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Realistic prediction of accuracy in urban environments with a GNSS simulation tool

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Nowadays surveying with the Global Positioning System (GPS) in undisturbed environments is a standard. Under normal conditions resolving the ambiguities is easily achieved, to yield precise positions at the cm level. However, it is often impossible to fix a solution in urban areas, because obstructions mask satellites and let the number of available satellites become too small. In the next years the Global Navigation Satellite System (GNSS) scenery will change. When the three GNSS systems GPS, Glonass, and Galileo are operational, they will provide more than 70 satellites. In order to evaluate the satellite visibility for future scenarios in urban environments, the Institute of Physical Geodesy (IPGD) has developed a simulation tool for GNSS which incorporates obstructions caused by buildings and vegetation. By the application of three dimensional city models obstruction masks are calculated. Further analysis will then be restricted to the visible satellites at a certain location. This article focuses on the realistic prediction of success rate and accuracy of real-time kinematic (RTK) measurements under future GNSS constellations. The simulation of several urban areas shows good prospects for improvements in the success rate of ambiguity fixing due to the larger number of visible satellites. On the other hand the improvement in accuracy will be marginal.

1 Introduction

The nominal constellation of the Global Positioning System (GPS) consists of 24 satellites, but currently there are more than 30 usable satellites in orbit. Under good conditions, which means without obstruction, it is no problem to receive the required minimum of four satellites. However, the situation is much more complicated in urban regions. Buildings and trees shield the antenna and prevent the reception of signals. In consequence there are only few short time-windows with enough visible satellites available. In a considerable amount of instances, ambiguity fixing will not be possible and thus no precise positioning. Nevertheless, satellite based measurements like GNSS-real time kinematic (RTK) are desirable and required in cities as well. They could replace a good portion of methods, like tacheometry, for the densification of the geodetic networks which require a significant larger amount of labour. In addition it would be valuable if GNSS based kinematic surveying and navigation systems could work more reliably in urban environments.

The prospects of GNSS development are promising. Currently the Russian system Glonass is in the process of modernization. The Russian space agency (RSA, 2008) reported that the constellation will expand up to 30 satellites until 2011. For Galileo the timeline for reaching a full operational capability strives for the year 2013. Together with the existing and by then modernized GPS system, there will be more than 70 satellites in orbit. Thus the user will be provided with a large number of satellites for a combined Multi-GNSS solution. The question arises, in which way this situation will improve the potential of precise positioning, especially the RTK mode, in urban regions.

Several studies investigating the benefit of future Multi-GNSS scenarios for precise differential GPS (PDGPS) applications like RTK have been published. Verhagen (2002) has shown the advantage of a combined GPS + Galileo constellation. For a global simulation she predicts a success rate of about 95 % for instantaneous ambiguity fixing for 98 % of the earth surface, however, without considering obstructions like in urban areas. In contrast O'Donnell et al. (2003) analyse the performance of the combined GPS + Galileo constellation in urban environments. Based on a city model, which contains information about the material of building surfaces, they model the multipath effects by generating power delay profiles along a path in the city. From the different GPS + Galileo configurations in their study they conclude that a GPS constellation extended with 12 Galileo satellites is already sufficient for a successful positioning in urban canyons. Nevertheless, this study only considers the code pseudo-range positioning mode. Bradbury (2007) describes an approach to incorporate multipath and signal diffraction into a 3D city model based simulation in order to enhance the pure line of sight visibility calculation. However, within the examples of the study this method is only applied to the reception of individual satellites, but not to precise positioning and to different GNSS combinations.

