GNSS Time Offset

Effects on GPS-Galileo Interoperability Performance

INGE VANSCHOENBEEK, BERNARD BONHOURE, MARCO BOSCHETTI, AND JEROME LEGENNE
CNES (LE CENTRE NATIONAL D'ÉTUDES SPATIALES)

Time is a crucial factor in satellite-based radionavigation. The elapsed time between the transmission of a GNSS signal and its reception by a receiver, multiplied by the speed of light, provides the basis for calculating ranges to the satellites. However, GPS and Galileo will use different reference time systems creating a time offset, which can complicate the positioning computations in user equipment employing signals from both satellites. A team of researchers at the French space agency CNES describe the effect of this time offset on positioning accuracy and examine three methods proposed to eliminate the offset.

By measuring the elapsed time between the transmission and reception of GNSS signals, navigation receivers calculate the pseudorange to each satellite and use this information to calculate their position on Earth. However, receivers not only have to calculate the user's position in a 3D environment; they also have to cope with an unknown time bias between the receiver and the GNSS system.

Therefore, to precisely estimate a user's position, receivers need to solve for four unknowns, which requires at least four pseudorange measurements between the receiver and the satellites. This means that a minimum of four satellites needs to be available to accurately estimate a user's position.

Because the positioning accuracy will improve as more satellites become available (better geometry measured with the well-known dilution of precision or DOP parameters), we should expect that a combination of Galileo and GPS will provide better performance than those of both systems separately. In the future, therefore, most GNSS receivers will calculate the navigation solution using measurements from GPS and Galileo together.

However, the European navigation system Galileo will not use the same time reference as GPS and, thus, a time difference arises — the GPS-Galileo Time Offset (GGTO). The navigation solution calculated by receivers using signals from both navigation systems will consequently contain a supplementary error if the GGTO is not accounted for. Users wanting to use measurements from both systems need to cope with this time offset if they do not want to degrade the final navigation solution.

This article discusses three different approaches to solve the problems faced when using both navigation systems together, proposed in the work by A. Moudrak *et alia* cited in the Additional Resources section near the end of this article. These three approaches are the following: GGTO determination at user level, at the system level, and a combination of these two methods.

We have extended the previous research into the methods of GGTO determination by examining the differences among the three proposed solutions with the aid of a software simulation tool in representative environments, including a 3D model of the city of Toulouse, France. Our research also took into account not merely the directly received signals from the satellites, but also signals reflected from the surrounding structures.

GPS-Galileo Time Offset in Simulation

The software that we used simulates GNSS performances in constrained 3D environments. It takes all the possible signal paths between the satellite and the receiver into account by simulating direct as well as reflected signals. Six error sources are included in the calculations: ephemeris and satellite clock error σ_{clock_sat}, receiver clock error $_{\sigma clock\_rec}$, ionospheric error σ_{iono}, tropospheric error σ_{tropo}, receiver noise σ_{rn} and errors due to multipath σ_{mp}.

The variance of the *i*-th measurement (corresponding to satellite *i*) is calculated according to:

$$\sigma_i^2 = \sigma^2_{clock\_sat,i} + \sigma^2_{clock\_rec,i} + \sigma^2_{iono,i} + \sigma^2_{tropo,i} + \sigma^2_{rn,i} + \sigma^2_{mp,i} \quad (1)$$

The user of the simulation tool defines all these errors through a set of parameters, as illustrated schematically in Figure 1.

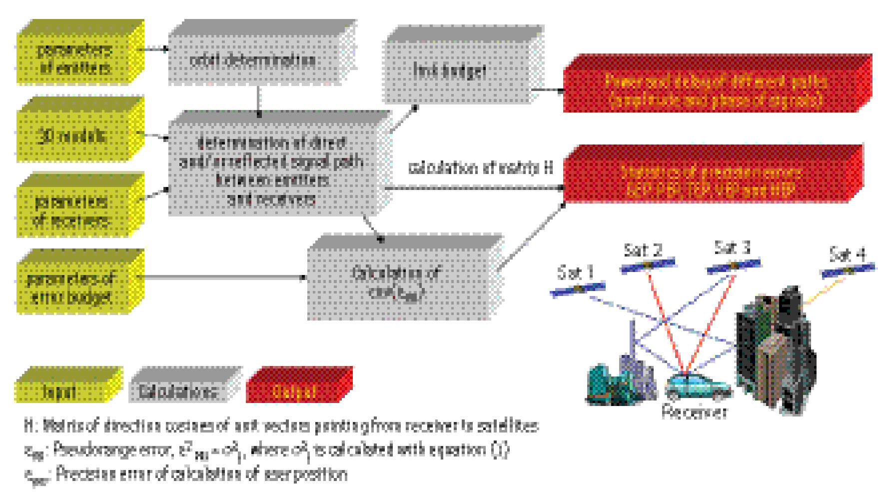

FIGURE 1 Schematical representation of the simulation tool. Direct signals are indicated in red and reflected signals in blue in the picture on the right.

The simulation program estimates the performances of the position determination process by defining a linearized system of equations that corresponds to the pseudorange measurements between the satellites and the receiver:

$$\Delta\rho + \nu = H \cdot \Delta X \quad (2)$$

where $\Delta\rho$ contains the differences between the estimated and measured pseudoranges and ΔX, the position and time evolution of the system. The ν-matrix accounts for the measurement noises, and H, finally, is the matrix that contains the direction cosines of unit vectors pointing from the receiver to the satellites.

The H-matrix is used to calculate the dilutions of precision (DOPs) and the precision errors (EPs). As will be discussed later in this article, these two parameters will be used, together with the number of satellites in view, in order to assess the properties of the various GGTO determination methods. The DOP parameters describe the distribution of the satellites in the sky and depend on the H matrix.

On the other hand, for the determination of the precision errors, the covariance matrix of the measurement errors is also used. However, we assume that the measurement errors from different satellites do not contain a bias and are independent from each other. The covariance matrix R is therefore a diagonal matrix with the variance of the *i*-th measurement error on row *i*.

Preliminary Considerations on GGTO

Position estimates are, when considering satellite navigation, obtained by measuring the pseudoranges between users and navigation satellites. These pseudoranges are obtained by determining the time delay between signal transmission by a satellite and its reception.

However, as Galileo and GPS do not use the same time reference, a time offset exists between both systems. To be more precise, the pseudoranges determined with Galileo are referenced to the Galileo System Time (GST), while the ones from GPS use the GPS Time (GPST) as a reference. The resulting time offset between GST and GPST is the GGTO factor, which receivers using measurements from both systems need to take into account in order to avoid degrading the final navigation solution. The signals broadcast by GPS and Galileo satellites will include the GGTO in the navigation messages.

CNES has specified and financed the development of the simulation module used in the analysis described in this article. The module includes the GGTO parameter in order to assess the positioning performance when combining GPS and Galileo measurements. This has been accomplished by redefining the matrices of the equation of navigation (2).

