Analysis of satellite signal propagation in the urban environment using point cloud data

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Terminology

- GNSS = Global Navigation Satellite Systems
- LBS = Location Based Service
- LoS = Line of Sight
- NLoS = non-Line of Sight
- DoP = Dilution of Precision
- GPS = Global Positioning System
- ECEF = Earth-centered earth-fixed
- DEM = Digital Elevation Model
- TLE = Two Line Element
- AHN4 = Actueel Hoogtebestand Nederland 4

1. Introduction

According to Lu et al. (2020), the performance of the Global Navigation Satellite System is strongly correlated to the position of the ground receiver. However, the quality of the results given by the GNSS assembly (the constellation of satellites and the ground receiver) is influenced by the environment in which the receiver is positioned. The urban areas, known as urban canyons, which contain tall buildings, narrow streets and trees can have thus a negative impact regarding satellite visibility. Satellite visibility implies the connecting line between the ground receiver and the satellites in the sky which will further be referred to in this study as the line of sight (LoS).

Combining different GNSS constellations will result in a larger number of LoS. It has to be mentioned that accurate positioning results cannot be obtained without the receiver connecting to four or more satellites. Most of these studies are carried using three dimensional models of the urban areas, in combination with other two-dimensional data, such as cadastral maps or rasters, in order to predict which satellites are visible from different locations and in what moment of time.

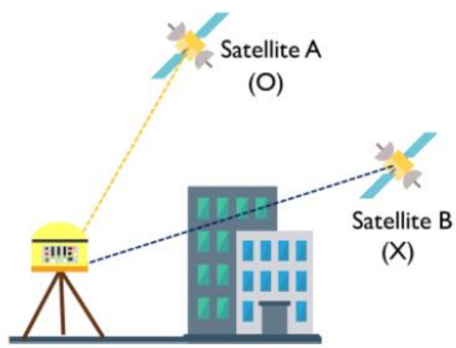


Figure 1: Signal obstruction from satellite to receiver (Lu et al. 2020)

Aerial borne point clouds were used for previous studies, due to their reliability when it comes to offering three-dimensional highly detailed information and representation of topographic elements which can influence the LoS. Based on Zhang et al. (2017), point clouds can be used without the need of generating surfaces. However, it has to be mentioned that point cloud analysis means a lot of resources and thus methods were developed to reduce the computation costs. The aerial borne point clouds were also mostly combined with other ways of representation. Zhang et al. (2017) also present a certain disadvantage of the aerial point clouds, as they do not capture the façade information correctly, but they can still be used as the position of the building is easy to determine from the position of the rooftop which is mostly accurately captured.

2. Related Work

Studies have been carried around the subject of satellite visibility in point clouds, as point clouds are a reliable source of 3D data.

Lu et al. (2020) presented the method of superimposed column which implied taking into consideration the height of the point cloud object and its position represented in coordinates, reducing considerably the size of the point cloud data that had to be used. After applying this method, the maximum elevation angle is calculated in order to determine the DoP values.

Dandurand et al. (2019) created a prediction model which took in consideration both the geometry of the satellite constellation and the environment in which the receiver is in. The model created will determine based on the shape of the local point cloud if the satellite signal will either have occlusion or absorption. The point clouds used for this study are dense and represent forest areas.

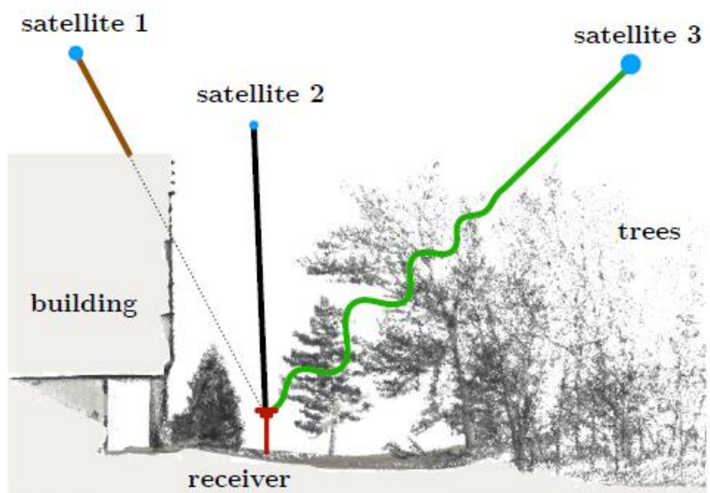


Figure 2: Complex environment in the case of satellite visibility (Dandurand et al. 2019)

Zhang et al. (2021) use occlusion analysis methods to determine the visibility between a viewpoint and a target point. Two methods are proposed for building and vegetation point clouds. The methods include choosing a threshold to decide if a LoS is blocked or not based on the number of obstacles surrounding the search point and creating a 3D sphere around a vegetation point to see how many points fall inside it and decide that the line is occluded.

