Guaranteed GNSS-based Road Charging Applications through User-Level Integrity

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Abstract

Integrity plays a fundamental role in the feasibility of “liability critical” applications. Road charging, e.g. road tolling in urban zones or on highways, represents a series of liability critical applications where a guarantee in integrity could be a true enabler: being the mechanism that prevents the incorrect charging of users and enabling the advancement of these applications using GNSS such as Galileo and EGNOS that provide integrity mechanisms. However, the integrity of the end user position is not guaranteed by the EGNOS and Galileo integrity services alone as provided. Algorithms have been developed to supply a guarantee on the performance attainable at the user level through the provision of a horizontal protection level that responds to local user conditions such as multipath or interference. In addition, an application has been developed that implements road charging mechanisms based on the availability of user-level integrity. Results obtained show that the user-level integrity algorithms provided the required level of integrity guarantee and granularity of the horizontal protection levels necessary for executing urban and rural (highway) road charging. In addition, the road charging application developed shows that the current application domain requirements can be met through the provision of guaranteed integrity and that further reductions in the horizontal protection levels along with increased signal availability will enable future road charging modalities.

Keywords: Liability Critical, Integrity, Galileo, EGNOS, Road Charging, Electronic Toll Collection, Protection Level

1. Introduction

Various studies undertaken by the European Commission have shown that there are hundreds of liability critical applications that would be enabled by GNSS-based positioning *if* there were some way to guarantee the integrity of the user position. An example of one of these applications is Electronic Toll Collection and, for instance, the Toll Collect scheme in place in Germany, or the congestion, or cordon, charging currently being enforced within the city-centre of London that as of now has zero reliance on GNSS-positioning, but which plans to add this facet in the future. With guaranteed integrity, these applications and others could be implemented using GNSS-only – resulting in the elimination of the need for costly infrastructure and potentially simplifying the enforcement mechanisms now being used for these applications.

1.2 GNSS Liability Critical Applications

GNSS Liability Critical Applications are a set of applications that is generating exceptional interest due to the clear financial gains that are predicted if these applications can be executed successfully. These applications represent those with a liability attached – either economic or legal – that depends upon GNSS performances. In this paper we refer only to those applications that are implemented using GNSS systems only such as Galileo and EGNOS. Meaning that GNSS user positioning is the basis for implementing these applications.

Examples of economic liability critical applications are road-tolling, pay per use insurance, taxi metering, or on-street parking. These applications must be able to guarantee the correct charging of a user for services rendered in order to succeed as a practical business venture.

On the other side are the legally binding liability critical applications such as vehicle speed enforcement, accident reconstruction or the tracking of special vehicles (e.g., hazardous waste or livestock). These applications result in legal recriminations, vs. economic, and are most often found within the jurisdiction of the national or local governments.

When based on GNSS, these applications must therefore be able to guarantee the user position data – to have confidence that the user was where the system indicated and to be able to back that up with solid proof.

2. The Integrity Chain

This proof can be provided in the form of an integrity guarantee. This guarantee must however be supplied at the user-level in order to be valid for use in the aforementioned applications. The distinction of “user-level” has significant implications on the integrity provision chain. The GNSS EGNOS, and later Galileo, provide an intrinsic integrity monitoring service of the signal-in-space (SIS) broadcast to the user. For civil aviation, this guarantee on integrity is sufficient since the user environment is very well characterised and thus controlled. Civil aviation is in fact what has been driving the requirements for integrity on the SIS.

This integrity guarantee, however, covers only the signal transmission up to when it leaves the GEO, or Galileo satellite, and crosses the atmosphere – but not through to an end user that is on the ground. What this implies is that the path of the signal from when it leaves the satellite to its final arrival at this end user has no full integrity guarantee as transmitted within the SIS itself. This has to be constructed on the ground through a separate process. Why is this necessary? Because the SIS will encounter a variety of obstacles between the emitting satellite and end user in the form of multipath, interference, non-line-of-sight signal reflections, etc., as outlined in Figure 1.

