GNSS positioning accuracy and availability within Location Based Services: The advantages of combined GPS-Galileo positioning

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ABSTRACT

This contribution addresses position accuracy and availability of satellite based radio navigation for Location Based Services (LBS). Standard standalone GPS positioning with a simple handheld receiver offers 5-10 meter accuracy. With corrective information received from a geostationary satellite, the European Geostationary Navigation Overlay Service (EGNOS) brings the accuracy down to the 1 meter level. Global Differential GPS, with a dual-frequency user receiver, reaches decimeter level accuracy, but only after a considerable initialization period. The highest accuracy, which is at the cm-level, is obtained using differential carrier phase positioning with high-end equipment and a local reference station.

Position availability has been analyzed for the historic town center of Delft in the Netherlands. The availability of standalone GPS is less than 50% (considered over a full day) for half of the chosen trajectory. In the heart of the town-center, with very narrow streets and alleys, the availability of EGNOS through the geo-stationary satellites is poor. The availability is in the order of only 10-20% per satellite. The inclusion of Galileo, by a largely increased resource in space, is shown to be particularly beneficial to the position-availability. Whereas an availability of 95% or larger is achieved for only 12% of the trajectory with GPS only, this increases to 75% of the trajectory with Galileo in this challenging urban environment and offers thereby great potential for Location Based Services.

INTRODUCTION

The possibility to determine the position of a hand-held device is one of the key-elements within the development of Location Based Services (LBS). One popular way of autonomous positioning for LBS is using a Global Navigation Satellite System (GNSS). With such a system, positioning is available anywhere on, and above the Earth, in principle without any local or regional infrastructure. The positioning accuracy can be enhanced with the aid of augmentation systems and this contribution starts with a demonstration of the range of position accuracy using today's Global Positioning System (GPS). Different modes of kinematic and real-time positioning, including EGNOS, are shown using a trial with a boat on the Schie-canal between Delft and Rotterdam.

Accuracy of GNSS is one aspect within LBS, availability another. As satellite based radio positioning relies on relatively weak signals, indoor positioning is a hard job, in particular without any support. Also an urban environment can pose a serious challenge to satellite based radio positioning. To get a grip on the influence of urban canyoning, we have analyzed the availability of today's GPS positioning using a three-dimensional model of the historic town center of Delft in the Netherlands. The results of this calculation have been validated by a field trial, using the current GPS constellation.

In five years from now, the European Galileo system is expected to get into orbit, next to the US GPS. Doubling the satellite constellation is expected to be beneficial to position availability, and the impact of the advent of Galileo on this aspect is analyzed with the same 3D-model of Delft. But as Galileo is an alternative for the future, we have to rely on GPS, including EGNOS, exclusively for the coming years. Therefore we have analyzed also the line-of-sight to the EGNOS geo-stationary satellites by means of this 3D-model of Delft.

This paper concludes with a short outlook on an alternative to actual satellite ranging, and just take the visibility pattern into account. This so-called finger-printing method could be applied especially in these areas where GNSS has its limitations and is therefore a fascinating complementary alternative in urban areas.

GPS POSITIONING ACCURACY

This section intends to give a partial overview of the current range of GPS positioning modes. With a focus on position-*accuracy*, practical results are shown for standalone GPS, Wide Area Differential GPS (WADGPS) with EGNOS, and Global Differential GPS, the latter offering decimeter accuracy, in real-time, seamless all over the world. Also an example of Real-Time Kinematic (RTK) GPS is given, that provides centimeter-accuracy.

The results shown - for the different modes of positioning – pertain to *real-time* operation (contrary to long site occupation times and post-processing of measurements). The results follow either from processing just a single epoch of measurements, or are the actual output of a recursive processing scheme (for instance a running Kalman filter).

Kinematic Experiment

All examples shown in the sequel are the results of a kinematic positioning experiment carried out in Spring 2003, with a small boat on the Schie-canal between Delft and Rotterdam in the Netherlands. The boat was sailing with up to 8 km/h, which is similar to a pedestrian walking/running. Also an example is given each time, of positioning results based on measurements collected simultaneously at a nearby stationary receiver.

