SYSTEM

Galileo Performance

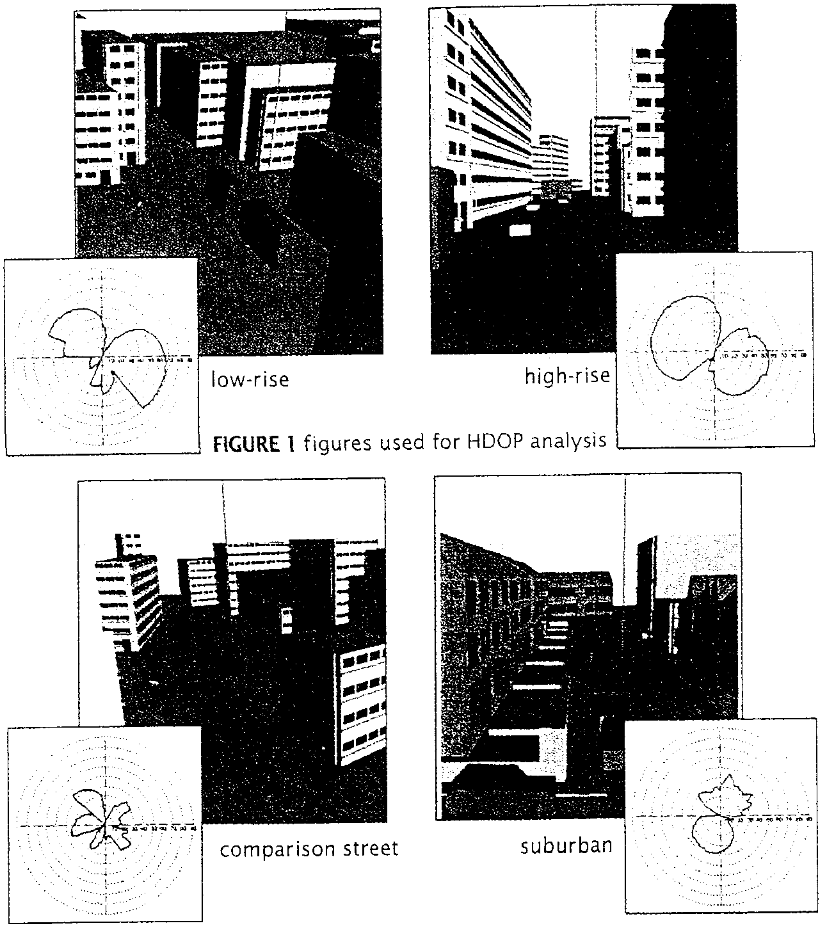

FIGURE 1 figures used for HDOP analysis

GPS Interoperability and Discriminators for Urban and Indoor Environments

A technical study examines potential discriminators for Galileo mass-market acceptance in the presence of a freely available GPS service. This approach seeks to provide commercial input to the Galileo signal design process, to optimize the GPS + Galileo "Super Constellation" for urban operation over Europe. The analysis further shows that GPS alone does not offer sufficient availability for "transparent" mass-market use in densely populated areas.

by Matt O'Donnell, Trevor Watson, James Fisher, Steve Simpson, Gary Brodin, Ed Bryant, and David Walsh

With a free GPS service increasingly being integrated into many consumer products to provide location information, Galileo must offer clear advantages to users to make it worthwhile for manufacturers or value-added service providers to incorporate Galileo into their product or service as well as GPS.

Obviously, placing more satellites in orbit will increase the number visible to a user's receiver. This leads to an improvement in both accuracy and availability. However, this is not the only benefit that Galileo can provide, as advances in signal design and signal processing since the introduction of GPS can also come into play. Galileo mass-market services must offer better multipath performance and continued usability despite obstructions, leading to enhanced operation in urban canyons and indoors, in order to show improvement. We examined three topics in particular:

- the effect of increasing the number of satellites in view
- signal simulation and system performance
- consequent impacts on the potential for market penetration.

We focus here on the first two topics and correlative engineering analyses. First, we look at a constellation modelling analysis undertaken to further optimize the performance of an interoperable Galileo, considering a "Super Constellation" of Galileo with GPS for urban operation over Europe, targeting a minimum cost mass-market solution.

We then examine the construction and use of a propagation model of the urban environment, using representative city data coupled to a Geometric Theory of Diffraction Electromagnetic Solver, and also a real-world measurement campaign using proprietary channel-sounding equipment to explore the propagation properties of several representative indoor locations. We used the results from the modelling and measurement tasks within a signal comparison activity to examine both the acquisition and tracking performances of GPS and Galileo receivers in the multipath-rich urban canyon and indoor environments, and undertook a further analysis to predict the likely accuracy and availability of several GPS and Galileo constellation scenarios.

