Low-Cost GPS Locomotive Location System for High Speed Rail Applications

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BIOGRAPHY

Tysen Mueller received his BS degree in Physics from Purdue University, Lafayette, Indiana, and his MA degree in Physics from the California State University at Long Beach, California. He is manager for locomotive location systems projects at Seagull Technology, with whom he has been employed for more than five years. At Seagull, he previously designed, developed, and delivered two real-time WADGPS correction codes for a commercial L-Band WADGPS network. While at Trimble Navigation, he helped define and direct the initial development of the Trimble AVLS product line as acting AVLS product manager. He also defined a new real-time GPS orbit error estimation algorithm and a unique global ionospheric delay model for which he was granted a patent.

Richard Bortins earned his Ph.D. and MS in Control Engineering at the University of Michigan, Ann Arbor, Michigan and his BS in Electrical Engineering at Michigan State University, East Lansing, Michigan. He is a Senior Research Scientist at Seagull Technology, with whom he has been employed for nine years. While at Seagull, he has participated in the design and development of a GPS-aided air data attitude and heading reference system (ADAHRS) for general aviation and a carrier-differential GPS attitude determination system.

ABSTRACT

The US Federal Railway Administration is exploring technologies that will allow high speed trains to operate on the same tracks as freight and other rail traffic. The specific requirement is to automatically determine when a train has moved onto a siding to allow another train to pass with a confidence level of 0.99999. To achieve this confidence level requires that the locomotive location system have a heading accuracy of 0.20 degrees for a high-speed (Type 20) switch.

This paper presents the results of a study that explored the use of a low-cost GPS-based locomotive location system to achieve this goal. The location system features a multi-antenna GPS heading system using low-cost GPS receivers. During periods of satellite masking, the train navigates with a low-cost (solid state) heading rate sensor and its own odometer. The rate sensor and odometer are calibrated dynamically with a Kalman filter using the GPS position, velocity, and heading measurements when these are available.

To demonstrate this concept, a prototype GPS heading system was taken into the field and measurements were recorded on a locomotive for 3 days in a rail yard as well as on several mainlines in the Pacific Northwest. These measurements were post-processed to determine the raw and Kalman-filtered GPS heading accuracy. The required accuracy of 0.20 degrees was achieved with the raw heading measurements and exceeded with the filtered estimates.

A parallel track resolution (PTR) algorithm was also formulated to determine the probability that a train has entered the siding. This algorithm uses the estimated path distance traveled and a GPS rail map database to determine if the locomotive is passing over a switch. When it passes over a switch, the algorithm compares the railmap database heading for entering the siding with the filtered estimate of the heading. Using the uncertainties in the path distance and the heading, the algorithm determines the probability that the train has entered the siding. This algorithm was evaluated for several mainline switches using the field test data and it was shown to achieve the required level of confidence for these switches.

BACKGROUND

This paper summarizes the initial feasibility study for the development and deployment of an extremely accurate and reliable Locomotive Location System. The system promises to solve one of the most challenging problems for positive train control (PTC), namely, that of establishing with 0.99999 confidence on which of two parallel tracks a locomotive is located. The Locomotive Location System is designed to feed its results to another onboard computer, or directly to a data link for transmission to the railroad control centers.

Key to the system design is an innovative technique for detecting turnouts, as shown in Figure 1. As illustrated in Figure 1, the heading and heading rate of the locomotive as it proceeds through a switch provides unique and useful information for determining whether the train has entered a siding to permit another train to pass.

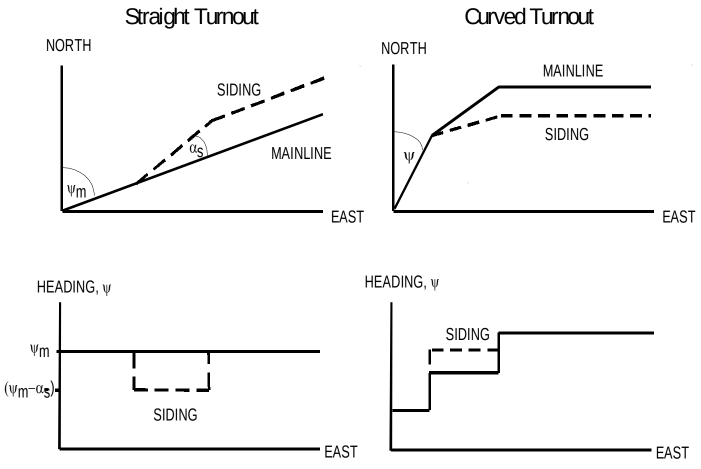

FIGURE 1. Locomotive Heading Signature on Mainline and Siding

In Figure 1, it can be seen that there is a significant difference in heading signature resulting from a locomotive taking one path versus another through a switch. In order to detect the heading signature with sufficient accuracy to determine with high confidence which path the locomotive has taken, a precise source of heading measurement must be available.

REQUIREMENTS

As stated in [1], "*The single most stressing requirement for the location determination system to support PTS [Positive Train Separation] system is the ability to determine which of two tracks a given train is occupying with a very high degree of assurance (an assurance that must be greater than 0.99999 or (0.9_5)). The minimum center-to-center spacing of parallel [tracks] is 11.5 feet. Direct GPS will not satisfy this requirement. The USCG LADGPS [Local Area DGPS] radio tower beacon system, as a first level of augmentation, also will not satisfy this requirement...*"

This requirement is illustrated in Figure 2. It shows that if there is uncertainty in the knowledge of the lateral position or heading of a train and the measured position or heading is to the left of the midpoint between the tracks, the PTR algorithm will place the train on the siding. Alternately, if the measured lateral position or heading of the train is to the right of the midpoint, the PTR algorithm will place the train on the mainline track.

The errors contributing to the lateral position or heading 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 uncertainty of 4.3 standard deviations (4.3σ) that the lateral position or heading of the train is to the right of the midpoint, when the train is actually on the siding.