Another visibility study, although the method described might not be suitable for point clouds, is the one described in Suzuki et al. (2015). Using virtual fish eye images and Google Earth simulated images, the algorithm creates a mask which takes into consideration only the open sky and thus the satellites that are above the area of the open sky based on their elevation angles. This method uses only images, having no need for any kind of laser scanning obtained data.

The paper written by Groves (2011) introduces shadow matching as a method to estimate satellite visibility in the urban environment. The method is tested on an ideal 3D model which has the needed width and spacing of streets and buildings and the position is discovered using the geometry between the user and the satellite. The real-life problem also raises the utility of the non-line of sight. This effect appears when the satellite signal is reflected by a building. A combination of LoS and NLoS can also result in accurate positioning. The method however takes into consideration direct LoS and their DoP values.

In another study by Adjrad et al. (2017), it is discussed the performance of the service using also the NLoS. In theory, using the NLoS might not influence the performance of the GNSS services in a good way as using NLoS also adds to the errors. However, in practice, there are very few clear LoS detectable in the urban environment, so using NLoS and signals influenced by multipath might add valuable contribution to the positioning accuracy. The paper presents two positioning algorithms and two integration approaches described in steps. The conclusion was that both the GNSS ranging-based algorithm and the shadow matching one worked better with a covariance based weighting approach rather than a deterministic one.

Verbree et al. (2004) describes a visibility algorithm which uses both GPS and Galileo satellite services to determine positioning in a 3D city model of Delft. This visibility algorithm determines the availability of the satellites. Using both the GPS and Galileo constellation asks for 5 satellites (2 GPS or 3 Galileo or the other way round). The conclusions state that a single satellites constellation is not enough to determine accurate positioning in urban areas. It is also stated that 3 satellites will be enough to determine the position if the height information is determined and constant and even provide better results than with 3 satellites.

Tiberius et al. (2005) describes a combination between GPS, EGNOS and Galileo positioning services for more accurate results. The availability study is focused on the user segment as the terrestrial geometry influences the receival of satellite signals. An additional algorithm next to the visibility algorithm is implemented. This algorithm calculates the availability of “enough” GPS and Galileo satellites while the receiver sits in a location. These numbers are represented on a map. The paper also has an outlook on finger-printing outdoor positioning. This method implies finding the user position by finding out which satellites at a given time can be tracked or not in an already known location and then match it with the user’s location.

Figure 3: Availability of GPS and Galileo combined during a one day span (Tiberius et al. 2005)

Kleijer et al. (2009) studied the availability of GNSS in the urban environment of the Schiphol Airport. Schiphol was considered due to its small size and potential for both outdoor and indoor LBS applications. The LoS computation were considered for satellites with an elevation angle of above 10 degrees as it would be easier to avoid multipath signals. The final conclusion was that the availability of the service is degraded by buildings blocking from more than one side and availability is improved when more than one satellites constellation is used.

3. Research Questions

Main research question: *To what extent can point cloud data be integrated in the behaviour of the satellite LoS and how does this relate to and influence the DoP values?*

The scope of this study is to determine how urban areas of Delft can be classified by the parameters of satellite visibility, such as number of LoS and the values of DoP from a certain view point in an area of Delft at a given moment of time. Delft was chosen as a use case as it has in its vicinity both open sky areas and urban canyon areas which are easy to go to. Viewpoints will be categorised based on how many satellites can be "seen" from them.

The purpose of this type of study has been explained in frequently in the scientific papers which research this field. Such a study is useful to evaluate the quality of the satellite navigation systems. Understanding the obstruction of satellite signals in the urban environments, due to tall vegetation or the urban canyon effect, can help improve the urban infrastructure. Further scope of this project is to use and improve existing methods for integrating point clouds into satellite visibility analysis tools and parameter determination such calculation of the DoP values. The used method shall be compared with the already existing online tools.

