Interactive planning of GNSS monitoring applications with Virtual Reality

Peter BAUER, Caroline SCHÖNBERGER and Werner LIENHART, Austria

Key words: GNSS, virtual reality, geodetic concept creation, gameful design

SUMMARY

Global Navigation Satellite Systems (GNSS) are used in challenging environments with increasing accuracy demands. Therefore, many systematic effects become significant and require a detailed planning of monitoring campaigns with high integrity. In conventional GNSS planning software, the local circumstances at the antenna locations are hardly covered. Due to uniform cut-off angles in the elevation of the satellite orbits the quality investigations are often not representative at inhomogeneous areas (e.g. in the vicinity of mountains or buildings).

In order to fulfil the requirements of modern deformation analysis, the prediction of the satellite visibility and the estimation of the point dilution of precision (DOP) is improved by the usage of high-resolution 3D data. Nowadays, with ray-tracing approaches from the entertainment sector, 3D computations can be easily carried out like in reality based data capture or digital terrain models.

For this purpose, experimental software was developed using Unity software to produce a human computer interface in a Virtual Reality (VR) environment. The VR gear overcomes the limitations of conventional 3D viewers in complex 3D scenarios and provides the user an immersive and interactive first-person view.

The software developed has been tested in a real-life use case for the simulation of GNSS measurements at an Austrian water dam. Furthermore, the predicted results of the simulations have been validated by actual measurements taken at the planned epoch at the site.

Interactive planning of GNSS monitoring applications with Virtual Reality

Peter BAUER, Caroline SCHÖNBERGER and Werner LIENHART, Austria

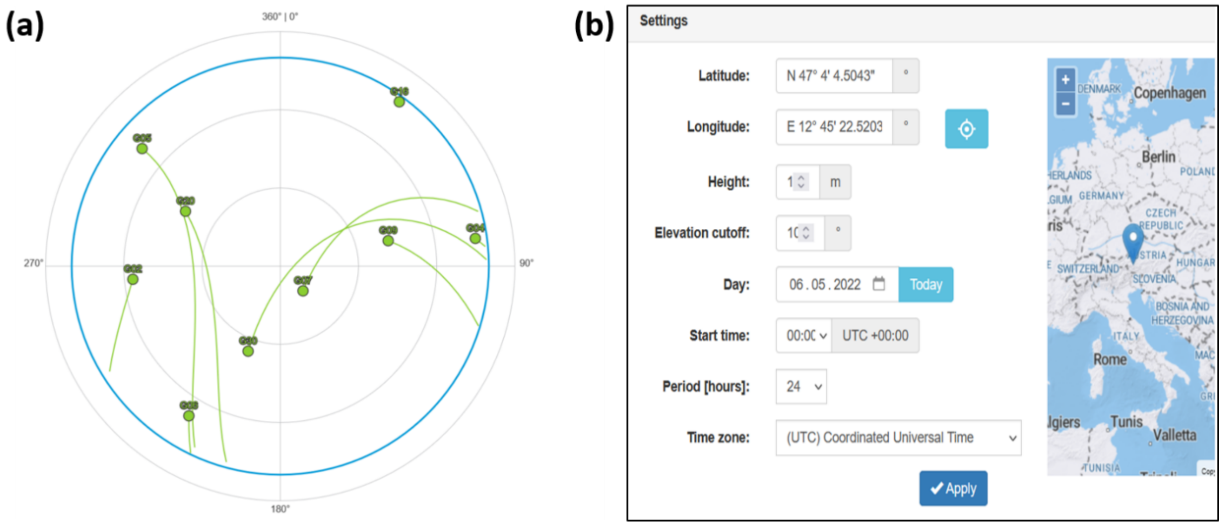
1. INTRODUCTION

Global Navigation Satellite Systems (GNSS) offer a wide range of possibilities in every price and accuracy segment. Geodetic monitoring is one of the more demanding applications, because instruments and methods are constantly evolving. New instruments and applications are challenging the accuracy and integrity limits of the systems in use. Therefore, the design process of monitoring installations with an analysis of relevant systematic effects is crucial.
The achievable precision of 3D positions is strongly time-dependent due to the dynamic behaviour of the satellite system. The number of visible satellites and the geometrical configuration changes constantly.
However, with the known orbit parameters of the satellites, the geometrical configuration can be computed in advance and simulated for any location on Earth. Due to the major influence of the satellite geometry on the quality of the measurement result and the predictability of this effect, the satellite constellation has been established as the main indicator for optimal observation times.