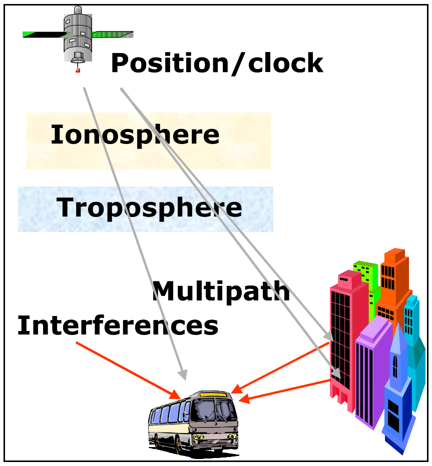

Figure 1. SIS Path Travelled.

In the frame of GNSS-based applications, integrity is what provides the guarantee that the system is functioning correctly and that it is reporting a position within a clearly delimited area. The users on the ground – service providers and end users alike – can be certain that this area, described by a Protection Level (PL), contains with an incredibly high, and known, probability the actual position of the vehicle. In other words, this means that the region circumscribed by the protection level always bounds the error in the position estimated by the system.

A protection level is a reliable limit on the position error calculated through an interpretation of the known error sources – including both system errors (such as ephemeris or ionosphere) and those derived from local user environment. It is formed as a circular limit around the current estimated position that establishes an area in which the position is guaranteed to be with a high probability.

The value added of this integrity metric is that it is a guarantee on the user position. The protection level, the radius of this integrity region, may grow or shrink depending on individual conditions at each position, but as long as it can be computed, the user position is by definition guaranteed to fall within the region it describes. This is shown in Figure 2.

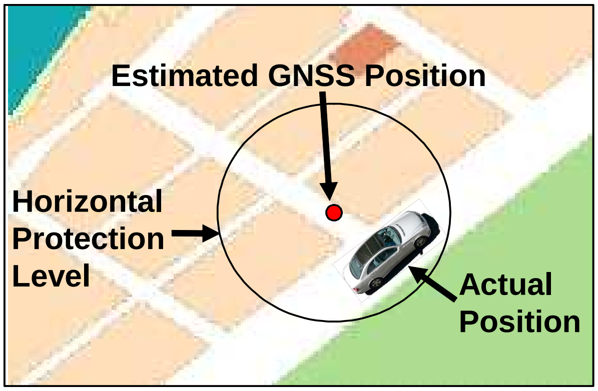

Figure 2. Horizontal Protection Levels.

This is a very powerful tool for GNSS-based applications if it can be computed. In particular, in the field of Liability Critical Applications, integrity is indispensable. It is the key to ensuring the correct accountability of a user for liability critical application services.

2.1 Integrity and Local Signal Effects

Local effects refer to those errors resulting as a consequence of the receiver processing a signal that is distorted by interactions with the local environment in the vicinity of the receiver. These effects include: multipath, thermal noise and interference from electromagnetic sources.

Some of the largest SIS distortion due to local effects comes from multipath. Multipath refers to the reception of the same SIS from two or more paths caused by, for example, reflection off terrestrial objects. The receiver then has difficulties in separating these multiple signals into that which has a direct line-of-sight to the originator and those arriving through alternate paths. Another source of significant errors are alternate path delays due to purely non-line-of-sight signal reflections. This may be a product of receiver sensitivity or a fast acquisition time.

Extensive effort is being dedicated to the field of isolating and identifying signal multipath and other local effects. For this application, multipath is mainly a problem in static situations – with the smallest addition of velocity the multipath errors average out considerably. Since the road charging application under study is a mainly dynamic application, static situations form a relatively small percentage of the solution set of this particular application so as to not affect the road charging results. Multipath becomes a considerable problem, then, for applications such as GNSS-based charging for on-street parking, which takes place in a solely static domain. Non-line-of-sight signal reflections are more difficult to isolate and present the greatest challenge.

Since the objective of the developed algorithms is providing guaranteed integrity, and not to provide high accuracy, the focus has been on the identification and bounding of such errors versus their mitigation.