The three different methods to determine the GGTO, as proposed by Moudrak et alia, are integrated in this simulation program: GGTO determination at user level, at system level and a combination of these two methods. These three different approaches are explained in more detail in the following section.

A GNSS positioning service is said to be available when a receiver can establish a position estimate. In the current case, where only GPS is available, a minimum of four satellites is required in order to estimate a 3D position. When combining measurements from GPS and Galileo, *service availability* means that at least five satellites are available when a GGTO determination at user level is applied and four satellites, when the broadcast GGTO is used.

Preliminary simulations have shown that service availability will improve drastically when Galileo becomes available. A simulation of a pedestrian in a typical dense urban environment has shown that the GNSS service is available for 51 percent of the trajectory if only measurements from GPS are used. However, when also considering the future Galileo system, the service availability over the same trajectory increases to 98 percent if the broadcast GGTO were used. If the user prefers to employ the user-level GGTO determination method, the service availability is 94 percent over this trajectory. In the future, GNSS receivers will therefore need to calculate the navigation solution using measurements from both GNSS systems together.

Nevertheless, when combining measurements from Galileo and GPS, data of two different origins is used. In order to optimize this fusion, different weights are assigned to all measurements. The applied weight reflects the thrust in a measurement, and a measurement with a large error can be taken into account without degrading the final navigation solution too much. Giving weights to the different measurements is accomplished by solving Equation (2) with a weighted least squares algorithm. For our purposes here, we assume that the weighting coefficients determined from error models are identical to those implemented in the simulation software. In this way, the covariance matrix R and the weighting matrix W can be written as:

$$W = R^{-1} \quad (3)$$

GGTO Equations of Navigation

As stated earlier, the equations of navigation need to be redefined in order to include the GGTO, which is defined as the time bias between GST and GPST.

Three methods to include the GGTO into the calculations are considered in this article and the new definitions of those equations depend on the method chosen. The equations of navigation, when including the GGTO, can again be written under matrix notation according to Equation (2).

GGTO Determination at System Level

Galileo and GPS will broadcast the GGTO within their navigation messages. When a determination at system level is chosen, the receivers apply this broadcasted GGTO to account for the time offset. This way, they only have to determine the 3D position and the time biases between the receiver and the navigation systems. The navigation solution can now be calculated from at least four pseudorange measurements, as if only one navigation system is used.

The matrices of Equation (4) contain the same information as those of Equation (2), except that the GGTO is now also taken into account. The new ΔX and H_{SYST} matrices are defined by:

$$H_{SYST} = \begin{bmatrix} a_{x_1 GAL} & a_{y_1 GAL} & a_{z_1 GAL} & 1 & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{x_n GAL} & a_{y_n GAL} & a_{z_n GAL} & 1 & 0 \\ a_{x_1 GPS} & a_{y_1 GPS} & a_{z_1 GPS} & 0 & 1 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{x_m GPS} & a_{y_m GPS} & a_{z_m GPS} & 0 & 1 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix}; \; \Delta X = \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ -c \cdot \Delta t_{GAL} \\ -c \cdot \Delta t_{GPS} \end{bmatrix} \quad (4)$$

where a_i are the direction cosines of unit vectors pointing from the receiver to the satellites. The measurements made with Galileo are marked with the index *GAL*, while the ones from GPS carry the index *GPS*. n is the number of Galileo measurements, m the number of GPS measurements. The last row of the matrix takes the GGTO into account. ΔX contains the position and time evolution of the system where c is the speed of light.

The DOP parameters also need to be redefined as the dimension of the matrix H has changed; these are called DOPg. When the broadcast GGTO is used, the simulation program will calculate the DOPg parameters by using the matrix H_{SYST}:

$$\left(H_{SYST}{}^{T} \cdot H_{SYST}\right)^{-1} = \left[D_{ij}\right]; \text{ with i,j} = 1,\ldots,5 \quad (5)$$

Five DOPg parameters are calculated by the simulation software: GDOPg (geometric dilution of precision), PDOPg (position dilution of precision), HDOPg (horizontal dilution of precision), VDOPg (vertical dilution of precision), and TDOPg (time dilution of precision). These parameters are calculated in a local coordinate frame by:

$$\begin{aligned} GDOPg &= \sqrt{D_{11} + D_{22} + D_{33} + D_{44} + D_{55}} \\ PDOPg &= \sqrt{D_{11} + D_{22} + D_{33}} \\ HDOPg &= \sqrt{D_{11} + D_{22}} \\ VDOPg &= \sqrt{D_{33}} \\ TDOPg &= \sqrt{D_{44} + D_{55}} \end{aligned} \quad (6)$$

The covariance matrix R of the measurement errors was described earlier. However, this matrix also needs to be redefined in order to account for the GGTO. The variances of the GPS and Galileo measurement errors are calculated by applying (1). The variance of the i-th GPS measurement error is indicated by σ^2_{iGPS} and the variance of the i-th Galileo measurement error by σ^2_{iGAL}. The variance on the GGTO is described by σ^2_{GGTO}. *The Galileo Systems Requirements Document* (see Additional Resources) specified that the GGTO shall be accurate to within 5 nanoseconds (2-sigma), which means with a standard deviation of 2.5 nanoseconds. Therefore, σ_{GGTO} has been defined equal to 2.5 nanseconds throughout this article unless specified differently. The covariance matrix of the measurements becomes:

$$
R_g = \begin{bmatrix}
\sigma^2_{1\,GAL} & 0 & \cdots & 0 & \cdots & \cdots & 0 \\
0 & \ddots & 0 & \cdots & & & \vdots \\
\vdots & 0 & \sigma^2_{n\,GAL} & 0 & & & \vdots \\
\vdots & & 0 & \sigma^2_{1\,GPS} & 0 & \cdots & 0 \\
0 & \cdots & \cdots & 0 & \ddots & 0 & \vdots \\
\vdots & & & \cdots & 0 & \sigma^2_{m\,GPS} & 0 \\
0 & \cdots & \cdots & 0 & \cdots & 0 & \sigma^2_{GGTO}
\end{bmatrix} \qquad (7)
$$

Once more, we assume that the measurements from different satellites do not contain a bias and are independent from each other. The precision errors (EPg) also need to be redefined as they also depend on the H_{SYST} matrix:

$$
EPg = \left(H_{SYST}{}^{T} \cdot H_{SYST}\right)^{-1} \cdot H_{SYST}{}^{T} \cdot R_g \cdot H_{SYST} \cdot \left(H_{SYST}{}^{T} \cdot H_{SYST}\right)^{-1} = \left[\sigma^2_{ij}\right] \quad ;\ \text{with i,j} = 1,\ldots,5 \qquad (8)
$$

The new precision errors, influenced by GGTO, are GEPg (geometric precision error), PEP_g (position precision error), HEPg (horizontal precision error), VEPg (vertical precision error) and TEPg (time precision error). These parameters are defined in a local coordinate frame by:

$$
\begin{aligned}
GEPg &= \sqrt{\sigma^2_{11} + \sigma^2_{22} + \sigma^2_{33} + \sigma^2_{44} + \sigma^2_{55}} \\
PEPg &= \sqrt{\sigma^2_{11} + \sigma^2_{22} + \sigma^2_{33}} \\
HEPg &= \sqrt{\sigma^2_{11} + \sigma^2_{22}} \qquad (9) \\
VEPg &= \sqrt{\sigma^2_{33}} \\
TEPg &= \sqrt{\sigma^2_{44} + \sigma^2_{55}}
\end{aligned}
$$

GGTO Determination at User Level

In the absence of broadcast GGTOs, when using the user-level method, the GGTO will be calculated by the receiver as a fifth unknown from the equations of navigation. Here, five unknowns need to be determined from the equations of navigation: the 3D user's position, the time bias between user and Galileo (or GPS), and the GGTO. This means that at least five equations, and thus five pseudorange measurements, are necessary to solve this system.

