GPS WORLD

Integrity Hits the Road

Low Cost, High Trust for Mobile Units

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By: Philipp A. Boysen, Hugo Zunker
GPS World

Telematics can fill the constantly growing need of vehicle fleet operators to extend electronic resource management systems to their mobile units and staff. Today, stand-alone GPS technologies serve most of our customers' positioning needs fairly well. But limited sky visibility caused by buildings, trees, tunnels, and other obstacles produces frequent interruptions of the positioning information. Galileo, when used in the future jointly with GPS, will improve this situation, but for an increasing number of sophisticated applications, even a combined GPS-Galileo service will not deliver the required continuity and reliability.

Therefore, integration of additional sensor information and the provision of a Horizontal Trust Level (HTL) constitutes a key technology for mobile-terminal applications that are dependent on continuous, EGNOS/WAAS-like quality of service in terms of positioning and integrity, in particular under limited visibility of these augmentation satellites. For example:

Service Vehicles. Public road-service vehicles, especially winter snow-removal and road-cleaning operators, form a key potential user segment, with fleet management, driver support, and documentation of road service tasks as the main features. Accuracy and continuity improvements, as well as HTL information, can assist the driving task and offer the possibility of legal, trustable data recordings.

Hazardous Materials. Tracking and monitoring the transport of dangerous goods (such chemicals), and high-value shipments, applies vehicle surveillance according to predefined routes, corridors, and exclusion areas. The HTL information will enable the enforcement of restrictions and regulations for these specific transports.

Road Tolling. This application will provide an OEM module for vehicle onboard units for flexible road tolling, as well as support for fleet operators concerning verification and control of official tolls. The accuracy and continuity improvements, as well as the HTL information, enables the trustworthiness of the recorded data.

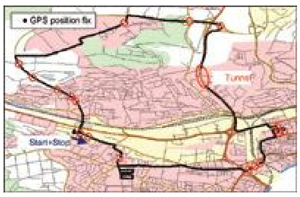


Figure 1: Availability of position fixes during a large circular course driven in the city of Ulm, using a standard GPS-only receiver.

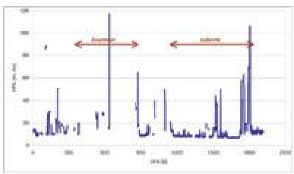


Figure 2: Six-sigma Horizontal Protection Level (HPL) obtained during the driving course shown in Figure 1

Figure 1 shows typical gaps of three seconds and more in position availability during a 30-minute route comprising downtown and rural portions. Availability of the integrity service provided by the satellite-based augmentation system (SBAS) is even further reduced, as shown in **Figure 2**, showing the Horizontal Protection Level (HPL) in meters, logged during the same course.

The HPL describes the accuracy of the position fix, using not only correction terms such as ionospheric parameters, clock offsets and ephemeris data, but also information about the level of errors remaining after applying these corrections. Originally defined for aviation purposes, HPL is the 6-sigma radius of the horizontal circle around the true position, meaning that it contains the computed fix with a probability of 99.99999 percent (as opposed to the 2-sigma probability of 95 percent often found in technical descriptions, or the 1-sigma standard deviation probability of 68 percent) — under the assumption of normal distributed errors and aviation conditions. The SBAS — for example, the European Geostationary Navigation Overlay Service (EGNOS) and the Wide Area Augmentation System (WAAS) — provides corrections and variance data.

In Figure 2, the first 900 seconds correspond to the downtown part in the lower quarter and lower right corner of Figure 1. The large gaps of HPL data are caused by bad visibility of the geostationary SBAS satellite, often with still enough GPS satellites in view to compute a position fix. The spikes, in contrast, can be caused by two different effects: on one hand, the SBAS data is attributed with an expiry time and degradation parameters, leading to increasing values of the HPL during short SBAS reception gaps and complete disabling of the functionality after long reception gaps; on the other hand, bad satellite geometries, which cause large positional errors, are also correctly reflected by large HPL values.

This indicates that whenever continuity of position information or reliability information is of importance, some kind of augmentation complementing GPS/EGNOS is needed. Within the framework of a project funded by the European Space Agency (ESA) to demonstrate the benefits of the EGNOS service, Euro Telematik AG developed a low-cost sensor hybridization incorporating velocity and turn rate information with the GPS/EGNOS position.

