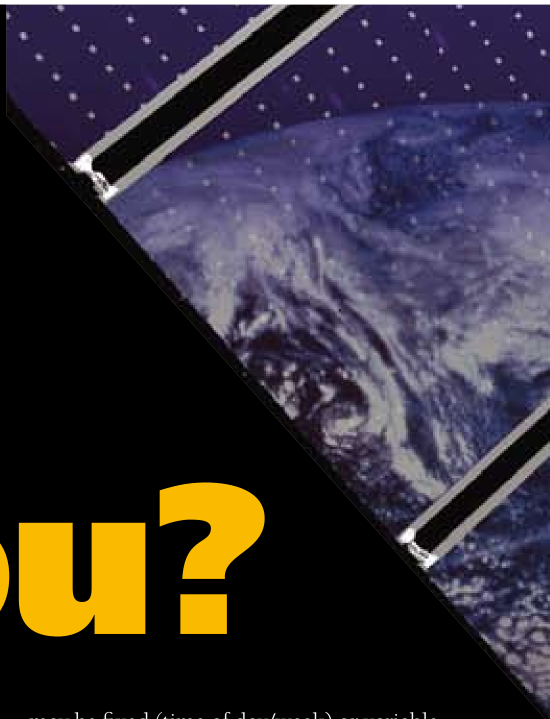
by Bern Grush



An evidentiary and assurance function for GNSS-based Road-User Charging may be just the solution to many a transport strategist's dilemma

Where were you?

Stockholm, Sweden's new membership among cities incorporating zone-based congestion charging in their transportation demand management arsenal provides more evidence of our shift away from an all-you-can-drive to a pay-as-you-go road-use paradigm. While Stockholm's use of DSRC technology is made easier by its peninsular geography (only 18 measurement stations were needed as compared to 200+ LPR-equipped intersections in the LCC system), most planners of such systems are looking to the greater flexibility of Global Navigation Satellite Systems for usage metering.In order to ensure accuracy, certainty and non-refutability, for GNSS metering, an evidentiary and assurance framework needs to be developed.

Many transport strategists see area-based road-user charging (RUC) as the single most powerful transport demand-management technology for the near future. Studies and plans are underway to make it widespread, if not universal, in the UK. In this road-pricing framework, private and commercial motorists would be liable for a usage fee based on journey distance, road or zone used, inferred or actual degree of congestion at the time of use, and class of vehicle used. Ideally, this will begin to replace less efficient forms of taxation and fees such as vehicle registration and fuel duties. As this economic approach matures, insurance premiums and leasing fees will increasingly include metered usage.

GNSS WILL BE THE WINNER

Wireless, barrier-free methods are required for pervasive usage-metering of existing transport infrastructure. For this there are two contending solution classes: Dedicated Short Range Communications (DSRC) and Global Navigation Satellite Systems (GNSS). There is an argument for license plate recognition but that technology is likely to play a sustained role in enforcement. GSM has also been considered, but is not yet accurate enough.

DSRC has an enviable 15-year track record in electronic toll collection (ETC) – the Austrian truck tolling system and now the Stockholm congestion charge are two EU examples, while EZPass and Toronto's 407 serve as North American examples. Recent developments related to 5.9 GHz devices promise to further entrench DSRC's role in ITS and telematics. However, the broad flexibility and low roadside infrastructure r equirement of GNSS makes it preferable to DSRC for wide-area RUC applications such as congestion pricing applied to private automobiles throughout an urban area. Indeed, of all potential road-use metering technologies, only GNSS offers the practical feasibility of metering everywhere at the granularity needed for fair and universal coverage.

It is likely that growth in wide-area RUC, as opposed to link-based or project-based charging, will soon dominate the worldwide ETC market view. Therefore, it is appropriate to look at the readiness of on-horizon GNSS technology to operate well in any potential signal environment, especially in heavily built-up areas, or urban canyon.

