

Demands of the Road

An Assisted-GNSS Solution Uses the EGNOS Data Access Service

For use in billing drivers in road-user charging schemes, onboard units employing GNSS must meet stringent reliability and availability requirements, and at the same time, be based on low-cost equipment systems. The SIGNATURE unit includes an assistance service which provides ephemeris data and corrections from EDAS, optimized for user location.

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As roads become more congested, governments and regional authorities seek better ways to manage their existing networks. Road-user charging (RUC) is increasingly promoted to tackle the congestion challenge: charging drivers a fee, perhaps on a monthly billing basis, derived from the distance their vehicles have traveled, time of travel, and whether congested roads were used.

Recording trip information with

a GNSS receiver in an onboard unit (OBU) provides a convenient and flexible means to support automated fee collection. For GNSS positioning to be used as the basis for billing drivers, however, it must meet stringent reliability and availability requirements, and at the same time be based on low-cost equipment.

We have developed a prototype to provide both the positioning availability and integrity required for this

application. The Simple GNSS Assisted and Trusted Receiver (SIGNATURE) includes an assistance service that provides ephemeris data and corrections from the European Geostationary Navigation Overlay Service (EGNOS) Data Access Service (EDAS), optimized for the user location. Assistance messages are sent to OBUs that can either host an experimental receiver or a commercial-off-the-shelf (COTS) receiver. Data from the receiver is processed with application-specific navigation algorithms on the OBU that aim to improve the integrity of the position solution relative to standard solutions.

Field trials have assessed the contribution that assistance can make to positioning performance, and illustrate options for enhancing standard assistance solutions. Enhancements to assistance encompass modifications to the message content and alternative means of communications, showing the benefits and feasibility of a broadcast service. The impact of including EGNOS corrections through a broadcast assistance service in urban areas is also under investigation.

GNSS Road-User Charging

RUC has the potential to reduce congestion, lower vehicle emissions, and generate revenue streams for infrastructure improvement. It can ensure that revenues are based on actual road usage, creating a financial incentive for changing driving behavior. This might include lower overall use of private cars and, in particular, reducing peak-time travel levels in urban areas by effectively spreading out the morning and evening rush hour. RUC can also encourage commuters to use alternative forms of public transport.

To automate the process of collecting charges, electronic fee-collection (EFC) systems have been developed

based largely on dedicated short-range communications (DSRC). In a DSRC solution, a simple tag on the vehicle receives a signal when it passes a roadside beacon and a charge is computed accordingly. Cameras with automatic number-plate recognition (ANPR) technology are also widely used, mainly as an enforcement tool.

Both technologies rely on fixed roadside infrastructure. As charging schemes to date have focused on specific areas (individual cities) or road infrastructure (major motorways, tunnels, and bridges) this type of technology provides an adequate solution.

To meet future policy goals, however, this is not feasible. More extensive charging schemes covering greater areas, more road types, more classes of vehicle, and which will vary charges depending on location and time of day require a far more flexible solution. Flexible schemes require the positioning element to be onboard the vehicle. GNSS-based devices, possibly augmented with other sensors, have been identified as the best option to achieve this.

Using GNSS, the OBU tracks the location of the vehicle, and this is matched against the road network to calculate a charge. A GNSS solution can support many different charging strategies including time distance and place (TDP) based charging for road sections, geographic areas, and cordon schemes. While GNSS offers great potential, several operational and performance limitations have prevented more widespread adoption. Operationally, OBUs are relatively expensive, fraud prevention is potentially complex, and charging schemes must also accommodate infrequent users. GNSS performance is limited in terms of the ability to provide sufficiently accurate positions with high availability and integrity in all operating conditions.

To be fully flexible and to target congested areas, OBUs must work in all environments including urban areas. Urban-canyon problems, with

satellite signals blocked and reflected, are well documented. In some cases, not enough signals are available to determine a position, and when there are enough satellites, the ranges will be prone to errors and the geometry is likely to be poor. Signals are more likely to be available in the longitudinal direction of the street, but with few or no satellites on either side of the vehicle. Signal blockage is a particular problem when the GNSS receiver is started up, and it attempts to decode satellite ephemeris data. This requires around 30 seconds of uninterrupted tracking with a relatively strong signal for each satellite, and in an obstructed urban environment it may take many minutes to determine the first receiver position.