Fig. 1. The small boat, with several GPS receivers and antennas on-board, all collecting measurements simultaneously, was cruising the Schie-canal forth and back for an almost 3-hours period. The boat is depicted here at the little village De Zweth.

For each of the examples in the following, GPS range measurements have been taken over the same 3 hours time span, at a 1 second interval. Generally, between 5 to 8 GPS satellites were used for the position solution. Either a 5 or 10 degrees satellite elevation cut off angle was used. The position solutions were referenced to the bottom of the antenna, the so-called Antenna Reference Point (ARP).

For all receiver antennas on board, a so-called ground truth trajectory was established with centimeter accuracy, using both classical survey measurements on the boat - after the experiment - when it was moored again at the quay in Delft, and, high-precision GPS position solutions for three of the (high-end) receivers. The latter solutions were computed from dual-frequency precise carrier-phase measurements, with cycle ambiguities fixed, in differential mode using a nearby reference site (at 3-5 km distance).

Position Accuracy Measures

The position solutions obtained in the various cases are differenced with accurately known reference positions (ground truth trajectory). Subsequently, the mean of the position differences is computed in each coordinate direction. The standard deviation (about zero) is determined empirically for the position differences, over the full time span, in each coordinate direction (each time in a local North-East-Height system). For the purpose of easy interpretation, the sample 95th percentile values are presented as well; 95% of the position samples are within the values given. The 95% values refer to the horizontal position error (North and East component together) and to the (absolute) vertical position error. For an introduction to position accuracy and its measures, the reader is referred to [1].

Standalone GPS

Based on pseudorange code measurements of a single receiver, the position can be determined anywhere on Earth. Only the satellite signals are needed. The satellite position and clock error are obtained from the broadcast navigation message. This mode of positioning is referred to as single point positioning, or absolute positioning (sometimes also as point positioning). No auxiliary means are needed, as with Differential GPS.

In the kinematic test with the boat, a simple commercial handheld receiver was used (a Garmin GPS76 with a small external GA-27C antenna). Table 2 lists the position accuracy figures and Fig. 2 shows the position error in all three components as a function of time. The accuracy lies in the 5-10 meter range. For more information about the standalone GPS positioning results, see [2].

Table 1. Position accuracy of static standalone GPS positioning.

standalone GPS	North	East	Height
mean [m]	1.39	-1.70	-5.11
standard deviation [m]	2.68	2.19	5.46
95th percentile [m]	4.80		8.12

Table 2. Position accuracy of kinematic standalone GPS positioning.

standalone GPS	North	East	Height
mean [m]	1.35	-2.65	-6.05
standard deviation [m]	3.13	3.05	7.02
95th percentile [m]	6.20		11.52

The results in Table 1 were obtained with a geodetic receiver (Trimble 4700 with choke ring antenna). The bias in the position solution, mainly due to unmodelled effects with standalone positioning, is similar to the kinematic results in Table 2; the noise with the high-end receiver is significantly less. This is also clearly visible in Fig. 2.

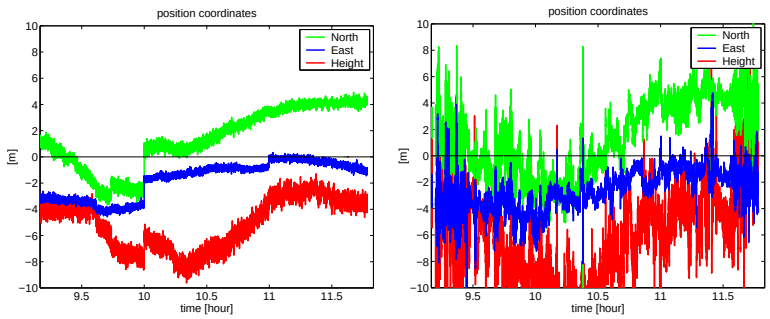

Fig. 2. Standalone GPS positioning errors, static at left, kinematic at right.

Wide Area Differential GPS: EGNOS

Augmentation systems to GPS can improve the accuracy of standalone positioning. The European Geostationary Navigation Overlay Service (EGNOS), as a Wide Area Differential GPS, covers the whole of Europe. Similarly, the FAA has developed the Wide Area Augmentation System (WAAS) in the US. Positioning with EGNOS is based on Differential GPS, but instead of a single reference station, an integrated *network* of reference stations is deployed. The correction signal is broadcast from geostationary satellites. The user needs in principle additional equipment to receive the EGNOS signal, though there are (relatively simple and cheap) handheld receivers on the market, which are WAAS (and EGNOS) capable.