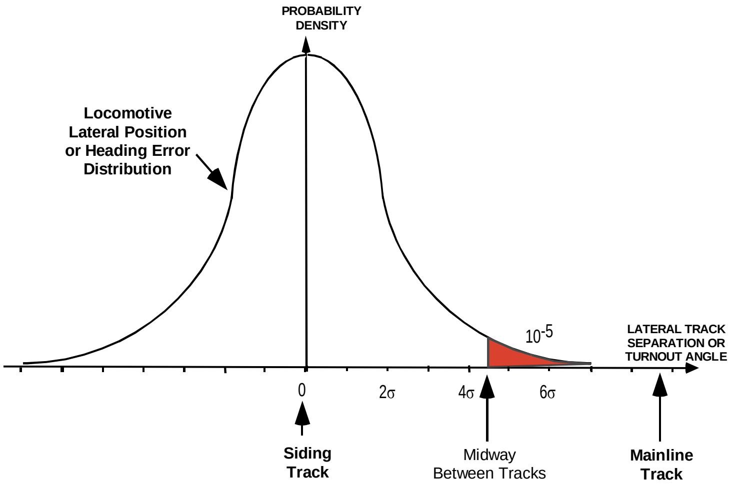

FIGURE 2. Parallel Track Resolution Problem (Not to Scale)

TABLE 1. PTR Accuracy Requirement (99.999% Confidence)

Parameter	Requirement	Required Accuracy (1 sigma)
Lateral Position	11.5 ft (3.5 m) Track Separation	**1.34 ft (0.41 m)**
Heading Angle	Type 20 (1.75 deg) Switch	**0.20 deg**

As shown in Table 1, this accuracy requirement translates into a maximum lateral position error of 0.41 meters (1σ). Alternately, it translates into a maximum heading error of 0.20 degrees (1 sigma) for a high-speed switch (Type 20).

ARCHITECTURE

The unique GPS Locomotive Location System (GLLS) design, illustrated in Figure 3, incorporates very accurate drift-free heading measurements obtained with a low-cost multi-receiver GPS system using antennas mounted on the cab roof of the locomotive. This GPS heading is augmented with measurements from a highly robust, low-cost (solid state) heading rate sensor. The two measurements are combined in a simple Kalman filter to improve the accuracy of the heading and dynamically calibrate the rate sensor 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, velocity, and heading are also used to dynamically calibrate the locomotive odometer and the heading rate sensor. When GPS satellite coverage is temporarily interrupted, the calibrated low-cost gyro and odometer are used to determine the location of the locomotive with dead reckoning algorithms.

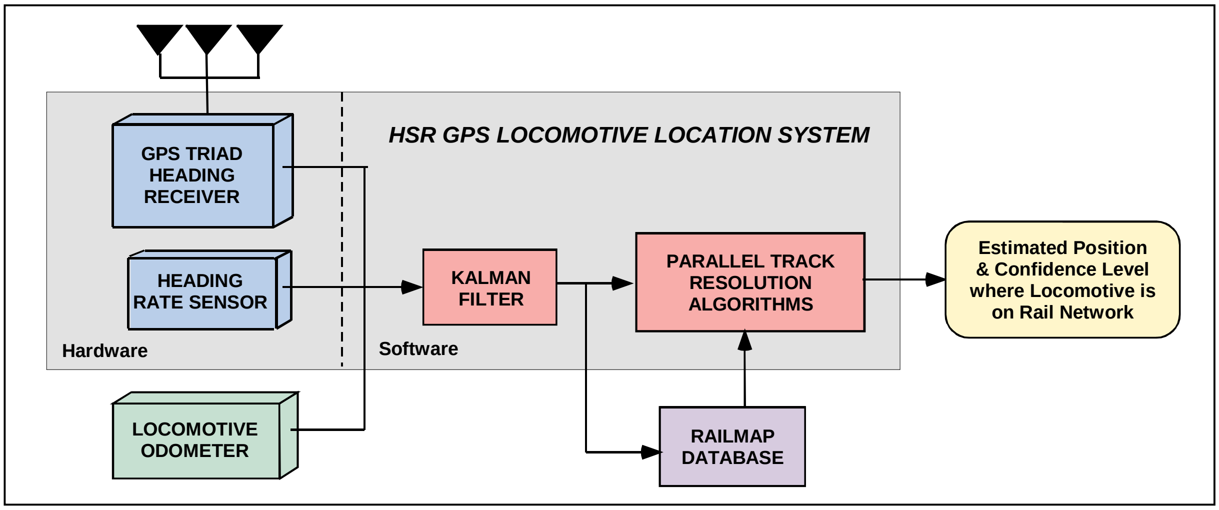

FIGURE 3. Proposed HSR GPS Locomotive Location System (GLLS)

This location system incorporates a sophisticated PTR software design that determines the level of confidence with which the location of the locomotive is known.This algorithm is based on the filtered position and heading, as well as their estimation error standard deviations obtained from the Kalman filter.

FIELD TEST SETUP

The field tests were performed with two GP-38 locomotives that were graciously provided by the Burlington Northern Santa Fe railroad, complete with crew. The field tests took place in October 2000 in a railyard north of Seattle for one day and on the mainline tracks both north and south of Seattle for two additional days. One day was used to install the instrumentation.

The processing of the heading measurements using a Kalman filter is illustrated in Figure 4. The principal measurements used to determine the locomotive heading are the GPS heading measurements and the heading rate sensor measurements. Additional measurements can be incorporated as well since they provide redundant measurements of the locomotive heading, as shown in Figure 4. The locomotive velocity provides a source of heading since the locomotive must be on a track. Also, the incremental position of the locomotive provides a crude source of locomotive heading data.

In Figure 4, the pitch and roll GPS attitude and body rate sensor measurements are also included. These might be required to fully decouple the heading motion of the locomotive from the pitch and roll motion. During the field tests, all the measurements in Figure 4 were collected and evaluated, as described later.

The test equipment consisted of a T-shaped, four-receiver, Seagull GIA-1000 GPS Attitude System configured as a data recording system that was placed on one of the two locomotives. The GIA-1000 is shown in Figure 5, with the receiver and its associated electronics shown on the left-hand side. The standard four GPS antenna configuration is shown on the right-hand side, while mounted on Seagull's rooftop motion simulator.