The above posed question about the future prospect of RTK mode precise positioning in urban environments under different Multi-GNSS scenarios has not yet been answered to a sufficient extent. For this reason the IPGD has developed its own GNSS simulation tool named PlanGNSS (Sudmeier, 2007). As a special feature PlanGNSS is capable to generate obstruction masks for predefined positions based on three dimensional digital city models. This enables the identification of the line of sight visibility of satellites at certain urban locations and thus a realistic simulation of RTK mode positioning. In this article the simulation tool and some results of possible future Multi-GNSS constellations are introduced. First the simulated 'nominal' constellations are outlined and the main features of the simulation tool are described. Real measurements were carried out in order to validate the simulation tool. The real measurements were analysed with respect to multipath and the signal to noise ratio (SNR) in order to get an insight into signal reception and quality, and in particular to check for indirect signals. In further projects these findings could be used e.g. for an advanced weighting strategy. In addition those measurements were used for the determination of a scaling factor for the PDOP (position dilution of precision). With this scaling factor the PDOP can be converted into position accuracy for the simulated scenario.

After the validation of PlanGNSS various obstruction scenarios were evaluated for different simulated GNSS constellations. Particular emphasis was placed on the accuracy and success rate for the typical RTK measurement mode.

2 Multi-GNSS prospects

The future will provide a huge amount of GNSS satellites. In this study only the GNSS systems GPS, Galileo and Glonass are considered. The simulation tool requires ephemeris for the calculation of satellite positions. With minor modification the nominal orbit constellations of the three GNSS are taken from Kaplan and Hegarty (2006) for GPS, from the Glonass interface control document (Glonass ICD, 2002) and finally for Galileo from Zandbergen et al. (2004). Ephemeris are generated in form of six Keplerian elements and provided to the simulation tool in RINEX 3.0 format for all GNSS. Table 1 gives an overview about the nominal constellation parameters.

The orbit eccentricity is set to zero in order to simplify the model, that means the modelled orbits are circular rather than elliptic. Thus the semi major axis equals the radius of the circular orbit. Since the eccentricity in reality is very small this simplification doesn't harm the validity of the simulation results. The orientation of the plane in space is defined by the inclination and the right ascension of the ascending node. The first parameter is taken from the nominal constellation for each system. The second describes the position of the plane with respect to the equatorial plane. This value is chosen to yield a regular distribution of the orbital planes along the equator. The remaining two Keplerian elements determine the position of the satellite inside the orbital plane. Due to the circular form of the orbit the argument of the perigee is arbitrarily set to zero and thus virtually transferred into the ascending node. The position of the satellite in the plane with respect to the ascending node is thus given by the argument of latitude by assuming that the satellites within one plane are equally distributed. Only the nominal number of satellites (without spares) is taken into account for simulating future Multi-GNSS constellations.

Tab. 1: Simulated GNSS constellations

	GPS	Glonass	Galileo
number of satellites (+ spares)	24 (+ 3)	24 (+ 3)	27 (+ 3)
number of planes	6	3	3
inclination	55 °	64.8 °	56 °
semi major axis in km	26561.750	25510.000	29600.318
numerical eccentricity approx.	0	0	0
orbital period	$11^h\ 58^m$	$11^h\ 16^m$	$14^h\ 5^m$
repeat time of constellation in days	1	8	10

3 Simulation of urban environment

In order to be able to calculate the satellite visibility and obstruction mask respectively at a specific urban location the simulation tool has to incorporate a 3D model of the buildings and vegetation in the vicinity. For this study 3D virtual city models are used. City model formats are not standardized which means that for each city suitable interfaces and algorithms have to be implemented. Currently PlanGNSS has been set up to use 3D city models of Frankfurt am Main, Magdeburg, and Wiesbaden.

For a simulation the user has to provide broadcast or precise ephemeris which can be real or simulated. Furthermore, he has to define a user position or a trajectory (simulation of kinematic positioning), a time interval, and a sampling rate for the measurements to be simulated. Based on this input the azimuth and elevation of the satellites with respect to the user position are calculated in a first step. The obstruction mask is computed from the city model as an azimuth-elevation table. It describes the roof edges and upper limit of vegetation in the area surrounding the user position. In the currently implemented models the buildings are provided as a coarse brick model in DXF or VRML format. This means that roofs are plane horizontal surfaces and jutties etc. are not considered. Each corner is represented by two planar coordinates and a height defined as height above the ground. In combination with a terrain model (5 or 10 meter grid in ASCII format) the relative heights can be transformed into absolute heights. In the same way the user antenna position's absolute height is derived from the terrain model and the antenna height.