We progressed further, to estimate the likely impact that the urban and indoor performance of Galileo would have on the "usability" and marketability of GNSS, and how this might impact on the proposed Public-Private Partnership for Galileo.

Satellite Visibility Analysis

A desirable property for successful Galileo penetration into mass-market applications is that of interoperability with GPS, and vice versa. A receiver should be able to use any satellite from any constellation to contribute to the final position solution. This minimizes the "urban canyon problem" (lack of visibility of satellites in built-up areas leading to failure to achieve a solution or achieving one of poor accuracy).

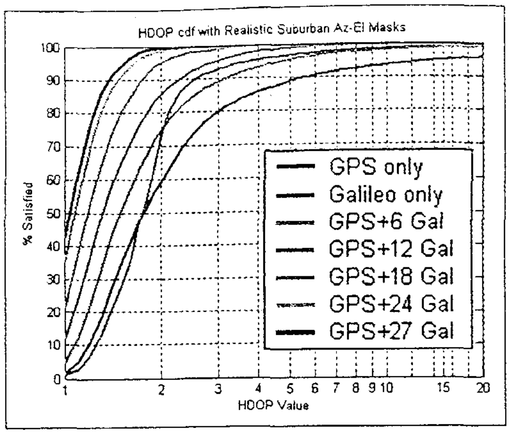

FIGURE 2 HDOP availability: GPS+n Galileo, suburban

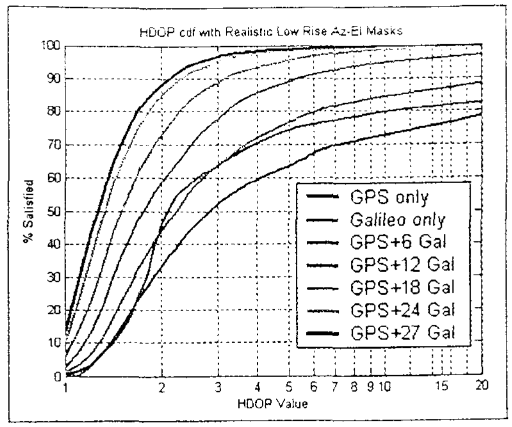

FIGURE 3 HDOP availability: GPS+n Galileo, low-rise

However, interoperability is only one of the design drivers used for the Galileo constellation — in particular, there is a requirement that Galileo be able to provide some services (such as aviation) independently of GPS. This manifests itself as a full tally of 27 operational satellites to be launched as quickly as possible.

Mass-market services, however, are not interested in the politics of independence, and we took the view that GPS was already present and would form the starting point of any future satellite navigation system. We therefore looked at the performance of the current 28-strong GPS constellation, and quantified the improvements obtained as Galileo satellites are introduced.

In interviews and workshops with mass-market users and service providers, we found most interest in the horizontal accuracy and availability of a given accuracy. (Horizontal accuracy is given by the product of horizontal dilution of precision [HDOP] and user equivalent range error [UERE].) Mass-market users have little interest in vertical accuracy, and no desire for integrity or liability.

We worked with both terms and also considered availability, in terms of the amount of time that a given accuracy is achievable. The analysis was conducted using a satellite orbit modeling suite, assuming a grid of test locations distributed at approximately 3° intervals over Europe.

HDOP is a function of the constellation size and orbit parameters, so increasing the number of satellites in view improves the odds of being able to select an optimal alignment, and leads to reduced HDOP (or increased availability of a given HDOP). If the user's view of the sky is constrained, for example, by city-centre buildings, then a larger constellation improves the minimum HDOP achievable at a given elevation constraint (mask angle).

Three mask angles were used in the HDOP and accuracy analysis of GPS and Galileo urban performance. "Snapshots" were taken of the azimuth versus elevation mask for various receiver positions in an electromagnetic model based on Piccadilly Circus, London, and these were used to define the view constraints for the points in the test grid.

The three cases are:

- in the middle of a wide intersection (average mask angle approximately 22°)
- in a street open at one end and containing buildings from four to seven storeys (average mask angle approximately 40°)
- surrounded by seven-storey buildings (average mask angle approximately 45°).

These three cases were assigned the identifiers suburban, low-rise, and high-rise, respectively. The first approximates an area of low-density buildings such as a residential district. **Figure 1** shows the profiles used for the HDOP analysis.

