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Jakob Jakobsen[1], Anna B.O. Jensen[2], and Juliette Marais[3]

[1]National Space Institute, Technical University of Denmark (DTU-Space), Lyngby, Denmark

jj@space.dtu.dk

[2]AJ Geomatics, Roskilde, Denmark

aj@ajgeomatics.com

[3]Univ Lille Nord de France, IFSTTAR, LEOST, Villeneuve d'Ascq, France

juliette.marais@ifsttar.fr

Abstract – This paper describes the development and use of a simulation tool, called QualiSIM. This tool simulates GNSS-based position accuracy under various operational and environmental conditions, in particular in environments with large amounts of signal reflections. The signal reflections are implemented using the geometric path length the signal travels when it gets reflected from the surrounding buildings.

Environmental influences on GNSS-based positioning are obstacles, such as buildings along streets which can lead to blocking and reflection of satellite signals. Examples of operational conditions are atmospheric effects and changes in the satellite geometry.

The tool has been developed to work either with Galileo or GPS or with both satellite constellations. Since Galileo is only pre-operational, the simulator is based on the nominal 27 satellite Galileo constellation. Further, the simulator uses: atmospheric models to simulate the effect on satellite signals through Earth's atmosphere, designs of representative environments e.g. urban and rural scenarios, and a method to simulate reflection of satellite signals within the close environment of the GNSS (Global Navigation Satellite System) antenna. The simulator thus models: the signal path from satellite to receiver, satellite availability, the extended pseudoranges caused by signal reflection, and the position accuracy based on a least squares adjustment of the extended pseudoranges.

In order to handle temporal and spatial variations of the different errors sources in GNSS-based positioning, the simulator has been developed for observing variations in position accuracy over time, along a given test trajectory, at different latitudes, and with different azimuths of the environment around the receiver.

The environments used by the simulator could be typical representative scenarios such as, a narrow city street, a t-cross or mountain landscape. The choice of not using specific streets or cities has been made in order to keep the simulator open for every kind of environment.

In this paper a simulation example is illustrated and shows the possibilities for visualisation of a narrow street with buildings on each side over a simulation time period of 24 hours. The impact of using reflected satellites in the position domain is significant. The DOP values are in general lower, but the error ellipses can be up to 8 times larger and furthermore deviate in shape.

Biographies

Dr. Jakob Jakobsen is researcher at the National Space Institute (DTU-Space) in Denmark. His main research interest is the effect and characterisation of multipath in the position domain in various challenged GNSS environments such as dense urban and indoor.

Dr. Anna B.O. Jensen is owner and founder of AJ Geomatics participating in GNSS R&D projects. She is also part time Associate Professor at DTU-Space. Her main research interests are high accuracy GNSS positioning, atmospheric effects on GNSS signals, and traditional geodesy.

Dr. Juliette Marais is a researcher of the French Institute of Science and Technology for transport, development, and networks (IFSTTAR). Her research interests focus on satellite-based navigation systems including performance evaluation, in particular, transport applications, accuracy enhancement, signal propagation modelling, and error estimation.

I. INTRODUCTION

The work described in this paper is carried out within the frame of the QualiSaR project that focuses on the development of a qualification procedure for the

use of Galileo satellite receivers for safety relevant applications. The QualiSaR project is funded by the EU seventh framework programme, and the project is lead by the Technical University of Braunschweig, Germany.

The aim of QualiSaR is to develop a qualification process to verify the measurement quality of satellite-based localisation services such as GNSS. Indeed the quality of GNSS based localisation systems in ground transportation highly depends on the environmental and operational conditions: obstacles, such as buildings along streets, trees in forest areas, as well as topographical factors, such as mountains can lead to blocking and reflection of satellite signals and degrade performances. Before performing field tests with a GNSS receiver, the test tracks and a methodology for designing the various test settings must be developed and these typical environmental influences have to be determined.

Thus, the purpose of the simulator QualiSIM is to provide a tool that simulates position accuracy under various GNSS conditions and along various trajectories in different types of environment.

It is noted that the purpose of the simulator is to estimate errors on the pseudoranges - not to simulate GNSS signals. The QualiSIM is therefore a software tool for estimating position accuracy with different scenarios (environments) around the receiver.