The new ΔX and H_{GGTO} matrices are defined by:

$$
H_{GGTO} = \begin{bmatrix}
a_{x_1} & a_{y_1} & a_{z_1} & 1 & \phi_1 \\
\cdots & \cdots & \cdots & \cdots & \cdots \\
a_{x_n} & a_{y_n} & a_{z_n} & 1 & \phi_n
\end{bmatrix} ; \quad \Delta X = \begin{bmatrix}
\Delta x \\ \Delta y \\ \Delta z \\ -c \cdot \Delta t \\ -c \cdot \Delta GGTO
\end{bmatrix} \qquad (10)
$$

where n is the number of measurements. If GPST is defined as the reference time t, the Galileo measurements need to use the GGTO and ϕ_i will be equal to 1 (10). (The term ϕ defines whether the GGTO should be taken into account for a particular satellite.) GPS measurements are already in GPST and, as the GGTO does not need to be used for them, ϕ_i will be equal to 0. When GST is the reference time, ϕ_i will be equal to 1 for GPS measurements and 0 for Galileo measurements. ΔX contains the position and time evolution of the system.

When the GGTO is determined at user level, the DOP parameters influenced by GGTO are all — except for TDOPg — calculated in the same way as for the system level method. However, now the H_{GGTO} matrix is used instead of the H_{SYST}. Also, a new DOP, the GGTO dilution of precision (GTDOPg), arises when the GGTO is determined by the receiver:

$$
\begin{aligned}
TDOPg &= \sqrt{D_{44}} \\
GTDOPg &= \sqrt{D_{55}}
\end{aligned} \qquad (11)
$$

The matrix R is described earlier in the section that discussed the equations in the simulator software. The precision errors, with the exception of TEPg, are also calculated in the same way from the EP matrix as in the system-level determination method, with the exception that now the H_{GGTO} matrix is used instead of the H_{SYST}. A new precision error (GTEPg, the GGTO precision error) has been defined:

$$
\begin{aligned}
TEPg &= \sqrt{\sigma^2_{44}} \\
GTEPg &= \sqrt{\sigma^2_{55}}
\end{aligned} \qquad (12)
$$

With this method, as well as for the system-level method, the simulation software also offers the possibility of determining the weighted precision errors.

Automatic Determination of GGTO

When applying the user level GGTO determination method, the prerequisite of five available satellites might affect service availability for users in constrained environments (e.g., urban canyons) due to signal masking. In such situations, a combination of the user- and system-level GGTO determination methods can offer a solution for a user who prefers to calculate the GGTO himself but is situated in a constrained environment.

This approach to determine the GGTO, a combination of the two previous methods, is called the automatic GGTO determination method. From the moment the reception conditions are acceptable, the GGTO is determined by the receiver; otherwise the broadcast GGTO will be used.

When applying the automatic determination of GGTO, the choice between the GGTO determination levels is based on thresholds. Six *thresholds* are present in the simulation software, and the user of the simulation tool has to define the

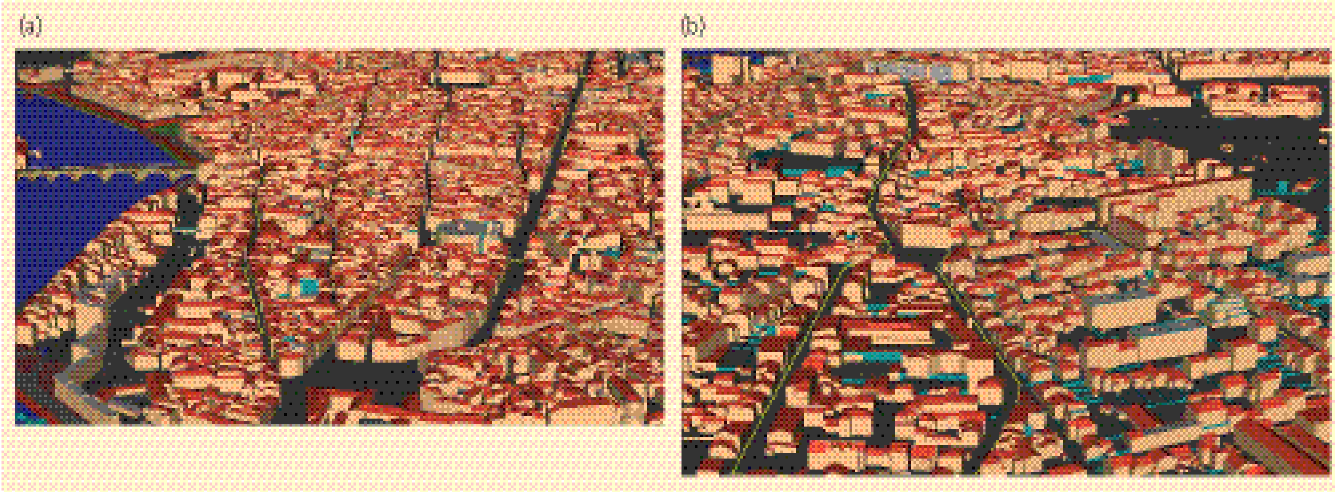

FIGURE 2 3D-model of Toulouse as implemented in the simulation software representing (a) a dense and (b) a regular urban environment. The trajectory of a pedestrian is shown in yellow. These 3D models have been developed by the town planning department of Toulouse.

values of the thresholds as well as which thresholds to take into account.

The available thresholds of the automatic GGTO determination method are:

- minimum number of available satellites (total GPS and Galileo)
- minimum number of available Galileo satellites
- minimum number of available GPS satellites
- maximum value of GDOP
- maximum value of PDOP
- maximum value of TDOP

When the situation during a simulation is such that the minimum/maximum values for all selected thresholds are respected, the GGTO is calculated at user level. Otherwise, the broadcast GGTO is used.

Simulation Setup

The different GGTO determination methods have been tested in two different urban environments. The first one is the "dense urban environment," which is characterized by the presence of large urban canyons (see **Figure 2a**). In this region, it is often very difficult to receive signals from four distinct GPS satellites.