Figures 2 and **3** show the availability (strictly speaking, the percentage of occasions where the HDOP is below a threshold value) for GPS, Galileo, and GPS plus Galileo in increments of six satellites, in suburban and low-rise environments. Galileo alone has a better performance than GPS (due to the higher orbital inclination), but of particular interest is the performance of the super-constellation: GPS + 6 Galileo improves the availability of low HDOP by some 15%, with further improvements as more satellites are added.

Figures 4 and **5** show the high-rise case, but with the orientation of the street rotated by 90° between runs. Generally, satellites to the North are only visible at high mask angles, while those to the East and West are at a range of angles. When the street is aligned East–West, lower elevation satellites become visible and HDOP improves. The effect of the rotation is to alter availability by 5–10 percent at low HDOP, and 10–15 percent at higher HDOP.

The calculated HDOP values can be combined with a UERE, derived from the equivalent value for GPS C/A code performance today and reducing it to allow for various performance improvements in Galileo

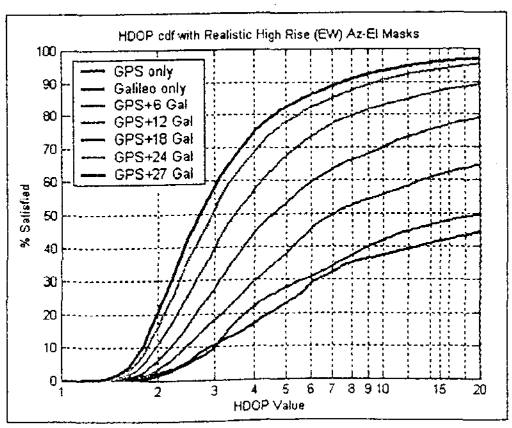

FIGURE 4 HDOP availability: GPS+n Galileo, high-rise, East–West orientation

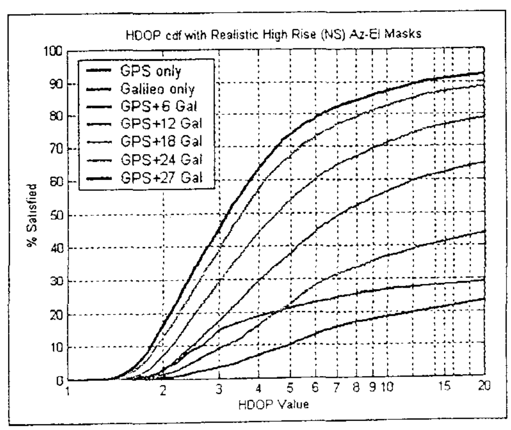

FIGURE 5 HDOP availability: GPS+n Galileo, high-rise, North–South orientation

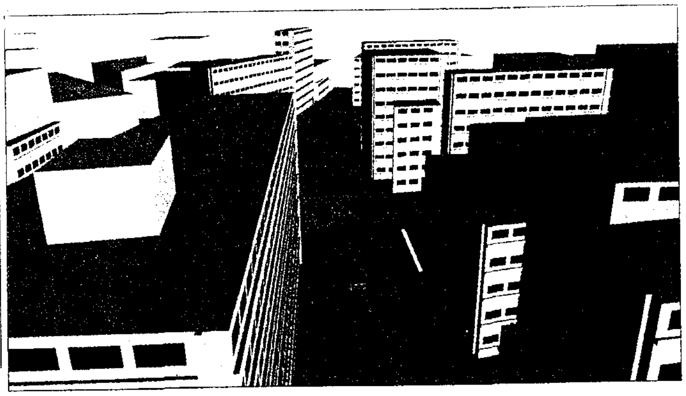

FIGURE 6 Receiver path in urban canyon, shown in yellow

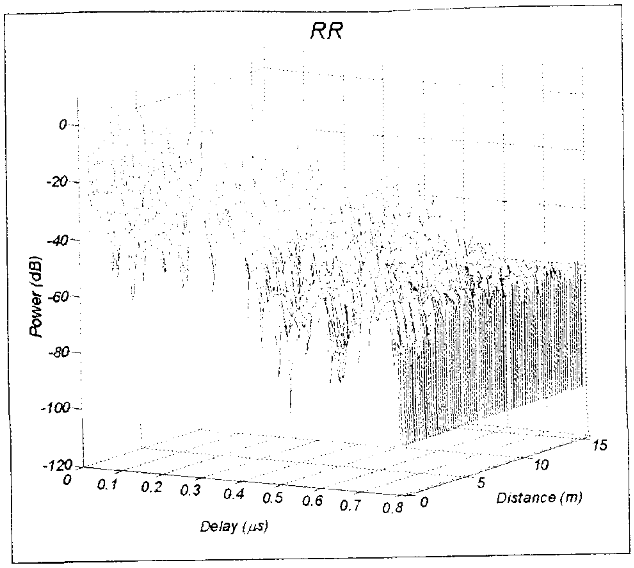

FIGURE 7 Sample power delay profiles (PDPs) using a circularly polarized antenna

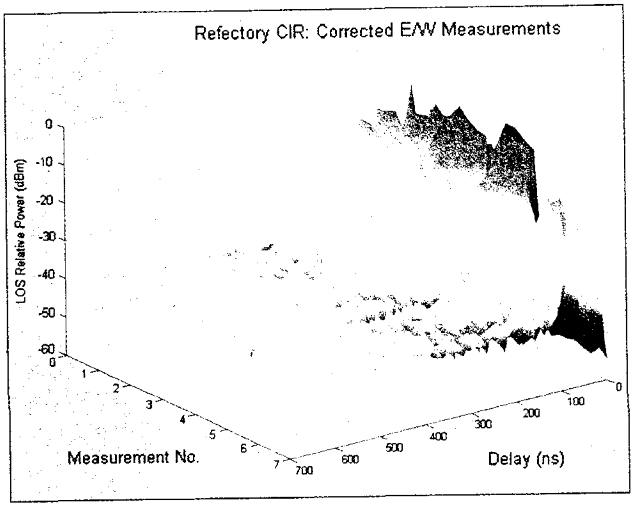

FIGURE 8 Power delay profiles for restaurant

and modernized GPS. This simplifies the overall process, as the study considers many parameters: number of satellites, user mask angle, deployment timeframe, modernization status, and so on). **Table 1** shows one view of the results, giving the predicted availability of a 20-meter (95 percent confidence) horizontal solution as the number of Galileo satellites increases from zero (that is, GPS today) to 27 (GPS plus full Galileo, neglecting spares).

The analysis shows that GPS alone does not offer sufficient availability for "transparent" mass-market use in densely populated areas, as there is a perceptible failure rate for each attempt to make a position fix. Galileo provides the benefit of increasing the availability much closer to commercially acceptable levels, but does not require the full 27 (plus three spares) constellation to do so. 12 satellites suffice for good coverage in most European cities outside of high-rise districts, and 18 or 24 satellites would suffice for city centers.

