Quality Assessment of GNSS Simulations for Flight Procedures based on Onboard Recorded Flight Data

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BIOGRAPHY

Dr. Maurizio F. Scaramuzza received his diploma in Geomatics in 1995 at the Swiss Federal Institute of Technology (ETH) Zürich. He joined the Institute of Geodesy and Photogrammetry at the ETH Zurich in 1995, where he received the Ph.D. in technical sciences in the field of satellite based flight approaches and landings in 1998. In 1999 he joined skyguide, Swiss Air Navigation Services Ltd., and built up and led the GNSS team. Since 2006 he is head of the expert group on Communication, Navigation and Surveillance (CNS). Dr. Scaramuzza is member of different working groups and panels, among others ICAO Navigation System Panel, Eurocontrol CNS Infrastructure Team and Swiss Geodetic Commission of the Swiss Academy of Sciences.

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Captain Marc Bertschi is a Swiss Air Force pilot, flying helicopter (AS332 Super Puma and EC635) and fixed wing aircraft (Super King Air and Beech 1900D). He has been involved in several GNSS approach implementation projects for the Swiss Air Force, especially RNAV approaches for helicopters in mountainous areas. As a technical pilot, he was involved in the upgrading of the Swiss Air Force Super King Air, including RF leg capability.

ABSTRACT

Implementation of new satellite based flight procedures in Switzerland are always accompanied by simulations in order to assess the positioning solution performance and the resulting availability. This approach is even more important when procedures are designed in mountainous environment such as the Swiss Alps, where terrain masking of more than 20 degrees may be present.
These simulations cover the desired flight path or relevant points in space where the most critical terrain masking is expected. An in-house software tool was developed to perform these studies. A Digital Elevation Model (DEM) and the designed flight path is loaded into the tool. In a first step, the horizon along the desired flight path is calculated. In cases, where the terrain elevation exceeds 10 degrees over a relevant azimuthal sector, a more in-depth assessment is required. In these cases, Global Positioning System (GPS) almanacs at different epochs are loaded and simulations covering a period of a sidereal day are carried out. Availability of satellite signals are finally derived from these calculations.

In this study, data recorded onboard of helicopters is used to compare real performance with simulated ones. Different areas of influence are analyzed including the required DEM resolution and sampling rate, signal masking caused by the helicopter and flight attitude. The findings lead to a qualitative classification of the input parameters for the simulation tool. The classes describe the severity of the impact on the simulation results. This helps to optimally choose input parameters to achieve high quality simulation results.

INTRODUCTION

The simulation tool is based on a model, which is described through a number of simplifications in order to keep processing time reasonably low. Signal propagation from satellite to receiver is reduced to line of sight (LOS) including a simplified refraction component \((4/3 \times \text{earth radius})\) and earth curvature. Diffraction and multipath effects are omitted. For satellite vehicles in view the corresponding satellite signal is used for position calculation. In reality, flight dynamics in terms of roll and pitch as well as the helicopter’s airframe are expected to influence the signal reception resulting in an alteration of the usable satellites. These effects are not taken into account in the simulation. Further, due to the movement of the receiver, a satellite may be masked by the terrain and reappear at a later epoch. The simulation tool assumes that, as soon as LOS is given, the satellite can be used by the receiver for a position calculation. However, it is expected that the receiver will act slightly differently. A tradeoff between the quality of the simulation results and the processing time has to be done. Ideally, a high resolution DEM in order to improve the simulation quality would be used, but this would be at the expense of processing time. Therefore, it is necessary to elaborate the impact of input parameter on the quality of the simulation results.