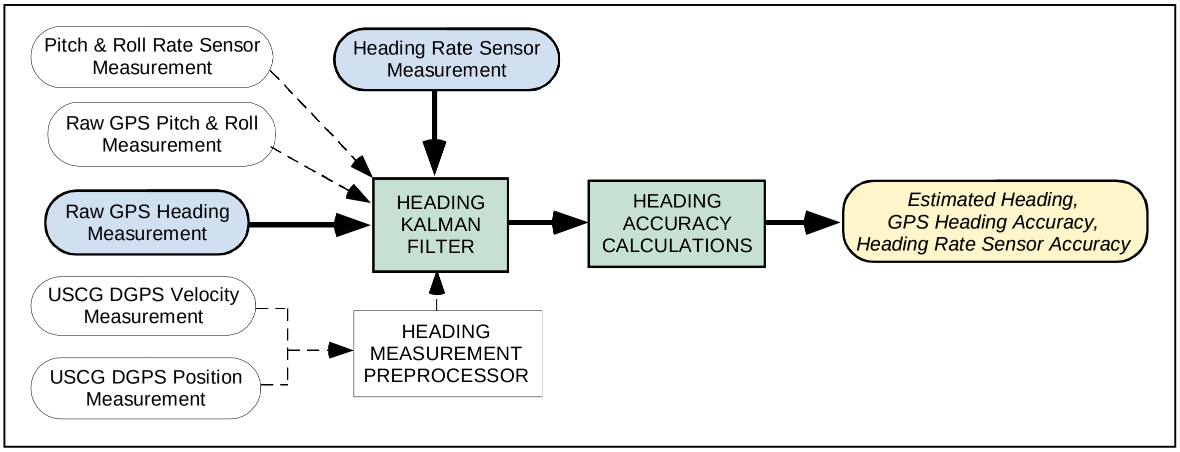

FIGURE 4. Best Heading Estimate and Heading Accuracy Calculations

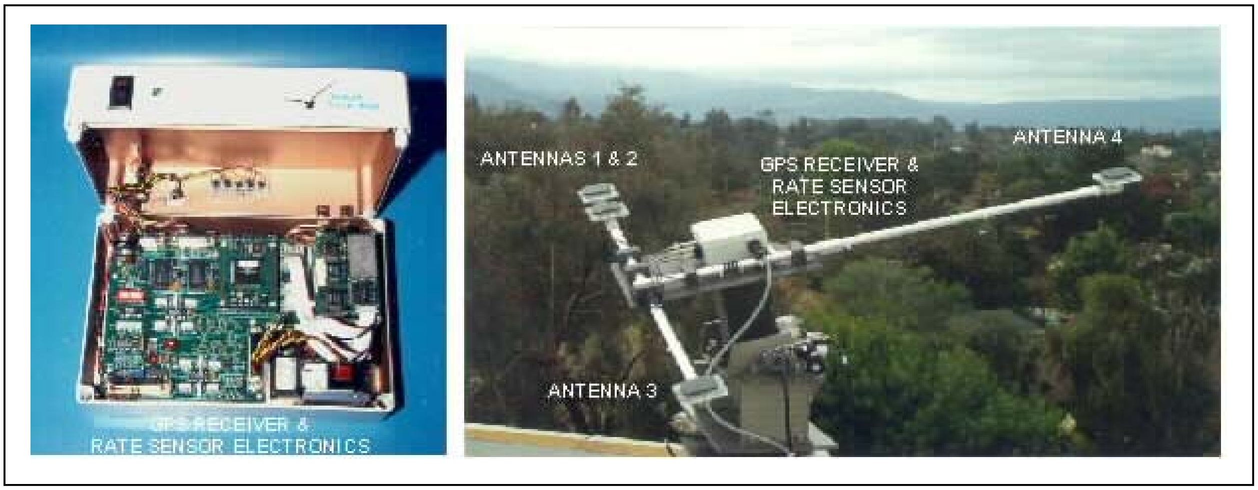

FIGURE 5. Seagull GIA-1000 GPS Attitude System

This hardware was used to collect raw field test measurements from all of the sensors as illustrated in Figure 6. Also shown are the measurements that were obtained from the individual sensors. For the design in Figure 3, only the linear antenna array (1 - 3) is used.

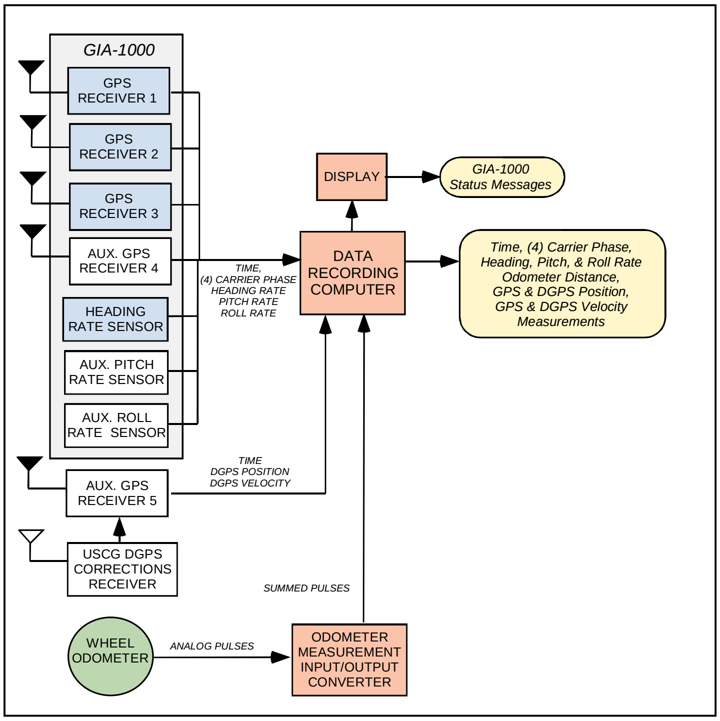

FIGURE 6. Field Measurement Hardware Configuration

This hardware was augmented with a DGPS receiver system consisting of a Canadian Marconi DGPS-capable receiver and a US Coast Guard marine beacon receiver for receiving the DGPS corrections. Finally, a locomotive axle generator pickoff and conversion box allowed the locomotive odometer readings to be measured. All measurements were recorded in a computer. All power was provided by the locomotive 72 VDC system and this was converted to 12 VDC by a power converter. A flat screen color monitor, in addition to a keyboard and mouse provided a means for monitoring the data collection process.

Figure 7 illustrates the locomotive rooftop GPS antenna geometry. The effective baseline for the GPS heading and pitch measurement is 200 cm (78.7 in) while the roll baseline is 174 cm (68.5 in). The latter baseline had to be shortened since the flat part of the locomotive cab roof was only slightly larger.