Vegetation data has been available only in case of Wiesbaden for the whole area considered in the simulation. Vegetation data is given as relative heights on a 1 meter grid and contains all trees taller than 5 meter.

As mentioned above the obstruction mask is parameterized as an azimuth-elevation table with step width of one degree for the azimuth and the respectively calculated elevation values of the upper limit of obstruction, building or vegetation. Blending each receiver-satellite line of sight with the obstruction mask from the digital 3D city model delivers the information about the visibility of the satellite. The result is presented by a sky plot depicting the obstruction mask for the buildings (grey) and vegetation (green) as well as the trace of all visible satellites. Figure 1 (in section 4) shows an example simulation for this study. Further outputs are the number of satellites (NOS), the dilution of precision (DOP), azimuth and elevation and the respective plots.

4 Observation analysis of real measurements

Real measurements were performed to validate and enhance the simulation tool. The validation is mainly done by a comparison of the received signals (real measurements) with the satellite visibility as calculated by PlanGNSS by use of the 3D city model (simulation). It is examined, whether the PDOP, as purely geometric parameter, can simply be scaled into the easier understandable and more intuitive 3D position accuracy. The aim is to determine this scaling factor from the accuracy of real RTK measurements as derived from repeated observations.

4.1 Scaling of PDOP into position accuracy

A primary output of PlanGNSS describing the quality of the receiver-to-satellites geometry is the PDOP. Its value equals the trace of the cofactor matrix of the coordinates. If all pseudoranges (including non-ambiguous phase observations) are introduced with equal weights the PDOP is considered as a indicator of the quality of the receiver-to-satellites geometry. But as a quality measure the PDOP is inconvenient for the user. A metric value for accuracy is much easier to interpret. Scaling the PDOP with the measurement accuracy σ_{range} (or alternatively the user equivalent range error σ_{UERE}) leads to the position accuracy σ_{pos} to be expected (Kaplan and Hegarty (2006)):

$$\sigma_{pos} = \sigma_{range}\ PDOP \tag{1}$$

From this it is obvious that the scaling factor looked for represents the accuracy of the receiver-satellite distance measurements. In case of RTK positioning this relates to the phase measurements with correctly fixed ambiguities. O'Donnell (2003) determines σ_{range} basically on material characteristics and the location next to the buildings. By contrast in this project the value results from empirical studies. For its determination repeated RTK measurements at different locations have been carried out, firstly in the financial district of Frankfurt and secondly in the city of Wiesbaden. From all cases of successful RTK positioning (which means enough visible satellites and successful fixing of the ambiguities) the root mean square (RMS) values of the positions with respect to the mean have been calculated as measure of repeatability (accuracy from repeated measurements). The total 3D repeatability is used in the next step as 3D position accuracy σ_{pos} in equation (1) for computation of the scaling factor σ_{range}. Such scaling factors have been calculated for both cities in order to represent the measurement conditions of the respective scenarios.

Table 2 lists the repeatability and mean PDOP of both locations. Frankfurt is characterized by a worse geometry (compared to Wiesbaden) due to higher buildings which cause more obstruction. Whereas, in Wiesbaden the diffusion of signals through vegetation leads to a slightly degraded position accuracy. This results in a larger scaling factor in case of Wiesbaden. However, both factors are close to each other and agree quite well to a respective scaling factor of 0.0056 m derived for a location without obstruction (on campus of TU Darmstadt). Therefore, it is reasonable to apply the mean scaling factor to locations in other cities.