In [1] and [2], the project called Helicopter Recording Random Flights (HRRF) is described. In the frame of this project, mini quick access recorders (mQAR) on board of roughly three dozen helicopters operated by the Swiss Air Force and Rega, the Swiss Helicopter Emergency and Medical Service (HEMS), were installed. On every mission more than 60 parameters originating from the onboard GPS/SBAS sensor, Attitude Heading Reference System (AHRS) and the Flight Management System (FMS) are retrieved. More than 10’000 hours of onboard recorded data is currently available. The quality assessment of the simulation results is mostly based on the comparison of the simulations with these recorded data. In this study the focus is on total number of visible satellites, Horizontal Dilution of Precision (HDOP), and Horizontal Protection Level (HPL). The vertical position domain can be treated in an analogous way. The HPL is based on SBAS because the onboard receiver uses these messages on all assessed flights. The HDOP is of interest due to certain Receiver Autonomous Integrity Monitoring (RAIM) algorithms being closely related to satellite constellation geometry.

This paper discusses in a first step the DEM, independently onboard recorded data. Emphasis is given to the DEM type and the dimension, which has to be taken into account as well as the sampling rate to be applied. Then a set of flights is selected to compare simulations with onboard recorded data. Two approach procedures are used for this purpose, one in a challenging terrain environment and another one in a relatively flat area. Further flights are used to assess the impact of helicopter’s roll and pitch angles as well as airframe signal masking.

DIGITAL ELEVATION MODEL

The selection of the DEM including its resolution and dimension, as well as the applied sampling rate, has a direct influence on the quality of the simulation results. It is therefore imperative to estimate adequate simulation input parameters in order to achieve the expected quality of the results. Obviously, the highest possible DEM dimension and highest resolution would lead to the highest quality of results, but at the expense of computer processing time and memory allocation. Therefore, a tradeoff between input parameters and result quality is needed.
DEM Type

In this paper, the term DEM is generically used for Digital Terrain Model (DTM) and Digital Surface Model (DSM). DTM represents the terrain elevation without any vegetation and buildings, where DSMs represent the physical surface of all static objects. The main vertical difference between DTM instead of DSM is mostly due to vegetation (e.g. forests) and buildings in urban areas. Within this study the Swiss Digital Height Model 25 (DHM25) is used, which is based on a regular grid of 25 m resolution and represents the terrain surface without vegetation and buildings. The area of Switzerland in its surroundings is covered [3].

DEM Dimension

The first step of the simulation includes the determination of the radio horizon, which is derived by sampling the DEM in radial and azimuthal direction seen from an observer’s position. Figure 1 depicts in red the sampling process limited to a sector only. Earth curvature and atmospheric refraction (4/3rd earth radius) is taken into account. The horizon range $R$ limits the terrain area to be assessed and defines the DEM dimension. The larger $R$, the more probable relevant distant terrain features are taken into account. However, at a given distance the terrain doesn’t contribute to the horizon anymore. The red dots in Figure 1 indicate the horizon distance $H(\alpha)$, i.e. the distance between the observer and the position in the terrain generating the horizon depending on the azimuth $\alpha$. Therefore, the horizon range is determined by the largest horizon distance and defines the DEM dimension to be used in the simulation.

$R$ depends on terrain structure (e.g. flatlands, mountainous area, etc.) and the observer’s altitude. An estimation of $R$ is derived by selecting an observer’s position on the ground and increasing its altitude stepwise while detecting the horizon distance at each altitude and for all azimuths. The vertical increment is stopped when the elevation angle of the terrain is below the cutoff angle, which is receiver dependent. Figure 2: Example of the derivation of horizon range while varying the observer’s altitude. (left) summarizes this approach while on the right an example with the locations of terrain contributing to the horizon are shown. The dot color indicates which terrain feature contributes to the horizon at which observer’s altitude. The cross indicates the observer’s location.
Figure 2: Example of the derivation of horizon range while varying the observer’s altitude.