Knowing the orbital details of satellites presented in either almanacs or TLE files is essential for tracking the satellites that will be present above the location at the moment in time of the field measurements. These details could help to calculate the position vectors of the satellites, as Mostafa et al. (2009) describe in their paper. However, in the paper it is discussed about ephemerides data, which is not present in TLE files, but it is in almanac or broadcast ephemerides.

The following subquestions will be taken into consideration:

1. How are obstructions represented in calculation of DoP?
2. How good is the carried analysis compared with the given result by simulation tools?
3. Should non-LoS also be taken into consideration? - The nLoS concept is researched in Adjrad et al. (2017), where it is defined as the received signal via reflected path as the direct signal is blocked.
4. How can point clouds be integrated in GNSS mission planning tools?

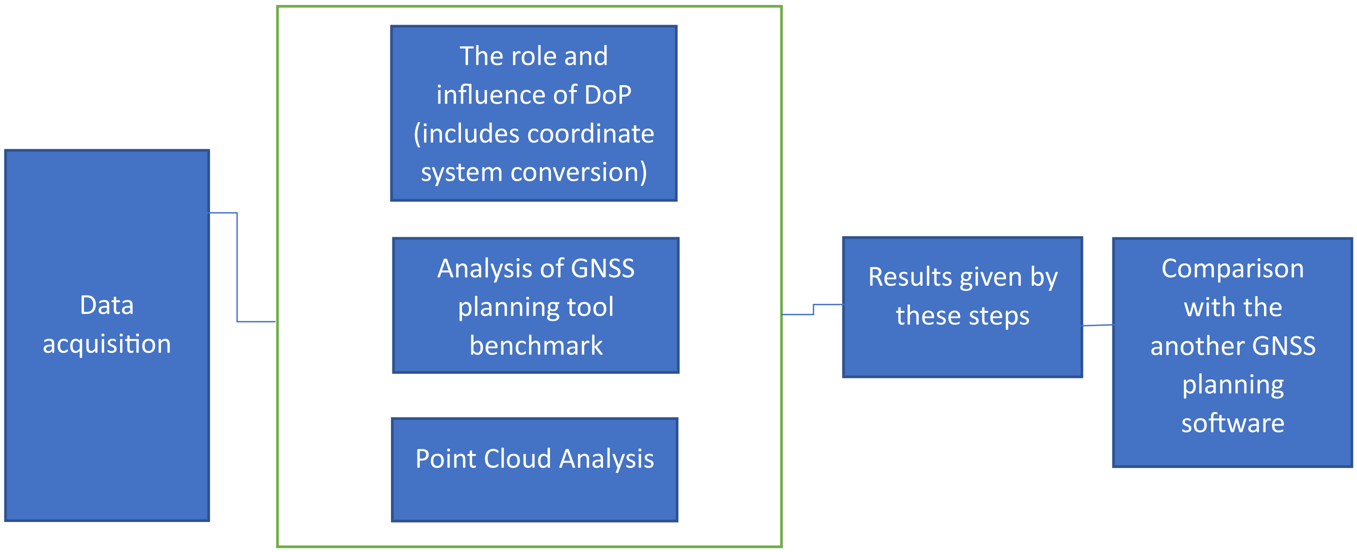
3.1 Dilution of precision analysis

Some surveying works will require a certain precision level. Studying DoP values will be helpful for this research as these given measurements will give details about the accuracy of the position determined by the satellite constellation. Not only it will provide information about the obstructed LoS, but also about the distribution of the satellites in the constellation and their elevation angle. The study of DoP values can also help to better understand the geometry of the satellite constellation and thus predict configurations that will give better results in terms of precise positioning.

There are already existing online tools which calculate the prediction of these values. The result given by these tools will be compared with the case study of this research.

For this research, a map will be created to show the behavior of the DoP values in an urban environment at the moment of the field measurements.

4. Methodology



4.1 Data acquisition

For the acquisition part, different locations in the city of Delft will be chosen to gather the satellite data from. The location will vary, as factors such as terrain, buildings and tall vegetation influence the connection between satellites and receiver. This part will be based on the connection between the user segment and the satellite segment. The user segment will be, depending on the details and quality of the data, either a smartphone or a more advanced GNSS receiver. The acquisition process of satellite data for the visibility analysis will involve the collection and analysis of information from satellites to determine the availability and quality of their signal. Depending on the type of file given by the receiver for the satellite data, the main details that will be analysed will be the lines of the files containing the position of the satellite related to the receiver and the DoP values. However, the type of line and file that will be analysed will be decided later, depending on which device was used for gathering the data.

