Mapping Motorway Lanes and Real-Time Lane Identification with Single-Frequency Precise Point Positioning

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Abstract: Modern advanced motorway traffic control requires lane-specific observations, and provide vehicles with lane-specific control measures. Single-Frequency Precise Point Positioning (SF-PPP) was previously demonstrated to provide sub-meter accurate positions in real-time using a low-cost mass-market receiver and patch antenna. Next to an accurate current position of the vehicle, accurate maps of the lanes of the motorway are also needed to identify in which lane the vehicle is actually driving. Theoretical derivations indicate that the lanes of the motorway can in fact be mapped using the same SF-PPP results from a number of previous runs over the motorway. In this paper the proposed technique is tested in practice and a map of the lanes of a motorway is created. To this end, a vehicle equipped with a mass-market GPS device runs 100 times up and down a stretch of the A13 motorway between Delft and Rotterdam in the Netherlands (approximately 5.5 km each direction, in total for 100 runs about 17 hours of driving). A detailed assessment of the quality of the SF-PPP solution is presented in this paper. The errors in each of the horizontal directions are smaller than 1.1 meters in 95% of the epochs. The root-mean-square error (rmse) in these directions is in the order of 50 cm. A moderate bias in the cross track direction is observed, which could be a result of multipath from the vehicle itself (given the fact that the antenna is located asymmetrically on the roof, close to the right side of the vehicle). However, despite this bias, and given the fact that lanes on Dutch motorways are 3.5 meters wide, the availability of a SF-PPP lane identification system would be about 99% for this dataset.

BIOGRAPHIES

Peter de Bakker obtained his MSc-degree in Aerospace Engineering at Delft University of Technology in the Netherlands and is completing his PhD-research on Precise Point Positioning and Integrity Monitoring.

Victor Knoop has a Tenure Track position as Assistant Professor at Delft University of Technology since 2012, at the department Transport and Planning. His general activities relate to traffic flow modelling and network management.

Christian Tiberius is an associate professor at Delft University of Technology. He has been involved in GNSS positioning and navigation research since 1991, currently with emphasis on data quality control, satellite-based augmentation systems, and precise point positioning.

Bart van Arem is a full professor Transport Modelling at and chair of the department Transport and Planning at the Faculty of Civil Engineering and Geosciences at Delft University of Technology since 2009. His research interest focuses on modelling driving behaviour and traffic flows in Intelligent Transport Systems.

1. INTRODUCTION

Modern intelligent transport solutions can improve traffic flow on motorways. One of the requirements for more advanced motorway traffic control is that lane-specific observations can be made, and vehicles can
be provided with lane-specific control measures. Additionally, lane identification on motorways may be required for next generation car navigation, and advanced driver assistance in general (e.g. lane identification can help drivers navigate more easily over complex intersections). SF-PPP can provide sub meter accurate positions using relatively cheap hardware and without the need for expensive additional infrastructure (Tiberius, 2003; Van Bree et al., 2011). This makes the SF-PPP method very well suited for lane identification of vehicles on motorways. Besides an accurate current position of the vehicles an accurate map of the lanes on the motorway is also required. Such maps might be available from a database of the road network, but are not always detailed enough or of sufficient quality. Theoretical derivations indicate that the lanes of the motorway can in fact be mapped using the same SF-PPP results from a number of previous runs over the motorway (Knoop et al., 2012). This finding is especially important when accurate maps are not available from another source, and also it enables a system that grows naturally to include more and new roads and adapts automatically when road layout is (temporarily) changed.

In September and October 2012 a measurement campaign was performed to test the proposed method. To this end a test vehicle was equipped with a single frequency GPS receiver representative of an automotive type of GPS chip. Over a period of approximately two weeks the car was driven 100 times up and down a 5.5 km stretch of the A13 motorway. Knoop et al. (2013) presented the first promising road and lane estimation results based on this dataset. This contribution takes advantage of the considerable dataset to analyze the quality of the SF-PPP solution in more detail and obtain statistically significant estimate of the success-rate for SF-PPP lane identification, reexamines the estimated lanes by comparing them to accurate roadmaps, and identifies some recommendations for improvement.