Some of the benefits of using a simulator are the following:

- A simulator can be used if it is difficult, expensive, or in some cases impossible to conduct field tests
- Various scenarios can be tested in order to find the best solution or most suitable case for a field test
- Each parameter can be controlled independently, and therefore the effect of each error source can be controlled and studied independently
- The Galileo GNSS signals in space are not all available yet. By using a simulator, tests can be performed in order to see the future effects on position accuracy.

QualiSIM is able to simulate various environmental conditions, various locations, various time of day, various orientations of the trajectory etc. in order to account for various GNSS error sources. In short, QualiSIM has been developed to comply with the following three overall criteria:

- Easy design of single test runs
- Easy change of environmental settings
- Visualisation of results

This paper first describes the implementation of the simulator in details. Then a simulation example obtained with QualiSIM is illustrated. The results illustrate how the simulator can be used for testing purposes in different ways. Finally, conclusions and perspectives are outlined.

II. IMPLEMENTATION OF QUALISIM

In this section the implementation of the QualiSIM simulator is described, focusing on the most important GNSS error sources, i.e. atmospheric effects and signal reflection, as well as the algorithms used for the estimation of satellite and receiver positions.

QualiSIM is developed in Matlab and Figure 1 shows the main graphical user interface of the simulator. The fields for the different input variables discussed in the following are provided in the right part of the screen. The left and middle parts of the screen are dominated by plot fields for visualisation of the most important results after a simulation run. Detailed plots of DOP values, number of satellites and error ellipses can be performed from a separate plot user interface. Parameters for the 4 different analysis methods (described later) implemented in QualiSIM are set in the lower middle part of the user interface.

A. GNSS satellite constellations

In our work the two GNSS in focus are Galileo and GPS

Galileo is not yet fully operational. Galileo satellite orbits have therefore been implemented using the nominal satellite constellation with 27 satellites in order to provide simulation results complying as much as possible with the expected situation when all Galileo satellites will be in orbit. The Kepler elements describing the satellite orbits are read into the software, and the Galileo satellite positions are then estimated from the Kepler elements using the algorithms described by [1]. A timer is implemented to model the motion of the satellites when QualiSIM is used for simulations as function of time.

GPS is fully operational since 1995 [2]. The constellation is today significant different of the nominal one (at the time of writing - spring 2013 - 31 satellites are in orbit). In order to provide simulation results complying as much as possible with the real life situation, GPS satellite orbits are read into the QualiSIM software from real GPS navigation files in the RINEX data format. By using a recently collected GPS navigation file, the results will be close to the actual conditions for the time of the simulation.