Charging schemes typically aim to charge for at least 99 percent of road usage. If a typical journey length is 30 minutes, this means that only 18 seconds with no usable position solution can be tolerated and hence time to first fix (TTFF) must be below 18 seconds, and ideally much lower.

When positions can be determined, they must be sufficiently accurate to identify the correct road segment that the vehicle was on, and they must be reliable. Reliability, or integrity, becomes critical if road users are to be charged on the basis of GNSS-derived positions. Users must have confidence that they are being charged correctly for schemes to be effective and to gain public acceptance.

Whilst GNSS-based solutions are entering the market, for example in Germany and Slovakia for heavy goods vehicles, barriers to wider adoption remain. Many countries are considering GNSS-based road pricing, and they all face similar challenges in ensuring the accuracy, integrity, and availability of a GNSS-based solution for nationwide deployment.

SIGNATURE Solution

The principal objective of the SIGNATURE project is to prototype a GNSS-

based solution for flexible road-user charging that can provide the required high integrity and high availability in a cost-effective and scalable manner.

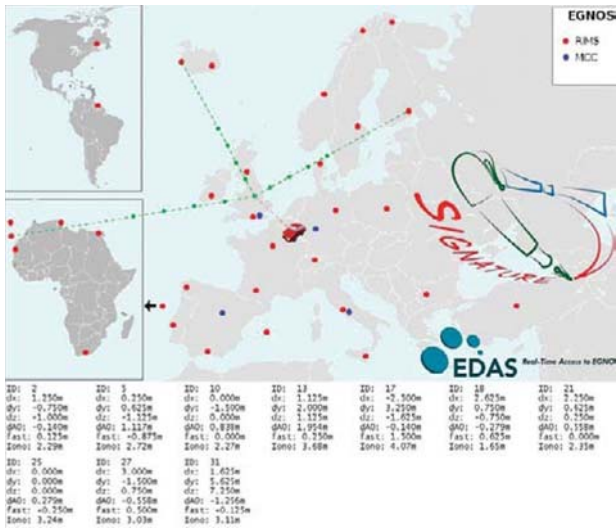
This robust, high-availability, high-integrity solution is delivered firstly through providing reliable assistance (A-GNSS) data from EDAS to optimize receiver acquisition and tracking capabilities and reduce TTFF, and secondly through implementation of embedded GNSS reliability algorithms into an OBU, providing assurance of positioning information (FIGURE 1).

These features are intended to make a positive contribution in terms of the key RUC performance criteria, as defined by the GNSS Metering Association for Road User Charging:

- Accuracy: right cost per trip
- Integrity: probability and amount of overcharging
- Availability: amount of charged usage.

Assistance Server. An assistance service supplying suitably equipped OBUs is one means to maintain rapid TTFF and meet the requirement for high positioning availability. The most significant contribution assistance can make to TTFF is to provide the ephemeris data, which takes around 30 seconds to download from a satellite signal. Assistance data can also reduce the frequency search space when a receiver is acquiring signals, as the expected Doppler frequency can be computed from the approximate receiver and satellite positions.

The assistance server in SIGNATURE is based on EDAS, currently available as a beta version. EDAS allows a user to plug into EGNOS to receive the data collected by all the current EGNOS Ranging and Integrity Monitoring Stations (RIMS). This makes it possible to access EGNOS data when there is no clear sight to the EGNOS geostationary satellites, which can often be the case in urban areas, particularly at higher latitudes. As well as supplying EGNOS messages, EDAS also provides GPS obser-