In February 2000, the EGNOS System Test Bed (ESTB) became operational, and results of this prototype EGNOS are shown below. These *single frequency* results pertain to instantaneous positioning, once the current message with correction data and integrity information has been acquired (hence *no* smoothing of the observed pseudoranges, not in the receiver, nor in the processing). EGNOS has become fully deployed last Summer.

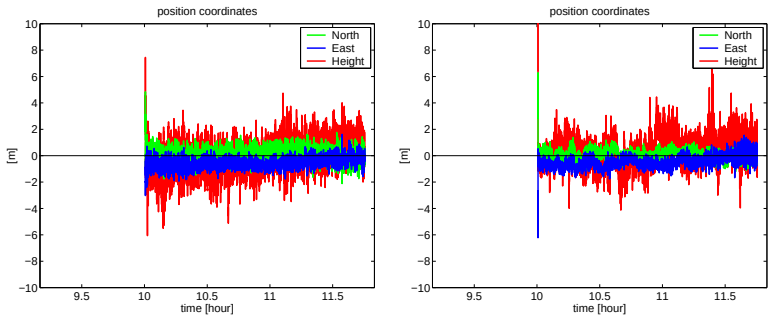

Fig. 3. Wide Area Differential GPS position errors with EGNOS, static at left, kinematic at right.

Table 3. Static position accuracy of Wide Area Differential GPS positioning with EGNOS.

WADGPS	North	East	Height
mean [m]	0.09	-0.53	-0.04
standard deviation [m]	0.50	0.66	1.20
95th percentile [m]	1.35		2.31

Table 4. Kinematic position accuracy of Wide Area Differential GPS positioning with EGNOS.

WADGPS	North	East	Height
mean [m]	0.07	-0.46	0.38
standard deviation [m]	0.38	0.63	1.22
95th percentile [m]	1.19		2.34

In the static set up, a high-end NovAtel OEM3 receiver with PinWheel 600 antenna was used. Similar equipment (but with a Leica AT502 field antenna instead) was used simultaneously in the kinematic test. Tables 3 and 4 list the position accuracy figures and Fig. 3 shows the position error (the time series start late by some 50 minutes, due to unavailability of the ESTB signal). The accuracy lies in the 1 meter range; the static and kinematic results are rather similar. These results were obtained using the Pegasus-software (version 2.1) of Eurocontrol. Further details can be found in [3].

Global Differential GPS

Global Differential GPS (GDGPS) offers yet a higher class of accuracy, seamless all over the world. The results shown below are obtained with Internet-based Global DGPS (IGDG), which relies on a subset of NASA's Global GPS Network (GGN) with currently some 40 real-time stations. The data of these stations result in rapid service (real-time) GPS satellite orbits and clocks. Differences with the current GPS broadcast ephemeris are disseminated over the Internet in real-time (and commercially via geostationary satellites) and allow users, anywhere on Earth (truly global), to exploit the highly accurate satellite ephemerides in real-time. Results and references on GDGPS can be found in [4].

The user needs to be equipped with a *dual-frequency* receiver (using the GPS L1 and L2 signals) delivering pseudorange code and carrier phase measurements. In addition a sophisticated modeling of these measurements is required. At present, dual frequency receivers are expensive, primarily because the current GPS L2 signal is not directly accessible for civil users, and the relatively small size of the high-end market. The situation might change with the modernization of GPS (with a new civil signal on the L2-frequency and the first satellite to be launched early 2005) and the advent of Galileo. Dual-frequency receivers are likely to become much more affordable.

In the experiment, an Ashtech ZXII-3 dual-frequency receiver was used, together with a choke-ring antenna (identical equipment in kinematic and static set up). Tables 5 and 6 list the position accuracy figures and Fig. 4 shows the position error (the initialization period, first 40 minutes in the kinematic case, is left out of consideration for the above accuracy figures). With Global DGPS decimeter accuracy can be achieved, though it should be noted that with a moving receiver, as in this kinematic experiment, a long initialization (convergence) time is needed (20-30 minutes) with continuous lock to the satellites' signals, to eventually reach this accuracy. For users on or near the Earth's surface, the long initialization time may be considerably reduced (e.g. halved) by treating the tropospheric zenith delay as a constant (over the 3-hour time span considered here) instead of as a stochastic process (e.g. random walk), see [5].