As for the Galileo satellites, the derived Kepler elements in the navigation file are used to calculate the satellite positions. For the GPS satellites the algorithms used for the calculations are from [3].
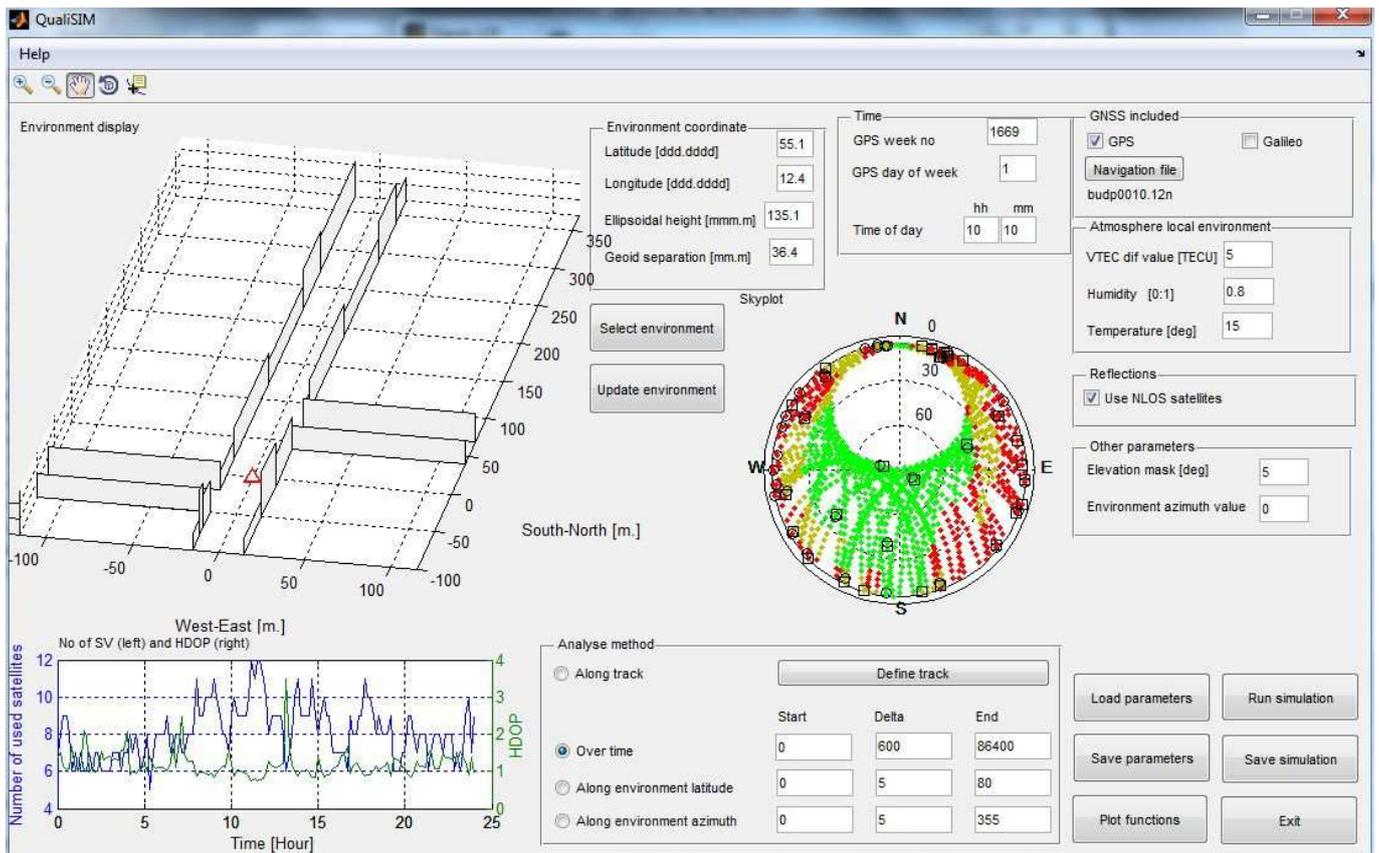
Figure 1: The main graphical user interface in QualiSIM.

QualiSIM has been developed as a multiconstellation tool, thus it can simulate scenarios using Galileo only, GPS only, or a combination of the two constellations.

An elevation mask has been implemented in the simulator and can be set by the user. The elevation masking angle is used to eliminate signals received from satellites which are located just above the horizon (i.e. satellites with a low elevation angle). Such signals are often very noisy as they travel along the surface of the ground, and in most GNSS receivers an elevation mask is therefore implemented to eliminate such signals. For all results shown in this paper, an elevation mask of 5 degrees has been used

B. Atmospheric effects

The atmospheric effects on GNSS satellite signals are one of the important error sources for GNSS-based positioning. The effects are modelled in all GNSS receivers in order to mitigate them, but some residuals stay.

In the context of the QualiSIM simulator it has been decided to model this residual effect of the atmosphere. This means that the error which is left after applying common atmospheric models is estimated in the simulations.

The atmospheric effects are divided into the effect of the ionosphere which is caused by free electrons in the ionosphere affecting mainly the speed of the GNSS

satellite signals, and the refraction effects of the troposphere caused by the weather conditions pressure, humidity and temperature.

The effect of the ionosphere is modelled using a differential value for the vertical total electron content (VTEC) at the time of the simulation. The differential VTEC value is converted to a slant signal delay in the direction of the satellite signal, for each GNSS signal. The slant residual signal delay is then used as a model of the residual ionosphere effect in the estimation of position accuracy.

In QualiSIM, the effect of the troposphere is modelled using the Hopfield troposphere model [4]. The Hopfield model is first used with standard atmosphere values commonly used in GNSS receivers. This provides a value for the tropospheric delay estimated by the receiver. Then the Hopfield model is used with the values for the time of the simulation as entered by the user and correspond to the actual atmosphere values. The difference between the two troposphere delays, provide an estimate of the residual troposphere effect used in the following estimation of position accuracy.