For the estimation of a generic horizon range for Switzerland, six different airfields are used. Four (ALP, LUG, SAM and SIO) are located within the Swiss Alps and two (DUB and GRE) in the Swiss Plateau (see inset Figure 3). This allows comparing two different terrain structures (mountains and flatlands) and its impact on $R$. For each airfield, the cumulative probability of $H(\alpha)$ is drawn in Figure 3. It can be seen, that $R$ is about 10 km for the two airfields in the Plateau and reaches a maximum of 50 to 60 km for the airfields located in the Alps. Therefore, $R$ is set to 60 km for all following simulations in this study. If only approximate calculations are required, then $R$ can be reduced. According to Figure 3, 95% of relevant terrain is taken into account if $R$ is halved to 30 km.

Figure 3: Cumulative probability distribution of horizon distances at six airfields. A horizon range of 60 km is needed to take all relevant terrain features into account, when generating the horizons.

DEM Inaccuracies

DEM inaccuracies are primarily caused by incorrect terrain data acquisition and by differences between terrain and surface altitudes. According to [3], the average vertical accuracy of DHM25 is 1.5 m within the Plateau and 2 to 3 m within the Alps. The minimum horizon distance at ALP is at ca. 1 km resulting in a horizon elevation angle error of 0.17°. However, the median of the horizon distances for ALP is at 6 km according to Figure 3. At this distance, the horizon elevation angle error is
only 0.03°. By contrast, the vegetation can reach heights of 40 m in the Plateau and decreases towards the Alps with trees stopping to exist at an altitude of roughly 2000 m. Assuming a maximum tree height of 20 m at ALP results in a maximum horizon elevation angle error of 1.15° at 1 km and 0.2° at 6 km distance. Therefore, at some circumstances the vegetation has a relevant impact on the calculated horizon accuracy and a DSM is then favored to a DTM.

DEM Resolution

DEM’s with lower resolutions, e.g. 250 m or 3 arc seconds, are available for this study, but it is more convenient to filter the DHM25 to lower resolutions in order assess its impact on the simulation results. This allows to exclude potential differences between the different DTMs. The effect of the DTM resolution is assessed by calculating the number of visible satellites, HDOP and HPL at different altitudes over ground and covering an entire sidereal day. The used DTMs are all based on the DHM25 and filtered to 50 m, 100 m, 250 m and 500 m resolution. Figure 4 (left) shows as an example the results of HDOP at the airfield ALP located in a valley (see Figure 2) and at altitudes from 0 m to 1400 m Above Ground Level (AGL). For each DTM resolution the histogram as well as the boxplot is depicted. The box represents the 25 %, 50 % and 75 % quantiles. The whiskers are set to 5 % and 95 % quantiles. The circle corresponds to the mean value while the triangles shows the minimum and maximum HDOP. Interestingly no relevant differences are visible for the different DTM resolutions. Only the 95 % quantile decreases by roughly 0.1 when the DTM resolution is decreased. The slight amelioration of the HDOP with lower DTM resolution is due to truncation of mountain peaks when filtering the DTMs. This results in slightly lower horizon elevation angles and consequently more visible satellites leading to better HDOP values.

The most critical part of an approach in terms of GNSS performance is usually at the minimum altitude of the procedure. Assume a LPV200 approach would ideally hold a Decision Height (DH) at 200 ft AGL. Performing the same simulation as in Figure 4 (left), but only at the DH, results in the histograms shown in Figure 4 (right). Due to the valley dominating the horizon at this altitude, the results are worse compared to Figure 4 (left).

The behavior of ameliorated HDOP while reduced DTM resolution is also visible in this case. The other parameters, especially HPL, behaves similar to the HDOP. Hence, using DTMs with a resolution of 50 m to 100 m, comparable to 3 arc seconds, deliver similar results as DTMs with higher resolutions.

Figure 4: HDOP distributions and boxplots for different DTM resolutions and varying observer’s altitude (left) and fixed altitude at DH (right) for the airfield of ALP located in the Swiss Alps.