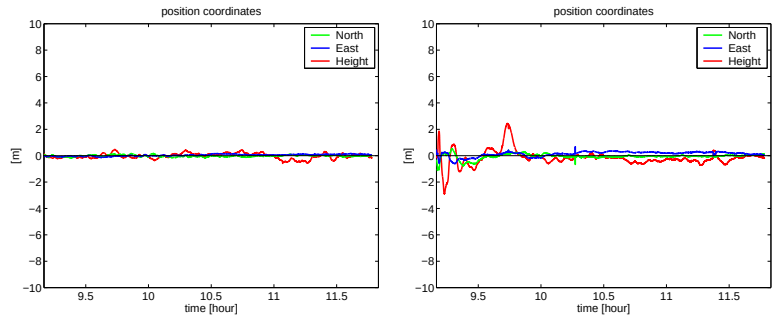

Fig. 4. Global Differential GPS position errors, static at left, kinematic at right.

Table 5. Static position accuracy of Global Differential GPS.

global DGPS	North	East	Height
mean [m]	-0.02	0.04	-0.02
standard deviation [m]	0.07	0.08	0.21
95th percentile [m]	0.16		0.43

Table 6. Kinematic position accuracy of Global Differential GPS.

global DGPS	North	East	Height
mean [m]	-0.02	0.19	-0.25
standard deviation [m]	0.08	0.23	0.32
95th percentile [m]	0.34		0.60

[6] shows that decimeter accuracy can also be achieved by using only *single frequency* (L1) measurements, though from high-end equipment. The so-called improved standalone positioning relies on precise satellite orbits and clocks and on ionospheric maps, which are publicly available, and optionally on (pseudorange) code hardware bias information and carrier phase usage as well. For the tropospheric delay an a-priori model is used, rather than it is estimated from the observed data. In [ibid] both static and kinematic results are given.

Real-Time Kinematic (RTK) GPS

Real-Time Kinematic (RTK) GPS relies primarily on the precise *carrier phase* measurements, either single or dual frequency. The complication with these measurements is the unknown cycle *ambiguity*, which needs to be resolved in order to exploit the centimeter or even millimeter carrier phase precision to the full extent for positioning. With precise *relative* GPS positioning, the user receiver is positioned with respect to a reference station at a known location (though the latter is not a strict requirement). Determination of the so-called baseline relies on measurements of *two* receivers. The coverage region is typically a local or regional area, near to the reference station(s).

In the example below instantaneous solutions have been obtained for the baseline vector. The carrier phase ambiguities could be resolved correctly, using just the single epoch of data. The ground truth trajectories have been obtained similarly using carrier phase measurements. In this case, therefore, no independent comparison with an accurately known ground truth can be made. Instead we consider the (ellipsoidal) *height difference between two antennas* that were both mounted on range poles next to each other, one meter apart, on the back deck of the boat. Both antennas were positioned (using *dual frequency* data) with respect to the same reference station (reference and rover fully synchronized), at a few kilometers distance. The height difference, shown in Fig. 5, gives an impression of the position accuracy (repeatability). The mean height difference between the two antennas (1.2 cm) was subtracted. Variations in the difference are generally at the few cm-level only. Roll motions of the boat, for instance due to large ships passing by in the canal and motions of the crew on board (4 persons on this little boat) are included in this graph. Table 7 gives the corresponding accuracy figures. The *distance* between the two antennas can be determined more precisely (standard deviation less than 1 cm).

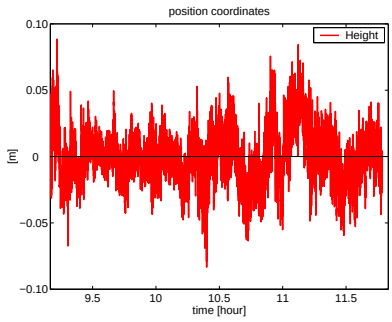

Fig. 5. Precise Real-Time Kinematic (RTK) GPS position errors: difference in height.