Tab. 2: Scaling factor computed from the position accuracy and PDOP of real measurements

location	Repeatability σ_{pos} [m]	Mean PDOP [-]	Scaling factor [m]
Wiesbaden	0.023	3.2	0.0072
Frankfurt	0.021	3.5	0.0060

4.2 Detection of indirect signals

Urban environments are suspicious to high multipath effects. If a satellite is obstructed but, nevertheless, measured by the receiver, the signal must have reached the antenna on an indirect i.e. reflected path. PlanGNSS is a well suited tool to detect these indirect signals because it allows the decision whether or not a satellite is obstructed. The visibility is determined by the calculation of the line-of-sight vector and its comparison with the obstruction from the 3D city model. As an example figure 1 depicts a sky plot with the real measurements on the one hand and the obstruction mask from PlanGNSS on the other. The existence of indirect signals is clearly visible for satellites G2, G4, R10, R17 and R24 (G for GPS, R for Glonass). Those signals were received from low elevations inside the obstructed area. At least in case of obstruction by buildings that signals must have been received indirectly by reflection.

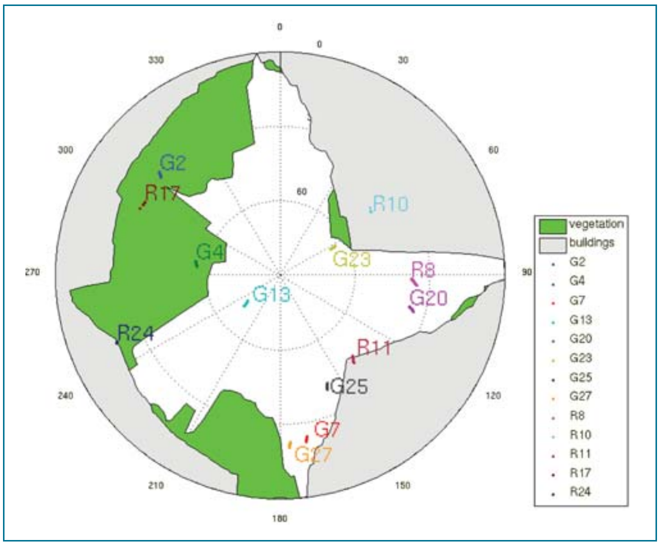

Fig. 1: Sky plot of a real measurement with obstruction mask from PlanGNSS (building obstruction in grey, additional vegetation obstruction in green)

In order to study the measurements of the example dataset, depicted in figure 1 in more detail, the multipath variation and the SNR values are shown in figures 2 and 3.
The multipath variation is calculated from the code-phase differences corrected for the ionospheric effect. Thus it is only provided if L1- and L2-phases have been measured by the receiver. In figure 2 horizontal bounds at +/− 0.4 meter are plotted, which is a typical multipath variation in unobstructed areas. Especially for indirect signals the observations from the L2 frequency are often missing. This phenomenon is also described in Butsch (1997). He investigates the SNR in presence of jammer signals and concludes that the L2 Signal is more affected by electromagnetic disturbances than L1. Due to the missing L2 phases the multipath variation plot can’t give a clear indication for indirect signals, even though the amount of variation is larger than in not obstructed areas.
The SNR characteristics in cases of diffraction and multipath are described in Wanninger et al. (2000). He shows that the SNR values decrease due to diffraction whereas multipath leads to SNR fluctuation. The inspection of the SNR on L1, depicted in figure 3, clearly unveils that the indirect signals have significantly worse SNR values while the signals ‘from the clear sky’ exhibit almost constant SNR values at a high level.