The second area considered in this study is the "regular urban environment" (see **Figure 2b**). The dense urban environment differs from the latter by higher constructions, narrower streets, and a denser concentration of buildings. The environments used during our study are 3D models representing Toulouse, which were developed by the city's town planning department. Simulations are executed over a trajectory of a pedestrian that has been defined in these environments (indicated in yellow in Figure 2).

The current GPS constellation has been used for the simulations described in this article. Furthermore, it has been assumed that the Galileo constellation consists of 30 satellites positioned at an altitude of 23,222 kilometers. For purposes of the simulations, these 30 satellites have been spread evenly around the three orbital planes, which are inclined with an angle of 56 degrees to the equatorial plane.

The simulation tool allows the receiver to take reflected signals into account through an additional term in the error budget Equation (1). Because state-of-the-art receivers capture reflected signals, in addition to direct navigation signals the simulations also included signals that arrived at the receiver after one reflection.

Figure 3 demonstrates the importance of including a reflection by comparing the vertical precision error in a regular urban environment for a trajectory with and without a reflection. This figure shows that the use of a reflected signal reduces significantly the precision errors.

By defining the parameters of Equation (1) and including a signal reflection, a performance budget of a navigation receiver has been simulated and used for the simulations described here. The main error is the ionosperic error which has been included with a rather conservative hypotheses: RTCA-model with a mean error of 3.5m at zenith. Furthermore, we assumed the same error budget for all GPS and Galileo satellites. This last assumption may need to be refined for future simulations.

The precision errors obtained with this programmed receiver have been compared to results obtained from real-life measurements with a state-of the-art receiver in an urban region. The results acquired by the simulation software and those from the measurement campaign have the same order of magnitude; therefore, we decided to use direct signals together with those reflected once during the simulations. Only mono-frequency measurements have been considered.

Simulation Results

List of Acronyms

CNES	Centre National d'Etudes Spatiales
DOP	dilution of precision
ENT	EGNOS Network Time
EP	precision error
GGTO	GPS Galileo Time Offset
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GPST	GPS Time
GST	Galileo System Time
SBAS	Satellite Based Augmentation System

A receiver can establish a position estimate when enough satellite signals are available. However, having the minimum number of navigation satellites in view is not always a sufficient condition for positioning as the measurement accuracy and the distribution of the GNSS satellites over the sky also affect the quality of a position determination.

For these reasons, the EPg and DOPg graphs have been investigated, together with the number of available satellites. The EPg and DOPg parameters correspond respectively to the precision errors and the dilution of precision parameters after taking the GGTO into account. We described these in the section on GGTO equations of navigation. In the following plots, an instantaneous value of 0 for these parameters means that, at that moment, not enough satellites are available to make a position estimate.

Time Reference Issues for the GGTO Determination at User Level. When calculating the GGTO at the user level, we need to define a time reference. Two time references are included in the simulation software: GST and GPST. In this section, we will investigate the influence of the choice of the reference time on the final navigation solution.

For all the considered environments, the choice of the reference time appears to have had a very small influence on the global precision error (GEPg). In **Figure 4a**, the GEPg with GPST and GST as reference times have been compared for a simulation in a dense urban environment. The plot clearly shows that the global precision error (GEPg) does *not* depend strongly on the choice of the reference time. However, the small difference that does exist can be explained when looking at the number of available satellites of each constellation.

In **Figure 4b**, the TEPg calculated with GST as a reference time has been subtracted from the one calculated with GPST. This differenced parameter will indicate which reference time, GPST or GST, provides the most accurate results. If it is positive, TEPg(GPST) has the highest value, and applying the GST as a reference time would be beneficial.

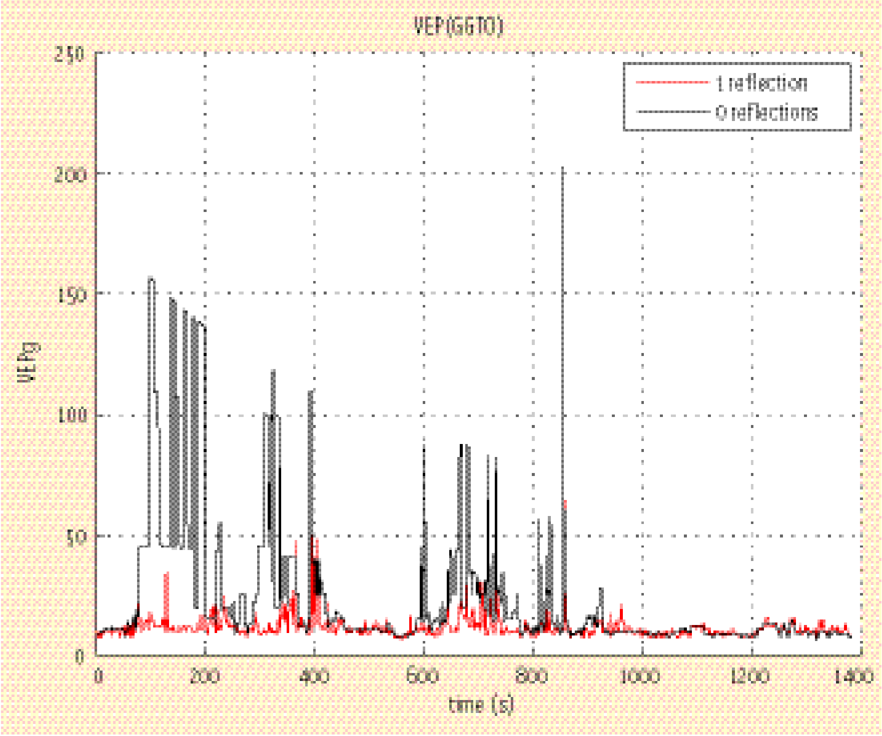

FIGURE 3 Influence of including reflections in calculations in a regular urban environment.

