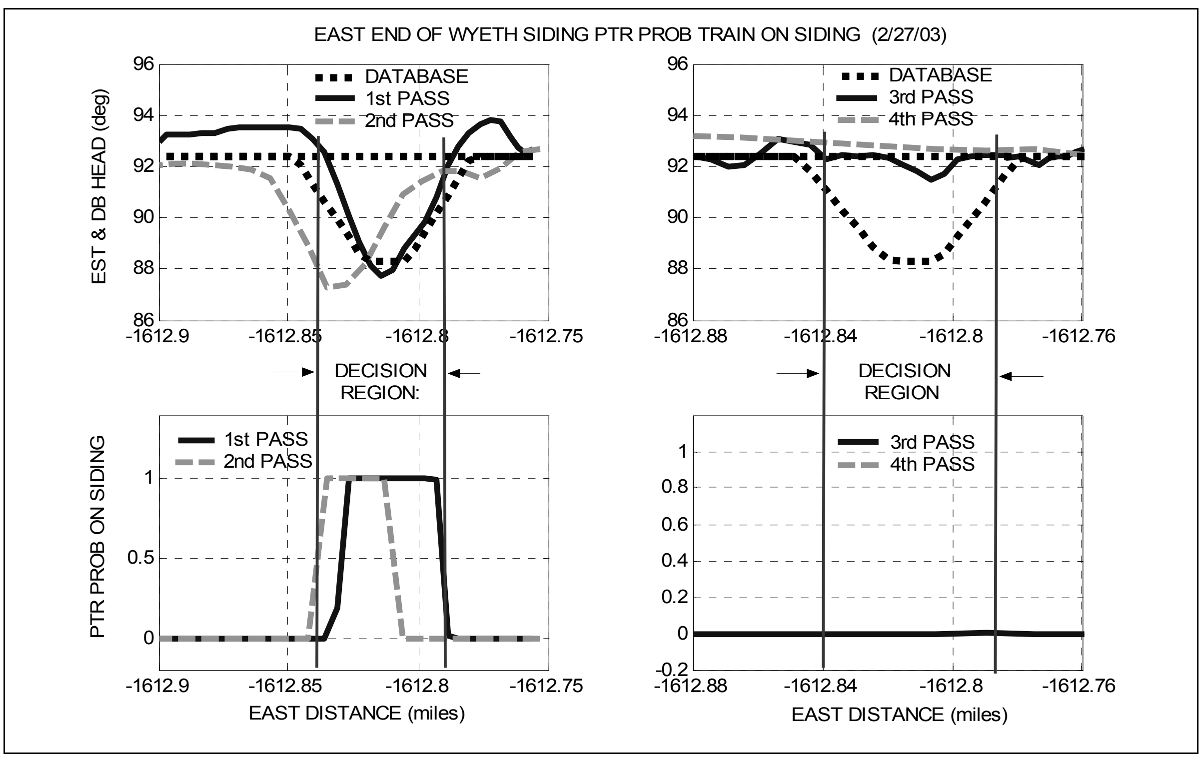

FIGURE 37 Heading and Probability Train has moved into Siding for East End of Wyeth Siding

The siding probabilities for Passes 3 and 4 for Figure 36 show some non-zero probabilities that the train is on the siding, although the train is actually on the mainline track. However for most of the PTR decision interval, the probability is zero. Hence, a robust PTR algorithm has to keep track of the number of near-zero and near-unity probabilities before assigning the train to the mainline or siding track. Alternately a statistical algorithm has to be developed that combines

the separate PTR probabilities to arrive at a final decision whether the train has entered the siding. The siding probabilities for Passes 3 and 4 in Figure 37 remain zero since the train remains on the mainline track and the heading estimation errors are not as large as for the results in Figure 36.

4.9.5 Parallel Track Resolution Combined with Map Matching

As Figures 36 and 37 indicated, the GPS along track position errors are large enough to influence the PTR probability calculations in the bottom panels of these two figures. A software solution is to incorporate a map matching algorithm. The map-match algorithm could be applied to the heading signature of a stretch of mainline track as illustrated in the top panel of Figure 38. In this figure, an unambiguous curved stretch of mainline track has been selected prior to the west end of the Wyeth siding. When the curved stretches of mainline track are corrected for an east position offset error determined with the map match algorithm, the estimated heading and rail database heading overlap as shown in the top left panel of Figure 38.