4.2 DoP values

The analysis of DoP values can aid in determining the status of a satellite line of sight. DoP values determine the effect of satellite geometry related to the positioning accuracy. A method to calculate the dilution of precision is to first calculate the vector between the observation point and the visible GPS satellites.

The algorithm used for calculating these values can be the one implemented by Mostafa et al. (2009). The paper was written in the university of Alexandria and presents a GNSS planning for a visibility analysis in Egypt.

The paper describes as needing the following data for the calculation:

- Observation point coordinates
- Mask angle
- Time epoch
- Satellite ephemerides – the paper describes as needing more precise ephemerides data such as almanac, broadcast or precise ephemerides data which is not provided by TLE files

The paper also describes the conversion steps to do before the calculation after the data is obtained:

- Coordinates of observation points to ECEF coordinate system
- Time epoch to GPS time frame
- Calculate the ECEF coordinates for the satellite using ephemerides data
- Determine the visible satellites at the time epoch required, using the mask angle effect

The known type of DoP values are:

- Position Dilution of Precision (PDOP) – equatorial system
- Geometric Dilution of precision (GDOP) – equatorial system; may not be possible in the field
- Time Dilution of Precision (TDOP) – equatorial system
- Horizontal Dilution of precision (HDOP) – local system
- Vertical Dilution of precision (VDOP) – local system

For a validation of these steps to show how correct the calculation algorithm is, the results were compared with those obtained from a commercial software used for observations on a working field GPS station.

Discussing further the GDOP value and its prediction purpose, P.H. Dana describes in GPS Overview The Global Positioning System (uconn.edu) as the volume of the shape of the vectors between the satellite segment and the user segment. When it comes to planning GDOP is calculated from almanacs and the estimated position and does not take into account obstacles blocking the line of sight, thus it may not be realizable in the field work. It is further explained how GDOP values indicate the geometric condition between satellites and receiver, as a small unit vector-volume represents poorer geometric conditions and a large unit vector-volume represents favorable geometric conditions. Good geometrical conditions and bad visibility can also result in high GDOP values.

4.3 Point Cloud analysis

It can be observed that frequently, the 3D data that is used in online planning tools are usually 3D objects used to represent obstacles and buildings in order to present the results while under the influence of obstructions from different sides of the observation point. However, these types of 3D representations are usually very generic and not accurate considering how detailed 3D data. This is where point clouds present an advantage over 3D models representing only buildings.

The AHN4 dataset is a point cloud dataset that provides detailed information about the elevation of the Earth's surface in the Netherlands. It was obtained using airborne LiDAR technology for acquisition. The resulting point cloud data contains millions of points with x, y, and z coordinates, representing the three-dimensional structure of the terrain. The point cloud set additionally contains classification for each point depending in what type of object is it part of. Point clouds are useful when providing 3D information. The clearly defined elevation details present in the AHN4 will be very useful when doing a visibility analysis.

The model of satellite visibility estimation proposed in Dandurand et al. (2019) proved to be useful in every environment it was used given it had point cloud data of the location as input. A very similar satellite visibility model could also be implemented for Delft and used to find out the correlation between the DoP values and the placing of the obstacles.

Lu et al. (2020) proposes as future work to improve the super imposed column method used with point clouds. The future work talks about improving and comparing the presented method in the paper with actual values obtained from a GNSS land survey.

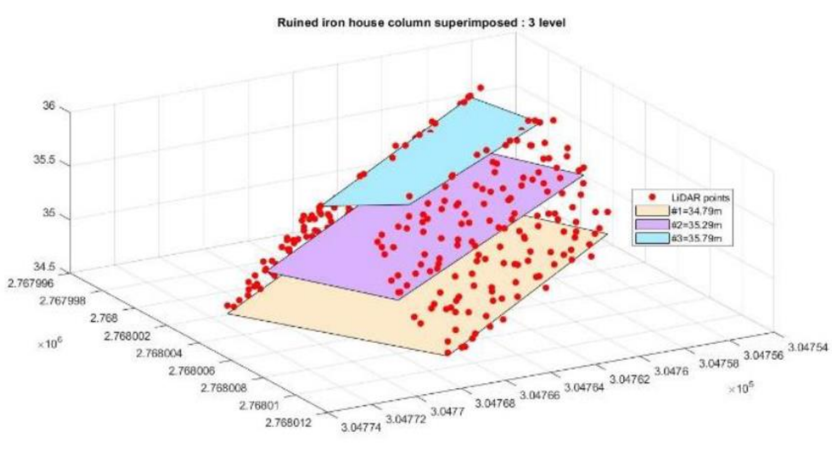


Figure 4: Superimposed building column sample (Lu et al. 2020)

