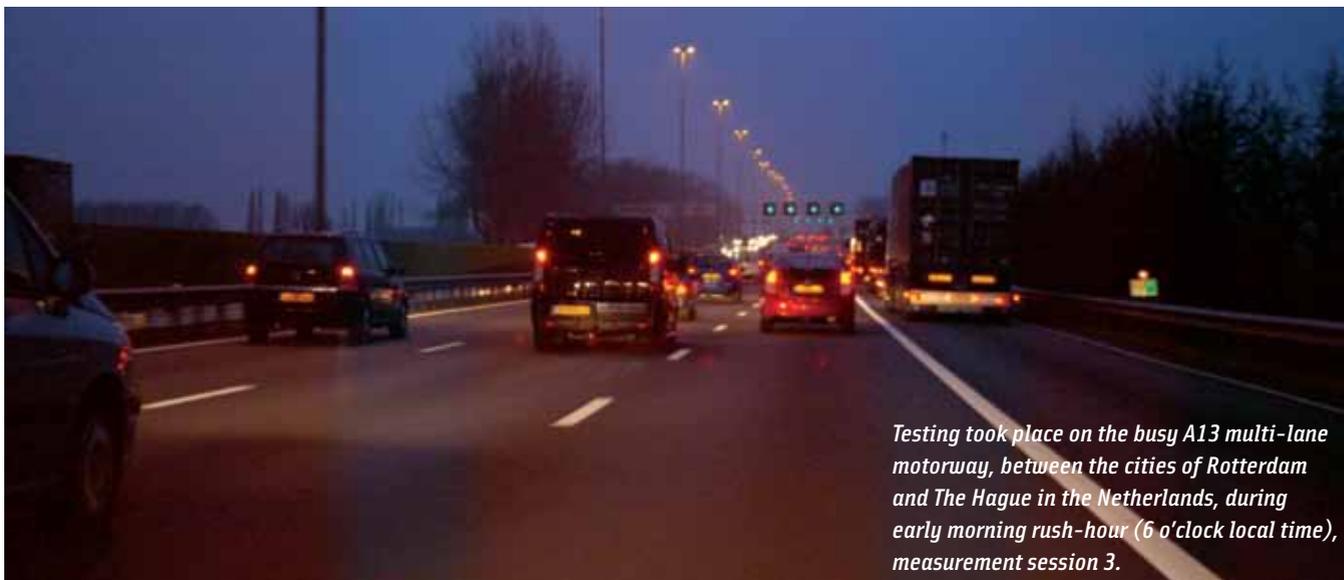


Staying in Lane

Real-Time Single-Frequency PPP on the Road



Testing took place on the busy A13 multi-lane motorway, between the cities of Rotterdam and The Hague in the Netherlands, during early morning rush-hour (6 o'clock local time), measurement session 3.

A single-frequency precise point positioning technique can provide high-accuracy post-processed results in static applications. But can it bring the same benefits to kinematic applications, such as identifying which lane a vehicle is in? Based on the results of field trials in the Netherlands, researchers at Delft University of Technology demonstrate the ability to position a vehicle in real-time to within 1.75 meters – accurate enough for lane identification.

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Next-generation car navigation may well require the ability to identify the lane in which a vehicle is operating on a motorway. This could support advanced driver assistance in general as well as the observation and study of driver behavior and traffic flow. Such road vehicle applications call for sub-meter positioning accuracy, often in real-time — all this preferably at low-cost.

In this article we will investigate whether real-time single-frequency precise point positioning (RT SF-PPP) can meet the demands set for such appli-

cations. Precise point positioning can provide improved position accuracy, as compared to standalone GPS positioning, but without the need for local or regional differential GPS (DGPS)-like infrastructure.

Static and Post-Processed vs. Kinematic and Real-Time

Researchers at Delft University of Technology have developed a real-time version of SF-PPP, based on an algorithm that uses undifferenced single-frequency pseudorange code and carrier phase observations of the user receiver in the vehicle. By combining these observations with predicted satellite orbits and global ionospheric maps (GIMs) as well as real-time satellite clock estimates, a

position solution is computed on an epoch-by-epoch basis. The result is truly kinematic, without (relying on) any modeling of the user receiver dynamics.