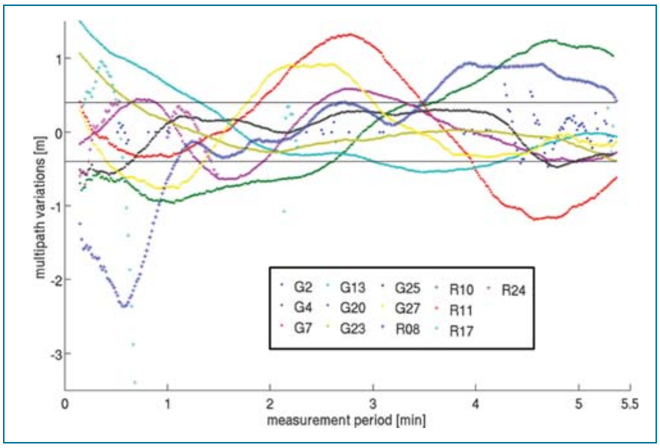

Fig. 2: L1-Multipath variations of the measurements in figure 1

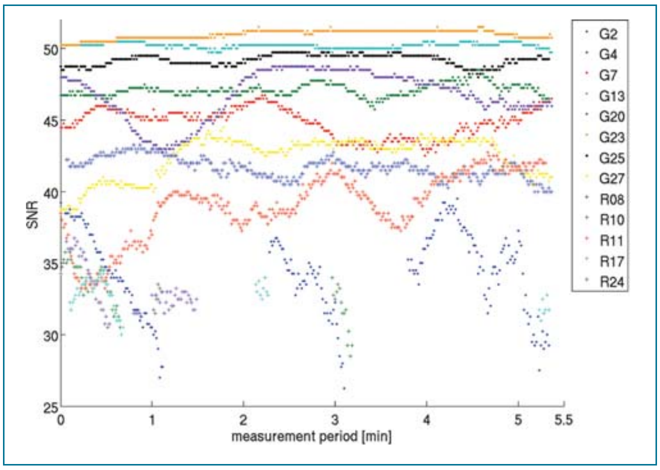

Fig. 3: L1-SNR of the measurements in figure 1

Theoretically indirect signals should not be used in the position calculation. Figure 3 shows that the SNR indicates disturbed signals. Thus SNR could be used to exclude indirect signals or at least reduce their weight in the processing. Respective methods have been developed e.g. by Brunner et al. (1999) and Wieser and Brunner (2000). However, one crucial problem is that each receiver has its own method and scale for SNR output; see e.g. Butsch (1997), even though there are efforts ongoing towards a standardized SNR output. As a further difficulty there are also direct signals with poor SNR values. The proper handling of the measurements with consideration of the SNR is still quite challenging, and clear thresholds for the determination of indirect signals are not easily found.

5 Simulation of static measurements

In the study four points are analysed over one day simulating a RTK positioning every full hour. Two points are situated in the financial district of Frankfurt with a high obstruction rate due to high rising buildings. The other two points are in the city of Wiesbaden where the vegetation contributes significantly to the obstruction while the buildings are less high. Figure 4 shows the obstruction masks of the four points.
Ephemeris were generated for the following four nominal (Multi-) GNSS constellations:

- GPS (G)
- GPS and Glonass (GR)
- GPS and Galileo (GE)
- GPS, Glonass and Galileo (GRE)

All in all a sample of 384 RTK measurements was simulated (24 RTK measurements per point and constellation). All observations are handled with equal weights during the evaluation. In order to conclude whether or not a successful RTK positioning is feasible for a certain measurement and thus to calculate an overall success rate per

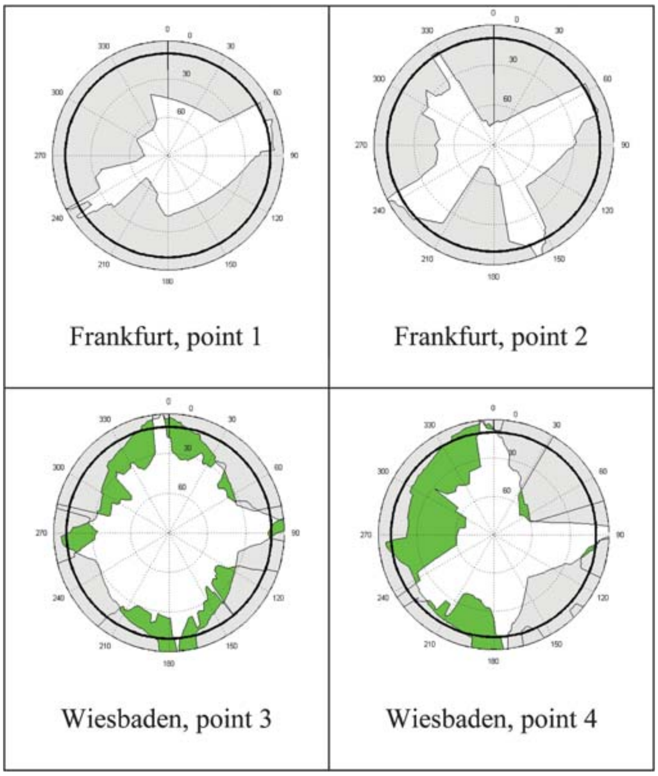

Fig. 4: Obstruction masks at four urban locations (points)