Any solution suitable for mass market by neccessity must utilize the least-expensive sensors — those subject to significant drift, nonlinearities, noise, and other limitations, resulting in noticeable decrease of accuracy in the inertial mode. Our challenge was to find an algorithmic solution that is robust to these effects and still provides accurate results.

Hybrid Concept Several options can determine vehicle heading and velocity. We selected a system that mixes information from additional sensors and vehicle data. It uses an EGNOS-capable GPS receiver, a single low-cost micro-electromechanical systems (MEMS) turn-rate sensor, and vehicle speed information, the latter derived either from the tacho-meter signal or from the controller area network (CAN) bus.

Figure 3 gives a system overview. The sensor unit conditions and preprocesses the velocity and turn-rate data and connects to a serial port of the GPS/EGNOS receiver. The sensor-hybridization algorithm retrieves this data and obtains the position and accuracy information from the positioning engine of the receiver. Based on this, the system generates a hybrid position fix and formats it as a standard NMEA sentence. The application process, designed to work with the standard National Marine Electronics Association (NMEA) protocol, can exploit the hybrid position fix without any adaptation.

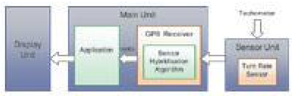


Figure 3: Block diagram of the complete system

To obtain this sensor hybridization, the sensor unit must be installed and the sensor hybridization software added to the GPS/EGNOS receiver.

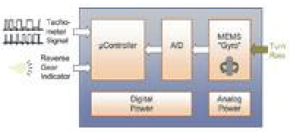


Figure 4: Block diagram of the sensor unit

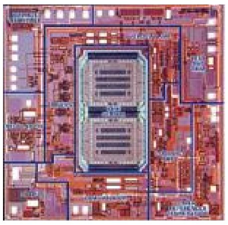
Figure 4 shows the components of the sensor unit, with its central elements the MEMS turn-rate sensor and a small microcontroller, performing not only the communication with the main unit, but also acquiring the speed signal from the tachometer and the backward indicator signal — that is, the back-up light.

The tachometer signal can be of different types: either a pulse-rate signal or a duty-cycle signal, depending on the vehicle. For newer vehicles equipped with a CAN bus according to the Vehicle Data Interface standard, sometimes no conventional tachometer signal is generated. In these cases the speed information can be obtained using a CAN controller module located directly within the main unit, without needing to adapt the sensor unit to the specific tachometer signal.

Cost. The most expensive component used within the sensor unit is the MEMS turn-rate sensor, with a price tag of a few tens of dollars per piece. In contrast to mechanical solutions, it is not only immune to vibrations, being a solid-state device of a few millimeters in size, but is also resistant to high accelerations, that can occur especially during assembly of the sensor unit.

LOW-COST sensor unit used for the fleet management work described here (courtesy of Euro Telematik)

On the other hand, it exhibits significant signal noise and a temperature-dependent and sensor-specific zero offset, to mention only the two most dominant unpleasant characteristics. To keep the production costs low, the techniques used to compensate for these characteristics must be able to automatically adjust their parameters to the signals of the specific MEMS sensor.



MEMS turn-rate sensor (courtesy of Analog Devices)

Algorithm Design Once acquired, the sensor signals must be integrated with the position fixes obtained from the GPS receiver. The algorithm must deliver a position fix and an equivalent to the HPL. A simple method often used for sensor hybridization is dead reckoning based on extrapolation; a more sophisticated solution is based on Kalman filtering.

Simple Dead Reckoning. As long as position fixes are obtained from the GPS receiver, they are used without further processing or consideration of the other sensors' signals. Whenever the GPS signal shows outages due to satellite maskings, the algorithm switches to usage of those signals obtained from the sensor unit to compute the position and heading, continuing from the last received GPS position fix.

Figure 5 shows one example of multipath effects in the realm of road applications.

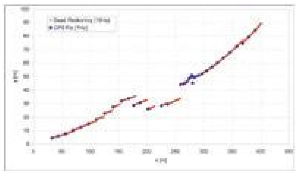


Figure 5: Discontinuities in position solution obtained by simple dead reckoning hybridization under severe multipath conditions (different scales for x and y axis)

An erratic behavior of the position fixes can be observed while slowly passing a truck on a multi-lane road. These position fixes will, for instance, not enable distinguishing between lanes or detecting vehicles leaving the road. These applications clearly require a more sophisticated approach for sensor hybridization.