Table 7. Position (ellipsoidal height) accuracy of precise Real-Time Kinematic (RTK) GPS.

RTK	Height
standard deviation [m]	0.020
95th percentile [m]	0.042

The typical accuracy for ambiguity fixed RTK GPS positioning over a 10 km baseline in practice is 1-2 cm for the horizontal components and 2-3 cm for the vertical (standard deviation). The position accuracy is distance dependent, primarily because of differential atmospheric delays (due to geometry and horizontal gradients in the atmosphere). When there is also a significant height difference between reference and rover, an additional differential tropospheric delay comes into play.

Applications and examples

The 5-10 meters accuracy of GPS has pushed the development of the most important LBS: standalone in-car navigation systems. The (sub-) meter accuracy offers field inventory of all kinds of objects with hand-held Personal Digital Assistants (PDA) equipped with a GPS-module. The highest accuracy on centimeter-level is needed for Augmented Reality systems, in which information (as text and images) about the environment is projected directly within the view-field of the user.

GNSS POSITIONING AVAILABILITY

The use of satellite based radio positioning is attractive within LBS as it can offer full three dimensional positioning (and timing). And compared to other means of positioning for LBS, for instance using radio-signals for mobile communication of Wireless Local Area Networks (WLAN), a GNSS has the advantage of offering worldwide coverage. On the other hand, its weakest property is the requirement of, in principle, direct lines of sight to the transmitting satellites, which can be hard to realize particularly in urban environment, where typically most of the LBS applications will be used.

For LBS applications as car-navigation and emergency call, the key driving elements or performance requirements as identified in [7] concern availability and accuracy of service. Next it is noted in [ibid] that accuracy requirements are best met by a GNSS based solution, but questions exist as to meet availability requirements, particularly in demanding environments such as city centers.

Availability and accuracy of standalone GPS positioning at Northern latitudes (Scandinavia), in particular in city centers, were measured and reported about in [8]. A recently developed tool for analyzing position accuracy and availability of GNSS and complementary sensors is described in [9]. [10] addresses road tolling in built-up (urban) area using GPS. Road user charging is foreseen at so-called Charging-Points (CPs), where roads enter or leave the charging zone. The positioning accuracy and signal availability are assessed in [ibid] for a hypothetical charging scheme in Nottingham at these CPs and their immediate vicinity, using both simulations and field measurements. [7] analyzes the various requirements and restrictions imposed by different LBS applications, with particular emphasis being placed on the benefits that Galileo can bring in order to meet such user requirements.

In the sequel we will analyze availability of GPS, EGNOS and Galileo as well, using a three dimensional model of the town center of Delft (at 52 degrees Northern latitude), followed by a presentation of results from a limited field test with a simple GPS handheld receiver, that was run in exactly the same area. For *availability* of positioning we focus on the user, rather than on the space segment. Local circumstances and geometry to receive the satellite signals ('visibility') are addressed, rather than the status of the GNSS itself and the condition of the Signal-in-Space.

GNSS Constellation

For GPS a nominal constellation was taken with 24 satellites. There are 6 orbit planes with 4 satellites each, see [11]. The orbit plane inclination is 55º and the semi major axis is 26560 km (which equals the orbit radius as the eccentricity was set to zero). For Galileo a 27 satellites constellation was taken. There are 3 orbit planes (with ascending nodes equally spaced) containing 9 satellites each (evenly distributed). The inclination is 56º and the orbit radius is 29600 km. Though the Galileo satellite constellation does not repeat after 24 hours for a fixed user on Earth (but only after 10 days), a 24 hours time period is used here. The GPS satellite constellation repeats after 24 hours (minus 4 minutes).

The geodetic reference frames for positioning - the World Geodetic System 1984 (WGS84) for GPS, and the Galileo Terrestrial Reference Frame (GTRF) for Galileo - are expected to be compatible (at the cm-level, and hence not of concern to LBS-applications). Concerning timing, a different time scale is assumed for GPS and Galileo. Consequently the user receiver has to solve for two clock errors (one in GPS time and one in Galileo System Time (GST)) or equivalently for one clock error and the offset between the two systems. It is anticipated that dissemination of the offset in real-time through (one of) the systems' control segments will not be accurate enough (currently an accuracy of 3 ns is mentioned for the broadcast GPS-GST time offset).