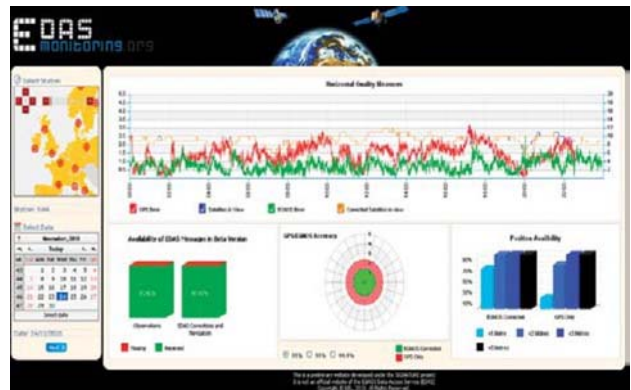
▲ FIGURE 2 Schematic of assistance solution.

vation and navigation (broadcast ephemeris) data, the key component as far as an assistance service is concerned. By recording the ephemeris data received at the extremities of the monitoring network, it is possible to ensure that the current ephemeris for any GPS satellite in view to users over Europe is available and can be supplied in an assistance message. Other data streams provided by EDAS can also be used to enhance the assistance solution.

The main enhancement tested in SIGNATURE was the use of EGNOS corrections within the assistance message. EGNOS today consists of a space segment of three geostationary satellites broadcasting correction and integrity information in the L1 band. Three sets of corrections are broadcast to users:

- Fast corrections: used to compensate short-term disturbances in GPS signals, generally attributable to satellite clocks;
- Long-term corrections: used to compensate for the longer-term drift in satellite clocks and the errors in the broadcast satellite orbits
- Ionospheric corrections: broadcast as a grid of vertical delays (GIVD) from which a user receiver can determine a slant correction to be applied on each range measurement to compensate for the delay experienced by the signal as it passes through the ionosphere.

Fast and long-term corrections are added to the ephemeris data in the assistance message. Rather than relaying the GIVD data to the OBU and letting the receiver reconstruct the ionospheric grid and calculate slant corrections, this is done within the assistance server. A slant correction is provided for each satellite that will be in view at the user location. This approach is valid provided the OBU updates the corrections regularly enough to take account of the changing satellite elevations and ionospheric conditions. It provides a significant saving in terms of processing and memory con-



▲ FIGURE 3 GNSS performance monitoring using EDAS.

sumption at the OBU, while still delivering the accuracy benefit of the EGNOS ionospheric data. To correct for the tropospheric delay, a zenith value (ZTD) determined from the RTCA model is also included in the assistance message. Mapping this zenith value to a slant correction to be applied to satellite ranges is a straightforward process easily accommodated on the OBU.

FIGURE 2 shows how data from EGNOS RIMS is collected at the assistance server at NSL in Nottingham, UK, and then used to generate messages. In this case, the assistance data was provided for trials conducted in Brussels. The figures at the bottom of the plot are the EGNOS correction values provided for all 10 GPS satellite in the positioning solution.

Further enhancements are also possible using the GPS observation data provided through EDAS. Firstly, for areas close to RIMS, a local differential solution can be applied using standard DGPS techniques to provide pseudorange corrections rather than wide-area EGNOS corrections. This has the potential to give greater accuracy for certain areas and is under investigation. By combining EDAS data sources, a GNSS performance monitoring and prediction service has also been created (FIGURE 3). This provides an assessment of GPS and GPS+EGNOS positioning performance (accuracy, availability of corrections, integrity) at known reference stations as well as monitoring the availability of EDAS data from its central server. Monitoring of this kind can be used as a further tool to identify system-level problems that might significantly degrade user positioning solution, perhaps to a level at which charges could not confidently be applied. It can also aid the enforcement process, as a diagnostic tool to identify if missing or misleading data from an OBU could be due to a system-wide fault or to a more localized source.

This approach relies on the approximate user position being known at the assistance server. To maintain the validity of the corrections, it would also require a receiver to update its assistance data at a much high rate than would usually be the case. For a large-scale operation this would be unfeasibly expensive using cellular communications (GSM/GPRS), however it would be possible using a broadcast assistance



▲ **FIGURE 4** SIGNATURE Prototype Onboard Unit (OBU).

approach. Using a radio data service (RDS) broadcast for example, ephemeris data and EGNOS corrections could be provided on a continuous basis. RDS is an auxiliary signal to the FM radio broadcast system and is used routinely for supplying travel information to in-car navigation systems. As data is broadcast from known locations and over a definable coverage area, messages can be generated that are applicable for all users receiving data from a given transmitter. A drawback of RDS is that it has a relatively low bandwidth, and it takes approximately 3.5 seconds to broadcast an ephemeris message for a single satellite. A further argument against RDS as a long-term solution is that analog radio signals are progressively being phased out in favour of digital alternatives. With the far greater bandwidth of digital audio broadcasting (DAB), ephemeris data for 12 satellites could be broadcast in less than 1 second.