3. Road Charging Requirements

The road charging application is characterized by requirements related to the correctness (integrity) of the computed user position, velocity and time as the basis to:

- Validate the application's correct performance in order to avoid loss of the provided service and revenues.
- To ensure that charging is computed correctly and in particular, that users are not charged if they have not used the service/infrastructure.
- Avoid spurious claims against the service provider by ensuring that the PVT data is recognized as a legal proof of application use.

In order to quantify these requirements it is necessary to analyse the system's performances in terms of availability and integrity. The two main performance metrics of concern for the road charging service provider are:

- Integrity – a measure of trust that can be placed on the system – necessary for the correct charging of users who have entered a charging zone, and to avoid charging incorrectly users who have not entered a charging zone, and

- Availability – the ability to detect that users have entered a charging zone.

If the proposed HPL can be established for a certain user position (availability), then by definition it can be guaranteed, with a known high probability, that the user was within the HPL at that time (integrity). This information can then be used as the basis for road charging if the HPL supplied is sufficiently small as to permit the practical application of its use. The capability to provide ever-smaller HPLs that meet an application's integrity probability requirements is the greatest challenge to integrity across all application domains.

The HPL is what can be used to prove a user's position at a specific time. For urban charging – settings within urban zones characterised as populated areas with dense groupings of buildings and other urban obstacles – the challenge is complicated by the reduced signal availability due to simple geometry and the other local effects previously touched upon (availability). Road charging applications taking place on highways (not within urban settings) have somewhat fewer restrictions and requirements that are in some ways more easily met due to the user environment.

The road charging concept using HPLs is illustrated in Figure 3. A vehicle has entered a charging zone depicted by the dashed line. Since the protection level bounds the position error and is fully contained within the charging zone then the vehicle can be charged. If the protection level was not fully contained within the charging zone then the system would not be able to verify that the vehicle had without a doubt entered the charging zone and should not exact a charge.

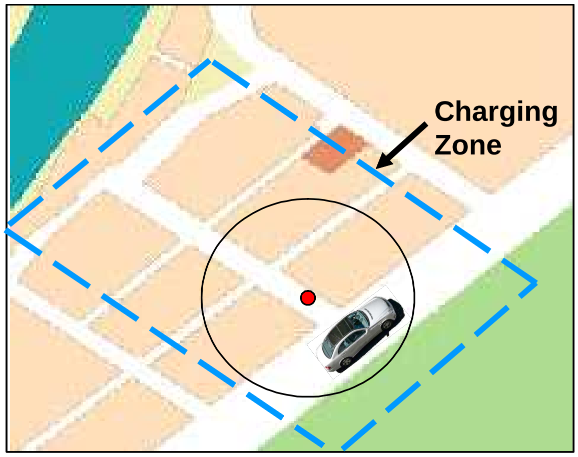

Figure 3. Charging Zone Definition.

In order for GNSS-based road charging to be viable as a practical application, the number of possible valid claims against a service provider must be guaranteed to be less than a maximum acceptable amount, per day, or week, etc.

The resulting probability of a user being incorrectly charged is what the authors refer to as "*Charging Integrity*" – the probability that a user is charged when they did not in fact enter a controlled zone, which would result in a valid claim against the service provider. If the user's GNSS position estimate falls inside a controlled perimeter, it will produce an incorrect charge only if the estimated protection levels do not bound the actual position error. The probability of this occurring is GNSS positioning non-integrity performance.

Since we do not have a way of measuring the position error exactly, certain assumptions must be made about the behaviour of the error, and its statistical and probabilistic components, and thus the protection level computation has been designed to meet certain integrity probabilities, e.g. the probability of a missed detection occurring, required for this particular application (to meet the road charging integrity requirements).

This process of apportioning the integrity requirements to user position requirements requires a complex engineering analysis similar to the one used in civil aviation for the definition of the Required Navigation Performance (RNP) requirements. This exercise is in many ways even more complicated due to the need for incorporating information regarding factors such as road topology.