2. METHODOLOGY

This section describes the methodology used for this study. It gives a brief introduction to the SF-PPP method and the used approach for road and lane estimation.

2.1. Single Frequency Precise Point Positioning
The SF-PPP algorithm developed at Delft University of Technology combines GPS L1C/A pseudo range and carrier phase measurements with precise predicted satellite orbits from the International GNSS Service (Dow et al., 2005), real-time satellite clock offsets from the REal-Time CLock Estimation (REITCLE) system from the German Space Operations Center / German Aerospace Center (Van Bree et al., 2009) and predicted ionosphere maps from the Center for Orbit Determination in Europe together with the corresponding differential code biases (Schaefer et al., 1998). Troposphere delays are corrected using the (a-priori) Saastamoinen model (accurate to decimeter level in local zenith direction). The estimated unknown parameters consist of the 3 receiver coordinates and clock offset (both estimated each epoch without using a dynamic model) and the carrier phase ambiguities which are kept constant (but not fixed to integer values). For more details on the SF-PPP method the reader is referred to Van Bree et al. (2011).

2.2. Lane Estimation
To create an accurate map of the lanes of the motorway from the data, the following two step method is applied. The first step is to model the curvature of the road itself from all runs over the road, then the lanes are mapped in a second step.

In order to map the carriageways they are divided in sections of about equal length (here 10m). For each of these sections a second order polynomial is fitted to all GPS positions available for that particular section, while constraining the endpoints to form one continuous road (much like a quadratic spline, but without constraining the derivatives at the nodes). In the second step the lanes are estimated at regular intervals (here again 10m) along the fitted polynomial. For each run of the test vehicle the point where it crosses a line perpendicular to the road is determined by interpolation. This gives a 1 dimensional distribution of all lateral crossings. This sample-distribution is thought to be drawn from a multimodal normal distribution with a mode for each lane of the motorway weighted by the relative share of the flow in that specific lane (the lane flow distribution). Generally the right most lane (the slow lane) is used most often in quiet traffic conditions. The fit of this multimodal distribution is then adjusted by varying the lane flow distribution, the standard deviation of the normal distribution, and the offset of the first lane
from the fitted polynomial to give an optimal fit to the sample distribution. The offset of the first lane for which this optimum is reached then gives the positions of the lanes. The width of the lanes can either be kept constant (which it is in this paper) or it can also be determined in the optimization.

3. MEASUREMENT CAMPAIGN

Knoop et al., (2012) determined that at least 100 passes are required for a single stretch of road to determine the position of the lanes with sufficient accuracy. In order to collect the necessary GPS measurements, a car was equipped with a single frequency u-blox TIM LP (evaluation kit) receiver (costing in the order of $100 and being representative of an automotive type of GPS chip) connected to a Tri-M Big Brother patch antenna (costing about $20), see figure 1 (left pane). During a period of approximately two weeks in September and October 2012 the car was driven the required number of laps on the A13 motorway between exits number 10 (Delft-Zuid) and 11 (Berkel en Rodenrijs), see figure 2. Different time frames were selected during the day, considering the ionosphere and traffic activity as well as the number of visible satellites in the sky. A satellite elevation cut-off angle of 5 degrees was used, and data was logged at 10Hz. Each lap consists of two parts of approximately 5.5 km of three lane motorway, and two parts of the underlying road network (intersections, roundabout), which we did not consider for the lane estimation but are included in the SF-PPP quality analysis. The roadway is fairly flat and there are no high rise buildings along the road, which might disturb the signal. However, the conditions are still considered operational as many overhead signs, street lights, trees and other traffic may cause temporary signal losses and reflected signals.

The precise satellite orbits, satellite clock offsets, global ionosphere maps and differential code biases were collected in the office, while the car was collecting the GPS measurements, and the SF-PPP processing took place after the fact, but strictly simulating real-time positioning.