We are evaluating alternative message content and transmission options to determine if real benefits can be gained by providing additional content, other than the ephemerides, in the assistance message.

Onboard Unit. The SIGNATURE OBU (FIGURE 4) is based on a single-board computer (SBC) offering a high degree of flexibility. Developed by ISMB, it can host alternative receivers and positioning algorithms and manipulate different assistance data with a high degree of configurability. It is a powerful platform for developing and assessing OBU devices and their component parts, particularly as it allows lots of useful diagnostic data to be logged.

The OBU hosts a bespoke receiver which exploits the continuous availability of assistance data available through a high-speed data packet access connection and does not attempt to decode navigation data directly from satellite signals. This allows its design to focus on rapid signal acquisition with high sensitivity and to achieve a rapid TTFF even in areas where conventional receivers struggle. The SIGNATURE prototype has been designed using the well known SAT-SURF & SAT-SURFER platform.

The receiver, developed by the EPFL, implements massive parallelization by making use of the fast Fourier



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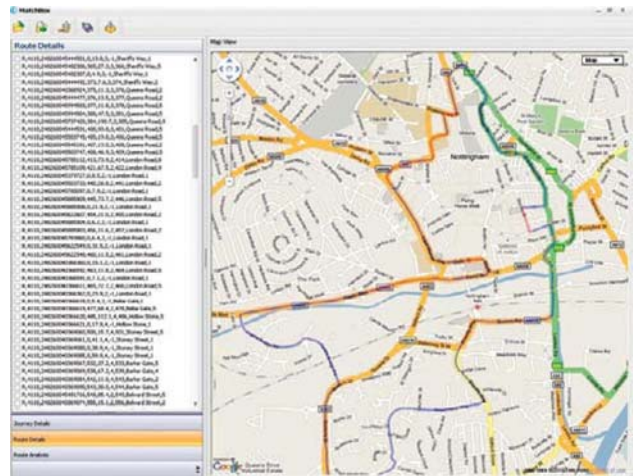


transform, leading to a processing power equivalent to approximately 650,000 equivalent correlators. The minimum sensitivity in acquisition is -145 dBm, obtained using coherent and non-coherent integrations. Thanks to the massive parallelization and the assistance, TTFF at -145 dBm is still below 3 seconds.

Positioning Algorithms. The OBU hosts positioning algorithms designed by NSL to provide high accuracy, availability, and integrity through exclusion of outlying measurements and provision of quality metrics (horizontal protection levels or HPLs). Numerous positioning algorithms and outlier detection strategies are being investigated. These include consistency checks applied to raw measurements and computed positions and receiver autonomous integrity monitoring (RAIM). EGNOS corrections are applied to improve accuracy and integrity indicators (user differential range error indices) are used as coarse fault-detection barrier. Consistency checks on measurements include differencing pseudoranges between epochs and checking that this rate is below a defined threshold. A RAIM algorithm is then applied to detect and exclude outliers before measurements enter the main navigation filter. Positions and velocities determined by the filter are then checked again as a further fault barrier. Checks at this stage identify if speeds are within expected ranges for the application and whether height changes are reasonable, for example.

The RAIM algorithm is based on the maximum normed residual method. For the detection procedure, the test statistic is calculated based on weighted sum of the squares of the residuals. This test statistic undergoes a globaltest (chi-square distribution), and is tested against thresholds that are computed based on the probability of false alarm (Pfa) and degrees of freedom (number of measurements minus number of unknowns). The exclusion procedure is based on an outlier detection technique also known as data-snooping, which is based on normed residuals and applied within the range domain. This technique uses measures of internal and external reliability, where the internal reliability gives estimates of how reliable the outlier detection procedure is, while the external reliability gives estimations of the influence of an outlier.