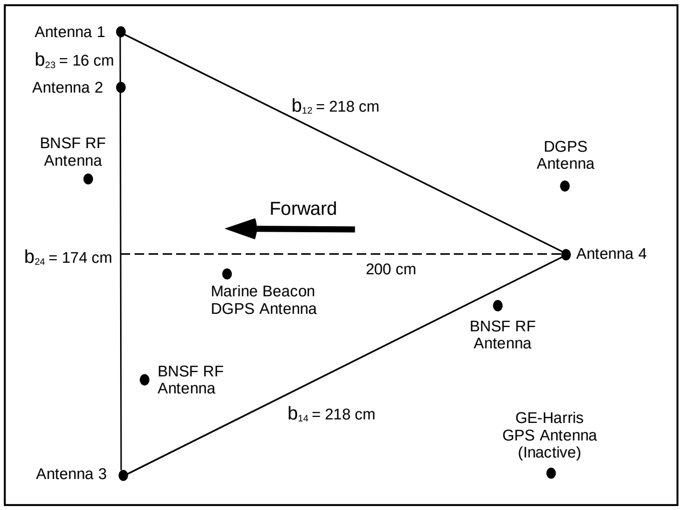

FIGURE 7. GIA-1000 Antenna Configuration and DGPS Antenna Location

CONSTANT HEADING YARD TEST

A long straight stretch of yard track, approximately 0.7 mile long, was selected in the BNSF Seattle Rail Yard 20 and the locomotive was moved back and forth on this track at 3 different speeds. The speeds were approximately 4, 7, and 11 mph. The heading of this track was obtained by taking a combination of GPS and DGPS position measurements for more than 1.5 hours while the locomotive moved back and forth at varying speeds over the 0.7 mile stretch of straight track. The 5800 position measurements were fit to a line using a Least Squares filter and this was used to determine the true heading of the track with respect to north. The position measurements were then rotated such that one of the axes was aligned along this heading estimate. Then by computing the lateral scatter of the positions combined with the total number of lateral position measurements, the 95% (2σ) confidence interval about the mean heading estimate was computed.

The basis for this test is the fact that when the locomotive moves along a straight track, the heading remains constant. Also, since the heading is constant, the heading rate measured by rate sensor should be zero. Using the estimated true heading of the track, as described in the previous paragraph, the GPS heading measurement accuracy can be determined for a moving train. This test was also used to determine the accuracy of the train heading as determined by GPS/DGPS velocity and position measurements. Finally, the train odometer was calibrated using the GPS/DGPS velocity data. During this constant heading test, DGPS position and velocity measurements were available for approximately half the time. When the DGPS corrections were not received, the GPS position and velocity measurements were used instead.

While the operational train location system will use only an inline GPS antenna configuration to measure heading, the test measurement system also included measurements of the pitch and roll attitude of the locomotive. With these measurements it was possible to determine how large the pitch and roll attitude using when the train is in motion. It will also allowed determining the accuracy impact on the heading when these two angles are ignored.

Figure 8 presents the Kalman filtered (smoothed) heading attitude when only the heading attitude and heading rate sensor measurements are used. It is also the baseline filter that is proposed for the low-cost GPS locomotive location system. Figure 8 indicates that the heading estimation error is very small (0.18 deg. 1σ) and also has a small bias of -0.06 deg. This bias is probably due to the GPS antenna installation alignment error.

When the measured and filtered heading accuracies are plotted on an empirical curve of heading accuracy versus heading antenna baseline length, the results of Figure 9 are obtained. The empirical curve is based on a theoretical algorithm with coefficients chosen to reflect observed GPS receiver clock timing errors.

While not discussed in detail here, heading estimates were also computed using the GPS velocity and the incremental GPS position as summarized in Table 2. This table clearly shows that the measured and filtered GPS heading exceeds the PTR requirements. In addition, this table shows that the heading derived from incremental positions or from velocity does not satisfy these requirements.

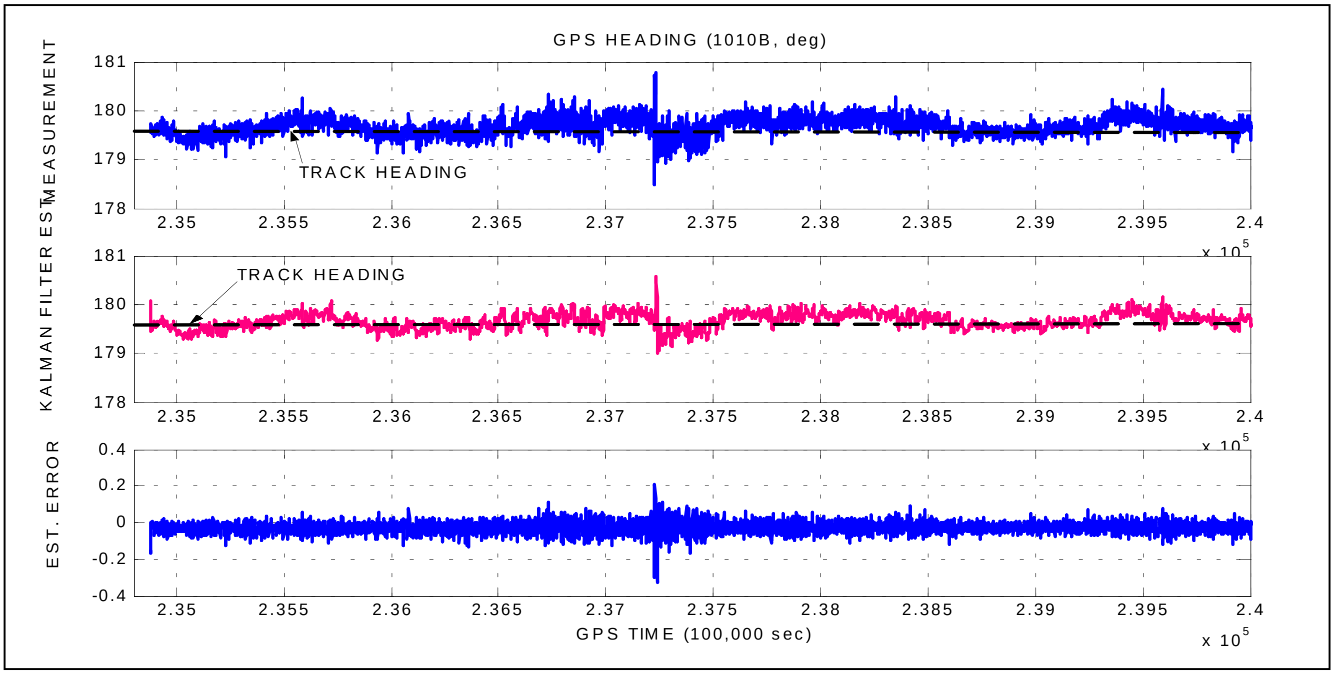

FIGURE 8. Measurement and Filtered GPS Heading (2-State Kalman Filter, Constant Heading Test)