However, since this application is not safety critical, and many calculations could indeed be performed in an off-line capacity, there exists the possibility of relaxing certain positioning availability and real time constraints that make feasible achieving guaranteed integrity in the target user environment.

Finally, it is important to mention that there is in addition a set of operational system requirements that must be met in order to implement a fully functioning road charging system. These include requirements on communications between vehicles (users) and service providers, standardisation, supporting legal framework, etc., which remain to be resolved.

3.1 Highway vs. Urban Road Charging

The highway road charging problem is characterised by the need to detect the entrance of vehicles onto a tolled highway, the use of individual sections of that route, and the exit of the vehicle from the tolled road. The toll road in this situation is a clearly defined route of usually multiple lanes, in a relatively open environment. Meaning that there are less natural or man-made obstacles to signal reception, in contrast to an urban, city environment where there may be tall buildings surrounding narrow streets, and a greater number of man-made obstacles to signal reception.

The urban road charging problem is defined by the modalities in which the charging is to take place. Ideally, a user would be able to be charged based on any number of parameters such as time of day, exact location, vehicle characteristics, etc., for applications such as parking metering, taxi metering, cordon charging (for entering different zones within a city), etc. A GNSS system that satisfies all those requirements would have to have high availability, and integrity, the last being what would guarantee the correct charging of a user (charging integrity).

In addition to the possible lack of a position integrity guarantee, a major obstacle to realising urban road charging applications is the limited visibility available in such environments. With Galileo operational, studies performed with the GMV service volume simulator Polaris show that every user position will benefit from at least 1 additional satellite in view over GPS only, and over 85% of all user positions will benefit from 3 additional satellites in view (Figure 4).

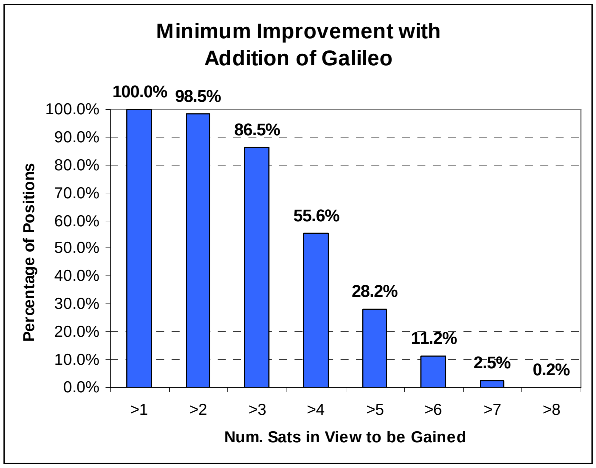

Figure 4. Galileo Visibility Prediction.

4. Road Charging Field Trials

A newly developed integrity road charging application was put to the test within Madrid, Spain, a representative, large European city filled with urban canyons. In this city, multiple opportunities arose to test the system against the effects of a local, urban environment, including multipath, non-line-of-sight reflected signals and reduced visibility in general. Figure 5 shows a sample test route taken to collect data with the on-board system.

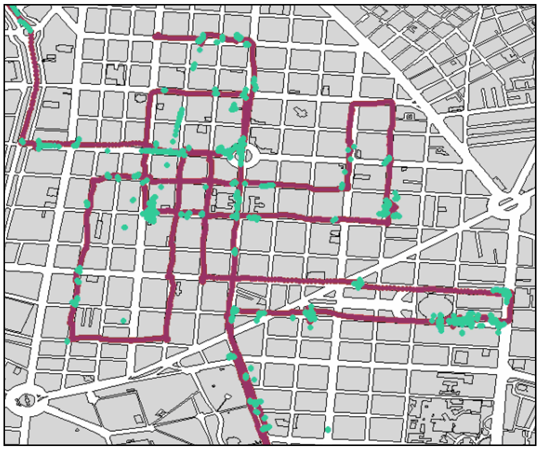

Figure 5. Typical Test Route.