Using an extrapolation-based algorithm, the computation of an HPL equivalent during phases of HPL unavailability must be done in a conservative manner. Since the variance of the vehicle sensors is known, it can be attributed to the measurements of speed y and turn rate w. This leads to a linear increase of the maximum variance for the measured data, which contributes integrative to the position's and heading's variances in quadratic order.

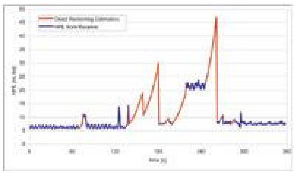
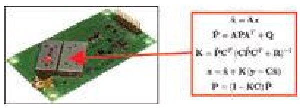


Figure 6: HPL estimation obtained by a simple dead reckoning method during SBAS-satellite maskings

With the next valid GPS position fix, the HPL can be reduced to the level obtained with this measurement. The form of the resulting HPL for a short test drive can be seen in **Figure 6**, where phases with a valid HPL are shown in blue, and phases without an HPL are shown in red, revealing the second order behavior for a linear extrapolation model, based on a conservative estimation of sensor accuracies. Like the HPL from Figure 2, it gives the radius in meters around the true position, that contains the computed position fix with a 6-sigma level, meaning a probability of 99.99999 percent.

To be strictly consistent with this number, it is not valid to mix GPS position fixes with an HPL extrapolation based on the inertial sensors. So whenever the computation of the original HPL value by the receiver is interrupted due to bad visibility of the geostationary SBAS satellite, even with enough GPS satellites still in view to compute a GPS-only position fix, one has to completely switch to the dead-reckoning solution. This leads to dramatically reduced performance of the overall system for applications requiring a measure of confidence like the HPL.

Kalman Filter. Using a Kalman filter for the sensor hybridization provides one way to overcome the limitations in continuity and accuracy of the simple dead-reckoning approach. This affords the opportunity to couple GNSS and sensor data, either on a pseudorange level (tight coupling) or position level (loose coupling).



Kalman filter sensor hybridization is directly integrated in the GPS receiver, requiring no adaptation on the application level to benefit from continuous positioning. Photo courtesy of u-blox AG.

The tight coupling has the advantage of continuing to exploit information from less than four satellites, even if a position solution from the GPS/EGNOS receiver is not possible. Its drawbacks are that it requires a very large Kalman filter and substantial processing power, and that any solution is quite specific to a particular receiver brand. Loose coupling requires a smaller Kalman filter, placed after the position solution. Thus it can operate with any GPS receiver on any host platform. For this activity, we decided to implement a loose coupling algorithm.

$$\mathbf{y} = (x_{GPS}\ \ y_{GPS}\ \ v_{GPS}\ \ \psi_{GPS}\ \ v_{vehicle}\ \ \dot{\psi}_{vehicle}\ \ \ldots)^T \qquad (1)$$

$$\mathbf{x} = (x\ \ y\ \ v\ \ \psi\ \ \dot{\psi}\ \ \ldots)^T \qquad (2)$$

$$\hat{\mathbf{x}} = \mathbf{A}\mathbf{x} \qquad (3)$$

$$\hat{\mathbf{P}} = \mathbf{A}\mathbf{P}\mathbf{A}^T + \mathbf{Q} \qquad (4)$$

$$\mathbf{K} = \hat{\mathbf{P}}\mathbf{C}^T(\mathbf{C}\hat{\mathbf{P}}\mathbf{C}^T + \mathbf{R})^{-1} \qquad (5)$$

The discrete Kalman filter incorporates the construction of a system-state vector **x** and measurements vector **y** , with at least the components listed in **Equation 1** and **Equation 2**, as well as the linearized system model matrix **A** and the description of how to derive the measurements from the system state vector, also using a matrix **C**. The filter additionally determines the state covariance matrix **P** in every iteration, using the measurements covariance matrix **R**, and a covariance matrix **Q** reflecting the errors introduced by the model chosen and the computational limitations.

The computation combines a prediction step, **Equation 3** and **Equation 4**, and the incorporation of the measurements, **Equation 5** to **Equation 7**. $\hat{\mathbf{y}} = \mathbf{C}\hat{\mathbf{x}}$ describes the prediction for the measurements vector **y** .

By adapting the used matrices **A**, **C**, **R,** and **Q** in every single iteration step, reflecting not only the changing number of measurements, but also the varying characteristics of the sensors and the system model, we can effectively influence and fine-tune the behavior and performance of the filter, forming an enhanced Kalman filter (EKF).