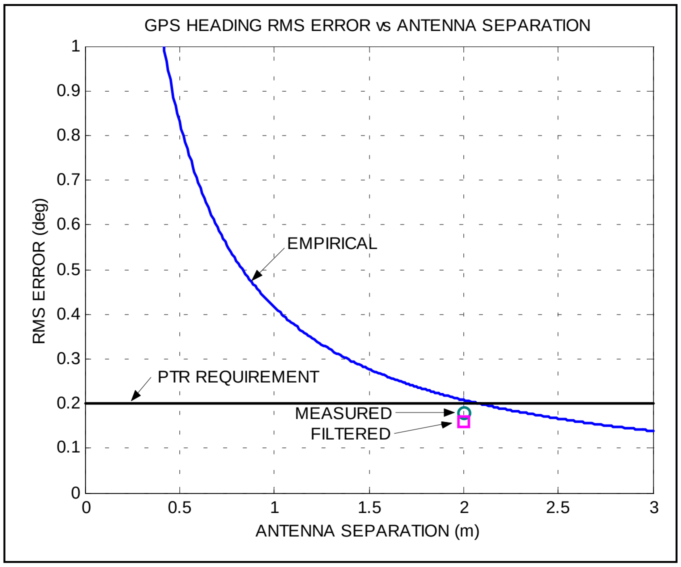

FIGURE 9. GPS Heading Accuracy vs Antenna Baseline

PTR FIELD MEASUREMENTS AND ANALYSIS

The basic PTR approach focuses on a simple set of algorithms that incorporate estimates from the previously described heading Kalman filter and a distance Kalman filter, as illustrated in Figure 10. Until 2000, the GPS signal available to non-military users was intentionally degraded by Department of Defense under a policy called Selective Availability (SA).

Since both GPS and DGPS position and velocity measurements were recorded during the constant heading with SA off, the statistics of Table 3 were obtained. This shows that the root-sum-square (RSS) GPS position error now is 11.6 feet while it was around 30 feet when SA was still on. With DGPS, the RSS position error is reduced to 4.8 feet, about 40% as large as the GPS position error.

Based on these results the need for the path distance Kalman filter was reduced. However, some algorithm must be used to periodically calibrate the odometer using the GPS position and velocity measurements. This algorithm might be as simple as performing an initial scale factor calibration and then periodically resetting the odometer path distance to the GPS integrated velocity derived path distance.

For the PTR test, a segment of mainline track was selected for which not only the GPS heading measurements were available but also a rail map database. More specifically, the segment also included a siding as part of the database. The data set that was used was recorded on the mainline while the train was moving from Seattle south to Tacoma, Washington.

TABLE 2. Measured, Filtered, and Derived Locomotive Heading Statistics Summary

Heading Source	Mean (deg)	Relative Mean (deg)	Standard Deviation (deg)	Root Mean Square (deg)
Reference	**179.602 ± 0.002 (95%)**	**0**		
PTR Requirement			**0.20**	**0.20**
Incremental GPS Position	180.08	0.48	0.84	0.97
GPS Velocity	179.85	0.25	0.43	0.50
Measured GPS Heading	**179.68**	**0.08**	**0.18**	**0.20**
Filtered GPS Heading	**179.66**	**0.06**	**0.16**	**0.17**

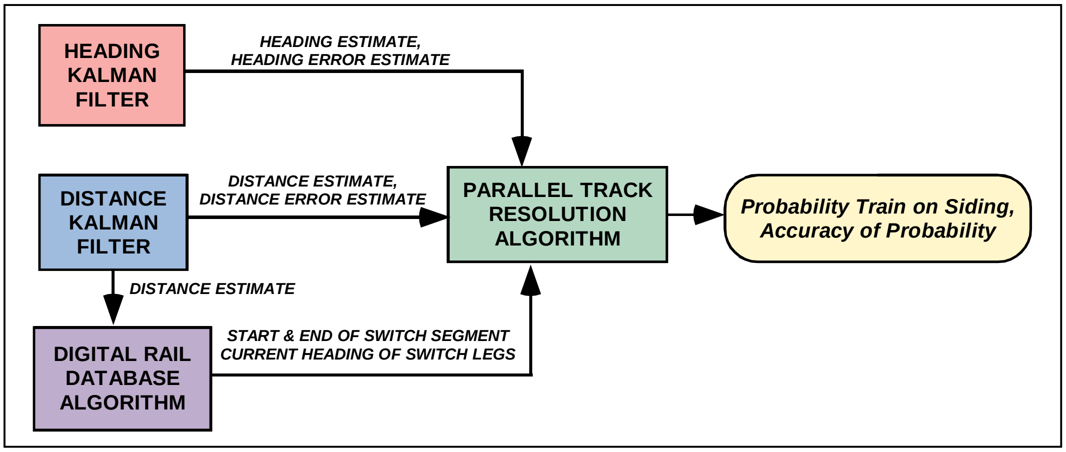

FIGURE 10. Baseline Parallel Track Resolution Algorithm Architecture

TABLE 3. GPS and DGPS Lateral Position and Velocity Statistics (Constant Heading Test)

Variable	Units	GPS (30 min)			DGPS (56 min)		
		Mean	Sigma	RSS	Mean	Sigma	RSS
Lateral Position	ft	-10.0	5.8	**11.6**	-3.0	3.8	**4.8**
Lateral Velocity	ft/sec	0.005	0.05	**0.05**	-0.001	0.04	**0.04**

Figure 11 presents a plot of the railmap database horizontal position for the two mainlines and a siding. A view from the train while it was stopped on the siding at the south end is shown in Figure 12.

Figure 13 presents the actual train position history superimposed onto the railmap database of Figure 11. The train was traveling south on Main 1 around the curve and past the first exit into the siding at the top of Figure 11. As it neared the stretch of Main 1 near the second exit to the siding in the south end of this figure, the train was notified that an Amtrak train needed to pass it on its way to Tacoma. As a result, the test train stopped and backed into the siding. About 10 minutes later after the Amtrak train had passed (Figure 12), the test train returned to Main 1 and continued on south to Seattle.

This scenario provides at least two opportunities to test the PTR algorithm. The first test determines whether the train entered the siding at the top of Figure 13; the second test determines whether the train entered the siding at the south end at the bottom of Figure 13.

FIGURE 12. Locomotive on Siding between Mainline 1 and 2 South of Seattle (View to South-East)

The measured and filtered heading time history is presented in Figure 14. The first switch into the siding is reached near the beginning of this figure. The second entry into the siding is shown around 321650 seconds.