SBAS-like PLs complemented with models of local effects and different barriers, and a modified RAIM (Receiver Autonomous Integrity Monitoring) algorithm were developed to supply the integrity monitoring necessary at the user level within the on-board unit itself (a mobile user platform which includes the receiver). The algorithms developed are based on GPS pseudorange measurements provided by the GNSS receiver, assuming an SBAS assisted solution through an EGNOS GEO or signal reception by way of SiSNet (Signal-in-Space through the internet) when GEO visibility was poor.

The modified RAIM algorithm permits the screening out of large position errors and to characterize properly the pseudoranges to be used for positioning through a process that adapts the weight matrix each epoch with the smoothed pseudorange noise information. In addition, it has been designed to account for the multiple failure case, taking into account possible previous failure misdetections. Through this process the adaptive RAIM algorithm determines the protection level of the computed positioning with the required level of integrity.

The receiver used was the Sirf Star II, chosen for its high navigation solution availability, which has proven to be another key parameter for this application, in contrast to having the most accurate navigation solution possible. Since the Sirf Star II does not have the capacity to receive EGNOS corrections, they were received whenever possible through the use of SiSNet for the duration of the trials.

5. Results

The position integrity performances were excellent for the tests where a good reference trajectory was available (computed with a Trimble 5700). The reference trajectory is what allows the evaluation of the performance of the system and the estimation of the system's error. Once this error is "known", the ability to bound it with the protection level can be assessed, i.e., the level of position integrity obtained.

While the targeted integrity performance was established as 99.999%, the goal during the trials (due to their short duration) was to reach a success rate of 100% position integrity, or, in other words, that the protection level region correctly overlapped the estimated position and the real position (i.e., that the horizontal protection level bounded the horizontal error), 100% of the time, guaranteeing that the system was able to establish a region that always contained the actual position of the vehicle. So if this region was within a charging zone, then the user could be reliably charged.

This behaviour is shown in the following Stanford plot, where the HPL always bounds the Horizontal Error (HE) for both static and dynamic situations.

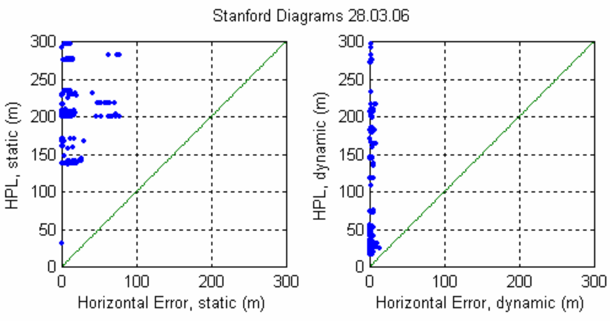

Figure 6. Stanford Diagrams, GPS+EGNOS.

In Figure 7, notice how the PL is substantially reduced under dynamic conditions (for velocities greater than 5 Km/hr).

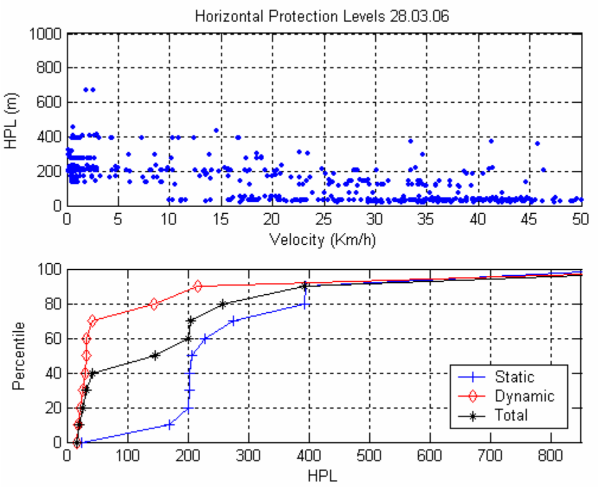

Figure 7. Horizontal Protection Levels, GPS+EGNOS.