2. STATE-OF-THE-ART IN GNSS PLANNING

2.1 Conventional planning tools

Tools for the evaluation of the satellite constellation are implemented in many software packages for GNSS processing. Nowadays, the individual realisations do not differ much in different software packages and provide comparable options. The observation area of interest is typically defined by its latitude, longitude and height information. The orbit parameters of the required timespan can be imported from an external file or the software automatically accesses a database with the satellite information.
Based on the input parameters the software generates 2D sky plots (as it can be seen in figure 1a). This polar plot shows the visible satellites and their orbits, which serves as an important visual quality check.
As numerical values, to measure the impact of the satellite constellation on the positioning result, the dilution of precision (DOP) values have been introduced. It can be distinguished between the horizontal dilution of precision (HDOP), the vertical dilution of precision (VDOP), the position dilution of precision (PDOP) and the geometrical dilution of precision (GDOP).
A representative example of state-of-the-art software can be seen in the planning tool of Trimble (*www.gnssplanning.com*). The homepage can be accessed online and the main input mask can be seen in figure 1b. Next to the input fields, a 2D map visualizes the observation area. The satellite systems in use can be selected in a separate drop-down-menu.



Latitude: N 47° 4' 4.5043" °

Longitude: E 12° 45' 22.5203 °

Height: 1 m

Elevation cutoff: 1 °

Day: 06 . 05 . 2022

Start time: 00:0 UTC +00:00

Period [hours]: 24

Time zone: (UTC) Coordinated Universal Time

Figure 1 Screenshots from the Trimble planning tool showing (a) a sky plot and (b) the main input mask

The individual circumstances at the receiver location (e.g. close by buildings or mountains) are usually not considered. A uniform cut-off angle, with a default value of 10° is typically chosen, to avoid signals with atmospheric distortion and possible multipath errors at low elevations (Leick et al., 2015).

Low-level approaches for sky mask customisation can be found in some state-of-the-art software solutions, for instance in *www.gnssmissionplanning.com* it is possible to insert cube-objects into a polar-plot interface. Also in the *Leica Geo Office* it is possible to import an obstruction digram. However ,the usability of these software solutions is very limited here, because the sky masks are created manually and the level of detail depends on the digitalisation effort.

Nevertheless, for many everyday-surveying tasks this approximations are still received as sufficient considering that the number of available satellites was constantly increasing over the last decades. Therefore, a suitable number of satellites is available nearly everywhere in open-field scenarios for moderate centimetre level point accuracy with real time kinematic (RTK).

For more challenging tasks in remote setups, satellite availability tools are still important for initial feasibility tests of planned monitoring setups. Although the design process requires a high error budget due to the vast abstraction of the sky mask.

2.2 Customised sky masks in navigation

A more sophisticated prediction of the visible satellite constellation became important in navigation. In contrast to surveying tasks, navigation tasks predominantly take place in crowded urban areas, where an obstacle free sky is often not available. Furthermore, navigation tasks miss the flexibility of monitoring tasks. Permanent installations are usually set up in an optimal location, whereas navigation devices have to provide solutions nearly anywhere. Additionally, the urban environment increases the risk of multipath effects by reflecting surfaces in the surrounding.

Therefore, many approaches can be found in navigation to replace the uniform cut-off angle by a more customised and automated sky mask computation. A well-established approach is the usage of 360° panoramic images (Lee et. al, 2020). The panoramic images (as seen in figure 2a) are used to segment the skyline with intelligent image processing algorithms and transform it into polar coordinates.