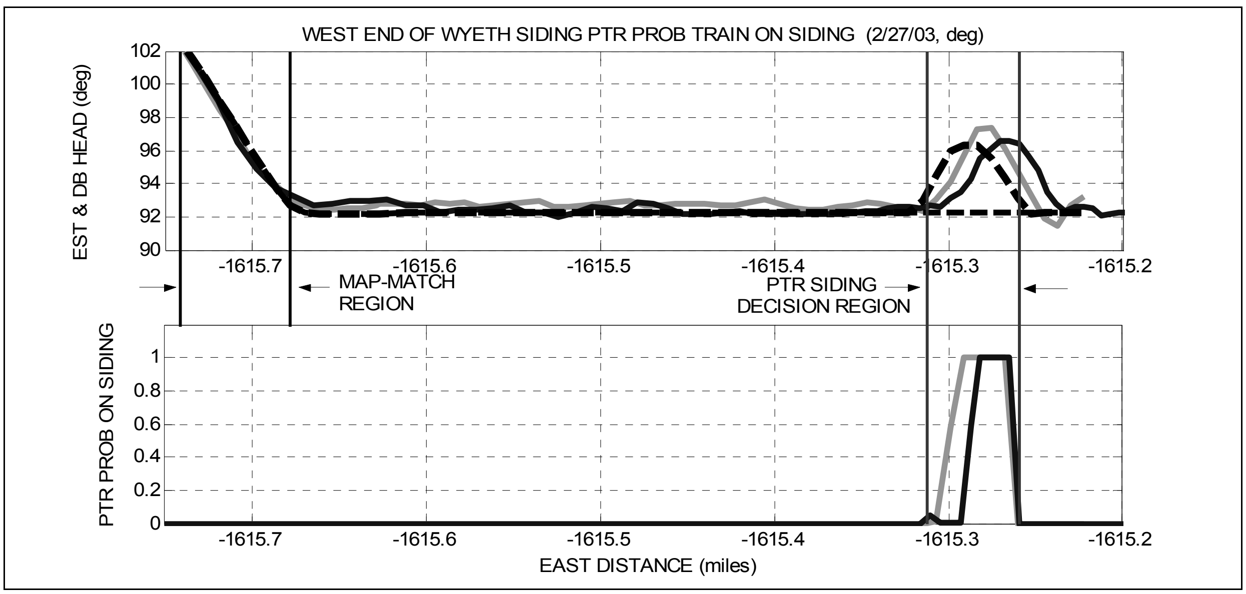

FIGURE 38 Map-Matching Applied Prior to PTR Logic

Unfortunately, these position corrections do not fully correct for the siding position offsets in the right hand side of the top panel, leaving the estimated heading into the siding offset laterally from the database siding heading. The difference in east position between the end of the mainline curve and the start of the siding is about 0.25 miles while the time interval is about 40-45 sec.

Another problem with this approach is indicated in Figure 36 in that the third and fourth pass (not shown in Figure 38) does not go through the curve to the left. For that scenario, these passes would have to rely on the second pass that recently went through that curve. Alternately an attempt would have to be made to calibrate against an unambiguous curved stretch of track past the east end of the Wyeth siding.

An alternate approach is to use the siding heading signature itself to perform the map-matching to remove the east distance error. This would be followed by the PTR probability calculation using the along-track adjusted position data. When this combined map-match plus PTR calculation is applied to the results of Figures 36 and 37, the corresponding results of Figures 39 and 40 are obtained.

In both figures, the east position offset from the most recent pass into the siding was applied to the results for the case where the train did not enter the siding. As can be seen in both figures, the PTR results for the cases where the train entered the siding are considerably improved. Improvement in the results is also observed for the cases where the train passed but did not enter the siding.