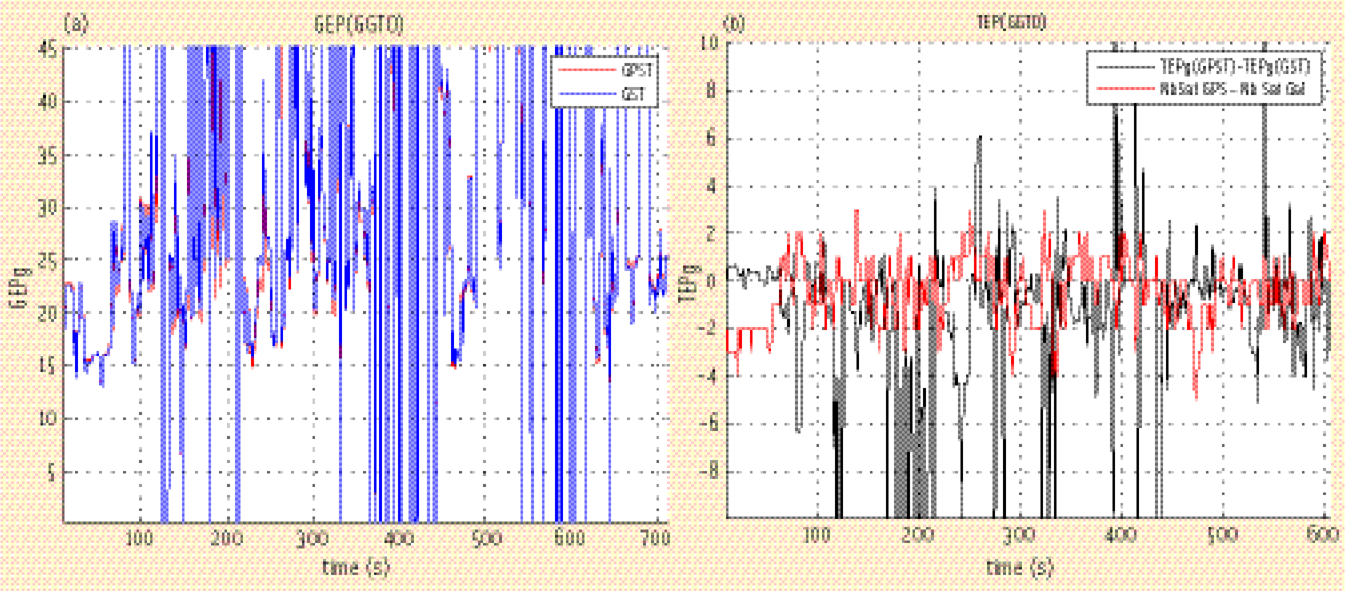

FIGURE 4 Influence of the reference time for a user level GGTO in a dense urban environment.

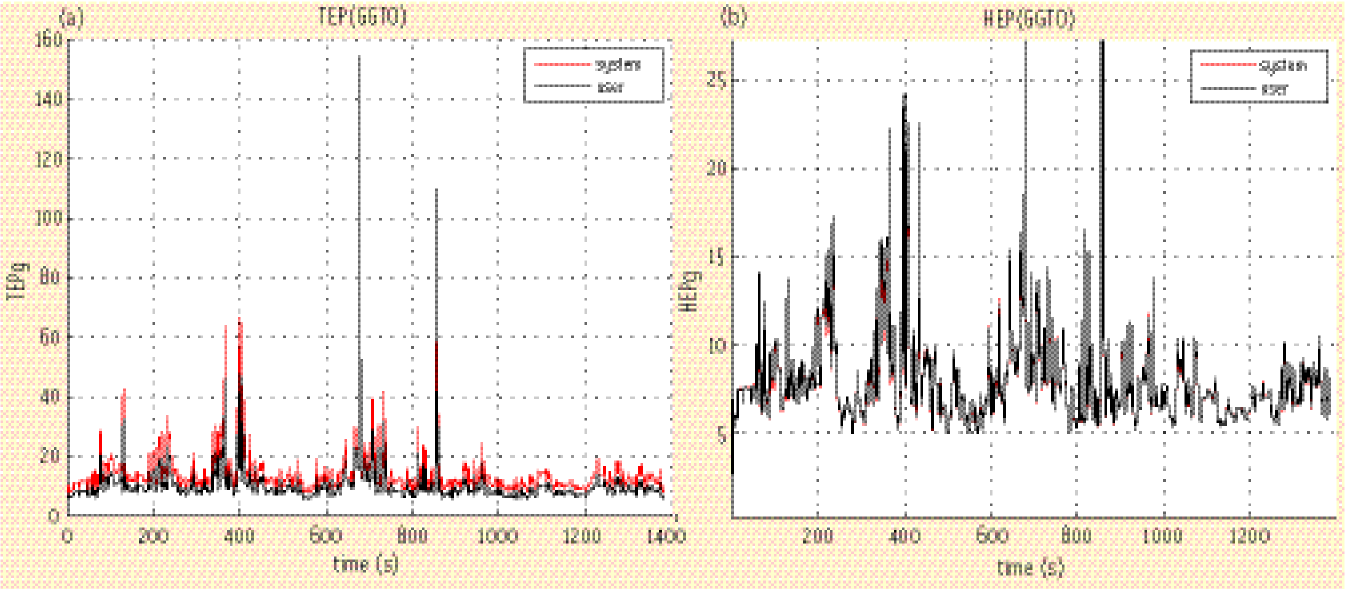

FIGURE 5 Influence of GGTO determination level on the precision errors in a regular urban environment. Fig. (a) contains the time precision error and Fig. (b) the horizontal precision error.

The influence of the number of available GPS and Galileo satellites on this differenced parameter is also shown in Figure 4. One can conclude from these plots that the best results are obtained when using the reference time of the constellation that has the most satellites in view. These conclusions also hold for the regular urban environment. However, as the results of these two methods are in general similar, GST has been selected as the reference time during this study.

Comparison of GGTO Determination Methods

This section investigates the differences in accuracy between the user and system level GGTO determination methods. Simulations have shown that the time precision error is always a few meters smaller when the GGTO is determined at user level. **Figure 5a** presents the simulation results of a regular urban environment. Moreover, the TDOPg provides better results when the GGTO is taken into account at the user level.

However, the results of both GGTO determination methods in a regular urban environment are almost identical as regards the horizontal and vertical precision errors (**Figure 5b**). But when these methods do differ, the system approach often delivers the lowest HEPg and VEPg.

The average values of HEPg and VEPg over a whole simulation in a specific environment are presented in **Table 1**. In the regular urban environment, the differences between both GGTO determination methods are very small (0 – 0.2 meters). In a dense urban environment, the GGTO determination method has a larger effect on the average values of HEPg and VEPg. In this environment, the user level solution provides an average horizontal precision error of 25.3 meters smaller than the system level one.

	GGTO Determination Method	Average HEPg [m]	Average VEPg [m]
Urban Environment	System	7.9	11.5
	User GST	8.1	11.7
Dense Urban Environment	System	42.7	143.1
	User GST	17.4	29.0

TABLE 1. Influence of GGTO determination level on the precision errors

The difference between both methods is even larger for the VEPg. However, when the median values for HEPg and VEPg are studied, the differences between both methods are not that pronounced anymore. The median value of HEPg with a system level–determined GGTO equals 10 meters, while it reaches a value of 9.8 meters with a user level–defined GGTO. The median values of both methods for the VEPg are, respectively, 16.2 and 15.8 meters. (The average error is probably more practical for users. However, the median value has been studied here to evaluate the distribution of the precision errors.) The user-level GGTO determination method provides slightly better results for the dense urban environment.

We should also point out that the dense urban region is a rather extreme environment as the DOPg and EPg parameters reach higher values here. As a result, six percent of the time a pedestrian has fewer than four navigation satellites available during his trajectory. The small difference between both GGTO determination methods can be explained by the fact that the GGTO introduces the same error on every measurement and, as many satellites are available, its impact on the final navigation solution is quit small.