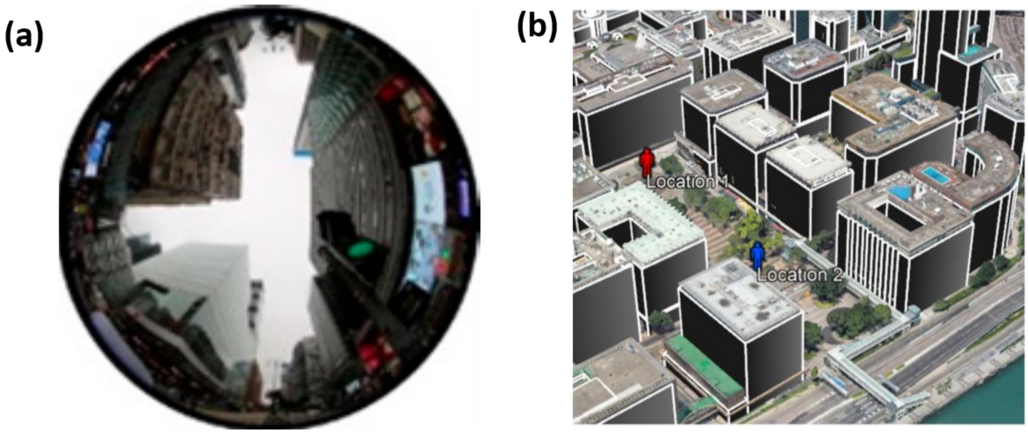


Figure 2 (a) Panoramic image from (Lee et al., 2020) and (b) low-poly city model from (Zhang et al.,2019)

Another approach is to carry out 3D computations with ray-tracing (Ibrahim et. al. 2006). By detecting intersections of the line of sight with representative 3D models the visibility can be investigated within its 3D context. Depending on the computing power and the used environment, investigations of larger areas are possible. On the basis of a low-poly city models (see figure 2b), GNSS error distribution maps can also be computed for a wide urban area (Zhang and Wen, 2019).

3. MOTIVATION FOR ENHANCED 3D SKY MASKS IN GEODETIC MONITORING

In GNSS based monitoring, the accuracy demands and complexity is increasing in modern monitoring applications (e.g. Septentrio, 2023). This places the focus again on a more detailed planning process in geodetic GNSS monitoring. The application of conventional sky masks often results in a significant underestimation or overestimation of the local obstructions. Therefore, the result is often non-representative enough for an adequate quality investigation and feasibility study.

This re-evaluation of state-of-the-art workflows is driven by a slow paradigm change in geodetic monitoring and more complex scenarios in narrow urban environments. Furthermore, the capabilities of the instruments to measure with high frequency has improved with a trend from static deformation analysis to more advanced dynamic models.

The feasibility of high frequency monitoring of bridges with conventional total stations was already investigated at Graz University of Technology (TUG) (Lienhart et al., 2017) in 2017. The feasibility of modern GNSS receivers in the same context was demonstrated by the University of Nottingham, who provided dynamic GNSS results within sub-centimetre accuracy (Roberts et al., 2010). Moreover, recent investigations at TUG have also shown that under specific circumstances even frequencies with low-millimetre-amplitudes can be detected with dynamic GNSS measurements (Schönberger et al., 2023).

This redefines the accuracy expectation of modern GNSS receivers. However, due to the increased data rate, the time required for a single measurement has decreased. This puts the integrity of the signal at the forefront, especially since many systematic effects become significant at the desired millimetre accuracy level.

To test the feasibility of an enhanced planning approach with an individual sky mask, a case study was carried out for a monitoring project of an Austrian water dam. Due to the challenging alpine environment (obstructions through high mountains) and the high accuracy requirements, a conventional approach with a uniform cut-off angle was not applicable. Experimental software had to be developed to integrate high-resolution 3D data into the design process of GNSS monitoring installations. For the software development, an approach for fully 3D computations in real time with ray-tracing was chosen.