In the final step of the exclusion procedure, the maximum normed residual is tested against a critical value based on the normal inverse cumulative distribution, which in turn depends on the Pfa, and a decision is made on whether or not to exclude measurements. Having performed fault detection and fault exclusion until no further outliers are found, an HPL is calculated. This is the maximum horizontal position error that is guaranteed by the algorithm not to be exceeded, in accordance with the required probabilities of missed detection and false alarm. HPL is a function of visible satellites, expected error characteristics, and user geometry. Measurements which have been screened using the RAIM



▲ FIGURE 5 Journey record view from Nottingham test.

fault detection and exclusion are then processed in a Kalman filter.

Within the project, many alternative algorithms and configurations are being tested. As well as using RAIM in a snapshot mode to screen measurements entering the Kalman filter, fault detection can also take place within the innovation sequence of the filter itself. Weighting strategies that consider signal-to-noise ratios (SNR) as well as satellite elevations are also being used. This combined weighting is useful in reducing the impact of measurements affected by multipath in urban areas where simple elevation dependent models are often not applicable. The ultimate aim is to produce a robust GNSS positioning solution optimized for RUC in urban areas that balances the requirements of providing high availability with high integrity.

Test Methodology

The SIGNATURE end-to-end solution was tested in a series of field trials in the UK and Italy between April and July 2010. Trials took place in a range of operating conditions from rural areas with open skies to dense urban environments. In all trials, assistance data was provided from the service center in Nottingham, with messages tailored for the designated test area. The OBU recorded real-time position solutions as well as logging all raw measurements. Journey records can be sent back to the service center over a GPRS connection or can be downloaded back at the office. This allowed alternative solutions to be applied to the original datasets in post processing.

The position solutions were assessed through comparisons with high-accuracy GNSS reference solutions provided by additional onboard equipment and through processing with a map matcher (NSL's Matchbox). Each journey record from a trial was compared against the known reference journey record to determine charging availability, accuracy, and integrity.

Using this approach, it is possible to assess whether improvements in the OBU position output are significant in terms of matching the vehicle location correctly to more road segments and with higher confidence. From direct comparisons between OBU positions and a high-accuracy reference solution alone, it is not possible to determine the significance of any changes in the OBU output in terms of final charging performance. Extensive trials of GNSS OBUs in London, for example, did not observe a relationship between location error (from OBUs) and performance at road segment level (map-matching) as map-matching can compensate for many errors. A strong relationship was observed between data availability and performance, though. Ultimately it is important to consider how successfully vehicle position can be related to charging objects, be they road segments, cordons or virtual toll-gates.

The objectives of the field tests were to:

- Demonstrate that all elements of the end-to-end solution work as expected.
- Assess the impact of assistance on TTFF.
- Evaluate benefits of EGNOS data.
- Investigate alternative positioning algorithms to optimize availability and integrity.
- Demonstrate the feasibility of broadcast assistance using RDS.

Results

Field trials around Nottingham and Torino tested all elements of the solution. The tests confirmed the successful generation, transmission and use of assistance data, including EGNOS corrections. Position solutions determined onboard were transferred back to the service centre and processed with a map matcher. **FIGURE 5** shows an example from a test in Nottingham city center, correctly identifying all the road segments travelled on.

Assess Impact of Assistance on TTFF. To examine the benefits of assistance, a

series of trials were conducted to compare the TTFF of a consumer-grade receiver typically used in road applications against the performance of the SIGNATURE receiver that is assisted in all cases. They assessed TTFF for the COTS receiver in the following modes:

- Hot Start: receiver has up-to-date almanac and ephemeris information so only needs to obtain timing/ranging information from each satellite to return its position fix;
- Warm Start: receiver has the almanac information stored in its memory, but it does not have any ephemeris information. It also has approximate time and position knowledge. It can use this information to search for satellites but will then need to demodulate the ephemeris data from acquired signals;
- Assisted: ephemeris provided over OMA-SUPL standard channel.