Influence of Broadcast GGTO Accuracy

When using the system-level GGTO determination method, the precision errors of the position estimate depend on the precision of the broadcast GGTO. In this section we study the influence of the accuracy of the broadcast GGTO on

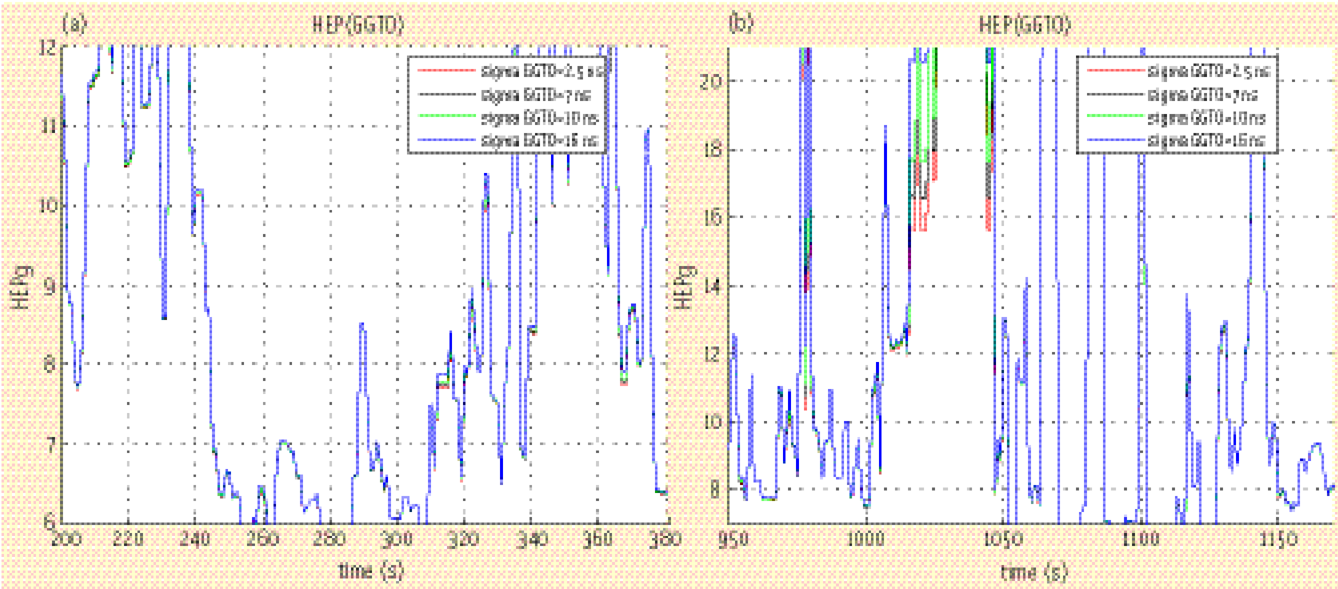

FIGURE 6 Influence of the accuracy of the broadcast GGTO in (a) a regular urban environment and (b) a dense urban environment.

the navigation solution by varying its related mean error from 2.5 nanoseconds to 16 nanoseconds.

One would expect that the accuracy of the position estimate degrades if the precision of the broadcast GGTO decreases when the system-level GGTO determination method is used. However, simulations have proven that the quality of the navigation solution varies only slightly with the accuracy to which the GGTO is known (see **Figure 6** and **Table 2**).

The horizontal precision error in a regular urban environment (HEPg) shows almost no dependence on the accuracy of the broadcast GGTO. If one zooms in on the graph (Figure 6a), a small difference of 0.2 meters between the different options can be noticed during some measurements.

However, this is not true for the dense urban environment. When looking at the same parameter in this environment, one can see that the effect of the GGTO accuracy is more pronounced. For example after 1,017 seconds, the HEPg is 20.6 meters for a GGTO mean accuracy of 16 nanoseconds (Figure 6b). But if the GGTO is known with a precision of 2.5 nanoseconds, the horizontal precision diminishes to 15.7 meters.

The same conclusions hold for the vertical precision errors. The influence of the accuracy of the broadcast GGTO on the navigation solution has also been tested in two mountainous regions: a regular and a constrained mountainous environment (Table 2). The latter "constrained" region is a mountainous area with extremely steep walls.

These results show an influence of the accuracy of the broadcast GGTO and the number of available satellites on the final navigation solution. During the simulations in the regular urban and mountainous environments, 11 satellites were available on average. In these regions, the average horizontal and vertical precision errors show almost no dependency on the GGTO accuracy.

However, in the constrained mountainous environment, the average number of available satellites is equal to 9 and the quality of the navigation solution shows more dependenec on the GGTO accuracy. The accuracy of the broadcast GGTO has the most effect on the position estimate in a dense urban environment where the average number of available satellites is equal to 8. So, the simulations have shown that the fewer satellites that are available for a position solution, the greater the effect of GGTO on accuracy is.

These results show again that the effect on the final navigation solution by introducing the GGTO can be elimi-

	Average number available satellites	GGTO accuracy [ns]	Aaverage HEPg [m]	Aaverage VEPg [m]
Urban Environment	11.4	2.5	7.9	11.5
		7	7.9	11.5
		10	8.0	11.5
		16	8.0	11.5
Dense Urban Environment	7.6	2.5	42.7	143.1
		7	44.3	150.0
		10	46.2	157.7
		16	51.4	179.0
Mountainous Environment	10.9	2.5	10.5	11.7
		7	10.5	11.7
		10	10.5	11.7
		16	10.5	11.7
Constrained Mountainous Environment	8.5	2.5	29.3	37.4
		7	29.5	37.7
		10	29.7	38.0
		16	30.5	38.9