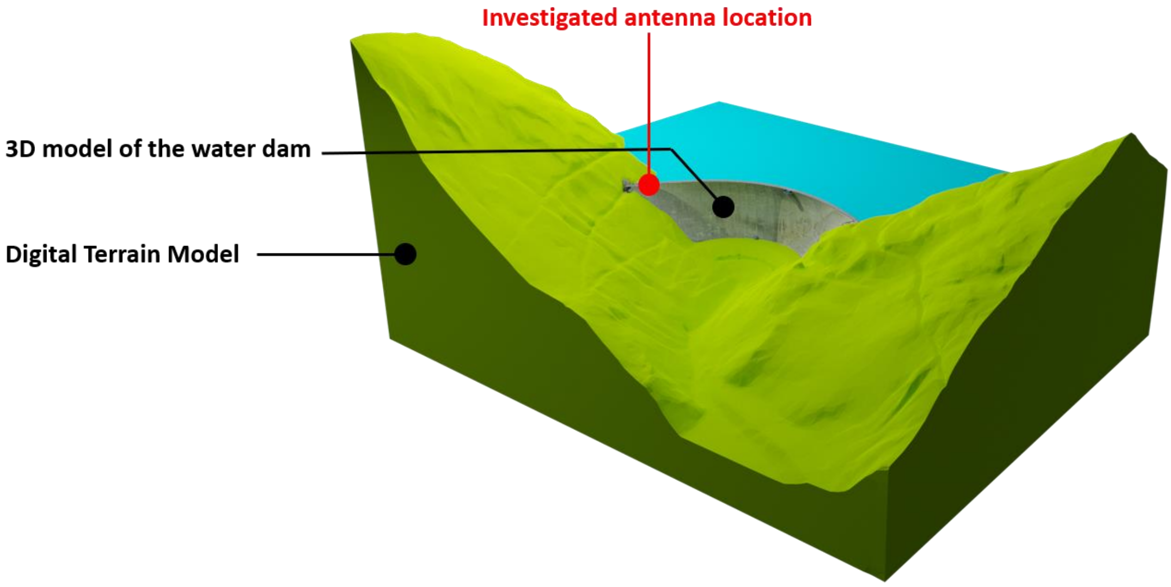


Figure 3 3D model and antenna location at an Austrian water dam

Figure 3 shows the composition of 3D models representing the basis for the 3D simulations. The model from the water dam has been provided by the structure-operator and was derived from UAV-photogrammetry. In addition, the model has been merged with the national digital terrain model (DTM) of Austria.

4. INTERACTIVE DESIGN AND VIRTUAL REALITY

A simulation and planning tool is always an abstraction of the real world. It is the aim to simulate the most relevant effects, but it is almost impossible to cover everything. Highly automated systems, like navigation devices in self-driving cars, lack the luxury of a human operator and therefore they must rely on a strict algorithmic framework in their decision process.

Regarding geodetic design processes, usually a high degree of flexibility is required. Besides predictable technical aspects (e.g. satellite constellation), also legal aspects (e.g. protection of historical monuments) and social aspects (e.g. vandalism) may become relevant and require individual solutions. Decision processes in new and changing situations are difficult to automate with algorithmic approaches. Therefore, it should be the aim in measurement planning to preserve the human experience and intuition as a key factor of the design process. On the other hand, the software should provide the user with sophisticated working tools to support the design process with rational arguments based on geometrical necessities and statistics.

A solution to integrate a human operator into a highly digital and complex workflow is provided by the Virtual Reality (VR) technology. This approach can be used to transfer the user with first person view into a virtual and immersive 3D environment (Korgel, 2018). The translation and rotation of the head are determined with an integrated indoor-positioning-system on the Heads-Up-Display (HUD). This way complex 3D scenarios can be prepared for the human perception and the user can easily interact with the datasets with controllers, see figure 4. The user can experience the results of real time computations and adjust the boundary conditions, such as the receiver location. A similar approach has already been applied for the design process of monitoring installations with total stations, see Bauer and Lienhart (2022).

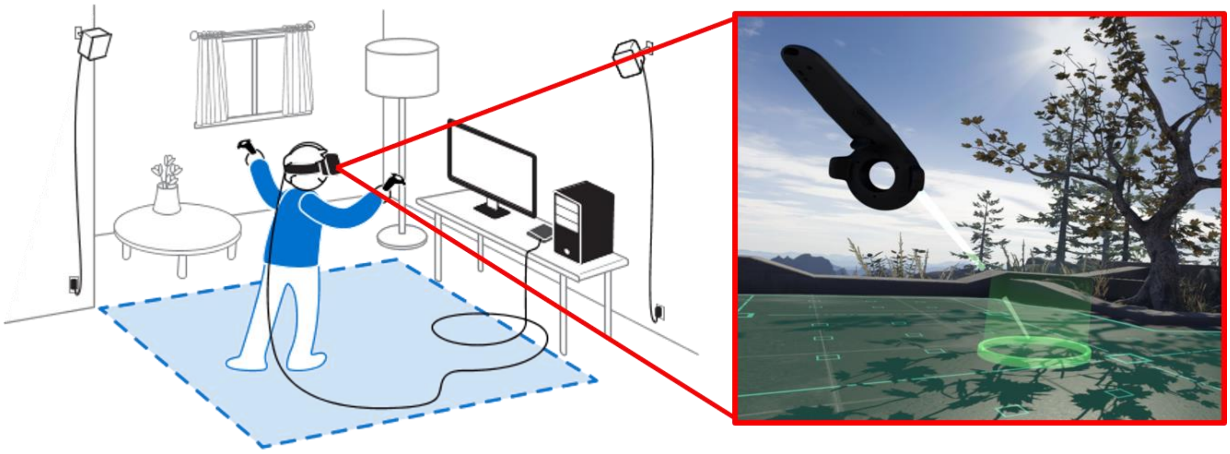


Figure 4 Schematic demonstration of the concept of Virtual Reality with a typical room setup (www.vive.com) and an in-game view (from steamVR)