A GEOMETRY OF ERRORS

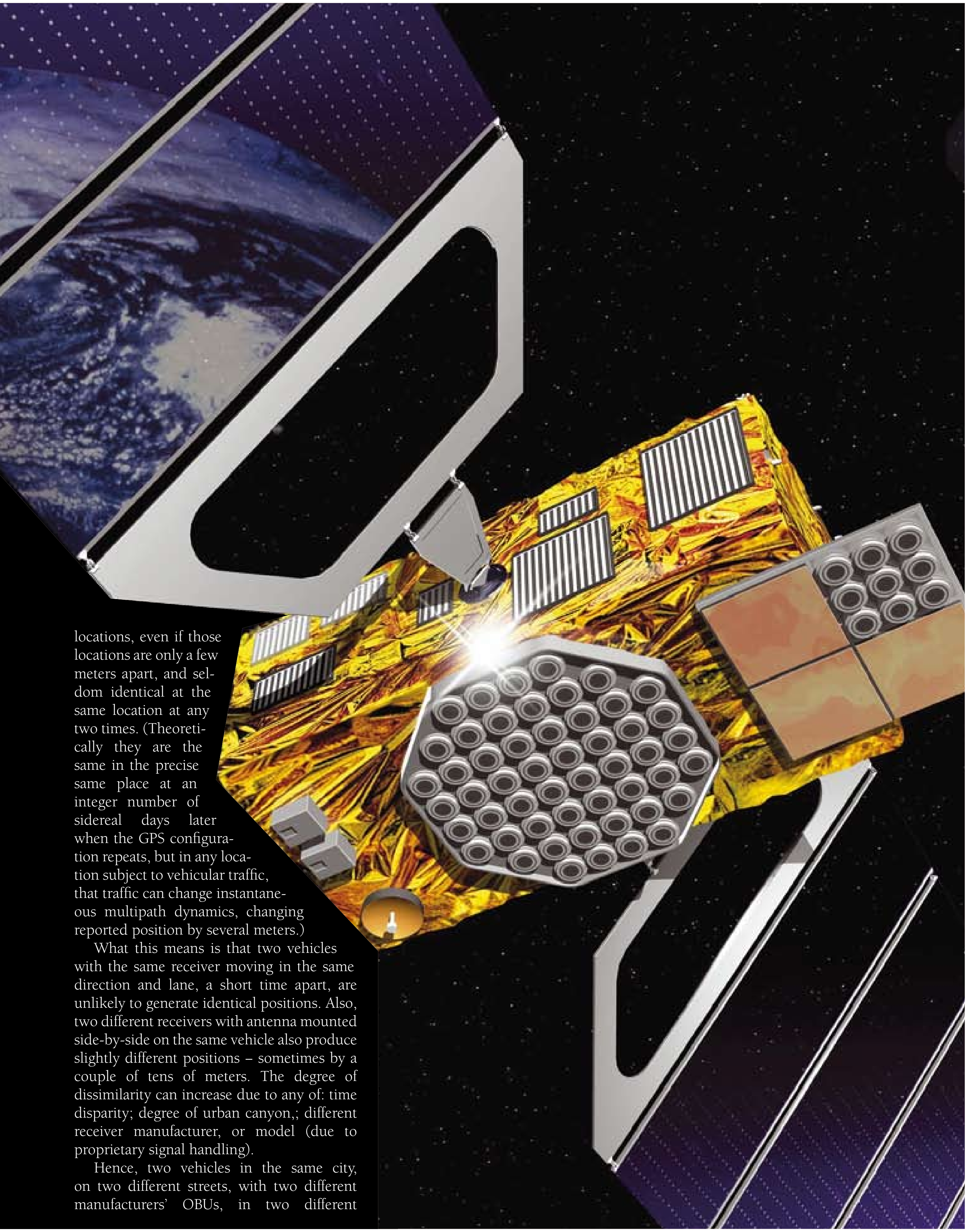
Assessing a fee for a vehicle's use of a roadway depends on:

- measurement of the vehicle's location on a chargeable road or within a chargeable zone (journey),
- measurement time and duration of the journey or journey segment,
- certain market-related information that may be fixed (time of day/week) or variable (assessment of actual congestion at the time of use), and
- assessment of a charge either on-board or in a data center, which in either case implies reliable transmission to a data center.