Figure 7 demonstrates the smoothing capability of the Kalman filter on a course around one block of houses, driven three consecutives times, with changing severe multipath conditions, in comparison to the GPS-only solution.

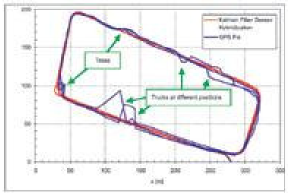


Figure 7: Comparison of position fixes obtained by GPS-only and by Kalman filter sensor hybridization on a racetrack-like course around one block, driven three times. The GPS positioning suffers from multipath effects caused by moving trucks and trees. The Kalman filter solution suppresses these multipath effects and leads to a smooth and stable positioning solution.

Even though the vehicle carried low-cost sensors, the smooth behavior and repeatable performance of the well-tuned Kalman filter is impossible to reach with a dead-reckoning approach, even when using far more expensive sensors.

The finding of the number of components for the measurements and the state model, for example the question of whether to incorporate the linear and rotational accelerations **a** and ϕ, as well as the number of iterations performed, depends on the sensors and the computational performance available, the required accuracy, and the quality of the sensor signals.

Horizontal Trust Level The use of the Kalman filter, which computes an integrated solution, always taking all available measurements into account, raises the issue of a substitute for the HPL as an accuracy measurement. As seen earlier, the HPL is defined as a measure for a pure GPS+SBAS receiver, without incorporation of additional sensor inputs. In contrast to the dead-reckoning approach with its switching between pure GPS+SBAS and pure vehicle sensor input, the Kalman filter solution often differs significantly from the pure GPS+SBAS solution, even with good satellite geometry, in fact leading to a better position solution due to reduced multipath and noise influence. Therefore, we need a replacement or extension of the HPL.

A key characteristic of the Kalman filter is the determination of the state covariance matrix P. It contains the squared variances and covariances for the position (x,y) in the first 2x2 submatrix (see **Equation 8**). This submatrix $\mathbf{P}_{xy}$ represents the two-dimensional quadratic form of the squared position error with 1-sigma scaling. As σ_x , σ_y , and σ_{xy} all are real valued and positive, and additionally $\sigma_{xy} < \sigma_x , \sigma_y$ holds, $\mathbf{P}_{xy}$ is symmetric and positive definite (SPD), describing an ellipse.

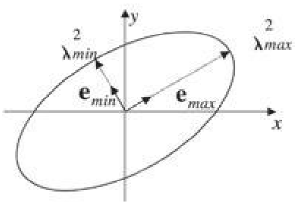


Figure 8: Construction of the error ellipse from the system covariance matrix Pxy

The larger of the two eigenvalues of $\mathbf{P}_{xy}$, λ_{max} , is found by **Equation 9**. It describes the semi-major axis of the ellipse, as depicted in **Figure 8**, and also gives the squared maximal horizontal position variance. From this, one can construct an estimation for the positional accuracy, that we call HTL, analagous to the HPL. To be comparable to the HPL, the HTL is also scaled to the same 6-sigma level by **Equation 10**.

It is essential to provide a number for the variance of the position fixes obtained from the receiver, as input to the Kalman filter's measurements covariance matrix. This could be the HPL; but as seen in Figure 2, the HPL often is not available, when not using additional communication links as, for example, Signal in Space through the Internet (SISNET) via GPRS connection.

Additionally, the aeronautical HPL cannot reflect the severe multipath effects found in road applications. Therefore, we use the receiver's own accuracy estimation number for this purpose, as we have found it for the specific receiver used to reflect the multipath errors in a very good degree.

Nevertheless, the GPS receiver in use here already has applied the correction terms provided by SBAS, thus eliminating the offsets in position found in simple GPS-only receivers, that are caused for example by satellite clock errors, ephemeris inaccuracies, and ionospheric delays.

By continuously adjusting the measurements covariance matrix according to this value, the HTL reflects a very good measurement for the actual accuracy of the integrated position solution, composed of the GPS+SBAS receiver and the additional vehicle sensors — scaled to the same level as the HPL.

Results We collected data using a relatively low-cost, commercial-grade, single-frequency GPS+SBAS receiver with the

$$\mathbf{P} = \begin{pmatrix} \sigma_x^2 & \sigma_{xy}^2 & \cdots \\ \sigma_{yx}^2 & \sigma_y^2 & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix} \qquad (8)$$

described sensor hybridization directly implemented onto it, including the HTL computation, and a high-end avionics-grade receiver for HPL comparison. The low-cost receiver delivers an internal Kalman filter solution and accuracy estimation, both used as input for our additional sensor-hybridization Kalman filter.