![Figure 1. (left pane) The u-blox TIM LP single frequency receiver evaluation kit and Tri-M Big Brother patch antenna used during the car tests. (right pane) The test vehicle equipped with two reference antennas, one at the front and one at the back, and the patch antenna in between attached to a wooden beam on the roof of the car.](image)

Besides the mass-market receiver, two high-end dual frequency receivers and antennas are also installed on the vehicle, see figure 1 (right pane) and table 1. For 54 laps, the data from both high end reference receivers was processed with NETPOS (www.kadaster.nl/rijksdriehoeksmeting/netpos/ in Dutch). NETPOS features a network of 35 permanent GPS reference stations across the country (inter-distances on average about 40km), and a relative (or differential) position solution is obtained for the moving receiver on the vehicle with respect to the network (in fact similar to the classical baseline set-up, with a GPS reference station at a few km distance from the vehicle, though with the network processing more advanced error modelling is involved). This results in a reference track with an accuracy on the cm scale.
Table 1. Used receiver, antennas and data-rate

<table>
<thead>
<tr>
<th>Receiver</th>
<th>Antenna</th>
<th>Logging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trimble R7-A</td>
<td>Trimble Zephyr Geodetic</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Trimble R7-B</td>
<td>Trimble Zephyr Geodetic</td>
<td>10 Hz</td>
</tr>
<tr>
<td>u-blox TIM LP</td>
<td>Tri-M Big Brother</td>
<td>10 Hz</td>
</tr>
</tbody>
</table>

Figure 2. The test was performed on a 5km stretch of the A13 motorway between Delft (North) and Rotterdam (South). The Southbound tracks are indicated with a red line; Northbound tracks are blue.

4. RESULTS

This section first provides a detailed analysis of the positioning results followed by results of the road and lane estimation.

4.1. SF-PPP Results

First some statistics are provided for the entire measurement campaign, then a detailed accuracy analysis is provided for a (considerable) subset of the data. As is well known for general GNSS positioning, a minimum of 4 satellites are needed to solve the 3 unknown coordinates and the unknown clock offset of the receiver. A minimum of 5 satellites are needed to have some redundancy, and in practice it turns out that 5 is also the minimum number of satellites needed to compute a precise position (with only 4 satellites in view a horizontal position bias of 3 to 4 meters was observed). Figure 3 (left pane) shows a histogram of the available number of GPS satellites for each measurement epoch. The total number of epochs of 6.0e5 is equal to the measurement duration (some 16.7 hours) divided by the measurement interval of 0.1s. Epochs for which no position solution could be computed have been added to the left-
most column (<4 satellites). The axis on the right-hand side shows the percentage of the total number of epochs. The figure reveals that 8 to 12 satellites were tracked for most epochs. For 99.21% of the epochs at least 5 satellites were available, enabling precise positioning for these epochs. The following quality analysis will focus on epochs where at least 5 satellites are available.

Figure 3. (left pane) Histogram of the available number of GPS satellites for all measurement epochs and also as a percentage of total number of epochs. (right pane) Average number of satellites for different segments of the track. The size of the circles corresponds to the number of data samples, while the colour indicates the average number of available GPS satellites for each track-segments.

To analyse the performance for different parts of the track, the track was split in 40 segments of equal length; figure 3 (right pane) shows the average number of available satellites for each segment. Each circle represents a segment of the track with the size of the circle indicating the number of data samples in that track segment, here between 6e3 and 18e3. The southbound and northbound carriageways are offset in East-West direction for better visibility. The larger circles at both ends of the track are due to the lower speeds and traffic lights at the intersections. Besides these segments the number of data samples is quite constant. The colour of each circle indicates the average number of available satellites for that segment of the track. From the range of the colour bar it can be seen that the number of satellites only varies slightly with the track segment from about 9 to 10. The minimum number occurs just after the start of the off-ramp from Northbound carriageway. At this part of the track, traffic leaving the motorway (including the test vehicle) has to move two lanes over to the right bringing them much closer to the trees at the side of the road at this point. This might explain the slightly lower average for this segment.

For 54 of the total 112 laps an accurate reference track was computed with the NETPOS service, covering 48% of the total number of epochs. However, given the operational conditions of the moving vehicle, the computed reference positions are not always of sufficient accuracy, i.e. at cm level, to act as a ground truth for the following quality analysis of the SF-PPP solution. To guarantee the accuracy of the ground truth the following two criteria were applied:

- The formal standard deviation of the solution (provided by NETPOS) should be below 5cm in each direction.
- The distance between the computed positions of the two reference receivers should not deviate from the known distance by more than 5cm.