C. Definition of environment

The local environment surrounding the GNSS antenna has a significant influence on the signal tracking and reception of the GNSS signals. Signals

can be obstructed or reflected from obstacles such as buildings.

The implementation of the environment in QualiSIM consists of a number of buildings each described with a height, length, a start coordinate (translation), and a rotation (azimuth) angle. The values are all given in the local coordinate system. Several representative scenarios, such as urban, dense urban, mountainous are predefined and can be used by the user, but any specific environments can be customized by the user and used for simulations.

D. Reflected satellite signals

Signals reflected from the surrounding environment follow a longer signal path. For signals from satellites that do not have a line of sight to the GNSS antenna, the effect will be an extended pseudorange, corresponding to the extra path length. In QualiSIM this is implemented for non-line of sight satellites with a point search routine. This routine first identifies the total number of reflection points. Secondly it calculates the extended path length geometrically and uses the shortest extended path in the positioning process. A reflection point is defined as a point on a building, where the ingoing signal angle equals the outgoing angle and hit the position of the GNSS antenna. That is like the building was acting like a mirror.

It is important to mention that using this feature no statistical model is used and it will depend solely on the geometry of the local environment. Thus the impact in the position domain for reflected signals only can be analysed and studied in detail with this simulator.

E. Estimation of position accuracy

Based on the input variables and algorithms described above, simulations can now be carried out. The procedure implemented in QualiSIM basically follows this description:

- Initialize input variables including environment
- Calculate satellite positions
- Estimate residual atmospheric effects on satellite signals
- Model satellite signal reflections between satellite and receiver through environment, and estimate extension of pseudoranges
- Estimate the receiver position and position accuracy using least squares adjustment. The least squares adjustment is implemented in QualiSIM as described in detail in [5].
- Save results
- Re-initialize variables before next simulation step

The position accuracies estimated with QualiSIM are provided as output along with error bounds from the least squares adjustment. This makes it possible to evaluate whether the position accuracy is within an error bound of for instance two times the standard deviation (95% significance in one dimension) which is often used for evaluation purposes. In areas with many signal reflections, the position accuracy will more often exceed the error bound compared to open areas with no obstructions or reflecting objects.

After a full simulation run, the results can be analysed. As shown in the following sections analyses are most easily carried out using various plots of the results.

F. Coordinate systems

For the sake of completeness it should be mentioned that several coordinates systems are used within QualiSIM.

The satellite positions are determined as Cartesian coordinates in the Earth Centred Earth Fixed (ECEF) reference system used for the GPS satellite orbits, i.e. the WGS84.

The environment is determined and shown in a local East, North and Up coordinate system in meters with Origo at the central point of the simulations (see Figure 1).

The UTM map projection is used as an intermediate step in the conversion of coordinates between the ECEF and the local coordinate system. For that purpose, the coordinates for the central point of the simulations must also be provided as latitude, longitude and height in the ECEF. The UTM projection zone number of the central point is determined automatically and used in conversion (transformation) of the coordinates.

For a description of the various coordinate systems see [2].

III.   METHODS OF ANALYSIS

To be able to analyse various situations and scenarios, four different analysis methods have been implemented. These four methods will each have a significant influence on the number of satellites and the geometric distribution of these satellites (DOPs), and thus on the estimated position and associated error ellipses.

A. Along track

Along track is an analysis method where the simulator is run for a predefined test trajectory (track) within the environment. The trajectory is defined by a sequence of points (creating line segments of the trajectory). When the along track analysis method is used, the simulator performs a simulation in each of the points in the track. For each simulation of the trajectory, an estimate of the position accuracy is provided.

This analysis method is suitable especially for planning test tracks in urban areas where the most important error source affecting position accuracy is expected to be the reflection of satellite signals between buildings in the environment along the track.

B. Over time

Over time is an analysis method where the simulator is run for a defined time interval (for instance a day) at given time steps (for instance a minute). For each time step a simulation is performed. For each time step, the satellite constellation changes providing new results. Simulations over time are static.

This analysis method is suitable especially for analysing the variation in position accuracy as a function of the changing satellite geometry over time. This will allow us to observe the satellite constellation effects for instance in open areas where the geometry is expected to be the largest contributor to the variation in position accuracy.

C. Along environment latitude

Along environment latitude is an analysis method where the central point of the environment changes using a fixed longitude but with varying latitude values.