To eliminate smoothing effects, we set it to high accelerated mode. The high-end receiver delivers a least-squares solution including HPL as a reference, with settings for an aeronautical final approach mode. Both receivers used the same EGNOS satellite for SBAS augmentation. The tests were performed in October 2004, using the signals from the EGNOS System Test Bed (ESTB).

Figure 9: Short course driven in Ulm, Germany, for testing the HTL computation.

Separate antennas, placed 89 centimeters apart on the longitudinal center line of the car roof, fed the two receivers.

Figure 9 shows a short sample course driven for testing the HTL computation. **Figure 10** shows the computed HTL for this course, in comparison to the HPL and the GPS+SBAS receiver's accuracy estimation; HTL and the HPL are both 6-sigma level, while the accuracy estimation in contrast is only 1-sigma level.

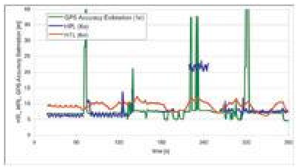


Figure 10: While the HPL is frequently interrupted, and the GPS receiver accuracy estimation exhibits steep transitions up to high values, the computed HTL possesses a smooth and continuous behavior. Being consistent with the two other measured parameters, it is scaled to the same 6-sigma-level as the HPL, and reflects the increased dynamic positioning quality compared to the 1-sigma level GPS receiver accuracy estimation.

Smooth variations of the HTL reflect the speed of the vehicle, as the accuracy of the vehicle's speed signal is not constant, and the time interval of the sensor hybridization's discrete Kalman filter directly influences the accuracy proportional to the distance traveled between two iterations. Sharper variations of the HTL in situations with a sudden large value for the receiver's accuracy estimation are also clearly found, for example around the 230-second point. As in these situations the hybridization Kalman filter automatically reduces the belief into the GPS data, its influence decreases.

Bad satellite geometry caused the four spikes in the receiver's accuracy estimation within the first 240 seconds, reflected also by the HPL (as long as available). The last spike around the 300-second point, in contrast shows a case of severe multipath. While the HPL does not show any indication of this, it clearly is reflected by the receiver's accuracy estimation, and thus also in the computed HTL.

Conclusions This loosely coupled GPS+INS sensor hybridization for road applications, using a single additional MEMS sensor, the vehicle's speed information, and a standard GPS receiver with hybridization software directly integrated as a user application, supplies a low-cost solution suitable for commercial use on a larger scale.

Further, the HTL method for computing an accuracy estimation for road applications uses the state covariance matrix elements of an extended Kalman filter. Scaled to the same level as the HPL used in aviation, and using EGNOS/WAAS corrections for improved accuracy, it takes into account the strong multipath effects and the signal outages typically found in road applications.

This solution, easily integrated into existing vehicle installations, can immediately improve the continuity and reliability of existing telematics solutions such as road-service vehicles, hazardous materials tracking, and road tolling. It adds significant value to any application requiring seamless positioning or increased reliability.

Acknowledgments This work was carried out within the framework of the EGNOS Navigation Terminals project funded by the European Space Agency, to develop and demonstrate the benefit of the EGNOS SBAS service for applications other than aeronautical; partners within the project are INOV Portugal and TeleConsult Austria.

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PHILIPP A. BOYSEN is senior systems engineer at Euro Telematik AG in the Satellite Navigation and Engineering Services department of the Aerospace division. He previously worked in numerical algorithms research at Germany's RWTH Aachen, University of Technology.

HUGO ZUNKER has worked for six years in satellite navigation systems and applications and with Euro Telematik AG for four years. He previously worked as scientific staff at the German Aerospace Centre (DLR).

Euro Telematik AG (Ulm, Germany) is a company of about 50 people, selling customer fleet telematics systems tailored for various applications in the road domain, as well as air traffic solutions and

customer-specific hardware and software developments in the aerospace domain.

Manufacturers The sensor hybridization system described uses a **u-blox AG** (Thalwil, Switzerland) RCB-LJ GPS+SBAS receiver, extended using the ANTARIS Software Customization Kit co-developed by u-blox and **Atmel Corp.** of Heilbronn, Germany, and an **Analog Devices, Inc.** (Norwood, Massachusetts) ADXRS-150 MEMS turn-rate sensor. A **Septentrio** (Leuven, Belgium) PolaRx2 receiver furnished the HPL comparison.