Modeling availability by line-of-sight calculations

Using a three-dimensional model of the historic town center of Delft, the availability of GNSS positioning is analyzed, both for the current GPS as well as for combined GPS and Galileo. The inclusion of Galileo is not expected to yield a significant improvement in position accuracy, but basically doubling the satellite constellation in space, over just GPS, is particularly beneficial to the position availability.

The 3D-city model of the old town of Delft, obtained through airborne laser scanning, is built up by a polygonal representation of the canals, the streets and the roofs of the buildings. The quaysides and the walls - the connections between the streets and the canals on one hand and the connection between streets and the roof tops at the other - are thought to be vertical and modeled as vertical polygons. The visibility calculation however is based on a triangulated irregular network (TIN) that does not allow vertical polygon constraints. The solution to that problem is found in a minimal negative buffering of both roofs and canals polygons by 10 centimeters. These datasets are the input for the surface model of this part of Delft represented by a TIN.

The basic algorithm, written within the scripting language of ArcView 3.2, is able to determine, with the TIN as the surface model at a certain time, whether or not there exists non-intersecting line-of-sights from a certain point-of-view (the simulated receiver) to the satellites above the horizon. If at a certain observation point four or more GPS satellites are visible then this points is marked as available given GPS, the same conditions holds for Galileo. The combination of GPS and Galileo is restricted to a combination of either 2 GPS and at least 3 Galileo satellites, or at least 3 GPS and at least 2 Galileo satellites.

An additional algorithm calculates the availability of 'enough' satellites during a day of time. We have chosen about 50 test observer points, with a height of 1.80 m above street-level. For each of these observer points the total number of visible satellites during a day is calculated. During a day of time means 60*24 = 1440 different constellations for both GPS and Galileo. The percentage of 'valid' cases gives an indication of the availability of GPS, Galileo and the combination of both within urban areas. The percentage of availability is indicated by the legend as given in Fig. 6 (red is poor, and blue marks high availability). The results of the test are shown on a map of the 3D model in Fig. 7 (GPS), Fig. 8 (Galileo), and Fig. 9 (Combination); the numbers in black denote the actual percentages. As can be determined by the figures, neither GPS nor Galileo alone will offer - as expected - the required availability for LBS purposes, although one has to notice the good marks at street crossings and junctions. And these spots are the places where the availability is of real importance, as there one has to make the decision which way to go. The results improve considerably when GPS and Galileo are combined; in this case holds: more is better. An availability of 95% or larger is achieved for only 12% of the trajectory with GPS only, and this increases to 75% of the trajectory with Galileo.

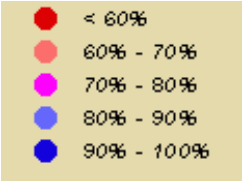

Fig. 6. Legend for visibility
(red – blue: <60% - 100% availability).

Fig. 7. Availability of GPS during a one day time span.

Fig. 8. Availability of Galileo during a one day time span.

Fig. 9. Availability of GPS and Galileo combined during a one day time span.

Actual Standalone GPS Availability: Field Trial

A few runs were made in Delft by a pedestrian, carrying a simple handheld GPS receiver. Each time the same route through the town center was taken, walking in principle in the middle of the narrow streets and alleys. The route started and ended at the central market-square with relatively good satellite visibility. The field trials took place early 2004. The GPS constellation at that time consisted of 28 healthy satellites, instead of a nominal 24 satellites constellation. Four runs were made, each separated by about 2.5 hours to allow for different satellite geometries during the day. One run took about 12 minutes. In this test, no raw measurements were collected, but instead we relied on the NMEA-messages output by the receiver (at a 2 seconds interval).

Fig. 10 shows the number of satellites tracked (i.e. satellites with a non-zero signal-strength as indicated by the receiver), cumulated over all four runs. For 45% of the time, the number of satellites tracked was only the minimum number of four, or even less.