A "first-cut" assessment to support the satellite visibility statistics underlies the analysis in Table 1. UERE values used are applicable in an average white Gaussian noise environment, and multipath effects are not taken into account. We then focused on predicting and understanding the impact of urban multipath in more detail.

Characterizing Local Environments

We performed urban channel modelling activities with an electromagnetic modelling tool, combined with 3D city modelling software. City environments can be created based upon satellite or aerial imagery, with a variety of building types and actual dielectric material properties. The modelling tool performs a complete electromagnetic simulation on the 3D city model and calculates the full phasor vector electric field seen by the receiver. This data can be post-processed to calculate the Power-Delay Profile (PDP) for the Satellite-to-Receiver multipath channel. Doppler analysis and processing for a variety of receiver antenna types is also possible.

Urban Channel Simulation. We created a 3D computer-aided design (CAD) model representative of an area of central London and performed simulations with a variety of receiver locations, receiver paths, and satellite locations, calculating more than 1500 PDPs. **Figure 6** shows a view of the 3D city model. In this example, the buildings on either side of the canyon are based upon glass and concrete office blocks. The office blocks include a certain amount of surface structure (such as window ledges, recessed windows and doorways), which it is necessary to model because it causes a noticeable increase in the resulting multipath environment. The receiver takes a path along the pavement at one side of the canyon (shown in yellow).

For this example, we performed the electromagnetic simulation with a satellite elevation angle of 25°, sampling the receiver path every 0.095 meters (half the L1 wavelength). At each sample point, the PDP is calculated to give the waterfall plot shown in **Figure 7**.

The PDPs demonstrate that the receiver is located in a severe multipath environment. The direct signal is quickly lost as the receiver moves along the distance axis into the canyon, and there is significant multipath with delays up to 400ns.

Furthermore, PDPs seen by a linearly polarized antenna are worse than those seen by a circularly polarized antenna. On average, switching from a circularly polarized receive antenna to a linearly polarized

TABLE 1 Availability of 20-meter 95% horizontal accuracy as Galileo satellites increase

Scenario	28 GPS +0 Galileo	28 GPS +6 Galileo	28 GPS +12 Galileo	28 GPS +18 Galileo	28 GPS +24 Galileo	28 GPS +27 Galileo
Suburban	~90%	~95%	~100%	~100%	~100%	~100%
Low-rise	~70%	~80%	~90%	>95%	~100%	~100%
High-rise E/W	~30%	~50%	~60%	~75%	~85%	~90%
High-rise N/S	~15%	~30%	~50%	~65%	~75%	80%

receive antenna will result in an increase in the mean excess delay values of 35 percent. The average RMS delay spread values increase by 21 percent.