The performance of RT SF-PPP was extensively demonstrated for static applications in the work described in the articles by R. J. P. van Bree et alia (2009) and (2011) listed in the Additional Resources section near the end of this article. The position accuracy presented in the latter article shows a 95 percent error of about 0.30 meter in the horizontal directions, and 0.65 meter in the vertical.

These results were obtained using high-end GPS receivers. Mid-range receivers produced values that were still smaller than one meter in all directions.

These findings have led to the question: can SF-PPP deliver the position performance required for lane identification of a road vehicle, in real-time, and preferably with low-cost equipment? Low-cost refers here to a fairly simple, single-frequency GPS receiver, with a patch antenna, delivering pseudorange code and carrier phase observations, and a price on the order of US\$100 or less.

Recently, in spring 2011, we conducted a real-world kinematic trial with a vehicle on a local highway. The multi-lane motorway (A13 — pictured in an accompanying photo) used for the test is located between the cities of The Hague and Rotterdam, runs past Delft, and is one of the busiest traffic routes in the Netherlands.

The test was carried out under ordinary driving conditions. The purpose of the trial was to assess the position accuracy and to test specifically the ability to identify the lane the car is driving in.

For the test we installed low-end and mid-range receivers in rigid mounts on the test vehicle's roof, next to several antennas of high-end GNSS equipment. The latter are employed to reconstruct an accurate (centimeter-level) ground-truth for the low-end and mid-range receivers.

The high-end dual-frequency receivers used post-processed differential carrier-phase GPS corrections from a nearby reference station, namely a permanent GNSS station at TU Delft's GNSS observatory, with accurately known position coordinates in the International Terrestrial Reference Frame (ITRF2005). In this way, a highly accurate reference track was available for quantitative error analysis of the obtained PPP-results.

Single-Frequency Precise Point Positioning

The best position accuracy with SF-PPP is achieved when we can use GPS data products that are as precise as possible, that is, when we have access to the final satellite clocks and satellite orbits, ionospheric maps, and differential code biases (DCBs). These products, however, are only available to a user with a significant latency of a few days or even weeks after

the measurement epoch, ruling out real-time operation.

In *real-time* operations, we must use *predicted* satellite orbits, *predicted* GIMs, and — in particular — *real-time* satellite clock estimates. For the latter, we used the Real-time Clock Estimation (RETICLE) products from the German Space Operations Center (GSOC)/German Aerospace Center (DLR), which have been shown to deliver comparable performance as that of the International GNSS Service (IGS) final products. The RETICLE system computes clock corrections for the entire GPS constellation in real-time, currently based on a worldwide network of 37 reference stations.

In addition to the RETICLE products, we use predicted GIMs and predicted DCBs from the Center for Orbit Determination in Europe (CODE) in Bern, in order to enable real-time SF-PPP. The predicted GIMs are provided in 24-hour batches.

In the experiment described here, measurements were collected in the vehicle, and the needed data products were logged — in parallel — in the office. The actual processing took place back in the office after the fact, but strictly replaying the real-time situation. Only measurements up to the observation epoch are used (hence, filtering but no smoothing), as well as only those data products available at the very time of the observation.

We only used GPS signals with a five-degree satellite elevation cut-off angle. Statistical testing of the measurements was performed specifically on outliers and cycle slips.

Requirement for Lane Identification

In the Netherlands, one lane on a motorway is 3.50 meters wide, and for successful lane-identification, the cross-track (or lateral) coordinate of the position fix has to lie within this lane.

Assuming that a car is driving exactly in the middle of the lane and with the antenna mounted exactly on the lengthwise center-line of the car, the probability of correct lane identification can be evaluated by integrating the posi-

tion coordinate error probability density function (which in our case we assumed to be normal) from $-3.50/2$ meters to $+3.50/2$ meters (i.e., a two-sided interval about zero, where zero represents the situation in which the estimated position coordinate coincides with the true position).

For a system of advanced traffic flow monitoring, which may also provide guidance instructions to enhance traffic flow, we set — as a first guess — the required probability of correct lane identification at 95 percent, meaning that the lane location of only 5 cars out of 100 is misidentified. This leads to a 95 percent error requirement on the (lateral) coordinate of 1.75 meters.

Equipment and Installation

As mentioned, we used three classes of equipment in this test. The low end was represented by a single-frequency (L1), 16-channel GPS receiver that, on the basis of measurement accuracy, we believed to be representative of a good automotive GPS-chip today. This receiver was connected to a suitable 30-decibel gain mobile GPS patch antenna.