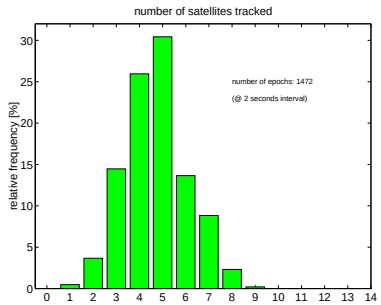

Fig. 10. Histogram of number of GPS satellites tracked, over all four runs.

Fig. 11 shows two of the runs, the poorest at left, the best at right. The positions as output by the receiver are color-coded in these graphs after the number of satellites tracked. For the run at left, one GPS satellite was close to the local zenith, one satellite was at 50 degrees elevation and one at 35 degrees; all other satellites were at lower elevation angles. This results in low numbers of tracked satellites; large parts of the trajectory are colored red, indicating *less than* the minimum of four satellites. And there are considerable deviations from the actual route. For the run at right, five GPS satellites were available at an elevation angle of 45 degrees or larger (next to several low elevation ones). The resulting trajectory quite well matches the actual route.

The receiver was able to provide 3D positions most of the time (though by a poor geometry the accuracy is poor part of the time, and obviously by straight extrapolation as well as can be concluded from Fig. 11 at left). The receiver switched back only temporarily to 2D positioning. As observed already from the line of sight calculations, availability is good at street crossings and junctions, see in particular the graph at right; where corners are taken or turns are made, the dots are colored yellow, green or even blue.

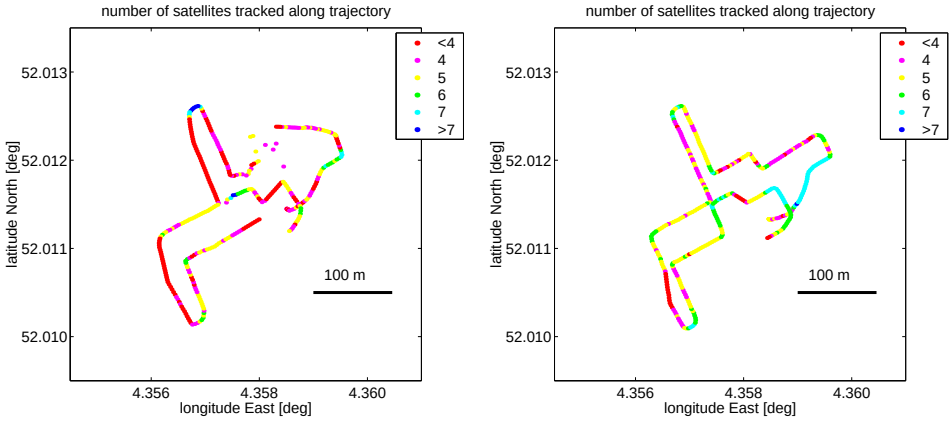

Fig. 11. Two of the runs through the town center: positions as determined by the handheld receiver, color-coded after the number of GPS satellites tracked. A poor run at left (about 40% of the time *less than* 4 satellites) and a good run at right (only 9% of the time *less than* 4 satellites).

EGNOS availability

Galileo is not available until 2008-2010. At present 1 meter position accuracy can be reached by using GPS in conjunction with (one of) the EGNOS geo-stationary satellites. The availability of EGNOS is analyzed using the same three dimensional model of the town of Delft. At the time of writing three geo-stationary satellites are in use for EGNOS; two of them, PRN120 and PRN124, are used in the following analysis, see Table 8. As could be expected the results depend largely on the layout of the street plan measured up to the azimuth of the EGNOS satellite. Fig. 12 shows the availability of the EGNOS geo-stationary satellites PRN120 and PRN124; a green dot means visible, a red dot not visible. The line in black indicates the direction (azimuth) of the satellite. Satellite PRN124 happens to present rather favourable results, as the azimuth parallels the local direction of the canals. Fig. 12 (left) with PRN120 shows results as expected with an availability of only 12%.

Table 8. Visibility of geo-stationary EGNOS satellites in Delft.

satellite	PRN	azimuth	elevation
AOR-E	120	204.7º	27.7º
Artemis	124	158.7º	28.4º

Fig. 12. Visibility of EGNOS geo-stationary satellite PRN120 (left) and PRN124 (right) in the center of Delft.