5. GAMIFICATION AND SOFTWARE ENVIRONEMNT

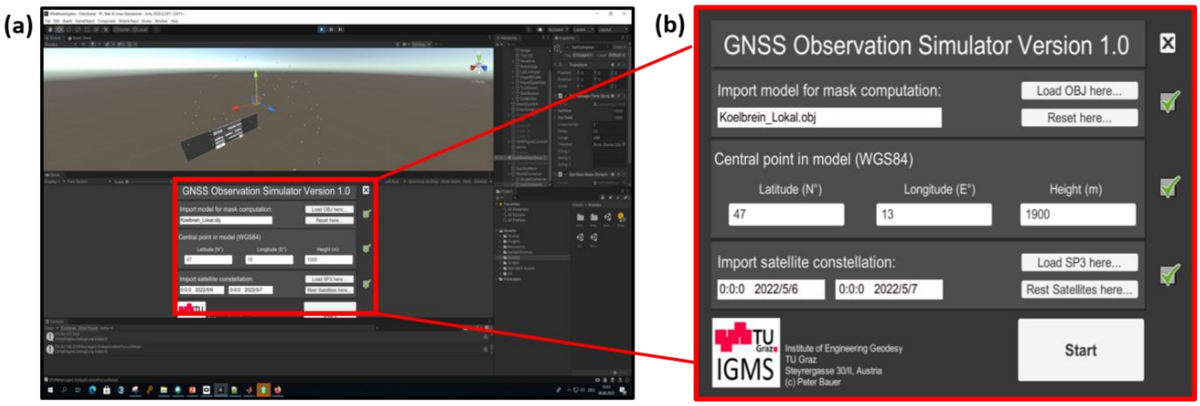
A suitable software and data environment for the experiments has been provided by a completely different industry namely the entertainment sector. The process of integrating game elements in a non-game context is summarised as Gamification (Deterding et. al., 2011). This term has gained popularity in recent years and is often mentioned in the context of digitalisation.

In current video games, the level of detail of virtual urban environments has often reached a comparable state to their real-life counterparts. The data structure and modelling principles in many game productions follow similar principles as the digital twins of real building projects. Therefore, it is not surprising that software developing environments, which were originally designed to produce video games, have become sophisticated 3D tools. Popular game engines are Unity, the Unreal Engine or the CRYENGINE (Plarium, 2022). All these software kits provide a suitable 3D coding environment.

For this work the software Unity (Borromeo, 2021) has been chosen. With the possibility to implement customised C# or Java routines, it provides an adequate degree of freedom needed for scientific research. Furthermore, basic tool kits for physical simulations (eg applying gravitation or casting light and shadow in the scene) are also available right from the start.

In Unity, geo-referenced virtual objects can be embedded and the functions and relations between the objects can be modelled. Figure 5a displays the main interface with the user options of the experimental software developed in Unity. Any 3D model in OBJ format can be loaded, which forms the basis for further calculations. The orbit data from the satellites (GPS, Galileo and GLONASS) can be loaded in SP3 format for a specific day and the orbits can be integrated dynamically.

By specifying the longitude and latitude, the centre of the local coordinate system of the 3D model and the global coordinate system of the path data can be brought into alignment. Using ray-tracing, collisions between the line of sight to the satellites and the 3D model can then be calculated.



GNSS Observation Simulator Version 1.0

Import model for mask computation: Koelbrein_Lokal.obj

Central point in model (WGS84)

Latitude (N°): 47
Longitude (E°): 13
Height (m): 1900

Import satellite constellation: 0:0:0 2022/5/6 – 0:0:0 2022/5/7

Institute of Engineering Geodesy
TU Graz
Steyrergasse 30/II, Austria
(c) Peter Bauer

Figure 5 (a) Interface of the Unity software and (b) customised input mask from the experimental planning software

For large-scale 3D computations, Earth curvature becomes a significant issue. Hence, it has to be assessed for every 3D project if the effect is negligible in the current applications.