For the mid-range equipment we used a single-frequency GNSS receiver, configured as a 16-channel GPS L1 receiver and connected to a relatively simple patch antenna; the equipment cost here was on the order of US\$1,000.

The high-end equipment consisted of a 12-channel dual-frequency GPS receiver with a geodetic antenna that cost on the order of US\$10,000. Actually two of these receivers were used on the car primarily to reconstruct the ground truth trajectories. (For purposes of this article, our discussion of results in later sections uses data from only one of the receivers — that in the front of the vehicle. However, the performance of the other one was very similar.)

All receivers collected data at a 10-hertz rate, and only single-frequency measurements (C1 and L1) from these receivers were used for the PPP processing. Accompanying photos show the equipment installed in the vehicle and the antennas mounted on its roof.

In addition to the receivers on the car, another high-end receiver was used as a reference station, located a few kilometers away at the TU Delft GNSS observatory. This reference receiver was connected to a choke-ring antenna.

All antennas were attached to a solid wooden bar, which was rigidly mounted on the vehicle. For the experiment described in this article, only the bar at right (in the photo) was used. The patch antennas for the low-end and middle class receiver were situated in the middle of this bar, and the two geodetic antennas for the high-end receivers were at the ends of the wooden bar.

Test Set-Up

Figure 1 shows a 5.5-kilometer section of motorway selected for the trial, which stretched from entrance/exit 10 (Delft Zuid) to exit/entrance 11 (Berkele en Rodenrijs/Rotterdam Airport). We next defined four one-hour sessions during the day, considering satellite visibility and geometry, ionospheric activity, and traffic activity on the A13 motorway. These one-hour sessions are listed in **Table 1**.

During these sessions, the minimum number of satellites available above a cutoff angle of five degrees was 9, and the maximum ranged from 11 to 13.

The 5.5-kilometer section of motorway was driven forth and back, and during each one-hour session five loops of the

section were completed, yielding a total driven distance of about 57 kilometers per session. All four sessions together provided 228 kilometers worth of measurements, and close to 150,000 measurement epochs (at 10 hertz).

While driving, the car changed lanes several times, and driving speeds varied between 75 km/h (typically imposed by busy



Equipment installation inside the test vehicle



Antenna set-up on the roof of the test vehicle



FIGURE 1 Overview of the 5.5 km section of the A13 motorway between Rotterdam (at bottom of the image) and Delft (at top left in the image).

traffic) and 105 km/h (obeying, more or less, the legal limit of 100 km/h on this stretch of motorway). The total average speed, which includes stopping at traffic lights at the exits and entrances, lay around 60 km/h.

Visual Impression of Results

In this section we will present the SF-PPP results at a “global” level, primarily through visual inspection and an analysis of position solution availability.

Figures 2 and **3** present examples (snapshots) of trajectory overlays on aerial images, and thereby provide a first general impression of the SF-PPP positioning performance. These two figures represent all the position solutions of all three receivers from session 3.

During this session five circuits of this stretch of motorway were driven; so, for each color there will be five dots on either side of the road. Measurements were collected at the rate of 10 position updates per second.

In **Figures 2** and **3** the green dots represent positions determined by the low-end GPS receiver, red dots for the mid-range receiver, and yellow for the high-end receiver. Usage of different lanes can be clearly distinguished from the trajectories produced by all three receivers, and in **Figure 3** a change from the middle to the far left lane can be properly observed.

Table 2 presents data on the availability of the SF-PPP positioning results, which always exceeded 99 percent of the total number of (theoretically) available epochs.



The test-vehicle (green van in front) on the A13 multi-lane motorway; the experiments were carried out under ordinary driving conditions, here during session 4.

Measurement data can be lost due to obstruction of the satellite signal by road infrastructure and other vehicles. This motorway typically has tall lamp posts every 50 meters, and on this stretch there are 11 overhead traffic portals, of which 9 “light” ones carry electronic signs for dynamic traffic management. (A shadow of one of these signs is visible in Figure 2.) The other 2 “heavy” traffic portals carry huge, traditional road and destination signs. And directly next to the motorway, there are trees and vegetation every now and then.