Currently the first element, location, is by far the least reliable of these. Determining the exact position of a vehicle using GNSS depends on the management of numerous sources of error. Broadly, these include:

- Errors in the originating satellite signal due to clock and orbital uncertainties. There are short-delay processes to handle these and some can be mitigated.
  Signal propagation delays through the atmosphere (ionospheric and tropospheric errors). There are processes to handle these errors that include real-time, partial mitigation at the receiver as position calculations are produced. Post-processing steps may also be used.
- Errors in the computed user position due to the receiver noise. These depend on receiver hardware, proprietary processing, antenna technology and potential interaction with environmental effects, such as EMS interference.
- Perturbation of the satellite signals due to the local environment of the user. These are caused by reflections, shadows or interference. The principle category of these environmental errors is multipath – both line-of-sight and non-line-of-sight.

Multipath errors are the most critical in the matter of evidence. Unfortunately, these are not amenable to systematic measurement and modeling as are orbital, atmospheric and even some receiver-sourced errors. The statistical behaviour of multipath errors in urban canyon is seldom identical at any two



Pic: European Space Agency (ESA)

locations, even if those locations are only a few meters apart, and seldom identical at the same location at any two times. (Theoretically they are the same in the precise same place at an integer number of sidereal days later when the GPS configuration repeats, but in any location subject to vehicular traffic, that traffic can change instantaneous multipath dynamics, changing reported position by several meters.)

What this means is that two vehicles with the same receiver moving in the same direction and lane, a short time apart, are unlikely to generate identical positions. Also, two different receivers with antenna mounted side-by-side on the same vehicle also produce slightly different positions – sometimes by a couple of tens of meters. The degree of dissimilarity can increase due to any of: time disparity; degree of urban canyon,; different receiver manufacturer, or model (due to proprietary signal handling).

Hence, two vehicles in the same city, on two different streets, with two different manufacturers' OBUs, in two different

	Evidence	Assurance
Definition	All journeys are metered precisely as taken	All journeys taken are metered and captured
Requires	Accuracy in location, time, duration	No OBU malfunction
System Design must include	System-wide error tolerance bounds Error characterization/fee segment Handling of out-of-tolerance errors	Data for health checks Integrated on-street enforcement Alternate payment (monthly passes, fines)
Easy Issues	Satellite errors Atmospheric errors OBU noise	Internal data consistency Partial OBU Failure
Hard Issues	Multipath errors Data gaps Zone ambiguity resolution OBU Equivalence	Complete OBU failure OBU occlusion OBU tamper

environments (one fairly open-sky, the other passing through the urban hi-rise core) can be expected to experience very different GNSS error profiles. Given current OBU technology we might expect one vehicle to be within 10 meters of it's 'true' position about 95 per cent of the time {10m,.95}, while the other might be {50m,.95}. The latter circumstance, when it occurs, translates to a 200m error allowance in order to be correct 99.99 per cent of the time. And even this assumes that at least three or four satellite signals are available to obtain a fix.

BUT WHAT ABOUT GALILEO?

Certainly, we can expect improved accuracy once Galileo signals are available. Predictions for cheap, automotive-grade Galileo receivers indicate {~1m, .95} instead of {~5m,.95} for open sky GPS readings. According to one 2004 study, the probability of a signal gap (insufficient signals for a position fix) in deep urban canyon is expected to plummet from 85 per cent to 15 per cent.

GPS Modernization, which is coming on stream in the same time frame as Galileo, will provide roughly equivalent improvement. Indeed, with the addition of high-sensitivity technology to dual GPS/Galileo receivers, one should be safe in assuming that an inexpensive GNSS receivers will soon boast of no gaps at all even inside a parking garage in Shanghai, surely one of the more challenging urban environments on the planet.

Unfortunately, whatever zone-based, road-pricing schemes are devised for this expected future, there will still be many deep-canyon locations wherein the effect of multipath especially non-line-of-sight multipath – which can be exacerbated by high-sensitivity technology – would still produce significant errors. Even if these are only 30-50m outliers rather than the 500-1000m outliers that occasionally appear in current tests, they still must be handled. It will not be conducive to acceptability to overcharge motorists.

Hence, while we will receive more and often better signals because of Galileo, GPS Modernization and high-sensitivity, we will still require context-dependent error mitigation at the receiver. Receiver-autonomous multipath mitigation (RAMM) is similar to receiver-autonomous integrity monitoring (RAIM), which was initially designed for real-time detection of signal problems from space segment before ground segment can rectify them in safety-of-life applications. However, RAMM strictly addresses signal disturbance within the local environment and must be handled in the immediate context of the receiver in question. For non-safety-of-life applications such as pricing, multipath can be handled with a post-processing approach that greatly reduces system demands compared to RAIM used in aircraft landing.