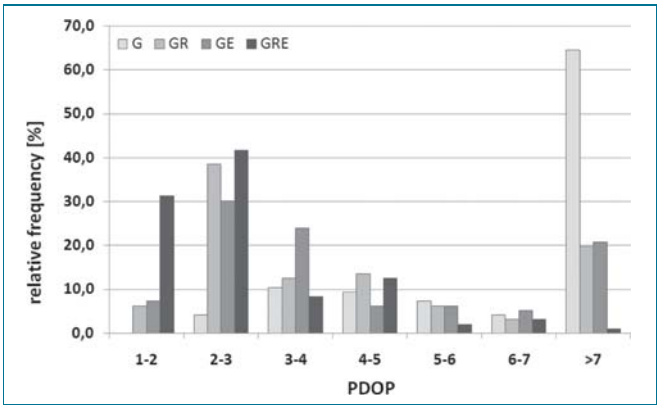

Fig. 5: Histograms of PDOP for four GNSS combinations

GNSS constellation, some criteria have to be set up. The first criterion selected is that the number of visible satellites has to be at least five. The second criterion depends on the PDOP and thus the receiver-satellites geometry. From practical experience the PDOP should be smaller than five in order to carry out a successful RTK positioning within few minutes of observation time.

Based on these two criteria the expected accuracy and the success rate was analysed for the four locations with the four GNSS combinations. First the PDOP criterion is ana-

Tab. 3: Two criteria for success, number of satellites and PDOP, and resulting success rate

GNSS constellation	**number of satellites (NOS)**				**PDOP for NOS ≥ 5**			**success rate in [%]**
	MIN	**MAX**	**MEAN**	**NOS ≥ 5 in [%]**	**MIN**	**MAX**	**MEAN**	
				point 1 (Frankfurt)				
G	1	5	3	4	3.0	3.0	3.0	4
GR	4	8	5	67	2.5	62.7	9.1	33
GE	3	9	6	83	2.4	17.9	6.1	46
GRE	6	12	9	100	2.1	6.6	3.5	92
				point 2 (Frankfurt)				
G	2	5	4	46	2.5	6.0	3.6	42
GR	5	10	7	100	1.7	10.2	3.2	87
GE	5	11	8	100	1.7	8.2	2.8	92
GRE	8	14	12	100	1.4	5.8	2.0	96
				point 3 (Wiesbaden)				
G	3	5	4	21	3.1	7.5	4.9	12
GR	5	10	8	100	1.9	6.0	3.1	96
GE	7	10	9	100	2.0	5.2	3.0	96
GRE	9	15	13	100	1.4	3.6	2.2	100
				point 4 (Wiesbaden)				
G	1	4	3	0	-	-	-	0
GR	3	8	6	87	2.3	8.0	4.4	67
GE	2	7	6	96	2.9	20.3	6.9	37
GRE	4	11	9	96	1.6	6.1	3.2	87