Also large road vehicles such as trucks can block signals from several satellites during the tracking. And finally the quality of measurement data may be too poor to use: after detection of cycle slips and removal of outliers, too few measurements to satellites remain to be able to compute a position solution.

Kinematic Results

Centimeter-level, ground-truth trajectories have been computed (using dual-frequency differential carrier phase GPS with respect to a nearby reference station) and reconstructed for all of the receivers. Specifically, we calculated the trajectories for a stretch of the kinematic portion of the vehicle trials (one northbound drive from entrance 11 to exit 10 on the motorway, amounting to about four minutes of data), for each of the four sessions.

	date dd-mm-yyyy	start time (UTC)	end time (UTC)
session 1	16-03-2011	13:15	14:15
session 2	16-03-2011	19:30	20:30
session 3	17-03-2011	04:45	05:40
session 4	17-03-2011	10:40	11:40

TABLE 1. Four one-hour sessions with start and end times, on Wednesday, March 16, and Thursday, March 17, 2011.

Receiver	session 1 (%)	session 2 (%)	session 3 (%)	session 4 (%)
Low-end	99.73	99.75	99.72	99.73
Mid-range	99.11	100.00	99.70	99.81
High-end	99.23	99.81	99.26	99.43

TABLE 2. Availability of SF-PPP results of the three receivers during the four sessions as a percentage of the total number of (theoretically) available epochs (at a 10 Hz rate). Availability of the SF-PPP solution is very good in all sessions with all receivers. The availability is always larger than 99 percent.



FIGURE 2 SF-PPP position trajectories from one session of the field trials overlaid on aerial image: green dots represents positions determined by the low-end GPS receiver, red dots for the mid-range receiver, and yellow for the high-end receiver. The colored trajectories indicate correctly the lanes in which the vehicle was traveling at the time. Note that on the northbound stretch (right-hand side) the emergency lane has also been used – which the dynamic traffic management system permits during rush hour when this session took place.



FIGURE 3 SF-PPP position trajectories from one session of the field trials overlaid on an aerial image. This figure demonstrates a lane change to the inside lane on the left side of the northbound traffic. Green dots represent positions determined by the low-end GPS receiver, red dots for the mid-range receiver, and yellow for the high-end receiver. The trajectories correctly indicate the lanes in which the vehicle was traveling at the time.

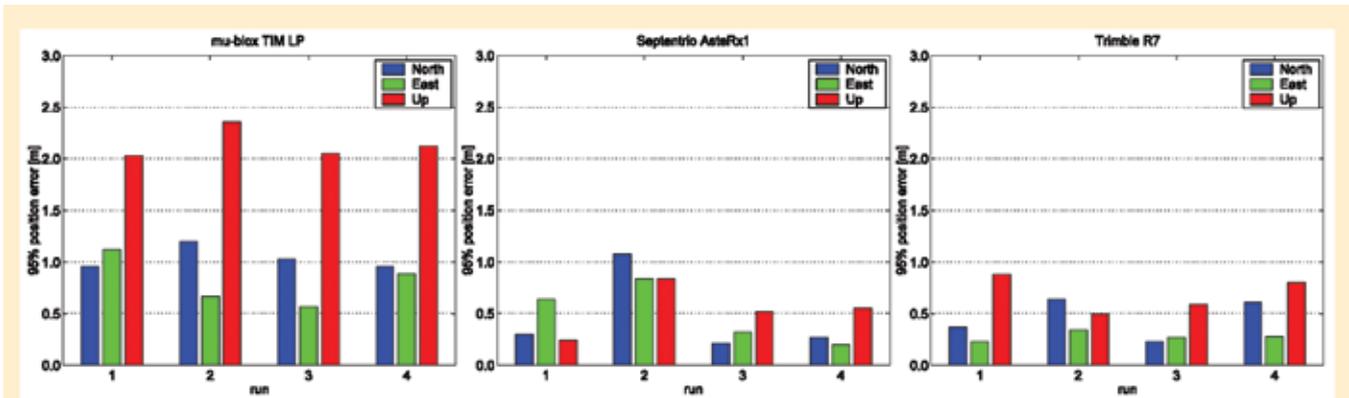


FIGURE 4 Kinematic SF-PPP results: 95% position errors, given in terms of local North, East and Up coordinates, for the low-end receiver at left, mid-range receiver in the middle, and high-end receiver at right.