The environment and the simulation point is moved for instance from the Equator to the North Pole at given latitude steps (for instance 5 degrees) while the longitude is kept fixed. Simulations along latitude are performed for one instance in time only.

This analysis method is suitable for analysing the variation in position accuracy as a function of geographic location, where the main factor causing the variations will be the difference in satellite geometry at different latitudes.

As an example, consider part of an urban environment. This analysis method can then indicate the expected difference in position accuracy at the different latitudes, and this could be a similar city block (for instance a t-cross) located in Rome, Munich, and Copenhagen, since these cities are all located close to 12°W of longitude, but at different latitudes in Europe.

D. Along environment azimuth

In this analysis method the environment is rotated around the central point of simulation at given azimuth steps, for instance 10 degrees azimuth. Simulations along environment azimuth are performed for one instance in time only.

The azimuth is the direction with respect to the North from 0 to 360 degrees. When the environment is rotated around the central point and the satellite constellation remains the same because only one instance in time is considered, the simulation will show the variation in position accuracy as a function of the rotation of the environment, i.e. the buildings, around the point of the GNSS receiver.

This analysis method is suitable for analysing different orientations of a specific environment. For instance to see the position accuracy variation for a road in a dense urban environment, the road will be oriented in different azimuth-angles. The main impact of accuracy variation will be given by changes in signal reflection and satellite visibility as caused for instance when a tall and wide building in the environment changes location from East, to South, to West, to North

of the GNSS receiver, so the blockage and reflections in turn affect signals from various satellites.

IV. EXAMPLES OF ANALYSES

An example of a simulation will be analysed in the following section. The example illustrates the analysis method over time, with one simulation over 24 hours at 5 minute time steps. The chosen environment is a narrow North-South directed street with varying building heights on both sides. The environment is located in the south-eastern part of Denmark and can be seen in Figure 1. The simulation is performed with satellites from GPS only and with an elevation mask of 5 degrees. The residual atmospheric effect is calculated using a Vertical TEC of 5 TECU, a relative humidity of 80%, and a temperature of 15° Celcius.

A. Skyplot

The skyplot for the entire 24 hour simulation is illustrated in Figure 2. The plot shows line of sight (green) and non-line of sight (yellow and red) satellites as they cross the sky during a day. The yellow dots indicate that this satellite is in a position where it arrives at the GNSS antenna after a reflection on a building surface.
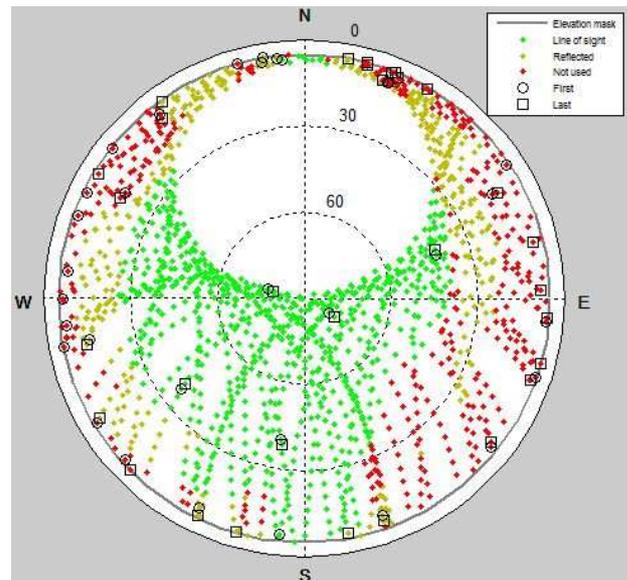
Figure 2: Skyplot for the 24 hour simulation. A red dot indicates a non-line of sight satellite and not used in the position calculation, a yellow dot indicates a non-line of sight satellite, but reflected and used in the position calculation, and a green dot indicates a line of sight satellite used in the position calculation.

It can be seen that reflected signals can come from various elevation angles, though they mainly come from the higher elevations of the non-line of sight part of the sky.