TABLE 2. Influence of the broadcast GGTO accuracy of the precision errors

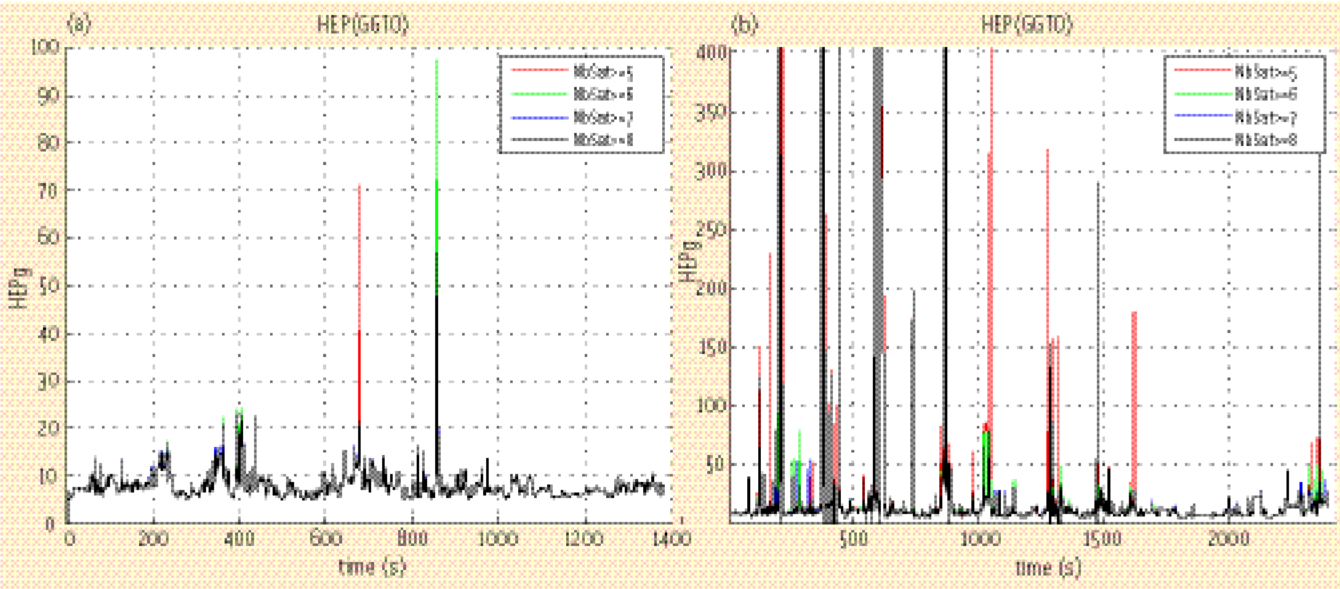

FIGURE 7 **The influence of the minimum number of available satellites for an automatic GGTO determination (horizontal precision error) in (a) a regular and (b) a dense urban environment**

nated quite easily when many satellites are available, because the error on the GGTO is the same for every pseudorange measurement.

In order to study the impact of a broadcast GGTO with a very low accuracy, simulations have been performed with a GGTO that is known with a precision of 100 nanoseconds. In a regular urban environment, the average value for the HEPg equals 9.2 meters and for the average VEPg 13 meters. These results show that, when they are compared with the values presented in Table 2, the final navigation solution is affected when a very inaccurate GGTO is broadcast.

Automatic Determination of GGTO

The automatic determination method of GGTO is a combination of the system- and user-level methods of GGTO determination and can offer a solution for users preferring to calculate the GGTO themselves but who are situated in constrained environments. The choice between these two options is made for every measurement and depends in the simulation software on user-defined thresholds discussed earlier in this article.

In our research, these thresholds have been varied in order to find the optimal value for each of them in every environment. The user-level GGTO determination method can only be used when at least one satellite of each constellation is available. When no Galileo satellites are available, the EPg parameters are indefinable, even when the receiver has sufficient GPS satellites in view. This is due to the method of calculating the GGTO. When GPST is used as a reference, the GGTO can not be calculated as no Galileo measurements are available. On the other hand, when GST is chosen as a reference time, GEPg can also not be calculated because GST is not available without measurements from Galileo.

As GST has been chosen for the reference time of the user-level GGTO determination method, the minimum number of GPS satellites will not be varied but taken as equal to 1.

The following thresholds have been tested for the two different environments:

- minimum number of available satellites (total GPS and Galileo): 5, 6, 7, 8;
- minimum number of available Galileo satellites: 1, 2, 3, 4;
- maximum value of GDOP, PDOP, and TDOP: 4, 5, 6, no limit.

When the situation during a simulation is such that the minimum/maximum values for all selected thresholds are respected, the GGTO is calculated on the user level. Otherwise, the broadcast GGTO is used with the related accuracy (2.5 nanoseconds for this study).

Regular Urban Environment. Varying the minimum number of available satellites does not have a large influence on HEPg and VEPg (see **Figure 7a**). However, when this threshold was set to 7 or 8, the maximum values of HEPg and VEPg diminished quite a bit.

Varying the minimum number of Galileo satellites had almost no influence at all on the horizontal and vertical precision errors. This shows that it is essential to have many satellites available when employing the user-level GGTO determination method. However, the number of satellites available from each constellation is not important for the precision of the final navigation solution.

VEPg, HEPg, HDOPg and VDOPg are somewhat improved when a GDOP threshold is applied. However, afterwards there was no difference between the tested values for this threshold. Testing different values of TDOP and PDOP revealed that they also did not have any significant influence on VEPg, HEPg, HDOPg and VDOPg.

The difference is that the system-level GGTO determination method is used more often if the DOP thresholds are set to stricter values. The horizontal and vertical precision errors are thus improved when the geometry of the satellites corresponds to a good DOP value. However, this DOP threshold does not need to be defined very strictly.

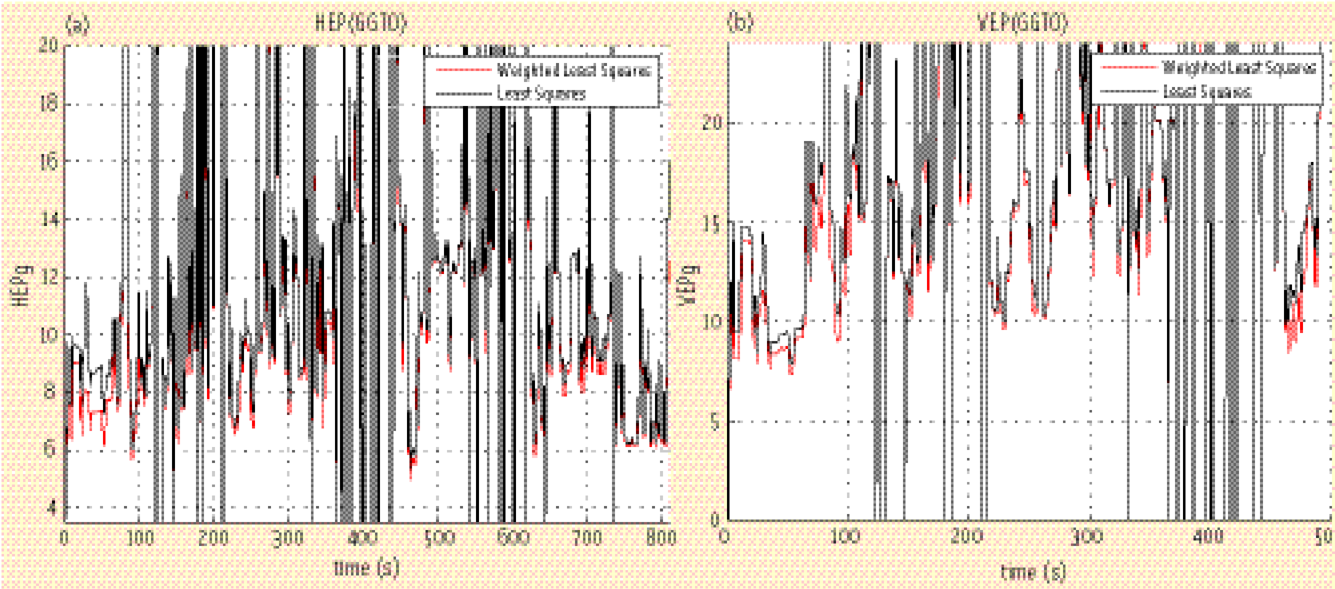

FIGURE 8 **Comparison between a Least Squares Algorithm and a Weighted Least Squares Algorithm in a dense urban environment (left plot: horizontal precision error; right plot: vertical precision error)**

Dense Urban Environment. HEPg, VEPg, HDOPg and VDOPg are already improved if the minimum number of available satellites for the user-determined GGTO method is set to 6 instead of 5 (see **Figure 7b**). Further, the results are still noticeably improved when the minimum number of visible satellites is chosen to be equal to 7. Varying the minimum amount of necessary Galileo satellites has almost no effect. This shows again that having many satellites available is essential when using the user-level GGTO determination method, but the number of satellites included from each constellation is not important.