TABLE 1 shows the results from testing the receivers in open sky and urban conditions, specifically chosen to assess an extreme acquisition environment. In these tests when no valid ephemeris is available on a receiver at start-up, it takes an average of 28 seconds to determine a first position fix in open sky conditions. This increase to an average of more than 2 minutes in the worst-case urban environment as the receiver struggles to decode the navigation message on weak, noisy, and intermittent signals. With assistance, the SIGNATURE receiver maintains a rapid TTFF, outperforming the COTS receiver. The slower TTFF in the assisted COTS case may be partly due to the OMA-SUPL standard procedure which is based on a more complex than the simple data transfer used in the SIGNATURE procedure. The COTS receiver is also decoding navigation subframes to determine signal transmission time. This can take up to 6 seconds depending on the point in the transmission cycle that acquisition begins.

Tests have also been carried out us-

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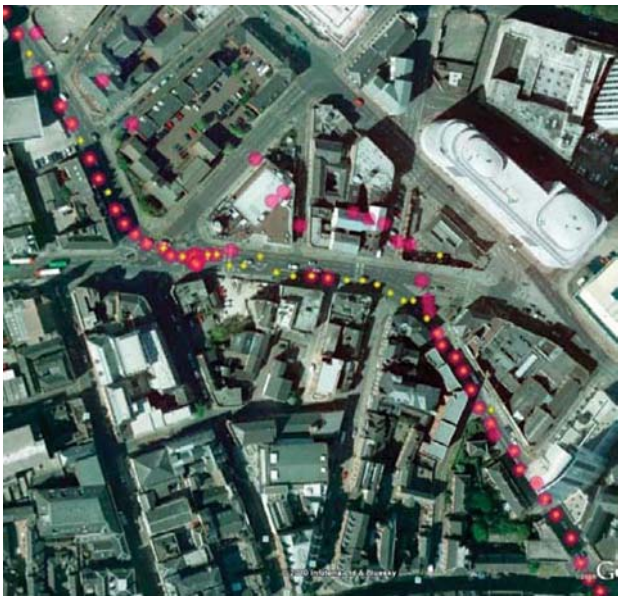


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	Mean TTFF(s)	
	Open Sky	Dense Urban
SIGNATURE	1	3
COTS - Warm	28	136
COTS - Hot	1	2
COTS - Assisted	8	9

▲ **TABLE 1** Time-to-first-fix results.



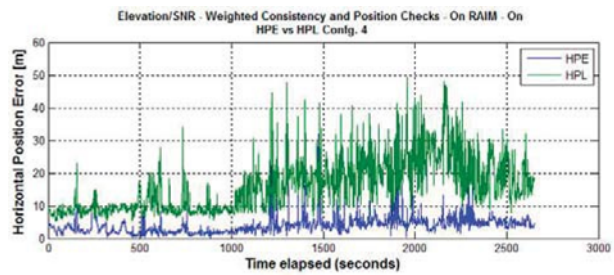
▲ **FIGURE 6** RAIM Impact (red = no RAIM, yellow = RAIM).

ing a signal generator to control the strength of the received signal to assess acquisition and tracking sensitivity. At -145 dBm, the SIGNATURE receiver takes an average of 1.1 seconds to acquire 4 satellites and determine a first fix, and 5.1 seconds to acquire 12 satellites.

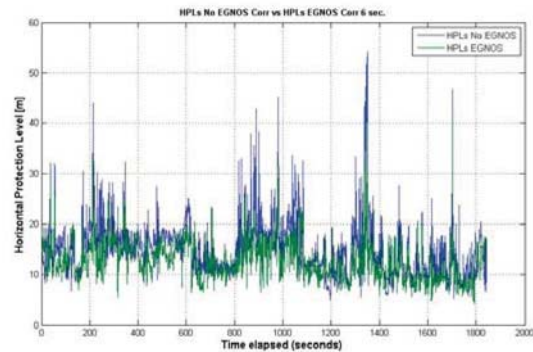
Positioning Algorithms. A variety of configurations have been investigated in the positioning algorithms, including applying outlier-detection routines at different stages of the solution and comparing snapshot and filtered approaches. **FIGURE 6** shows a simple example of how the RAIM algorithm has been effective in detecting and excluding outlying measurements contaminated by multipath. By removing these measurements and re-computing the OBU location, better position estimates are obtained.