DTM Sampling Rate

The DTM sampling rate for horizon derivation has an impact on the simulation results too. The two relevant parameters are the azimuthal sampling rate \( \Delta \alpha \) and radial sampling rate \( \Delta \rho \) (see Figure 1). Analogous to the case in Figure 4 the HDOP is calculated for the airfield ALP at altitudes between 0 m and 1400 m above ground. In a first step, the following parameters are selected: \( \Delta \alpha = 0.01° \), \( \Delta \rho = 10 \) m and \( R = 60 \) km. This allows to take terrain features of the size of 10 m at 60 km distance into account. The unfiltered DHM25 is used for these calculations. The resulting mean HDOP and its standard deviation is then
used as reference. Then the parameters $d\alpha$ and $d\rho$ are now varied and the resulting HDOP compared to the reference HDOP. The resulting differences are depicted in Figure 5 (left: mean HDOP difference, right: HDOP difference standard deviation). It can be deduced, that $d\rho$ is the dominant error source compared to $d\alpha$. Values of $d\alpha \leq 0.1^\circ$ and $d\rho \leq 20\text{m}$ yield to minimal differences. The HPL difference behaves similar to the HDOP.

Figure 5: Comparison of HDOP differences between very high terrain sampling rate and reduced ones. Mean HDOP difference (left) and standard deviation HDOP difference (right).

SIMULATIONS VERSUS REAL FLIGHTS

Knowing the adequate DEM input parameters allows to compare simulated GNSS performance with onboard recorded data originating from real flights. Differences between measurements and simulations are mainly due to:
- DEM (see previous chapter)
- inaccuracies of satellite positions
- signal masking due to helicopter airframe and rotor blades
- roll and pitch angles
- signal diffraction
- other sources such as elimination of satellite signals for position solution by the receiver itself

The first error source is already discussed in the previous chapter while the last error source cannot be assessed with the available data. The other topics are discussed in the following chapters.

Inaccuracies of Satellite Positions

Inaccurate GPS satellite position estimation leads to differences between simulations and onboard recorded data. While GPS almanac is used for the simulations, the GPS receiver relates to the more accurate ephemerides for position calculation. The differences in satellite azimuth and elevation as seen from an observer in Switzerland is in the range of $\pm 0.15^\circ$, which corresponds to the rule of thumb that the absolute satellite position error calculated with almanac is about up to 70 km. Minimizing these errors would require to apply ephemerides or precise orbit data instead of almanacs.

Helicopter Signal Masking

Estimation of signal masking due to helicopter airframe and rotor blades is best assessed during a flight phase with low roll and pitch angles and with low impact on signal masking due to terrain. For this purpose, 20 Instrumental Flight Rules (IFR)
approaches at DUB, which is located in the Swiss Plateau, are used. The angle between the helicopter’s vertical (yaw) axis and the nadir for these flights, indicating the amount of roll and pitch during the approaches, is mostly below 2°. Terrain horizon elevation angle larger than 2° appears only at the end of the approach. Maximum elevation is 2.8° and covers an azimuth range of less than 10°. Hence the impact of the terrain on satellite visibility is negligible.

Next, the satellites are identified for which the visibility difference between simulation and onboard recorded data is apparent. This occurs only to four satellites during the 20 flights. Having a closer look to these four cases reveals that they all occurred when the satellites were rising or setting, i.e. at an elevation angle close to the receiver’s cutoff angle. In all cases, the elevation angle calculated by the simulation tool differs from those derived by the receiver yielding to discrepancies in satellite visibility. Therefore, none of these cases can be attributed to airframe or rotor blades signal masking. However, the satellite positions relative to the GPS antenna are nearly constant during an entire approach. Consequently there is a certain probability that no satellite would have been masked by the helicopter itself leading to a misinterpretation of this result.