The NETPOS solution fulfils these criteria about 52% of the time (so 25% of the total number of epochs). This gives a total of 1.5e5 epochs that are considered in the following quality analysis. Many of the epochs that do not fulfil the criteria occur in stretches of consecutive epochs, which suggest that undetected cycle-slips corrupt these reference positions.

Figure 4 shows a histogram of the SF-PPP horizontal position errors in 2 directions. In the left pane these are the North and East directions, in the right pane the along-track and cross-track directions. For the
epochs under consideration, the error in each of the horizontal directions was never larger than 3.5m and on average much smaller. A close comparison of the left and right pane reveals that the errors in North and East direction seem quite symmetrical while the errors in especially the cross-track direction are a bit skewed. This is confirmed by the statistics in table 2, which shows the mean position error in each direction on the top row. The cross-track direction shows a bias of 30cm, while all other horizontal directions are much less biased. The table also shows that the standard deviation (std) in the cross-track direction is smaller than the other horizontal directions which leads to root-mean-square errors (rmse) of about 50cm in each horizontal direction. The more systematic behaviour in cross-track direction might be due to multipath from the roof of the car itself, given the fact that the antenna was positioned asymmetrically on top of the car (i.e. the antenna is close to the right side of the car). As expected, the errors in Up direction are larger than in each horizontal directions, but they are not critical for lane identification.

![Figure 4](image)

Figure 4. Histogram of the horizontal position errors in 2 directions (left pane) North and East (right pane) along and cross-track direction. The position of each dot in the figure indicates the position error in these directions, while the colour indicates the number of occurrences.

<table>
<thead>
<tr>
<th></th>
<th>Cross-track [m]</th>
<th>Along-track [m]</th>
<th>North [m]</th>
<th>East [m]</th>
<th>Up [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean error</td>
<td>0.30</td>
<td>0.01</td>
<td>0.07</td>
<td>0.00</td>
<td>0.34</td>
</tr>
<tr>
<td>std</td>
<td>0.43</td>
<td>0.49</td>
<td>0.50</td>
<td>0.52</td>
<td>1.08</td>
</tr>
<tr>
<td>rmse</td>
<td>0.53</td>
<td>0.49</td>
<td>0.51</td>
<td>0.52</td>
<td>1.13</td>
</tr>
<tr>
<td>95\text{th } percentile</td>
<td>1.06</td>
<td>1.03</td>
<td>1.02</td>
<td>1.06</td>
<td>2.15</td>
</tr>
</tbody>
</table>

Given the North-South orientation of the test track, the presence of a cross-track bias and the absence of a bias in the Eastern direction might seem surprising, but can be explained with figure 5. Figure 5 again shows statistics for 40 track-segments of equal length. Compared to figure 3 (right pane) the circles are now much smaller, and show more variation on the straight parts of the track (note that the circles on the Southbound track are smaller than those on the Northbound track). This indicates that the availability of an accurate reference position is not only much lower in general than the availability of the SF-PPP solution, but also much more sensitive to the environment of the road. The colour of the circles in the left pane of the figure 5 shows the mean error in Eastern direction for each of the track-segments. The mean error changes sign when the car turns at the Northern and Southern end of the track and, as confirmed by the information in table 2, the mean error evens out over the complete track. This is consistent with a bias in the cross-track direction, which changes direction with the vehicle itself.

In the middle pane the colour of the circles corresponds to the rmse in cross-track direction. It shows that at the segments where the availability of the reference position is lower (the smaller circles)
the rms of the SF-PPP solution also tends to be larger, although there are exceptions to this rule. This might suggest that even larger errors in the SF-PPP solution are masked by a lack of an accurate reference at those epochs. However, a visual inspection of the SF-PPP solution drawn on a map of the road does not confirm this suspicion. Instead it shows that under difficult conditions the accuracy of the reference position degrades much more dramatically than does the accuracy of the SF-PPP solution. The right-hand pane in figure 5 shows the percentage of epochs that the cross-track error is smaller than 1.75m (half the minimum width of the lanes on the Dutch motorways). This percentage can be interpreted as the success-rate of SF-PPP lane identification if there is no error in the map of the lanes itself. Even for the most challenging segment of the road, this success-rate stays at 95%.