lysed. For this purpose the PDOP values of the complete sample have been classified and depicted in figure 5. The figure exhibits four histograms of relative frequency (one per GNSS combination) with 96 values each (four points with 24 measurements each).
A PDOP smaller than five is achieved only in 25 % of the cases for the GPS only constellation. If another GNSS (Glonass or Galileo) is added, the amount of cases with PDOP smaller than five rises up to 70 %. The maxima are located in a PDOP range of 2–4. The best results are obtained with a combination of all three GNSS. In this case more than 90 % of the RTK measurements fulfil the PDOP criterion for RTK success and the maximum value moves to the range 1–3. The high relative frequency of the GPS constellation with PDOP greater than seven is mainly caused by cases with too few (less than four) satellites to calculate the PDOP. This fact shows the need to assess the PDOP together with the second criterion, i.e. the number of satellites, in order to obtain a reliable statement for the expected success rate.
Table 3 summarizes both criteria and the resulting success rate for the different points and GNSS combinations. The first columns (number of satellites) verify that with GPS alone there are not enough satellites due to the high obstruction. While in low obstruction areas at least five satellites are visible in 21–46 % of the test cases, this criterion is met in only 0–4 % cases at points 1 and 4 with high obstruction. This confirms that the use of GPS alone will hardly enable a successful RTK positioning in urban environments. If a second GNSS is added, more than 67 % of the cases have more than five satellites. In low obstruction scenarios even 100 % of test cases fulfil this criterion. When all three GNSS systems can be used there will be five and more visible satellites in almost all cases.
The PDOP columns analyse all cases which fulfil the first criterion (NOS $\geq$ 5). There are some cases which have a high PDOP although the number of satellites criterion is met. In these cases the geometry of the visible satellites is too weak due to the obstruction. Especially with high obstruction (points 1 and 4) the second criterion (PDOP $<$ 5) causes the removal of about further 30 % of the cases from expected RTK success.
The last column sums up the success rate. For GPS a RTK success can be expected on average in only 14 % of the test cases. By combined use of two GNSS the success rate increases to almost 70 %. In scenarios with moderate obstruction (points 2 and 3) the success rate is even higher. The use of all three GNSS reveals an average of 94 % for the expectable success rate. For an efficient RTK positioning in urban environments it can be clearly stated that the combined use of at least two, better more GNSS is of utmost importance.
Finally the scaling factor determined from the real measurements yields an idea about the accuracy which can be expected by using the different GNSS constellations. Table 4 shows that the accuracy of the position will improve only marginally. Since even a few (at least five) satellites can make a good geometry, additional satellites lead only to a small improvement. Therefore, the increase in number of satellites does not result in a much improved accuracy.

Tab. 4: Position accuracy and success rate: averages for the various GNSS constellations

constellation	G	GR	GE	GRE
Accuracy [cm]	2.1	2.0	1.9	1.7
success rate [%]	14	71	68	94

A short remark is appropriate on the small differences between the GR and GE constellation results. The higher accuracy and success rate for the GR constellation is achieved for the chosen points with their individual obstruction scenario. But this cannot be generalised to a better performance of the GR constellation compared to GE. Both constellations can be considered equivalent from this study's point of view.

6 Simulation of kinematic measurements

For precise real time kinematic positioning it is important to track the satellites with fixed ambiguities as long as possible without signal loss. Loss of signal could appear due to obstructions because of the fast changing environment of the buildings etc. If at least four fixed ambiguities remain, the receiver position is precise and new ambiguities will be fixed instantaneously. Clearly the larger the number of satellites, the smaller is the risk that a re-initialization of the ambiguities will be necessary.
To gain insight into the potential of future Multi-GNSS for kinematic precise positioning a simulation was carried out for a trajectory in Magdeburg. The three dimensional city model of Magdeburg was implemented and the trajectory depicted in figure 5 was analysed with PlanGNSS.

Fig. 6: Simulated trajectory in the city of Magdeburg (photo: source Google Earth)