Figure 8 shows a sampling of the protection levels, those less than 200 meters, superimposed on a map of the test trajectory.

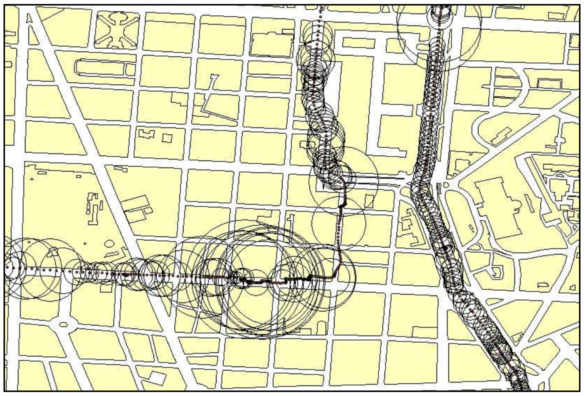

Figure 8. Horizontal Protection Levels <200m, GPS+EGNOS.

Table 1 presents the statistical information for percentage of time a solution was available and the 95% accuracy achieved during the test run for the different modes of operation.

Table 1. Availability and Accuracy, GPS+EGNOS.

MODE	**Solution Availability**		**Accuracy 95% (meters)**		
	Pos	Pos+HPL	Total	Static < 10Km/h	Dynamic > 10Km/h
GPS Only or GEO Ranging	24.5	7.8	4.3	23.4 (12.63%)	4.2 (87.3%)
Degraded EGNOS	9.9	7.8	63.4	67.5 (24.1%)	9.0 (75.9%)
EGNOS	58.7	55.8	18.8	50.2 (51.3%)	5.1 (48.7%)
ALL MODES	**93.2**	**71.4**	**17.6**	**51.9 (42.7%)**	**5.1 (57.3%)**

The case where EGNOS corrections are never available shows a clear degradation in performances as can be seen in the following data. Although HPLs were able to be calculated for a percentage of the test run greater than 50%, without EGNOS they are considerably larger. This level of degradation would seriously jeopardise the feasibility of most liability critical applications.

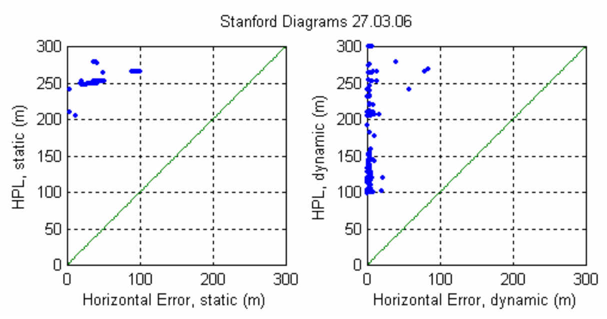

Figure 9. Stanford Diagrams, Without EGNOS.

As a matter of fact, the availability of PLs smaller than 100 m meters are dramatically reduced from 49.5% to 0.1% when EGNOS is not used.

The percentage of time a solution was available in position and integrity (HPL) is shown in Table 2 along with the corresponding static and dynamic 95% accuracy.

Table 2. Availability and Accuracy, Without EGNOS

MODE	**Solution Availability %**		**Accuracy 95% (meters)**		
	Pos	Pos+HPL	Total	Static < 10Km/h	Dynamic > 10Km/h
GPS Only or GEO Ranging	99.4	63.4	40.6	94.4 (21.4%)	11.3 (78.6%)
Degraded EGNOS	0	0	-	-	-
EGNOS	0	0	-	-	-
ALL MODES	**99.4%**	**63.4%**	**40.6 m**	**94.4 m (21.4%)**	**11.3 m (78.6%)**

Certain instances of non-line-of-sight signal reflections were also identified during the trials and the following figure clearly shows one of these cases. In this case, the reflected signals are not detected and rejected because the pseudorange and carrier phase are consistent, and multipath hardware mitigation methods and pseudorange smoothing filters are not effective.