The receivers' position errors are obtained by differencing the SF-PPP results with the ground truth trajectories. Position accuracy is then presented in terms of the 95th percentile (about zero) for each of the three coordinate components, north (N), east (E), and up (U). **Figure 4** presents the results for the three types of receivers tested.

Little difference in performance appears between the mid-range (with patch antenna) and high-end receivers. The low-end receiver's SF-PPP results are generally a factor 2–3 times worse when looking at the 95-percent figures, in particular in the Up-component. All receivers seem to meet the 1.75-meter (95%) requirement on the horizontal coordinates.

As noted earlier, both the low-end and mid-range receivers used a patch antenna. Nevertheless differences can be observed between the results of them. The low-end receiver likely uses (close to) the minimum bandwidth (two megahertz) for the GPS C/A-code signal, while the mid-range receiver uses a much wider band. The latter translates into capabilities for multipath mitigation by receiver signal processing (hence, smaller biases compared to the low-end receiver). In turn, that translates into higher measurement precision (smaller standard deviation values) and together in clearly smaller 95-percent error figures.

Again, we want to point out that these SF-PPP results are truly kinematic; they include no modeling of vehicle dynamics whatsoever. The measurements are processed recursively, epoch-after-epoch. Receiver position coordinates are estimated together with the receiver clock error, each epoch anew, and only the carrier phase ambiguities are propagated — as constants — from one epoch to the next (as long as no cycle slips occur).

Conclusions

A 95-percent position error of less than 1.75 meter is met in all cases for the horizontal coordinates. As a lane on a motorway in the Netherlands is 3.50 meters wide, these results show that real-time SF-PPP can be used for lane identification, when relying on fairly inexpensive equipment. The kinematic test showed a SF-PPP solution availability of larger than 99 percent.

Acknowledgments

The continued provision of RETICLE products by André Hauschild at DLR (German Aerospace Center) is acknowledged. The u-blox TIM LP receiver was kindly made available for the experiment by Mr. Sam Storm van Leeuwen.

Manufacturers

The road test used as the “low-end” equipment a TIM LP receiver (Evaluation Kit) from **u-blox**, Thalwil, Switzerland, and a Big Brother patch antenna from **Tri-M Technologies Inc.**, Port Coquitlam, British Columbia, Canada. The “mid-range” receiver was the AsteRx1 from **Septentrio Satellite Navigation NV**, Leuven, Belgium, and an AT575 patch antenna from **AeroAntenna Technology, Inc.**, Chatsworth, California, USA. The “high-end” equipment on the vehicle was represented by R7 12-channel dual-frequency GPS receivers from **Trimble Navigation**, Sunnyvale, California, USA, connected to a Trimble Zephyr Geodetic antenna. The reference receiver was also a



The green test vehicle on the A13 motorway, during session 4, when the dynamic traffic management system has closed the right most lane (actually the emergency lane) for ordinary traffic, as indicated by the red cross on the overhead portal.

Trimble R7 connected to an Ashtech/Dorne Margolin choke-ring antenna. The aerial imagery in Figures 1, 2, and 3 used Google Earth, from **Google, Inc.**, Mountain View, California, USA.

Additional Resources

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[2] Hauschild, A., and O. Montenbruck, "Real-time Clock Estimation for Precise Orbit Determination of LEO-Satellites," *Proceedings of ION GNSS 2008*, pp. 581-589, Savannah, Georgia, USA, September 16-19, 2008

[3] Kouba, J., "A Guide to Using International GNSS Service (IGS) Products," online publication at IGS website <<http://igsweb.jpl.nasa.gov/components/usage.html>>, 2009

[4] van Bree, R. J. P., and C. C. J. M. Tiberius (2011), Real Time Single Frequency Precise Point Positioning - accuracy assessment. *GPS Solutions*, DOI 10.1007/s10291-011-0228-6, 2011

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Authors



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Roel van Bree graduated in astronomy from Leiden University in the Netherlands in 1997. He worked for 10 years at TNO Defense and Security on synthetic aperture radar (SAR). Currently, he is working as a

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Peter Buist is a GNSS researcher at DUT, where he received his master's degree in the field of aerospace engineering. After eight years in the Japanese industry working on GNSS applications for space, Buist returned to Delft and is working on integrated attitude determination and relative positioning. 

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