This is important because manufacturers of small, mass-market GNSS receivers will demand a simple, low-cost antenna solution. Size and space constraints may also require that the antenna be multi-purpose and capable of operating at other frequencies (for example, GSM). As a consequence, the antenna is highly likely to be linearly polarized. The degradation in signal quality when using a linearly polarized antenna highlights the need for innovative receiver and antenna design for GNSS to take full advantage of this mass-market potential.

Indoor Channel Modelling. We modelled the satellite-to-indoor multipath channel with a combination of deterministic and statistical modelling. The modelling tool calculates the multipath environment between the satellite and the building points of entry (for example, a window). The signals are then attenuated, and a statistical indoor model applied. This is intended to represent generalized indoor environments, since the internal structure is too complex to be efficiently modelled. However, we also made real measurements of specific locations.

Indoor Channel Measurements. A 100MHz channel sounder developed at the University of Leeds was modified to operate at GPS L1 frequencies for the measurements. The campaign addressed three environments: bar and restaurant, restaurant mall and office, and a covered carpark. Measurements imitated the planar radiation of a Galileo constellation transmission by minimizing the effect of point-source reflections with a wideband, circularly polarized, highly directional transmitting antenna (a twin phased axial mode helix), with the source located at as long a range as possible.

We characterized each measurement site by choosing test locations spaced 2 meters apart; at each location four measurements were made, separated by $\lambda/4$ in X, Y, and Z from a reference point. This highlights the effects of constructive and destructive interference (fast fading) and hence provides a comprehensive picture of the multipath environment at each location.

Figure 8 presents the measured PDPs along a path in the restaurant area. It highlights the potentially high level of attenuation of L1 signals into a concrete/glass structure. The test locations progress out of the plane of the paper, and the zero-delay amplitude increases and then decreases as an unobstructed line of sight (LOS) is gained and lost. For the non-LOS profiles, increases in the relative amplitude of multipath signals are evident, due to signals arriving via paths of lower attenuation than that of the direct path. This is a problem that should be expected for non-LOS signals in an indoor environment.

Overall Performance

The UK Civil Aviation Authority Institute of Satellite Navigation (CAA-ISN), University of Leeds, developed a high performance software-based signal/channel/receiver simulator. The simulator can generate a range of input signals that can then be modified in accordance with the channel characteristics. All receiver hardware operations such as correlators, image reject mix (IRM), and automatic gain control (AGC) are emulated in order to assess the performance of different implementations. The receiver component of the simulator performs all signal processing from acquisition to steady-state tracking. The primary simulator outputs are code- and carrier-phase measurements, correlator totals, carrier to noise ratio (CNR), and tracking state, all on an epoch-by-epoch basis (1 ms). The simulator assessed two key areas of receiver performance: acquisition capability and tracking performance.

BOC versus BPSK Signals. As we focused on determining Galileo discriminators, we considered whether there are any performance differences that result directly from the choice of signal structures. We used the current baseline signal parameters, comparing the GPS C/A code and the Galileo L1 data-carrying signal. The key signal parameters used for the Galileo L1 data-carrying signal are the chipping rate (2.046 Mchips/s) and the binary offset carrier (BOC) modulation rate (BOC(2,2)). The code repeat period is yet to be confirmed, but values of 1 ms or 5 ms were specified at the study outset. As no codes have been published yet for Galileo, a 2047-length Gold code, truncated to 2046 bits, has been used. The correlation properties of the code used are very similar to those of the GPS Gold codes. This ensures a like-for-like comparison, in the absence of published Galileo code sequences.

TABLE 2 Key receiver parameters

	GPS C/A code	Galileo BOC(2,2)
Sampling	9 MHz, 3-bit	22 MHz, 3-bit
IF Filter BW	6.5 MHz	18 MHz
IRM	3-bit	3-bit
Correlator Spacing	0.23 chips	0.19 chips
Code Discriminator	Early minus Late Power	Early minus Late Power
Integration Period	1 ms	1 ms

There are of course many different ways of processing these different GPS and Galileo signals in a receiver. In particular, given knowledge of the user environments and the desired performance, it is possible to optimize acquisition and tracking performance accordingly. This study was not concerned with performing such optimizations at this stage; its aim was to first determine the differences in performance due purely to system properties, and not receiver configurations. Therefore the receiver configurations were designed to be as similar as possible.