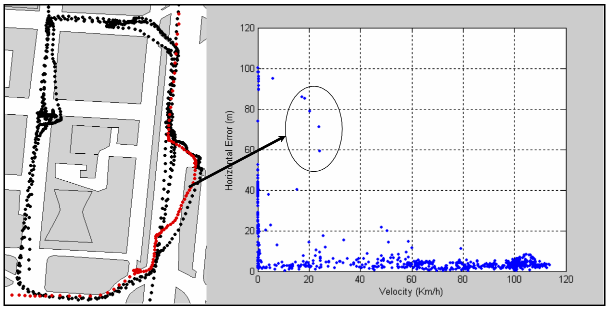

Figure 10. Non-Line-of-Sight Signal Reflection.

Results show that if signal visibility can be guaranteed, then for an area of 5 Km by 5 Km, in a major metropolitan city, up to 600 different 200 x 200 meter charging zones could be established with guaranteed integrity, assuming that one position with integrity could be established within each zone. This is obviously dependent also upon the visibility conditions within each particular zone.

Using the previous example showing the protection levels, the resulting granularity of urban charging zones is approximately what is shown in Figure 11. The test vehicle in Figure 11 would have been charged correctly for transiting 9 different zones. The vehicle would not be charged with the current system for crossing the zone immediately above zone 9 because it could not be confirmed, by the protection level standard, that the vehicle had indeed been within that zone.

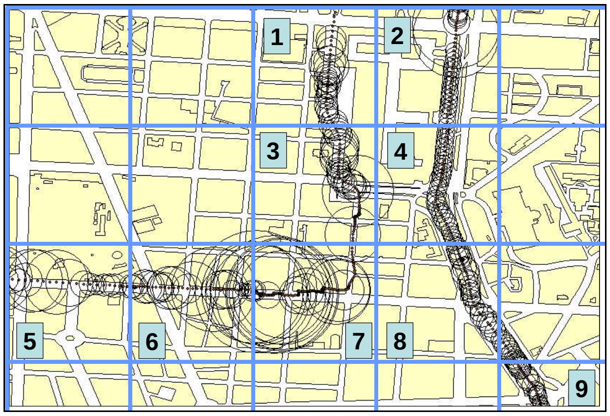

Figure 11. Charging Zone Granularity, 200m x 200m.

All current highway tolling application requirements can be fully met by the integrity performances provided through the developed application, including those within environments which are not perfectly clean.

Charging zones as short as 150 meters and as narrow as 40 meters could be established along most sections of highway, depending upon local conditions. In comparison, these charging regions are shorter than the shortest highway charging zone in the German Toll Collect system, which is 200m.

6. Conclusions

Liability Critical applications require the provision of guaranteed integrity on the user position, just as is the case of safety critical applications such as in civil aviation. However, unlike civil aviation, liability critical applications take place in uncontrolled environments, which require additional mechanisms implemented at the user level, apart from the GNSS integrity monitoring of the SIS, in order to counter specific local effects, especially multipath and non-line-of-sight signal reflections.

The integrity algorithms developed provide HPLs that satisfy both urban and highway road charging application requirements. The granularity of the urban charging zones is such that within a city centre with a radius of 2 Km, 300 separate charging zones could be established. The most stringent highway road charging requirements can be met using the integrity algorithms developed.

A focus of continued investigation will be on reducing the HPL as much as possible while still maintaining the required level of guaranteed integrity. This reduction will contribute to the enabling of many more road charging methods in addition to other applications in this and other application domains based on the sole use of GNSS positioning with guaranteed integrity.

As noted, the application of GNSS positioning data hinges on its acceptance as legally binding within each country, and across borders. The corresponding national and international legal and regulatory frameworks must be established and enforced. In addition, the use of GNSS systems in this field could reduce the reliance that exists today on physical infrastructure for exacting payment and enforcing user compliance.

Finally, achieving guaranteed integrity in the local user environment has been proven to be the key for the correct and successful implementation of GNSS-based liability critical applications, and in particular that of road charging.

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