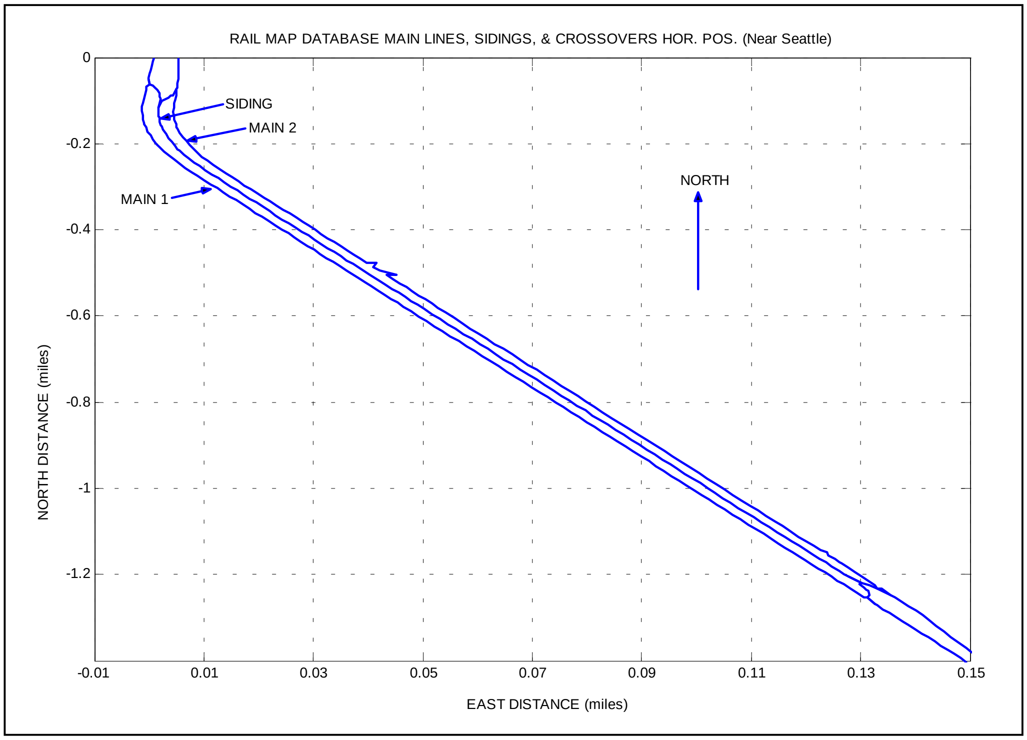

FIGURE 11. Rail Map Database Main Lines and Siding Position (Mainline Test s South of Seattle)

EAST DISTANCE (miles)

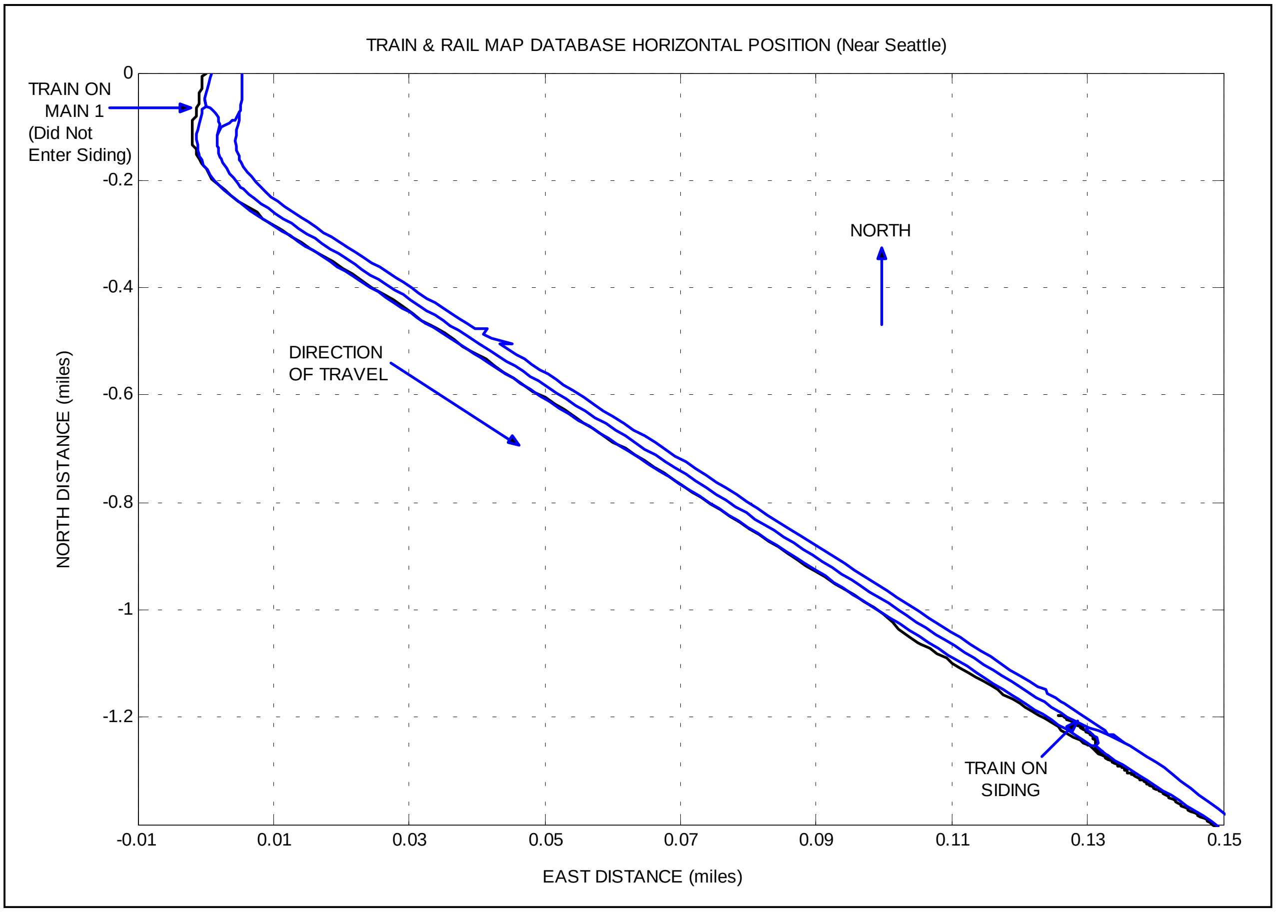

FIGURE 13. Locomotive Position on Rail Map Database (Mainline Test South of Seattle)

Between 321650 and 322300 seconds the train was waiting on the siding for the Amtrak train to pass. Figure 14 also shows the two periods where the GPS heading measurements were not available. For these periods the Kalman filter used the calibrated heading rate sensor to establish the heading history of the train. In the lower panel of this curve is shown the Kalman filter estimation error with a 95% confidence interval band. This confidence band was obtained by using twice (2σ) the Kalman filter estimation error standard deviation obtained from the estimation error covariance matrix. Since most of the estimation error oscillations are contained within this confidence band, the heading Kalman filter is tuned.