B. Number of satellites

Figure 3 shows the number of satellites observed during the 24 hours. Visible satellites mean all satellites

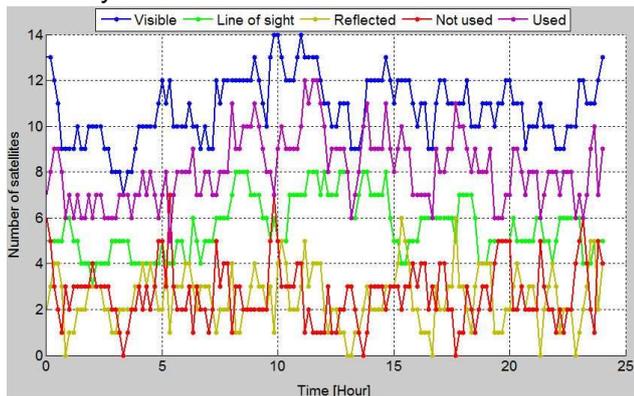above the elevation mask, but they are not necessarily tracked by the receiver.

Figure 3: Number of satellites for the 24 hour simulation.

In this figure the number of used satellites (the purple) is between 6 and 12 and the number of reflected satellites is in the interval from 0 to 6. If the reflected satellites are excluded and only the line of sight satellites are used in the position calculation, there will be several time slots with only 4 satellites and also a small time slot with only 3 satellites. In these time slots, the DOP values will be relatively high.
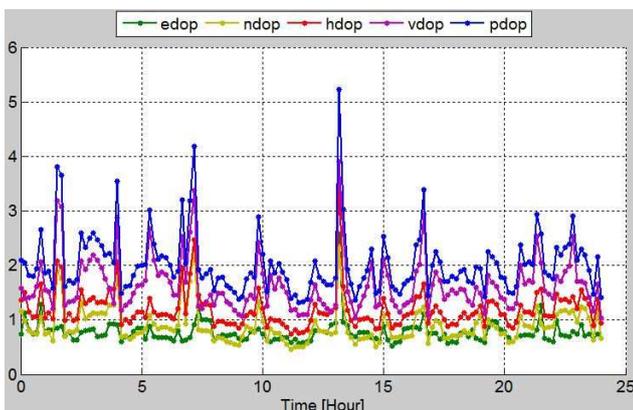
C. DOPs with and without reflected satellites

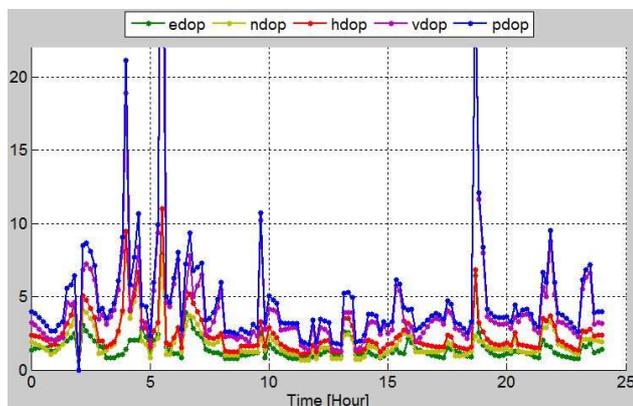**Figure 4: The DOPs based on line of sight and reflected satellites during the 24 hour simulation.**

Figure 5: The DOPs based on line of sight satellites only during the 24 hour simulation

Figure 4 represent the different DOPs based on line of sight and reflected satellites. The DOP values do not vary significantly during the 24 hours, though short time slots (the spikes) with high values can be seen. The HDOP is mainly equal to 1.0 although values above 2.0 are observed.

In Figure 5, the different DOPs are illustrated based on line of sight satellites only during the 24 hour simulation.

The values are significantly higher than using the reflected signals. PDOP reaches 45 and 26.5, though this is mainly caused by a high VDOP. HDOP is also higher in general, values around 2.0, and reaches values above 10.

D. Position accuracy

The position accuracy and associated error ellipses is illustrated with three figures. The result is from UTC-time 00:20, where the satellite constellation consisted of five line of sight satellites and three reflected satellites. The figures consist in one skyplot, showing the constellation at UTC-time 00:20 and two position accuracy plots with and without using reflected satellites. See Figure 6, Figure 7 and Figure 8.

Using the reflected signals large error ellipses are observed, up to 8 times larger than using signals from line of sight satellites only.

As mentioned above, the DOP values are lower when using the reflected signals indicating better position accuracy. But here we see that the position error is actually increased. This is important to remember, because often DOP is used as an indicator of position accuracy. But DOP values are calculated based on the satellite and receiver positions, not considering variations in noise level on the various satellite signals. Therefore, in urban areas with much signal reflection where some pseudoranges are extended, and others are not, the DOP cannot be used as a reliable indicator of position accuracy.