A closer look has to be taken to the geometrical relation of the GPS antenna and the helicopter airframe and rotor blades in order to understand where satellite signal masking might occur. Figure 6 shows the side view of the EC135, which is the civilian version of the EC635 used in this study. The GPS antenna is located on the top of the tail. Only the rotor blades and the tail strobe light exceeds the GPS antenna height. The rotor axis can be tilted in a range of 5°. At maximum forward tilt, the rotor blade reaches a maximum elevation of 8° in forward direction relative to the GPS antenna and decreases to 0° elevation at antenna azimuth of ± 28°. Satellites signals in this area might be altered. The C/N₀ of more than 600 hours of recorded 1 Hz data is assessed in order to detect any of these signal degradations. Figure 7 shows the azimuth – elevation diagram referred to the antenna coordinate system. The colors indicate the mean C/N₀. The red arc indicates the area where rotor blades with maximum tilt might interfere with the GPS signals. A degradation of up to 10 dB is visible in this area. However, a degradation of the C/N₀ at lower elevations is common for these types of antennas. The undulation pattern at larger elevations might be caused by the rotor blades, but are negligible. Clarification on the origin of this pattern could be achieved through static measurements, i.e. without rotating blades, in order to see if this effect is reproducible or not. The signal degradation is more prominent at antenna azimuths of 150° and -170°. This is most probably caused by the tail strobe light, which is installed slightly higher than the GPS antenna. C/N₀ degradation reaches more than 15 dB.

![Figure 6: Side view of EC-135 with location of GPS antenna, tail strobe light, rotor blades with minimum and maximum rotor axis tilt (dashed red lines) and resulting elevation angle in an antenna perspective (dashed blue lines).](image)

It can be concluded, that the airframe and the rotor blades have in general only a minor impact on the C/N₀. This conclusion cannot directly be applied to other vehicles, though.
Roll and Pitch Angles

The impact of roll and pitch angles on satellite visibility is assessed with another set of flights covering 10 hours of recorded data. These were selected in the Swiss Plateau in order to avoid effects from the terrain. All flights were conducted during training missions where many turns were performed. During roughly 25% of the flight time the angle between the yaw axis and nadir was larger than 5° while reaching in some cases values of more than 30°. The absolute difference between recorded and simulated number of visible satellites is shown in Figure 8 and is never larger than one. The figure shows for both cases the histogram as well as boxplot related to the angle caused by roll and pitch. The box represents the 25%, 50% and 75% quantiles. The whiskers are set to 5% and 95% quantiles. The circle corresponds to the mean value. On the left side of the figure it is visible that even at larger angles of 20° and more the satellites are still used by the receiver. This is an indicator, that satellites are also tracked at negative antenna elevation angles. As expected, the values for the attitude angle increases on the right side of the figure. It is concluded that the impact of roll and pitch on satellite visibility is relatively low. This conclusion is only valid for the EC635 with the antenna position shown in Figure 6.
Signal Diffraction

Simulations using LOS are based on a purely geometrical interpretation of signal propagation. Tough, a signal propagating in proximity of terrain is subject of multiple effects, among others diffraction. The signal of a satellite setting at the horizon behaves in such a manner, that signal attenuation starts to occur when LOS is still given and a signal can still be received when LOS is lost. The transition time from first signal attenuation to loss of signal depends on satellite’s setting rate and helicopter’s movement. One case of a satellite setting during an approach at ALP is discussed more in detail. Figure 9 (left) shows the recorded $C/N_0$ (blue line) during 10 s before loss of track. The continuous decrease from 45 dB-Hz to 25 dB-Hz is clearly visible. In contrast, the black dashed line indicates the loss of LOS according to the simulations, which occurs 5 s before receiver’s loss of signal. Figure 9 (right) depicts the horizons as seen by the GPS antenna for the time 6 seconds before until 6 seconds after loss of signal. The color of the horizon allocates the time relative to loss of signal and is indicated in the legend. Further, the measured $C/N_0$ are listed in the legend too. The black cross depicts the satellite position.