A closer look at the heading history near the two switches into the siding is presented in Figure 15. This figure also shows the railmap database siding heading. The top panel shows the train heading as well as the mainline and siding headings when passing the first switch. The middle panel shows the train heading as the train enters the siding together with the mainline and siding heading. Finally, the third panel shows the train heading when the train returns back to the mainline. The first two cases were used to evaluate the PTR algorithm.

An examination of Figure 15 shows that there is a amplitude offset between the GPS heading and the railmap database at the second switch. This appears to be database or a GPS heading error, the velocity-derived GPS heading was also plotted. Since the latter is obtained from a different GPS receiver, the apparent similarity between the GPS heading and velocity-derived heading indicates that the bias is a railmap database error.

Another reference source is the complete rail chart for this section of track. This chart shows that both switches are Types 11. This requires the railmap database to show the same siding heading history for both of these switches. In addition, a Type 11 switch has an approximately 6-degree frog angle. The frog angle is the angle made by the outer rail when it crosses the inner rail of the switch. A 6-degree difference between the mainline and siding heading can be seen at the first switch. The railmap database only shows a 5-degree difference at the second switch. Hence, the railmap database heading is approximately in error by 1 degree at the second switch.

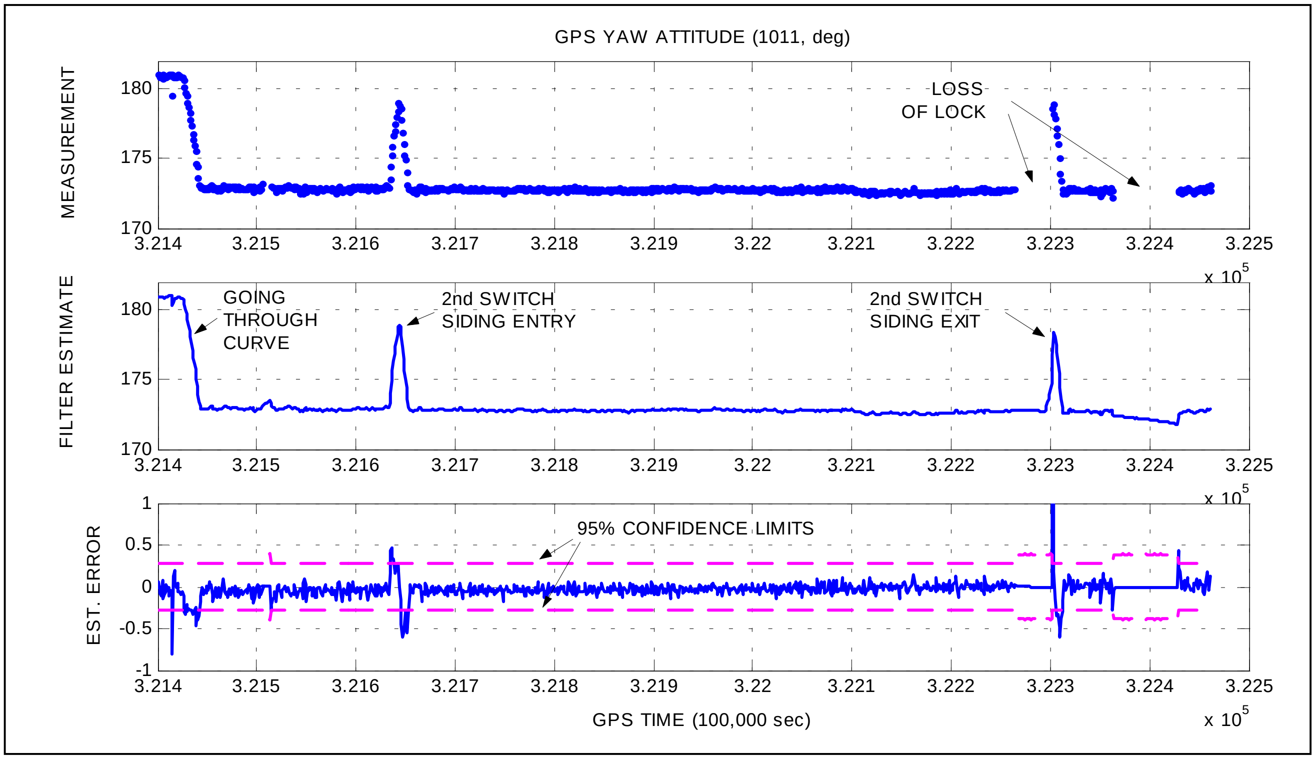

FIGURE 14. Kalman Filtered Heading during Mainline Test (2-State)