Further, the plots in Figure 8 show that the shape of the ellipses are more circular when including reflected signals as the used satellites are more evenly distributed on the sky. When using line of sight satellites only, a certain part of the sky is omitted, which cause the error ellipses to be larger in one specific direction. In this case in a North-West to South-East direction because the line of sight satellites are located in a perpendicular direction.
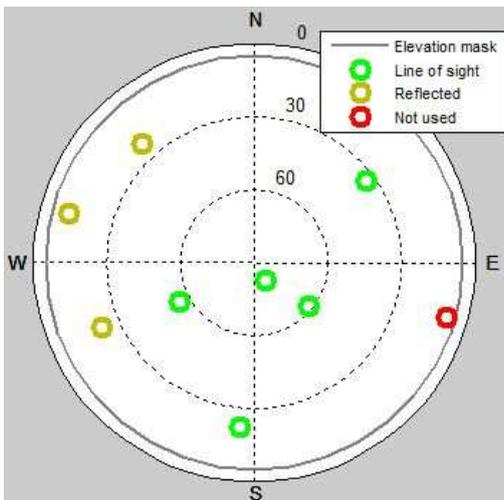
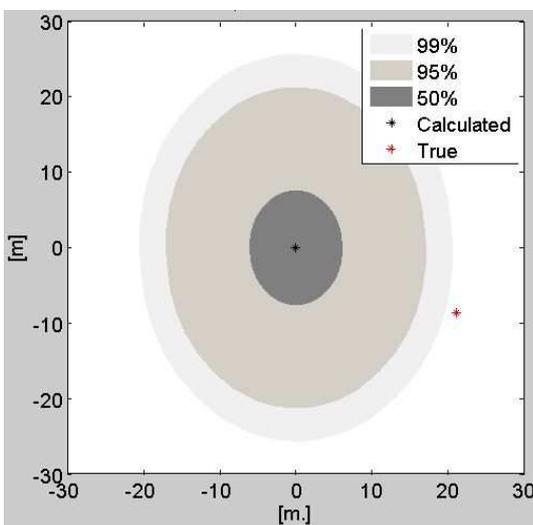**Figure 6: The satellite constellation for UTC-time 00:20.**

Figure 7: Error ellipses and true position from position estimation including reflected satellites.
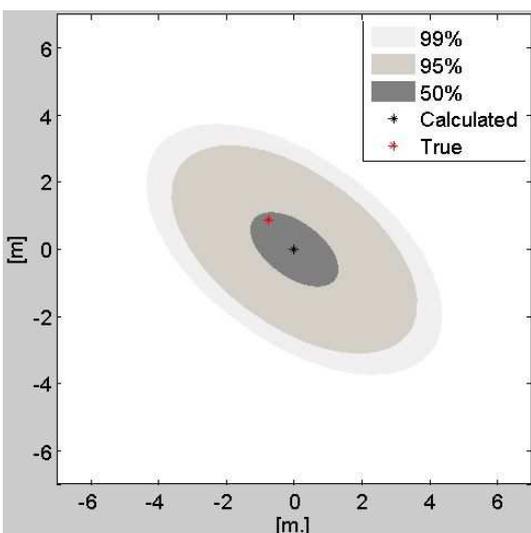

Figure 8: Error ellipses and true position from position estimation including line of sight satellites only.

V. CONCLUSIONS AND PERSPECTIVES

This paper describes the implementation of the QualiSIM simulator. This simulator can be used to perform simulations of GNSS signal reflections from buildings surrounding an antenna and their impacts in the position domain.

It has been showed that reflected signals can come from various elevation and azimuth angles, though they mainly come from the upper part of the non-line of sight area of the sky.

The impact of reflected signals on the position accuracy is significant. Though they contribute to a higher amount of satellites used in the positioining and lower DOP values, the position error caused by extended pseudoranges influence the error ellipses with a factor of up to 8 times larger in the example shown.

QualiSIM provides an interesting tool to analyse the effect in the position domain when using reflected signals. This tool is suited for preliminary analyses in applications like road tolling and safety critical applications, where the position accuracy along with error bounds and reliability is essential.

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