It should be pointed out, that normally DTMs are already reduced for the Earth curvature by the post processing of the airborne laser scanning data. Therefore, if computations take place in "real" 3D space, Earth curvature must be applied again to the dataset.

In the current setup, orbit data (via the SP3file) is loaded with a temporal resolution of 5 minutes, which corresponds to an orbit resolution of 0.8°. The sky mask has been computed with a resolution of 0.1° of the elevation angles. At an approximate distance of 3 km between the antenna and the mountain ridge, 0.1° corresponding to a detectable height variation of 5.2 m. Compared to the influence of Earth curvature (70 cm @ 3km) the effect of Earth curvature is negligible. However, if a sky mask is required with a resolution of 0.01°, the influence of Earth curvature would become significant.

6. SIMULATION OF THE ANTENNA LOCATION

In the simulation the user defines the GNSS-antenna location by pointing with a virtual laser pointer at the desired location and placing the surveying equipment. For a more detailed planning of the mounting process it is also possible to implement tripods, pillars or consoles.

In figure 6a a 3D model of an antenna is placed on a centred holding device. Upon set-up the lines of sight from the antenna to the satellites are visualized for the user. The same scene can also be viewed in the video provided as additional research material to this paper by the TUG repository, Bauer and Lienhart (2023).

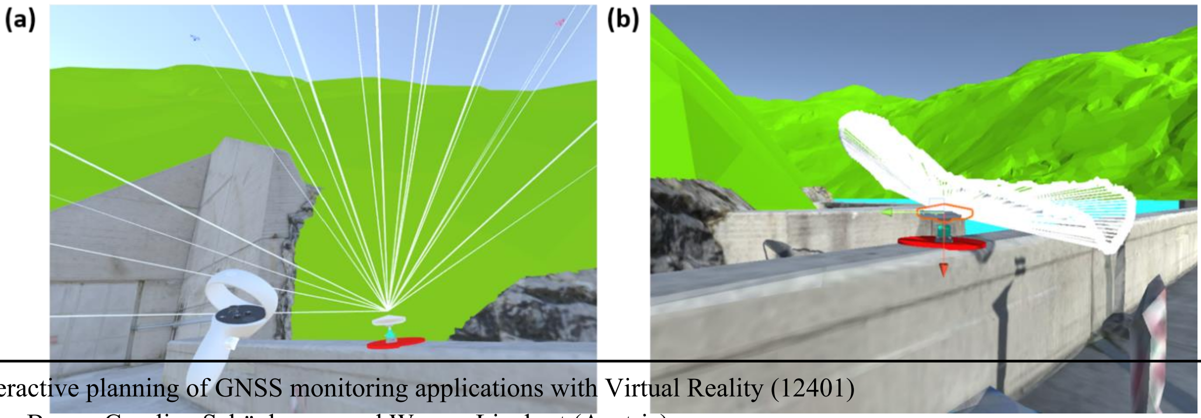


Figure 6 Visualization of (a) the line of sights between antenna and satellites and (b) the 3D sky mask in the VR application

The virtual antenna can be deleted and readjusted, if needed. By pressing a button, the 3D sky mask is computed and visualized in the simulation in its 3D context (see figure 6b). All the results are displayed in the simulation for instant quality checks of the operator or for educational purposes. All information can also be exported as text files for further usage in conventional workflows on the computer.

The derived custom sky mask, of this scenario, can be seen in figure 7a and it differs significantly from the default sky mask (10°). The predicted PDOP values (figure 7b) show that no continuous operation can be guaranteed with the usage of a single satellite system, because the PDOP values exceed the limit of 10 several times. A 100% position coverage can only be realised by the combination of GPS and Galileo or GPS, Galileo and GLONASS signals. Therefore, it was decided to integrate GPS and Galileo satellites in the concept design.

The results differ to the conventional planning approach. The Trimble planning tool predicts a continuous operation with only a single system (GPS as well as Galileo) for a cut-off angle of 10°. If the cut-off angle is adjusted to the maximum extent of the custom mask (38°) the online planning tool states issues with a mixed usage of GPS and Galileo satellites. Therefore, it can be clearly seen that in this setup a conventional approach does not lead to a satisfactory result.