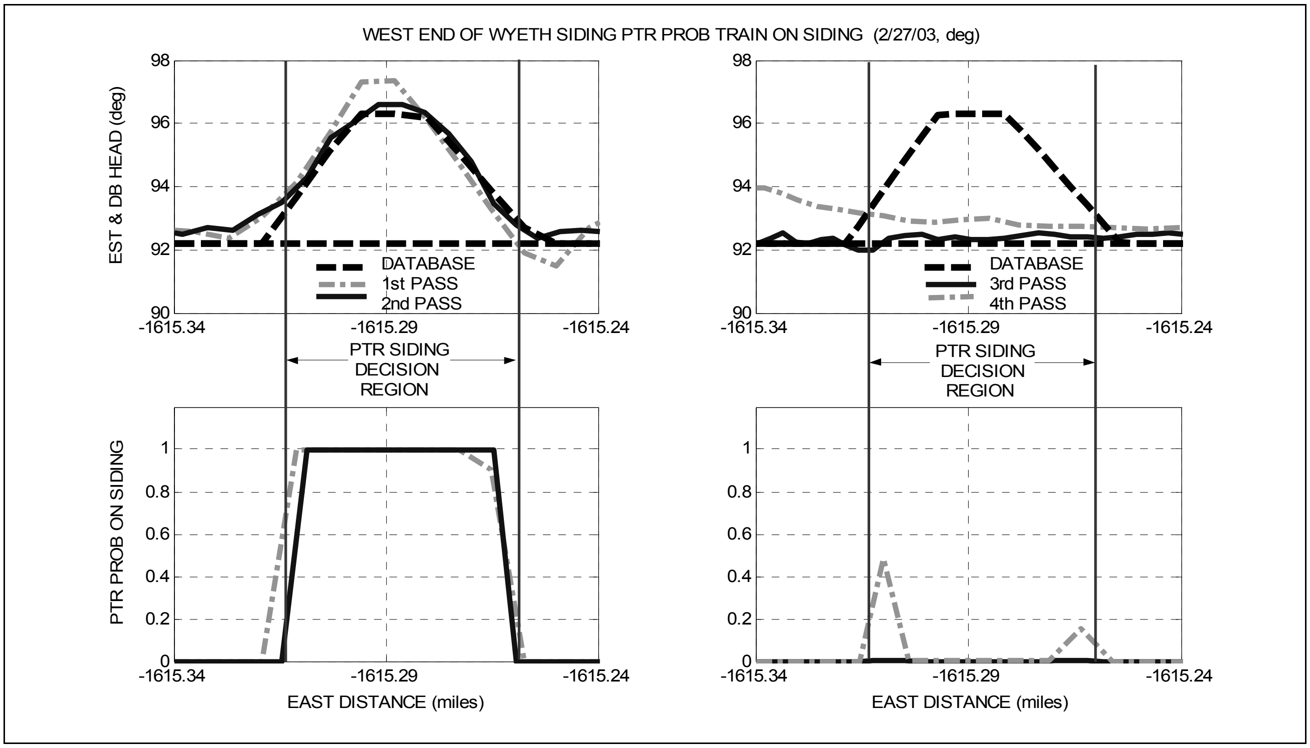

FIGURE 39 West End Wyeth Siding PTR Resolution Results Combined with Map Matching