Specifically, receiver sample rates and bandwidths were chosen to match the received signal power. Considering the full system bandwidths, the minimum received power specified for the Galileo L1 data carrying signal is essentially the same as that specified for the GPS C/A code. Hence the GPS and Galileo signal bandwidths can easily be selected such that the same power is received for both. The receiver bandwidth should therefore be large enough to allow use of narrow correlation, but it should not be so large such that the required sample rate is too high. **Table 2** shows configurations selected for the Galileo and GPS receiver architectures.

To determine CNR at receiver input we also had to define the antenna characteristics. For the receivers considered, we assumed the use of an active RHCP antenna, with a typical LNA noise figure of 2dB.

The simulated urban canyon power delay profiles described earlier were generated at elevation angles of 25°, 45°, and 80°. With assumed antenna gains of –1dB, +1dB and +3dB at these three angles respectively, the minimum CNR at the receiver front-end was calculated to be 44.6dBHz, 47.1dBHz, and 47.4dBHz for both GPS and Galileo (Galileo will broadcast at a higher minimum specified effective isotropic radiated power [EIRP] than GPS but divides the carrier power between three signals).

Having determined the nominal CNR for these three elevation angles, we can apply the simulated power delay profiles at correct signal levels. Hence the simulations performed are highly representative of the signal conditions that would be experienced in the simulated environments.

Simulated Urban Canyons. The main analysis determined the effect of the multipath-rich urban canyon and indoor environments on the Galileo and GPS receiver tracking performances in terms of tracking ability, tracking bias (offset compared to signal without multipath), and tracking precision (variation over simulation epochs). We assessed these parameters by configuring the simulator so that the nominal line of sight signal was acquired first and steady-state tracking reached. We then introduced the power delay profile to see if the receiver could maintain tracking.

If it was the case that the simulator lost signal lock, the profile was introduced incrementally to ensure that the loss-of-lock was due to the profile and not a large discontinuity in signal power. In general, this is more likely to be representative of a true multipath scenario which will be a continuous function.

If the simulator maintained lock, the tracking configuration was maintained for a large number of epochs so that the tracking offset, or bias, could be determined along with the tracking precision and the steady state CNR. The simulator was then reset and the process repeated for a new power delay profile (the work reported here therefore describes both a static receiver and a time-invariant multipath environment).

Accompanying figures show one of the simulated urban canyon scenarios, representing steps along a street with an open intersection at one end and an urban canyon at the other. The profile number corresponds to the particular power delay profile for each step. **Figure 9** shows the tracking biases produced for the GPS and Galileo configurations, **Figure 10** the tracking precisions, and **Figure 11** the steady-state CNRs.

Evidently, this is quite a severe environment in terms of signal obscuration once the receiver is within the canyon, after profile number 51. The receivers cannot maintain signal tracking in all cases, most likely due to the signal level falling below the receiver tracking threshold of approximately 30dBHz. Tracking biases are relatively large in the urban canyon for both GPS and Galileo. Tracking precision is better for Galileo than for GPS.

The overall results of the many simulations we performed show that the Galileo BOC offers better tracking precision than GPS C/A BPSK. The tracking bias (offset due to multipath) is also reduced, but is strongly dependent on the contribution of short-delay components — a large population of nearby reflections, or a single close reflection, will disturb both GPS and Galileo solutions by an equal amount. There is, however, still scope for some fine-tuning of signal parameters, and for definition of optimal BOC processing architectures.

Estimating System Performance. The constellation and signal performance analyses can be combined to give an idea of the performance achievable by Galileo and/or GPS in urban environments. This has been undertaken for a number of satellite-only combinations (including different timeframes to account for the introduction of modernized GPS), plus system augmentations such as differential, simple inertial guidance, and network aiding. UERE budgets were generated for each