FIGURE 7 shows the accuracy and integrity of the SIGNATURE solution assessed using a high-grade GNSS/INS reference in Nottingham city center. In this case, the horizontal accuracy is 4.4 meters (95 percent), and the computed protection level is shown to bound the actual position error with the required confidence.

In rural, semi-urban, and urban (Nottingham) conditions, a positioning solution has been demonstrated that supports all charging accuracy, integrity, and availability require-



▲ **FIGURE 7** Position error and protection level, Nottingham city center.



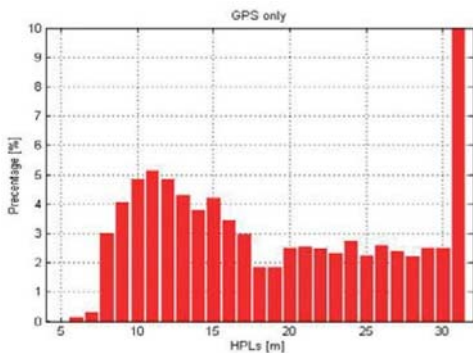
▲ **FIGURE 8** HPL GPS vs GPS + EGNOS.

ments.

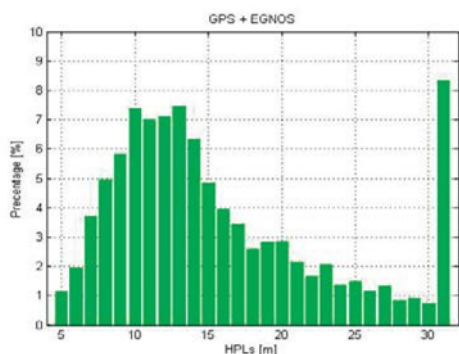
Further tests were also conducted in the center of London, in a worst-case obstruction environment. In this area the current solution falls just short of the requirements defined for this project. In such cases, better performance could be obtained using a hybrid solution making use of additional sensor inputs, but this will increase equipment costs and potentially installation costs, too. A more practical approach may be to simplify charging schemes in the densest urban environments, using zones and cordons rather than using more detailed approaches that require a continuous high-performance positioning solution to be maintained in all conditions.

Benefits of EGNOS Data. The SIGNATURE solution has the ability to provide EGNOS data to positioning algorithms on the OBU and to vary the rate at which this information is updated and used. Field tests have assessed the potential benefits of this source of data in various environments, starting from the case in which EGNOS messages are continuously available for the positioning solution and then investigating how any beneficial effects lessen as the data is provided less frequently. The greatest benefit from EGNOS was derived by applying corrections prior to performing the RAIM FDE algorithm. This led to more consistent measurements and produced lower HPL values. **FIGURE 8** shows a comparison for a Nottingham test in which a GPS-only solution is compared against an EGNOS solution in which a full set of corrections is provided.

This reduction in HPL values through the application of EGNOS corrections is clearer when the distribution of HPL values falling into discrete bins is assessed (**FIGURES 9** and



▲ **FIGURE 9** HPL distribution GPS.



▲ **FIGURE 10** HPL distribution GPS + EGNOS.

10). Similar levels of relative improvement have been found through using this approach in all test datasets. The significance of these improvements can only be judged against the detailed specifications of a particular charging scheme.

Conclusions

Using an assistance service based on EDAS, it is possible to achieve a TTFF of a few seconds, which supports the high availability requirements of RUC. Field trials showed that providing EGNOS information over the assistance data link had an integrity benefit. Applying corrections prior to a RAIM algorithm leads to more consistent measurements and reduces HPLs. Robust positioning solutions have been developed and implemented on the OBU, and a test methodology has been put in place to assess the impact on charging availability, accuracy, and integrity. Results indicate that GNSS-based road charging offers the performance and flexibility to meet current and future requirements, provided availability and integrity issues are properly taken into account.

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not necessarily represent the EC.

Manufacturers

The SIGNATURE receiver is based on the **Terasic Altera DE3** System with a high-density Stratix III FPGA (EP3S260), and on the **Rakon GRM8652** high-performance front end.

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