The EGNOS corrective information can be extrapolated over a period of a few minutes, without compromising the accuracy too much. The time-out interval typically ranges from a few tens of seconds to a few minutes (up to 10), dependent on the type of correction. This relaxes the requirement of a direct and permanent line-of-sight to the geo-stationary satellite, for the purpose of position accuracy (not of course for integrity, which is the primary purpose of EGNOS). An alternative to disseminating the augmentation information through geo-stationary satellites, which are seen at low elevation angles at high latitudes, is presented in [12]. By the Signal in Space through the Internet (SISNeT) the EGNOS messages are available to the user over a wireless Internet connection. In [ibid] several test results, with land mobile applications, are given using the EGNOS System Test Bed (ESTB), and aspects as accuracy, availability and integrity are discussed and traded off.

OUTLOOK: POSITIONING BY FINGER-PRINTING

An alternative to positioning by actual ranging is the so-called foot- or fingerprint method. It might be possible to determine the user position by assessing which satellites at the given time can be tracked and which ones not (no matter the actual range). The logical zero/one state per satellite at a certain unknown user position at a certain time can be matched with locations that have the same property (fingerprint) of satellite visibility based on a three-dimensional model of the topography in the local environment.

The fingerprint method relies on certain resources. Firstly there is the presence of topography near the user as in built-up area. Next a (large) database or a resulting template with the fingerprints of all locations needs to be available (and the generation of the template for matching might be computationally intensive). Another option is to provide the 3D-model of the area under study to the device and perform the calculation in real-time. This kind of visibility-reckoning will also be computationally intensive.

A single fingerprint at a single (measurement) epoch may/will still be ambiguous in position; an example is shown in Fig.13. A (natural) sequence of fingerprints along a trajectory (walked or driven) will resolve the ambiguity (also a sequence in time at the same location may work, as the satellite geometry changes). And fingerprinting may not yield full three-dimensional position determination; in practice one will restrict the user position to the local road surface (or slightly above it).

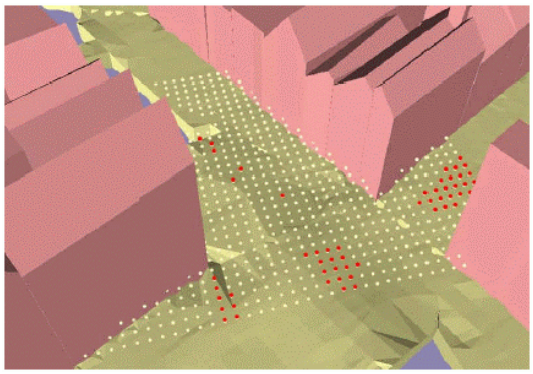

Fig. 13. Example of the concept of positioning by finger-printing. Shown are the possible locations (in red), for the first epoch of the simulation, with 8 GPS satellites above the local horizon, for which holds, based on the 3D model, that a specific subset of 3 satellites are visible (line-of-sight), and 5 satellites are not. The other grid-points (in yellow) do not match the finger-print.

The advantages of finger-printing is that visibility to at least four GNSS satellites, to solve for the three position coordinates and the receiver clock error, is not needed to determine the user position. The method can be a valuable complement to GNSS positioning based on ranging, in particular in urban areas. Within map-based LBS applications one can imagine to center the map by the obtained finger-printing position, before the actual and accurate position obtained by GPS-ranging is available.

CONCLUDING REMARKS

Practical examples have been given of a range of GNSS positioning modes. The primary purpose has been to present an impression of the attainable position accuracy, for a moving using, in real time. Compared to other positioning sensors for LBS, a Global Navigation Satellite System (GNSS) may suffer in urban environment, from its weakest property, the requirement of direct lines of sight to the transmitting satellites. Using a detailed 3D-model, obtained through airborne laser-scanning, of the historic town-centre of Delft at 52 degrees Northern latitude, the availability of GNSS positioning has been analyzed, for the current GPS, EGNOS, as well as for combined GPS and Galileo. The paper was concluded with an outlook on positioning using so-called finger prints. This method can be a valuable complement to GNSS positioning based on ranging, in particular in urban areas, and will be investigated further on implementation and practical applicability.

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