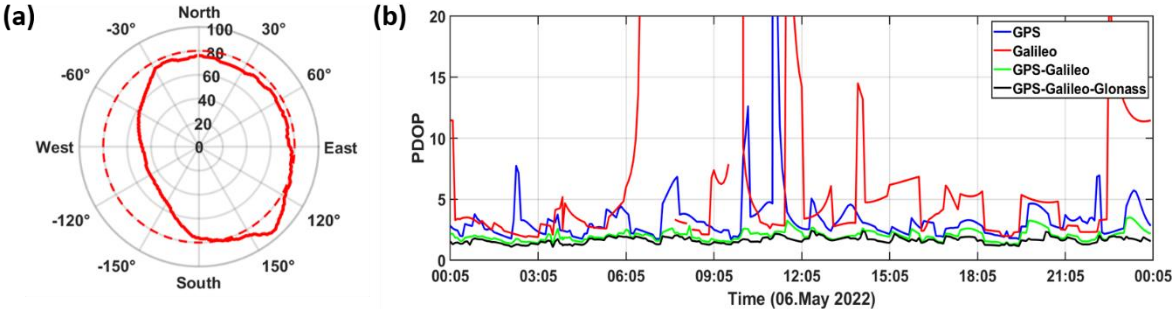


Figure 7 (a) Sky mask of the antenna location and (b) predicted PDOP values for the May 6th 2022

After the simulation, actual GNSS measurements have been carried out at that position on May 6th, 2022. The predicted satellite visibility and the measured satellites for the GPS system can be seen in figure 8.

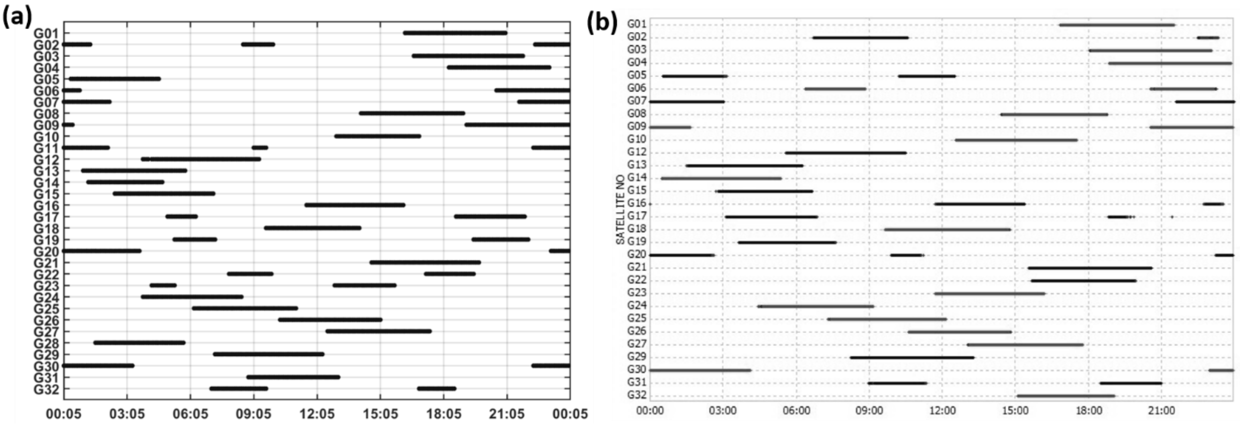


Figure 8 Visualisations of (a) the predicted Satellite constellation (plot with MATLAB) and (b) the measured GPS satellites on-site (plot from RTKLIB)

The predicted satellite visibility and the actual conditions on-site match quite well. There are differences for a few satellites, which hardly rise above the horizon. Further work will be placed on the detailed evaluation of the differences to improve the simulation.

7. Summary

The workflow of the GNSS planning has been enhanced with 3D data and transferred into a dynamic and interactive 3D environment to cope with the requirements of modern monitoring projects. The simulated satellite visibility presented in this paper shows great congruence with the actual field data gathered later at the area of interest. This demonstrates a satisfying result even on the basis of only geometrical parameters, which opens up promising fields of research for more detailed physical simulations in this context (e.g. atmosphere, multipath).

The usage of VR gear, in this experimental software, supports the perception of a human user of the 3D content. The expert can rely on the individual knowledge and intuition with an immersive experience. Nevertheless, the software package is not aimed to outdate onsite inspections or practical teaching programs, rather it should be seen as an augmentation that can be used when conventional approaches reach their limits.

For the development of the software the game engine has been a valuable tool which supports the required flexibility with the coding interface for C# routines. The use case has shown that Unity supports all frequently used geodetic datatypes and conventional workflows can easily be implemented.