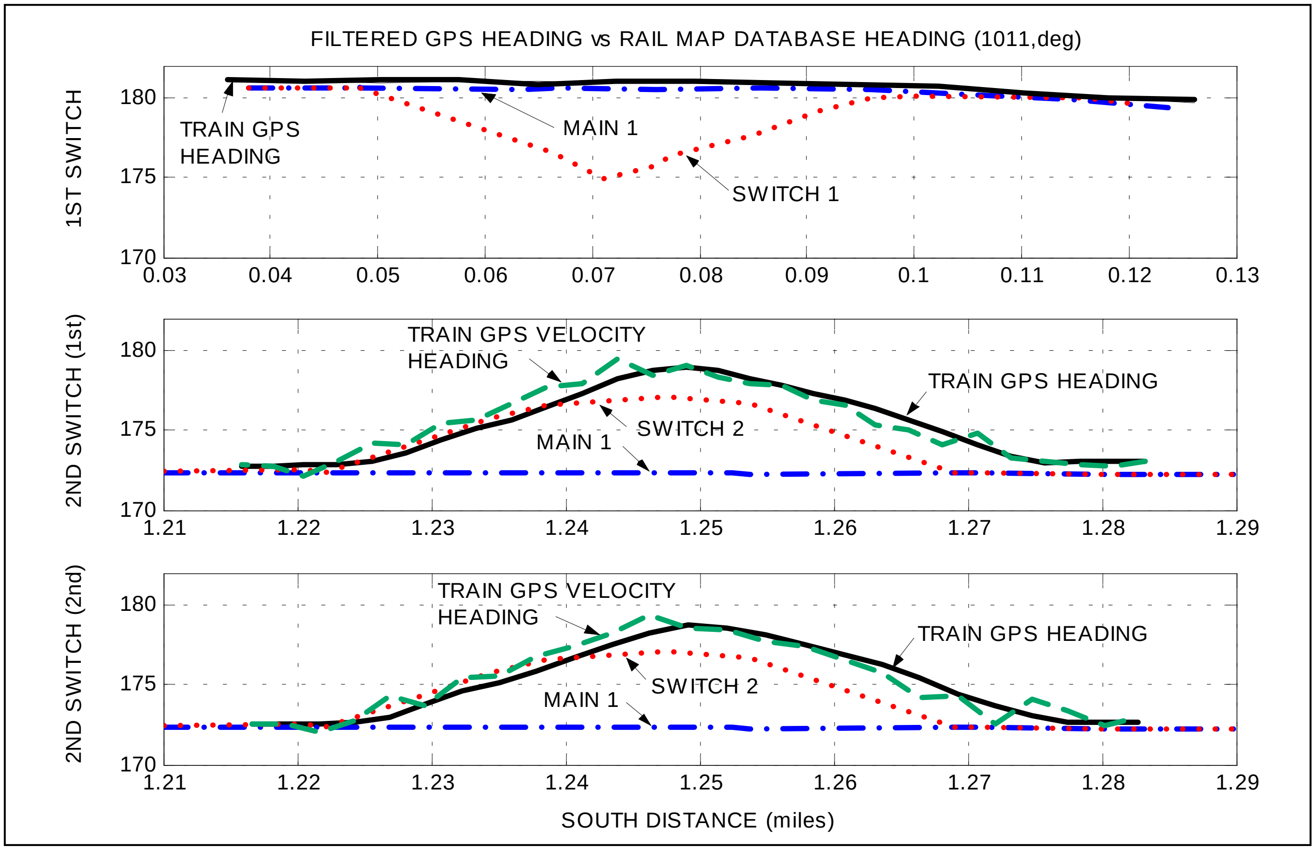

FIGURE 15. Locomotive Heading and Railmap Database Mainline and Siding Heading (Near Siding Switches)

Using the PTR algorithm on the heading data of the first panel in Figure 15 produced the results shown in Figure 16. Likewise, applying this algorithm to the heading panel in the second panel of Figure 15 produced the results shown in Figure 17.

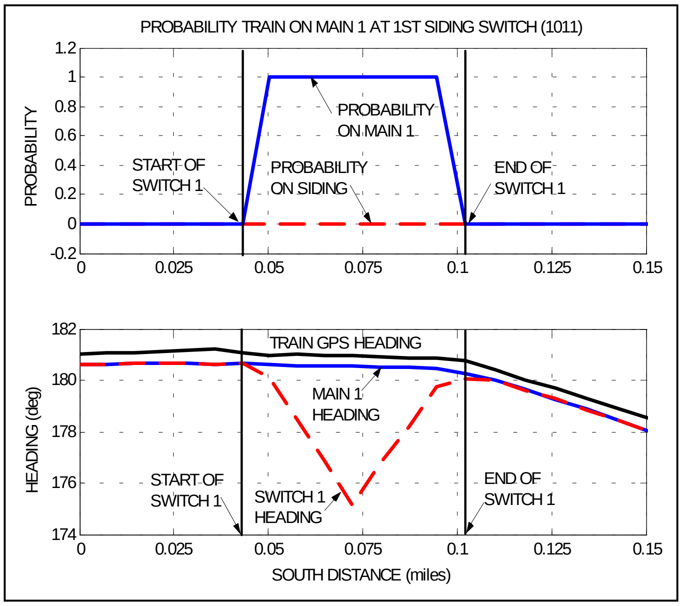

FIGURE 16. Probability that Locomotive Has Entered 1st Siding Switch

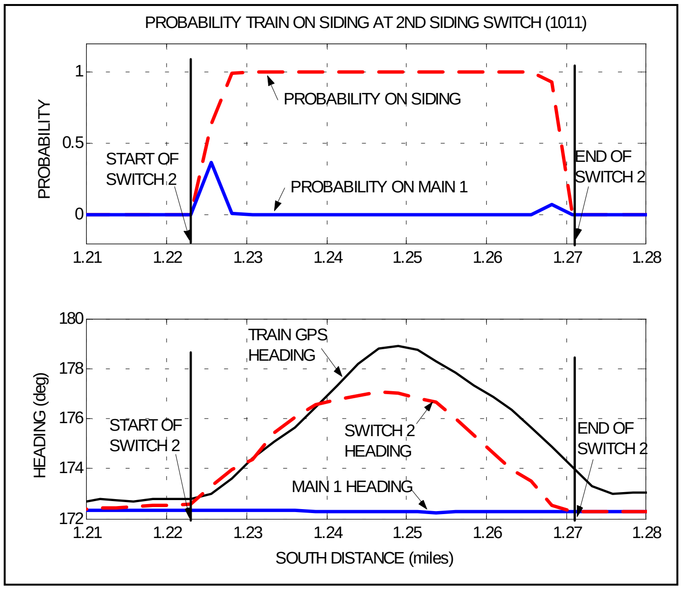

FIGURE 17. Probability that Locomotive Has Entered 2nd Siding Switch

In Figure 16, the probability that the train is on the mainline or siding is computed only during the segment when the train is passing over the switch. Prior to and after passage of the train over this switch, the mainline and siding have the same heading. As a result the PTR algorithm must remember which track the train is on prior to or after passage over a switch. In this figure it is very clear from the probability that the train is on the mainline and that it has not entered the siding.

In Figure 17, it is clear that the train has entered the siding from the high probabilities shown while the train is passing over the switch. These high probabilities indicate that the differences between the railmap database and the train heading did not affect reaching the correct conclusion.

CONCLUSIONS

This paper investigated the feasibility of a hardware and software design that will provide a low-cost drift free highly accurate and robust locomotive location system that can be used for HSR applications. Field test measurements established a raw (unfiltered) heading accuracy for this design of 0.18 degrees (1σ). Using a simple Kalman filter that combines low-cost heading rate sensor measurement with the GPS heading measurement, increased the heading accuracy to 0.16 degrees (1sigma). Since the PTR heading accuracy specifications require an accuracy of 0.20 degrees (1σ), the hardware and software design has met these requirements.

Hence, it is recommended to take the hardware design that was evaluated under this study and build a prototype HSR GPS locomotive location system. The Kalman filter and PTR algorithms would also be added to this prototype system. The prototype system would then be taken into the field to demonstrate that it can achieve the performance dictated by the HSR requirements in real time.

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REFERENCE

[1] Anon, "Differential GPS: An Aid to Positive Train Control," Federal Railroad Administration, pp. 6-7, June 1995.