BETTER, BUT STILL NOT PERFECT

Let's return to our original problem. While GNSS signal acquisition will improve dramatically, low-cost GNSS receivers will still provide imperfect positioning in urban canyon for the foreseeable future – long past the full deployment of Galileo. How can we be sure that the information we use to calculate a toll will always provide a fair calculation?

The first thing we will need to agree on is a test for accuracy appropriate to our application. Rather than stating accuracy in terms of meters which is of course the natural units we work with, pricing applications are really concerned with a consistent, correct, fair and repeatable calculation. What happens to the position accuracy from moment to moment is secondary to our ability to derive a reliable toll. In other words, we must be able to show that two vehicles passing through the same zone(s) under the same distance, duration, vehicle class, and time-of-day circumstances will be assessed the same toll to within a very small tolerance. While this may seem like splitting hairs, it is not. If a motorist takes the same journey every day at the same time (same expected congestion), she should expect to be assessed the same fee each time – certainly to within a tiny fraction of the toll. Indeed, it should be possible to query an on-line trip planner with route, departure time and vehicle class, to receive an estimate of journey tolls accurate to within a percent or two (unless real-time congestion weighting is incorporated). The tolling system should then be able match this in a non-refutable manner.

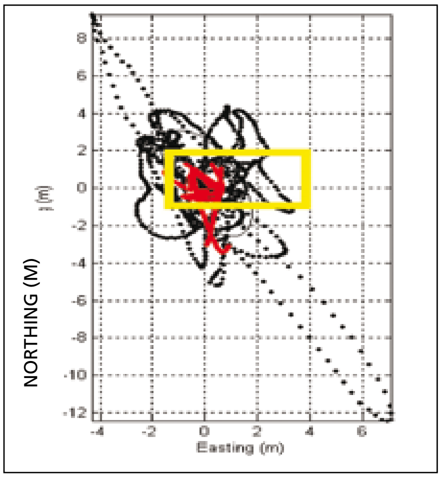


FIGURE 1: THE BLACK POINTS ARE THE ESTIMATED POSITIONS OF A STATIONARY RECEIVER SECOND-BY-SECOND POSITIONED FOR 15 MINS NEAR THREE 20-STORY BUILDINGS. THE RED OINTS ARE THE ESTIMATED POSITIONS AFTER APPLICATION OF ONE OF THE NOISE-REMOVING RAMM PROCESSES MENTIONED IN THE ARTICLE. THE RED DATA SCATTER IN THIS EXAMPLE IS ABOUT 2.5M X 5M REPRESENTED BY THE YELLOW RECTANGLE.

It is possible to achieve this with two sets of processes. One at the receiver operates only on signal and positioning noise through a series of filters and processes, designed to mitigate urban multipath. This improves the evidence. Characterization of this improved evidence adds evidentiary weight and can support a subsequent process in the datacenter to develop an invariant price.

We are developing two forms of RAMM – one for metering moving vehicles (RUC) and another for metering stationary vehicles (parking meter). Each form of RAMM requires a process that detects and removes multipath faults and further cleans (de-noises) the remaining signals. An example of the effect of this is shown in Figure 1.

In addition, we are developing two forms of characterization and compression, one pair suitable for journeys (a 'zonelog') and another for parking events (a 'parklog'). When uploaded to a datacenter these two usage logs will be processed by two final stages of processing that provides for price invariance – and a reliable, repeatable description of journey or parking events that allow non-refutable tolling.

What all this means is that while Galileo will not make urban canyon error-free, it will soon be possible to use the rich set of signals receivable by inexpensive, high-sensitivity, dual GPS/Galileo receivers to provide reliable, repeatable, and provable toll calculations that will far exceed the pricing efficiency of fuel-tax or even DSRC-based tolling. ■

BERN GRUSH IS WITH APPLIED LOCATION CORP., TORONTO, CANADA. THE WORK DESCRIBED IN THIS ARTICLE IS PART OF THE PATENT-PENDING PROCESS FOR A COMBINED PARKING, ROAD-USE, AND PAY-AS-YOU-DRIVE INSURANCE METER.
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