A first attempt to derive the amount of signal attenuation due to diffraction is to apply the model of single knife edge diffraction attenuation, which is based on the Huygens – Fresnel principles. The attenuation is derived through the determination of the cross section of the Fresnel ellipsoid between transmitter and receiver at the horizon distance and the amount of terrain covering this cross section. The ellipse in Figure 9 shows this cross section. Actually, it should have a circular shape, but it is distorted to an ellipse due to the non-proportional diagram axes. The red line in Figure 9 (left) shows the calculated $C/N_0$ based on the expect $C/N_0$ according to satellite’s position in the antenna coordinate system (Figure 7) and the derived diffraction attenuation. The resulting $C/N_0$ matches surprisingly good with the measurements. However, this result has to be handled with care due to the fact that following attenuation calculation errors might be present:

- The single edge attenuation is a simple model and describes the real attenuation in a first order only. Higher order estimation might result in a more accurate attenuation value.
- The DEM inaccuracies are negligible, but the presence of vegetation at the horizon distance would lead to an horizon elevation error of roughly 0.3° and consequently errors of a few dB.
- A simple model approximates the atmospheric refraction only. These inaccuracies results in inaccurate horizon elevation angles and consequently affects the attenuation estimation.

The discussed case shows, that the loss of satellite signal is calculated with an error of ± 5 seconds. This value varies depending on the horizon shape. A more accurate assessment could be achieved by dedicated flight trials.

![Figure 9: Recorded (blue line) and simulated (black and red lines) of $C/N_0$ during loss of signal due to terrain (left). Calculated horizons during loss of signal and satellite position (right).](image)

COMPARISON OF ONBOARD RECORDED DATA AND SIMULATED SATELLITE NUMBER, HDOP AND HPL

Twenty IFR approach flights at each of the two airfields of DUB and ALP are finally assessed. Remind that ALP is located in the mountainous region of the Swiss Alps and DUB in the Swiss Plateau. Figure 10 (top) shows the difference between the number of simulated visible satellites and the number of used satellites by the GPS receiver. The histogram on top left is related to the approach of DUB while the one on top right is that of ALP. While the simulation for DUB delivers a high correlation with the onboard recorded data, that of ALP is as expected less accurate. Nevertheless it matches to 75 % of time.
The comparison of the HDOPs in Figure 10 (middle) shows a high correlation for both airfields, while the variation of the HDOP difference is larger for ALP than for DUB. However, more than 97% of the simulated HDOP matches with the recorded ones with an error of less than 0.1. The weight matrix for the simulations is set to unity while the receiver might use weights leading in small differences between recording and simulations.

Finally, the HPL is compared in Figure 10 (bottom). Remind that the receiver uses the SBAS messages for this calculation. Note that no degradation factor is used for the simulations. These factors are applied when data transmission between SBAS satellites and receiver is interrupted. This event can occur when terrain masks the SBAS satellites, which can be excluded for the geographic latitude of Switzerland. Again, simulations and recordings match with high degree. The maximum difference is always below 0.003 NM.

Figure 10: Comparison of simulations with recording for satellite number (top), HDOP (middle) and HPL (bottom). Left column refers to an approach at DUB while the right column refers to ALP.
CLASSIFICATION OF INPUT PARAMETERS AND DATA

A qualitative classification on the influence of the input parameters and data on simulation results is given, based on the assessments within this study.

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<td>negligible to minor</td>
<td>high altitudes</td>
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<td>mountainous environment at medium to high altitudes</td>
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CONCLUSIONS AND OUTLOOK

This study has shown that accurate simulation results can be achieved with relative simple approaches such as use of LOS and without taking airframe masking and aerial vehicles attitude into account. However few basic principles have to be respected. These includes the dimension of the DEM, the DEM type, and the DEM sampling rate. Signal masking due to helicopter and roll and pitch angles do not have a major influence on the simulation results. This is valid for this type EC-135/635 only, tough. It is concluded, that for performance assessment of GNSS based approaches the simulations described in this paper are adequate.

Improvement of simulation results can be achieved through a better understanding of the behavior of airframe signal masking and signal diffraction caused by the terrain. Additional theoretical investigation as well as dedicated flight trials will support the achievement of the objectives.

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