![Figure 5. Statistics for different segments of the track. The size of the circles indicates the number of available data samples per segment. Smaller circles along the track indicate missing epochs. The colour of the circles corresponds to (left pane) the mean error in Eastern direction, note that it changes sign when the car turns, (middle pane) the rms of the cross-track error, and (right pane) the percentage of epochs with cross-track error smaller than 1.75m (half of the lane-width).](image)

The convergence period for SF-PPP is very short and the accuracy improvement is not as pronounced as it is in the case of conventional dual frequency PPP (Van der Marel and De Bakker, 2012). SF-PPP offers a position accuracy close to the final accuracy already from the start. As a result convergence can easily be drowned out by other effects, such as a change in the available satellites or multipath, especially for a moving platform such as the test vehicle. Therefore, the first part of the Northbound carriageway, just after the test vehicle has merged with the traffic on the motorway, is selected for a convergence analysis. The data for this part of the track is relatively homogenous as can be seen from the different panes of figure 5. The data was processed again, now restarting the positioning filter each time the vehicle passes this point on the road. Figure 6 (left pane) shows the position errors for the first 600 epochs for each of these runs in North, East and Up directions. Note: the along and cross-track directions are almost equal to, respectively, the North and East directions for this part of the track, although figure 5 might give a different impression due to the different scaling in North and East directions. Figure 6 (left pane) shows a moderate convergence in each direction as the distribution of the time series becomes slightly more narrow over time. Remember that the position is estimated purely kinematic mode, i.e. no dynamic model is used.
The horizontal directions th convergence is confirmed by figure 6 (right pane), where the dark blue line shows the rmse over all runs for each epoch individually and decreases slightly over time, the cyan line gives the rmse over all epochs. However, the rmse in Up direction does not show any convergence. During the convergence period the quickly changing errors, such as (pseudo range) measurement noise and multipath from the surroundings of the car, are averaged out by keeping the ambiguities constant, while the slowly changing errors remain much the same. As such the initial position solution can be said to converge to the biased solution, reducing the noisy behaviour to some extent, but only marginally reducing the total position error. In the up component, where the systematic errors are larger, the convergence cannot be observed at all in figure 6 (right pane). To make the convergence more perceptible, an attempt is made to subtract the bias from each time series. For a recursive least squares algorithm as is used in the SF-PPP software, the best available estimate of the position bias is the final position error for each time series. After subtracting this final value per time series, and again taking the rms value for each epoch over all runs results in the red lines in figure 6 (right pane). The magenta line gives the rmse over all epochs. Now the Up component does show some convergence and (due to subtraction of the final value) keeps on decreasing to zero. Based on figure 6 (left and right pane), some basic time series simulation, and previous experience the convergence period is thought to extend over the first 100-200 epochs, i.e. 10-20s. All apparent convergence after this period is suspected to be an artefact of the bias subtraction method.

Before moving on to the lane estimation results, two more figures are provided here to give an indication of the quality that can be expected of the estimated lanes. Figure 7 (left pane) shows the mean cross-track error for the different segments. Since there is no way of eliminating this bias in the lane estimation procedure, the estimated road and lane positions will contain a bias in the same order of magnitude, i.e. 15-20cm for well observed sections and up to 50-60cm for poorly observed sections. Figure 7 (right pane) shows the positioning precision of the cross-track direction by means of the standard deviation. Since the road and lanes are estimated from 100 crossings of the car over each segment the precision of the estimated road and lanes is expected to be about 10 times better, i.e. 3 to 6cm. These results also indicate that the accuracy of the road and lane estimation will not improve much by further increasing the number of laps unless the bias can also be varied (e.g. by placing the antenna at different positions on the roof of the car).
4.2. **Lane Estimation Results**

This analysis focusses on the two parts of the track (Northbound and Southbound) where the test vehicle is driving on the motorway, i.e. the intersections are not considered. This is done both because the goal of these experiments was lane identification on the motorway, and because the test vehicle is always driving on the same lane at the intersections. The Northbound and Southbound carriageways are divided in 10m segments and to each segment a second order polynomial is fitted. A visual inspection of the fitted piece-wise polynomial shows that this provides a curve that accurately follows the road and is sufficiently smooth.