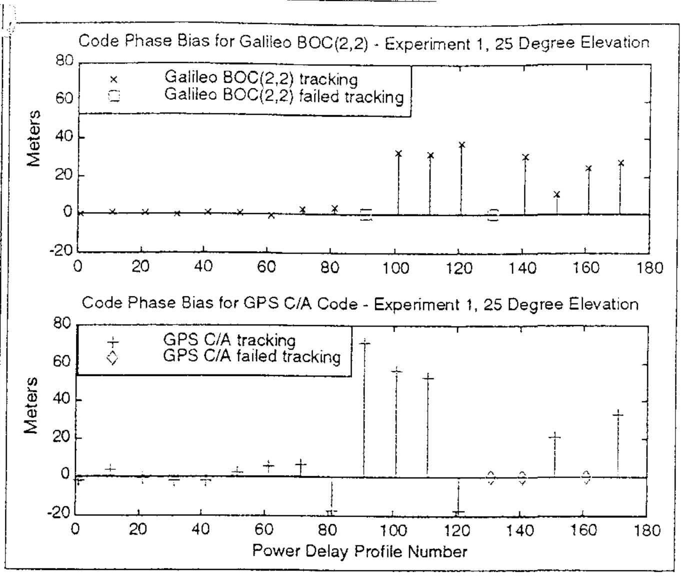

FIGURE 9 Biases for one urban canyon scenario

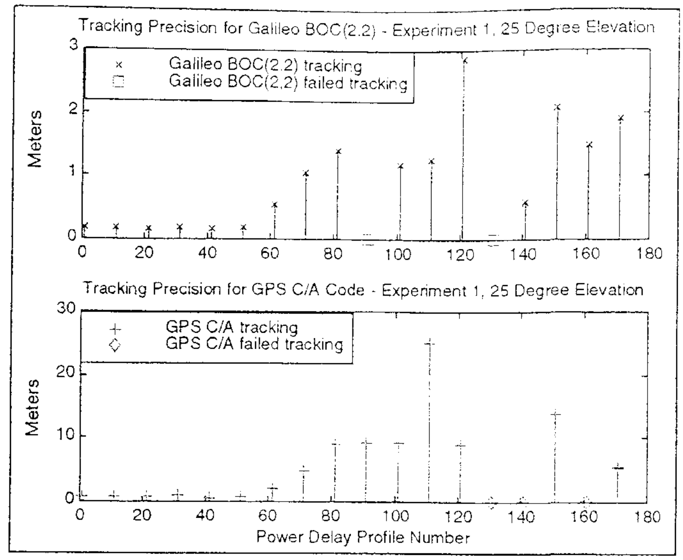

FIGURE 10 Tracking precisions for same scenario

scenario, starting from an appreciation of the achievable performance of the GPS Standard Positioning Service (SPS) today. We used bias and precision values from the receiver simulation work as inputs to the multipath and receiver noise components of the UERE, and then obtained accuracy by multiplying with the HDOP values derived in the visibility analysis.

In all cases simulated, where there is a clear LOS, the multipath contribution to UERE is less than or equal to the ionospheric error (for single-frequency receivers). However, in non-LOS conditions, signals may still be received but the size of the offset dominates the position error.

Table 3 shows an example case of predicted accuracy and availability for various combinations of GPS and Galileo, rounded to the nearest metre. The value of 7 meters at 95 percent availability for GPS alone in a clear sky, low multipath environment agrees well with practical experience. Reading down the column, both the accuracy and availability degrade significantly as the mask angle is restricted and multipath is introduced, to the point in a high-rise environment where for mass-market purposes the signal is simply not visible often enough to be counted.

A Galileo-only constellation exhibits similar though improved behavior; however it is only necessary to add 12 Galileo satellites as part of an interoperable super-constellation for the performance to exceed that of GPS or Galileo alone. The availability of a practically useful accuracy is still too low in city centers, but a full super-constellation solves this.

Tables 4 and **5** show the same data for differential augmentation and network aiding of the satellite constellations. Differential aiding improves the accuracy by a factor of approximately two, while network aiding improves both accuracy and availability, the latter allowing services to be used in high-rise surroundings.

Conclusions

Analysis of the potential for Galileo to serve mass-market users in high mask angle environments indicates that Galileo has a slightly better availability over Europe than GPS, but neither system alone provides reliable visibility of satellites. Assuming the continuance of the GPS constellation and the use of both by mass-market receivers, the addition of Galileo satellites can significantly increase urban availability. The minimum number of satellites required is somewhat lower than the full constellation of 27 (plus three spares). Alternatively, a commercially driven approach to deployment would allow Galileo to begin providing useful services substantially earlier than the currently baselined date for full operations.

Indoor measurements demonstrate that attenuation levels can be as high as 25dB, varying considerably even on a small distance scale. Extensive simulations to determine receiver performance concluded that simulated multipath conditions have a significant effect on the code tracking bias, of a similar magnitude for both GPS C/A and Galileo BOC signals. The tracking precision for BOC(2,2) is substantially better than that of BPSK(1) in all scenarios.