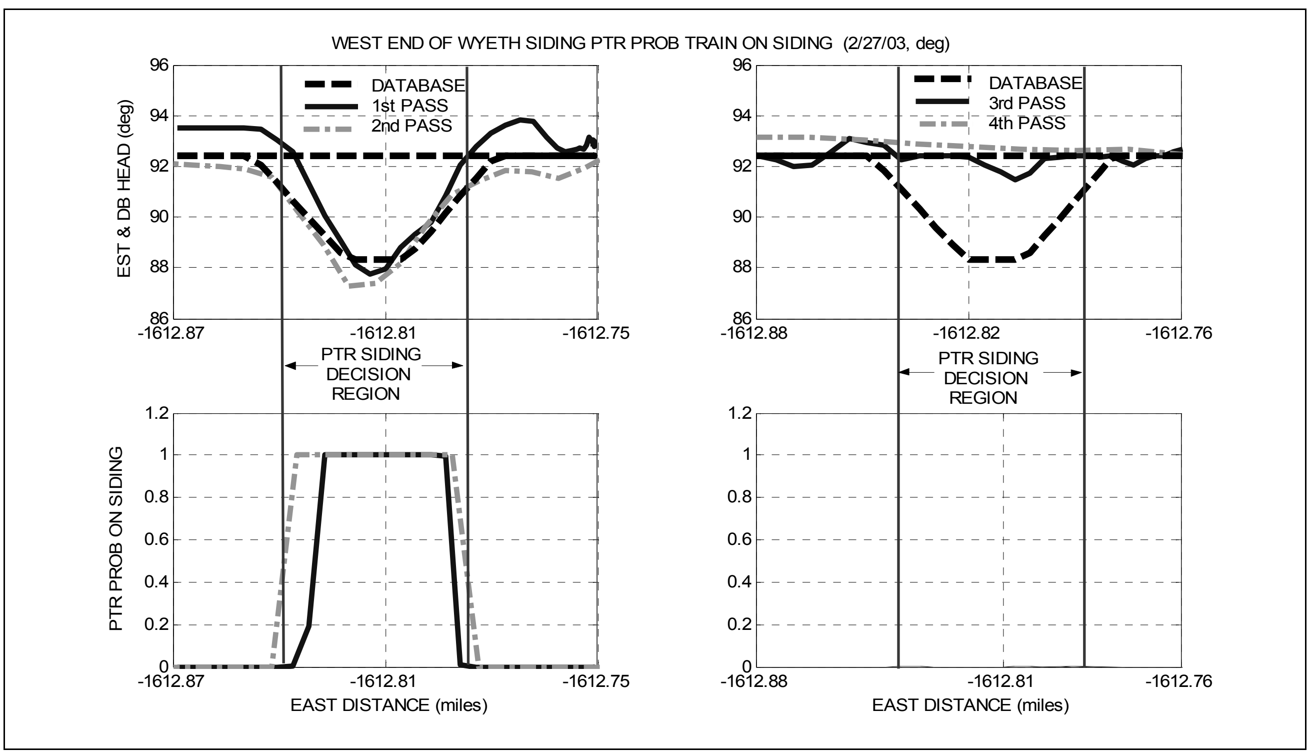

FIGURE 40 East End Wyeth Siding PTR Resolution Results Combined with Map Matching

The map-match results for the passes into the both ends of the siding are summarized in Table 7. Also shown are the highest correlation coefficients for the passes that did not enter the siding. The offsets are applied as corrections by

subtracting them from the estimated east distance positions. The offset results are based on strong correlations (map matches) between the siding rail database heading and the estimated train heading into the siding.

TABLE 7 Map Match Offset Results

Pass Into Siding?	Pass	Siding Correlation Coefficient	East Position Offset (ft)		Pass Into Siding?	Pass	Siding Correlation Coefficient	East Position Offset (ft)
West End of Wyeth Siding					**East End of Wyeth Siding**			
Yes	**1**	**0.952**	**42**		**Yes**	**1**	**0.896**	**0**
Yes	**2**	**0.976**	**-82**		**Yes**	**2**	**0.945**	**-79**
No	3	0.028	NA		No	3	0.113	NA
No	4	0.261	NA		No	4	0.120	NA

A proposed operational implementation of this combined map-match plus PTR probability approach is to use the following steps:

1. Perform map-match correlations using the siding heading signature to all train heading estimates in the vicinity of the estimated position of the siding.
2. If the best correlation coefficient is low (<0.8), conclude that the train has not entered the siding
3. If the best correlation coefficient is high (>0.8), conclude that the train may have entered the siding
4. Adjust the along track estimation position with the offset computed in Step 3
5. Perform the PTR calculation with the estimated track heading referenced against the corrected along-track estimated position and the rail database siding heading to establish the level of confidence in the tentative conclusion of Step 3.

Other considerations are how does this logic perform for Type 33 switches, instead of the current Type 14 switch that were used during the field tests? Also, how will this logic perform when there are stacked multiple sidings – a so-called siding ladder?

Figure 41 shows the (along track-cross track) position signatures for switch transition track segments into a siding for a Type 14 and Type 33 switch as well as for a double siding with two Type 14 switches. The mainline track is along the abscissa. The corresponding heading signatures as a function of the along track relative position from the point of switch are shown in Figure 42.