A hybrid approach between conventional 2D screen and VR was chosen for the software design. Using both immersive and conventional input methods gives the user the possibility to interact with the data in VR and to carry out detailed analysis in MATLAB and Python afterwards. This avoids the risk of motion sickness because the VR interaction is reduced to its minimum and the best is taken out of both worlds.

REFERENCES

Bauer P. and Lienhart W. (2022). 3D concept creation of permanent geodetic monitoring installations and the a priori assessment of systematic effects using Virtual Reality, Journal of Applied Geodesy, vol. 17, no. 1, 2023, pp. 1-13. https://doi.org/10.1515/jag-2022-0020

Bauer P. and Lienhart W. (2023). Interactive simulation of GNSS satellite visibility with Virtual Reality, research material (video), Graz University of Technology. https://doi.org/10.3217/9wrbc-za771.

Borromeo, N.A., (2021) Hands on Unity 2021 – Game Development, 2nd. ed, ISBN 978-1-80107-148-2, Packt Publishing Ltd, Birmingham (UK).

Deterding S., Khaled R., Nacke L. and Dixon D. (2011). Gamification: Toward a definition, Conference: CHI 2011 Gamification Workshop Proceedings. p. 12-15. Homepage accessed: http://gamificationresearch.org/wp-content/uploads/2011/04/02- Deterding-Khaled-Nacke-Dixon.pdf

Ibrahim A., Ismail M, Jumari K. and Kiong T. S. (2006). Simple Method for Outdoor LOS Propagation Model Using Ray Tracing Tools. Journal of Applied Sciences, 6: 2652- 2656. DOI: 10.3923/jas.2006.2652.2656.

Korgel, D. (2018) Virtual Reality – Spiele entwickeln mit Unity. ISBN 978-3-446-45147-6. Carl Hansen Verlag, München (Germany).

Lee M., Jwo L., Shang L., Hoi-Fung Ng, and Hsu L.T. (2020). Skymask Matching Aided Positioning Using Sky-Pointing Fisheye Camera and 3D City Models in Urban Canyons. Sensors 20, no. 17: 4728, https://doi.org/10.3390/s20174728.

Leick A., Rapoport L. And Tatarnikov D. (2015). GPS satellite surveying. ISBN:9781118675571, John Wiley & Sons. DOI:10.1002/9781119018612.

Lienhart W., Ehrhart M. and Grick M. (2017). High frequent total station measurements for the monitoring of bridge vibrations. Journal of Applied Geodesy, vol. 11, no. 1, https://doi.org/10.1515/jag-2016-0028.

Plarium Global Ltd (2022) Turn Your Ideas into a Reality with the Right Game Engine, company homepage - blog, Homepage accessed: https://plarium.com/en/blog/game-engine/ (21.07.2023)

Roberts G. W., Brown, C. and Ogundipe O. (2010). Monitoring Bridges by GNSS. In FIG Congress 2010: Facing the Challenges: Building the Capacity. Sydney, Australia, 11- 16 April 2010 Article 4452 http://www.fig.net/pub/fig2010/papers/ts01d/ts01d_roberts_brown_4452.pdf

Schönberger C., Lienhart W. and Kaden B. (2023). Static and Dynamic Structural Monitoring of Civil Infrastructure Objects with GNSS. In SMART 2023: Smart Structures and Materials: Proceedings of the 10th International Conference on Smart Structures and Materials.

Septentrio, (2023). Dynamic structural health monitoring with high-accuracy GNSS, Homepage, Accessed: https://www.septentrio.com/en/learn-more/customer-stories/dynamic-structural-health-monitoring-high-accuracy-gnss (2.10.2023)

Zhang G., Wen W. and Hsu L.T. (2019). Rectification of GNSS-based collaborative positioning using 3D building models in urban areas. GPS Solutions 23, https://doi.org/10.1007/s10291-019-0872-9

ACKNOWLEDGEMENT

We acknowledge the funding of this innovative project by the Austrian Research Promotion Agency (FFG) within the Austrian Space Applications Program (ASAP PNO: 888310).

CONTACTS

Dipl.-Ing. Peter Bauer
Graz University of Technology (Institute of Engineering Geodesy and Measurement Systems)
Steyrergasse 30/II
8010 Graz
Austria
+43 316 873 **6329**
peter.bauer@tugraz.at
https://www.igms.tugraz.at