The lane estimation performs without problems and an example for a 14m section of the road (both carriageways) is provided in figure 8. The top pane shows a map for this section of the motorway with three lanes in each direction taken from the ‘digitaal topografisch bestand’ (DTB) from Rijkswaterstaat, the Dutch ministry of infrastructure and the environment (http://www.rijkswaterstaat.nl/zakelijk/zakendoen_met_rws/werkwijzen/gww/data-eisen/digitaal_topografisch_bestand/) in Dutch). The lane separations on the DTB (drawn with black solid and dashed lines) are accurate to 5cm or better, and the different parts of the road are identified in the figure. In the middle pane the computed SF-PPP tracks from all 100 laps of the test vehicle are drawn on the map (thin coloured lines). The lane in which the car was driving can be identified quite clearly for each track. The fast lane in Southbound direction (Lane 3) was not used at this part of the road, and for several tracks the car has just started to change lanes. The bottom pane shows the lanes as they have been estimated from these tracks in Northbound (blue) and Southbound (red) directions, again drawn on top of the DTB map. The figure shows that the estimated lanes in this example are very close indeed to the lanes from the DTB. The Northbound lanes are biased by some 20cm, the Southbound lanes are even closer.
Figure 8. (top pane) 5cm accurate map from the ‘digitaal topografisch bestand’ from Rijkswaterstaat the Dutch ministry of infrastructure and the environment for 14m of the A13 motorway. (middle pane) The computed SF-PPP tracks (thin coloured lines), and (bottom pane) the estimated lanes in Northbound (blue) and Southbound (red) directions drawn on the map.

Note that although the test vehicle did not drive in Southbound Lane 3 all three lanes are accurately estimated anyway. However, some examples were encountered where the lane estimation procedure was actually fitting the hard-shoulder and the two right-hand lanes instead, since no logic is implemented yet to distinguish these two cases. However, when all three lanes are occupied this does not occur.

From figure 7 (left pane) it is obvious that not all estimated lanes fit as well as this example. However, from a visual inspection of different parts of the road (no numerical data was available) the final lane estimation seems to perform somewhat better than figure 7 (left pane) predicts. This suggests that including all 100 laps (remember that figure 7 only includes about 25% of the data) reduces the mean error in cross-track direction, but this remains unconfirmed for now.
5. **CONCLUSIONS**

A detailed analysis of the SF-PPP solution of 100 laps over a 5.5km stretch of motorway was provided. The errors in each of the horizontal directions where shown to be smaller than 1.1 meters for 95% of the epochs. The root-mean-squared errors in these directions are in the order of 50 cm. Moderate convergence of the SF-PPP solution was observed; the horizontal position accuracy improves slightly over the first 10-20 seconds. Or, in other words, the position accuracy is close to the final level, already from the start.

A moderate bias in the cross track direction (30cm) was observed, which could be a result of multipath from the vehicle itself given the fact that the antenna is located asymmetrically on the roof, close to the right side of the vehicle. This should be further be investigated by placing the antenna at different positions on the roof of the test vehicle. However, despite this bias, and given the fact that lanes on Dutch motorways are (at least) 3.5 meters wide, the availability of a SF-PPP lane identification system would be about 99% for this dataset; and still about 95% for the most challenging segments of the road.

The results show that the lanes can be successfully mapped from the data with a few dm-accuracy, and much higher precision, although larger biases where observed for some parts of the road. With these mapped lanes, vehicles can be tracked down to a specific lane with the SF-PPP method in real-time. The estimated lanes are in good agreement with the digital topographic maps of the Dutch ministry of infrastructure and the environment.

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**REFERENCES**