When varying the GDOP, PDOP, and TDOP thresholds, it became clear that results improved when these thresholds were set to 6 instead of using no threshold. However, when these threshold values were diminished, it had no effect on the various types of precision errors.

The HEPg and and VEPg are also improved when the geometry of the satellites corresponds to a good DOP value. However, this DOP threshold does not need to be defined very strictly.

Weighted Least Squares Algorithm

All the results presented in this article have been obtained by applying a least squares algorithm. However, as noted in our preliminary consideration of GGTO, a weighted least squares algorithm improves the fusion between Galileo and GPS measurements. In order to show the improvement in accuracy by applying weights to the measurements, two plots are presented in **Figure 8**. These plots show clearly that the HEPg and VEPg are improved by 1–2 meters when a weighted least squares algorithm is used.

Conclusions

Receivers using a combination of GPS and Galileo pseudorange measurements have been simulated. As GPS and Galileo do not use the same time reference, a time offset called GGTO arises. Three methods to take the GGTO into account have been tested using a simulation tool for pedestrians following a pre-defined trajectory in a "regular" and a "dense" urban environment. The performance budget of the navigation receiver simulated for this study is based on conservative hypothesis.

The simulation outputs are mainly the precision errors and the dilution of precision parameters. The urban environments are included in the measurements by representative 3D models that allow the simulation of reflected and masked signals.

The first method is the user-level GGTO determination method. When applying this method, a reference time needs to be selected. Two possible reference times are integrated in the simulation software: GPS Time and Galileo System Time. Simulations have shown that the global precision error is hardly influenced by the choice of the reference time.

GPS and Galileo will also broadcast the GGTO within their navigation messages. If this GGTO is applied, the system-level GGTO determination method is used. Simulations during this study have proven that, in a regular urban environment, the average HEPg varies only slightly with the accuracy to which the broadcast GGTO is known. However, this is not true for the dense urban environment in which the average horizontal precision error is 42.7

Because the GGTO introduces the same error on every measurement and because many satellites are available, its effect on the final navigation solution is quite small.

meters when the accuracy of the GGTO is 2.5 nanoseconds and 51.4 meters at 16 nanoseconds.

When applying the same simulation conditions, the time precision error is also always a few meters smaller if the GGTO is determined at the user level compared to the one determined at the system level. This is true for a regular as well as for a dense urban environment. However, the results of both GGTO determination methods for the horizontal and vertical precision errors are almost identical in a regular urban environment. Here, the differences between both methods, when looking at the average values of VEPg and HEPg, are very small.

This is not true for the dense urban region, where the GGTO determination method has a large effect on these average parameters. However, when the median values of HEPg and VEPg are studied in this environment, the difference between both methods is not that large anymore.

The third approach is the so-called automatic determination of GGTO. This method is a combination of the two aforementioned options and offers a solution for users preferring to calculate the GGTO themselves but who are situated in constrained environments.

The choice between both methods (system or user level) is based on thresholds: either the user calculates the GGTO from the five-parameter solution (determination on user level) or the broadcast GGTO is used (determination on system level).In order to use the user level GGTO determination method, one satellite of each constellation needs to be available. Otherwise, it is not possible to make a position estimate.

Thus, we can conclude that, because the GGTO introduces the same error on every measurement and because many satellites are available, its effect on the final navigation solution is quite small.

Satellite-based augmentation systems (SBAS) have not been considered during this study. However, we should note that the GGTO is no longer valid when SBAS corrections are applied to GPS measurements.

The European Geostationary Navigation Overlay Service (EGNOS), the SBAS over Europe, uses the EGNOS Network Time (ENT). When GPS measurements are corrected using EGNOS transmitted data, the reference time of the GPS measurements is no longer GPST, but ENT. In this case, it is not the GGTO that would need to be accounted for, but an EGTO (EGNOS Galileo Time Offset) when combining GPS and Galileo measurements. The same conclusions hold for WAAS, the SBAS over North America. The interested reader is referred to the paper by J. Delporte et alia for detailed information regarding this subject (see Additional Resources).

At the moment, we are performing simulations over a longer time period. Future studies will include simulations with lower masking constraints and a variable elevation cut-off angle. By comparing the results of these simulations with those obtained in 3D environments, the added value of the usage of 3D environments will be shown.

As the 3D environments are realistic representations of the French town of Toulouse, the simulation results described in this article can also be compared to real measurements taken during the same trajectory as for the simulations. Also the effect of taking reflected signals into account will be studied in greater detail.

Manufacturers

The simulation tool used in the research described in this article is the software *ergospace*, developed by the company **Ergospace,** Toulouse, France <www.ergospace.fr>.

Additional Resources

[1] Delporte, J., et al., "Performance Assessment of the Time Difference between EGNOS-Network-Time and UTC," *Proceedings of the 19th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS 2006)*. Fort Worth, Texas. September 2006

[2] Dinwiddy, S.E., *Galileo Global Component; System Requirements Document*, Issue 4, p.47, July 2004

[3] Moudrak, A., et alia, "Interoperability on Time; GPS-Galileo Offset Will Bias Position," *GPS World*, pp. 24-32, March 2005

Authors

Inge Vanschoenbeek graduated from Delft University of Technology with a M.Sc. degree in aerospace engineering. Currently she is working as a simulations and systems engineer in the field of satellite navigation at CNES.

Bernard Bonhoure graduated as an aeronautic engineer from ENSICA. He joined CNES in 1989 and has worked on several successful space programmes such as TOPEX/POSEIDON, SPOT, ENVISAT, and JASON. As a navigation system expert, he is now involved in many activities linked to satellite positioning and performances.

Marco Boschetti graduated as telecommunications engineer from UPC (Universidad Politécnica de Cataluña) in Barcelona and aerospace engineer from Sup'Aéro in Toulouse. He entered CNES in 2003 and he is responsible for GNSS simulation activities in the Location and Navigation System Engineering Department.

Jérôme Legenne was graduated as an aerospace engineer from Sup'Aero in Toulouse. He occupied several positions at CNES Toulouse and French Guiana space centers, including four years integrated within the European Space Agency's EGNOS project team. Since 2004, he has been the head of CNES's location and navigation system engineering department. IG