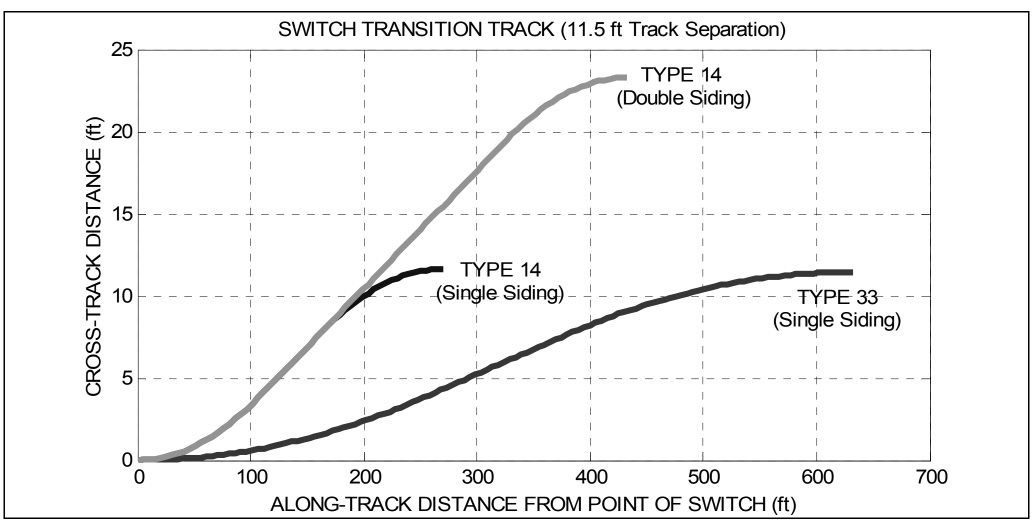

FIGURE 41 Transition Track Signatures

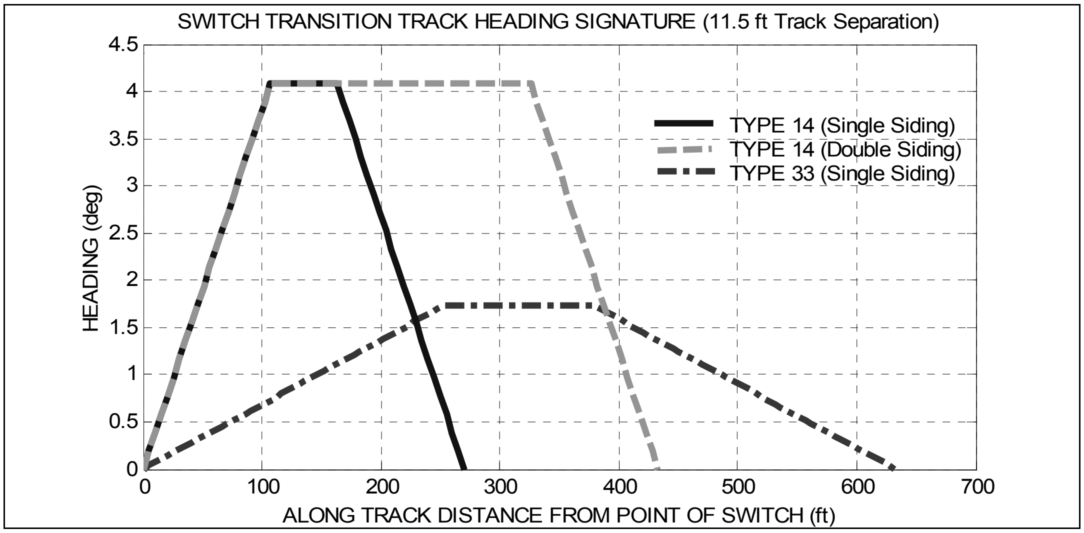

FIGURE 42 Transition Track Heading Signatures

Examining Figure 42, both the Type 14 and Type 33 single siding heading signatures are distinct, with the latter stretched out over a longer distance. Also, the single and double siding Type 14 heading signatures are quite distinct. Hence, the proposed combined map match - PTR logic should work quite well when the heading accuracy satisfies the requirements of Table 5.

5 PLANS FOR IMPLEMENTATION

5.1 PRODUCT COMMERCIALIZATION

With additional development, enhancements, and testing of the prototype system (Figure 43), the system will be repackaged into a convenient form for commercialization. To further this goal, Seagull was awarded a contract from the Federal Railroad Administration in August 2003 to perform additional GLLS pre-production product development and testing.

A successful prototype will offer Seagull a number of options for commercialization. One option is to identify an industry partner who can modify the prototype for mass production and has the resources and market-specific experience to distribute and support the HSR GLLS.

FIGURE 43 Seagull GLLS Prototype

Alternatively, the prototype hardware concept and software can be licensed by companies who have the manufacturing, distribution, and marketing organizations as well as the associated resources to bring this prototype system to market. Another option is a mixture whereby Seagull provides the GPS heading system and an industry partner licenses the locomotive-specific portion of the design.

Since the end user for this locomotive location system is the railroad, the railroads will probably select a systems integrator to perform the full PTR system installation. Hence, Seagull will market this prototype to key railroad systems integrators such as GE-Transportation Systems, WAB Tech, and Lockheed-Martin.

Figure 44 shows how the GLLS product can be incorporated into a PTC architecture. This figure shows that the GLLS product is a ‘black box’ that contains location sensors, a central processing unit, and algorithms. This black box requires an external rail database and power. In turn, this black box provides estimates of the locomotive position and level of confidence to an onboard computer or display unit and to the dispatch center via an onboard communications system.