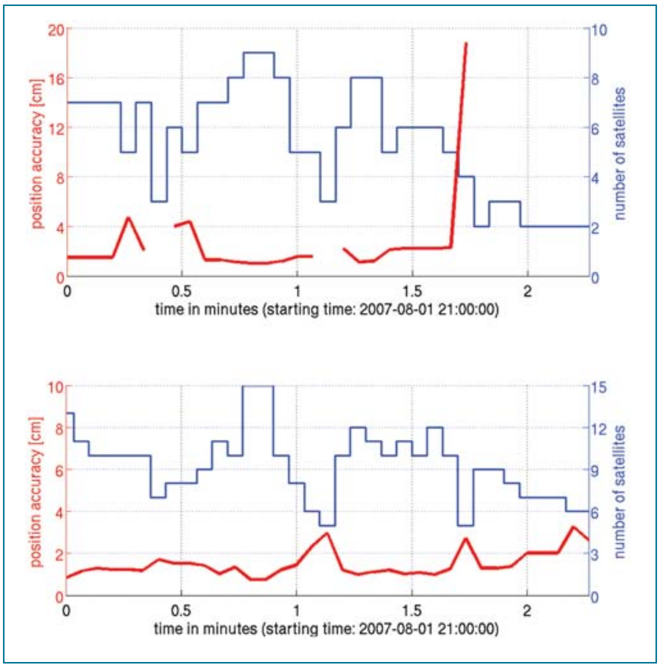

Fig. 7: Position accuracy and number of satellites for one simulated drive: GPS solution (real ephemeris, upper figure) and combined GPS + Galileo solution (below)

Ephemeris for the above (section 5) listed constellations were generated and additionally real GPS ephemeris from the constellation of August 1, 2007, were used. In the simulation a drive along the trajectory was simulated four times for each constellation. Figure 6 displays the expected position accuracy and the number of satellites for one of the drives. With the real GPS constellation two regions appear were no position could be calculated because of too few satellites. The respective gaps at 0.4 and 1.1 min correspond to the same area inside the N-S loop. At the end of the trajectory there is an additional gap because of high obstruction. As can be seen at the lower graph in figure 6 for the combined nominal GPS + Galileo simulation the gaps are closed due to the higher number of satellites. Over the whole drive a minimum of five satellites is achieved, which means a 100 % availability.
In order to summarize the results of all simulated cases table 5 lists the mean of all four repeated simulations for each constellation. The same criteria as in section 5 are applied to decide about RTK success. It can be seen that the nominal GPS constellation is far more pessimistic than the real GPS one. Thus for the future an even more favourable situation can be expected than simulated in this study. The real constellations may provide more satellites than defined in the nominal constellations as can be seen today for GPS.
Further the essential outcome of the simulation of kinematic positioning is similar to the static scenario. The number of satellites rises with the use of a second GNSS which leads to an increase in the RTK success rate accordingly. Of course the limiting factor is the geometry which primarily depends on the grade of obstruction. A combined GPS + Galileo solution is much more promising than a pure GPS solution.

Tab. 5: Percentage of cases which fulfil the criteria about the number of satellites and the PDOP. The last column represents the resulting success rate.

GNSS constellation	NOS > 5 in [%]	PDOP < 5 in [%]	success rate in [%]
G real	65.0	51.4	51.4
G nominal	42.1	47.1	42.1
GR nominal	92.1	74.3	74.3
GE nominal	95.7	83.6	83.6
GRE nominal	97.9	92.9	92.9

7 Conclusions

IPGD has developed PlanGNSS, a tool for simulating the positioning with various GNSS constellations and by inclusion of 3D city models, buildings and vegetation. With this tool the visibility of satellites at a certain location and time can be determined, thus enabling the calculation of positioning geometry, expectable accuracy, and the RTK success rate which can be expected for the different obstruction scenarios. As a specific characteristic the accuracy is derived from empirical data and, therefore, more realistic than a theoretically chosen UERE.
By comparison with real measurements in urban environments PlanGNSS provided evidence of the existence of indirect signals. A signal quality analysis of the indirect signals confirmed that a SNR based weight model for the observations makes sense and should be implemented and applied for such type of RTK applications.
The simulation of four scenarios at points with different obstructions for future Multi-GNSS constellations showed an expected increase of the success rate for RTK positioning with respect to the number of GNSS systems used. However, the larger number of satellites does not result in a significant improvement of the position accuracy in general. A combination of different GNSS systems will be of little benefit in environments without obstructions. But in urban environments the use of combined GNSS is of real importance due to the expected increase of the success rate of RTK positioning.
Further development of PlanGNSS will aim at the refinement of the 3D city and vegetation models. Inclusion of material properties may in future allow the assessment of signal strength and, furthermore, improve the evaluation of kinematic measurements in urban areas.

8 Acknowledgements

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