System performance predictions suggest that an interoperable GPS/Galileo can offer significantly improved accuracy and availability over GPS alone, particularly in

TABLE 3 Predicted typical accuracy and availability for satellite-only scenarios in urban environments

Satellites only:	28 GPS + 0 Galileo	0 GPS + 27 Galileo	28 GPS + 12 Galileo	28 GPS + 27 Galileo
Open Sky	7m / 95%	5m / 95%	5m / 95%	4m / 95%
Suburban	32m / 90%	17m / 95%	15m / 95%	8m / 95%
Low-rise	17m / 50%	23m / 75%	59m / 95%	14m / 95%
High-rise	-	-	26m / 50%	42m / 90%

TABLE 4 Predicted typical accuracy and availability for differential augmentation in urban environments

Differential plus:	28 GPS + 0 Galileo	0 GPS + 27 Galileo	28 GPS + 12 Galileo	28 GPS + 27 Galileo
Open Sky	3m / 95%	2.5m / 95%	2m / 95%	1.5m / 95%
Suburban	16m / 90%	8m / 95%	7m / 95%	4m / 95%
Low-rise	9m / 50%	9m / 75%	15m / 95%	7m / 95%
High-rise	-	-	15m / 50%	25m / 90%

TABLE 5 Predicted typical accuracy and availability for network-aided scenarios in urban environments

Net aiding of:	28 GPS + 0 Galileo	0 GPS + 27 Galileo	28 GPS + 12 Galileo	28 GPS + 27 Galileo
Suburban	11m / 95%	7m / 95%	7m / 95%	5m / 95%
Low-rise	41m / 50%	14m / 95%	24m / 95%	12m / 95%
High-rise	34m / 50%	25m /75%	42m / 90%	22m / 95%

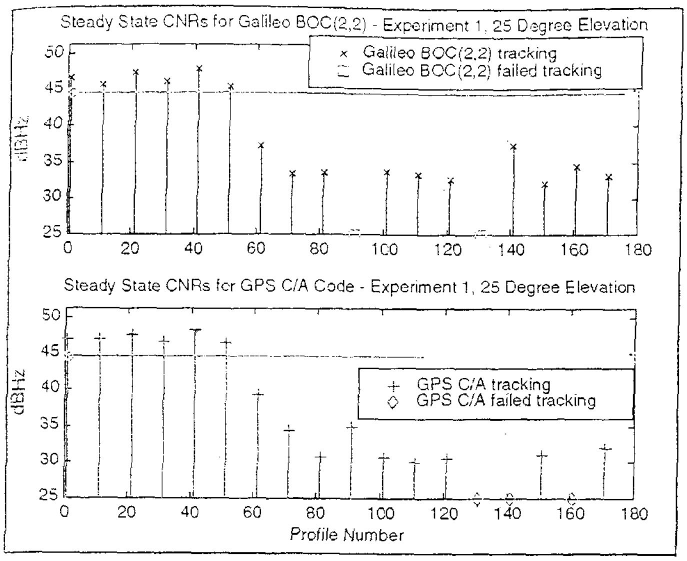

FIGURE 11 Steady-state CNRs for same scenario

urban areas. The addition of Galileo satellites, even as a subset of the final tally, brings a greater benefit to L1 operation than that anticipated from future GPS modernization. Our analysis suggests there will still be scope for augmentation systems to further improve accuracy and/or availability, although their adoption for mass-market applications would have to assess whether the additional cost of infrastructure and user terminals was justified, considering that the increase in addressable market could be limited to high-rise areas where satellite-only availability is insufficient.

Future work within the study will focus on using predicted performance in mass-market environments as an input to a commercial exploitation model indicating the potential benefit to mass-market users.

Acknowledgments

The work reported here was undertaken with funding assistance from the British National Space Centre's S@TCOM program. It was first presented at ION-GPS 2002, Portland, Oregon.

The authors are grateful to Alan Baker and James Brighton at Astrium, Thomas Welsh at RMRL, and Enrique Aguado and Andrew Cartmell at Leeds University for assistance throughout this project.

Matt O'Donnell *is a senior navigation engineer at Astrium, UK.*
Trevor Watson *works in signal definition with the Astrium Navigation Group.*
James Fisher *is a senior engineer within the Antennas and Electromagnetic Solutions group at Roke Manor Research Limited, UK.*
Steve Simpson *leads the Antennas and Electromagnetic Solutions Group at Roke Manor Research Limited.*
Gary Brodin *is a senior research fellow at the UK Civil Aviation Authority Institute of Satellite Navigation (CAA-ISN), University of Leeds.*
Ed Bryant *is a research fellow at CAA-ISN, conducting research into multipath radiowave propagation.*
David Walsh *is deputy director of the CAA-ISN and conducts research into precise GNSS positioning.*

Manufacturers

Satellite visibility analysis used **Analytical Graphics'** (Malvern, Pennsylvania) *Satellite Tool Kit.* **Roke Manor Research Limited** (Romsey, Hampshire, UK) developed the *Epsilon* electromagnetic model.