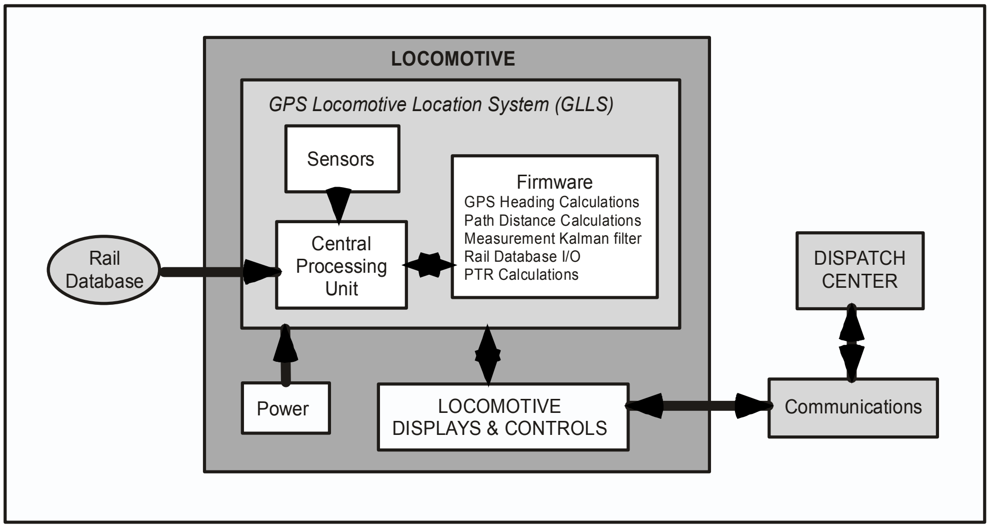

FIGURE 44 GLLS Product as Part of a PTC Architecture

6 CONCLUSIONS

In conclusion, the GLLS hardware performed flawlessly in the field, demonstrating that the design is very robust and suitable for the harsh environment of the railroad. The GLLS software did not perform well in the field due in part to geodetic conversion algorithm coding error that prevented the PTR algorithm from accessing the rail database. Since a full end-to-end rail database access analysis was not possible until the measurements were performed on the actual rail network, this error was not detected prior to the field tests. After the coding error was removed, post-processing of the corrected real field data showed that with an accurate rail database, the GLLS was able to predict the train was on a siding 100% of the time using two siding switches and four passes over each siding switch.

The desired heading accuracy of 0.15 deg was achieved while the train moved along straight stretches of track. Under the previous concept feasibility study, a heading accuracy of 0.16 deg was achieved while the train moved along a straight stretch of track; however a shorter antenna baseline was used for these concept feasibility tests. The heading accuracy during the current field tests only degraded to 0.20 deg during variable heading stretches of track as well as during dead reckoning periods.

The heading algorithm needs further refinements and field testing to achieve a fully mature software product; however the core logic is solid. The innovative capability of this heading software to obtain single satellite heading solutions is very promising. Hence, it will add robustness to GLLS when the train is in a canyon, under leaf canopy, or other regions of partially blocked sky visibility. Note that under the concept feasibility contract, a more mature GPS heading algorithm was used. This earlier algorithm was sold to Garmin by Seagull for use in cockpit instrumentation displays of general aviation aircraft, and hence it was unavailable for this contract.

Future development efforts include:

1) Create or obtain a rail database with an accuracy of 0.11 deg. The rail database used for these field tests was accurate only to approximately 0.55 deg.
2) Refine and enhance the combined map match plus PTR algorithm that was developed and demonstrated under this contract.
3) Continue enhancements and field testing of the core algorithms
4) Refine the single satellite heading solution for robust performance in all environments
5) Refine the dead reckoning requirements, with customer coordination, and then further enhance the dead reckoning algorithms

7 REFERENCES

1. Mueller, K. Tysen, “Low-cost, Drift-free DGPS Locomotive Navigation System IDEA Program Final Report,” Seagull Technology, Inc., 31 March 2001
2. Anon, “FLI-MAP,” John Chance Land Surveys, Inc., www.flimap.com
3. Pellegrino, F., “Positive Train Control,” Lockheed Martin, 13 November 2000
4. Anon, *2001 Federal Radionavigation Systems*, Department of Transportation, DOT-VNTSC-RSPA-01-3.1, 2001
5. Hay, W. W., *Railroad Engineering*, Second Edition, John Wiley & Sons, 1982