4.4 Analysis of GNSS planning tools workflow

In order to understand how the calculation work, a study of the GNSS planning tools workflow must be done as the methods of calculation are not presented when using the tools and only the result charts are displayed. The main product to show the visibility of satellites in these types of tools is the skyplot containing the satellites

For the research in this project, there is more than one way in which this type of tools can be used. One way it can be used is before the data acquisition part in order to have an idea of the visible satellites and DoP values. This might not provide the best prediction as the tools provide only solid 3D objects to insert into the planning as obstructions when the real life environment is way more difficult to represent. The second way these tools can be used is as a comparison to the method to be used which is researched in one of the papers from the literature study.

An issue usually present in mission planning tools is described in Gandolfi et al. (2010) where it says that predictions without using natural or anthropic obstacles presents an unrealistic simulation. The paper presents the implementation of a GNSS mission planning software using C++ programming language, satellite data from broadcast ephemerides and a DEM as input data. It describes the formulas used for the calculation of the DoP values while knowing the position of the receiver and those of the satellites. The tool provides two modes: one for a single point to see the change of the satellite data over a given and a second one to evaluate the performance of several GNSS in a given area.

The paper describes at the beginning the workflow of their tool:

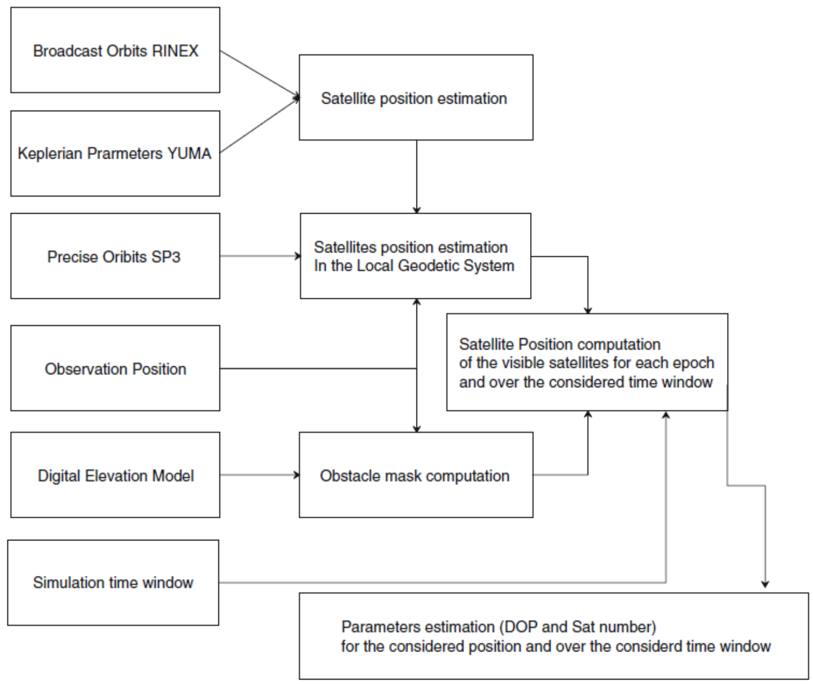


Figure 5: Flowchart of the software (Gandolfi et al. 2011)

The next mission planning tool that will be assessed is the online tool from Navmatix Home - Mission planning (gnssmissionplanning.com) which offers the user the possibility to create and modify obstacles and insert them into the scenery to see how they affect the visibility of the satellites. It can be observed that the objects to be inserted are simple and not very detailed. This case is hardly ever possible when gathering GNSS data in the field work, where the environment is way more detailed. Thus, using more detailed 3D data such as point clouds, where tall vegetation, shape of buildings and terrain is described would be an improvement for online planning tools such as this one. The online tool also presents no algorithm or details about how the charts are generated, especially the DoP ones.

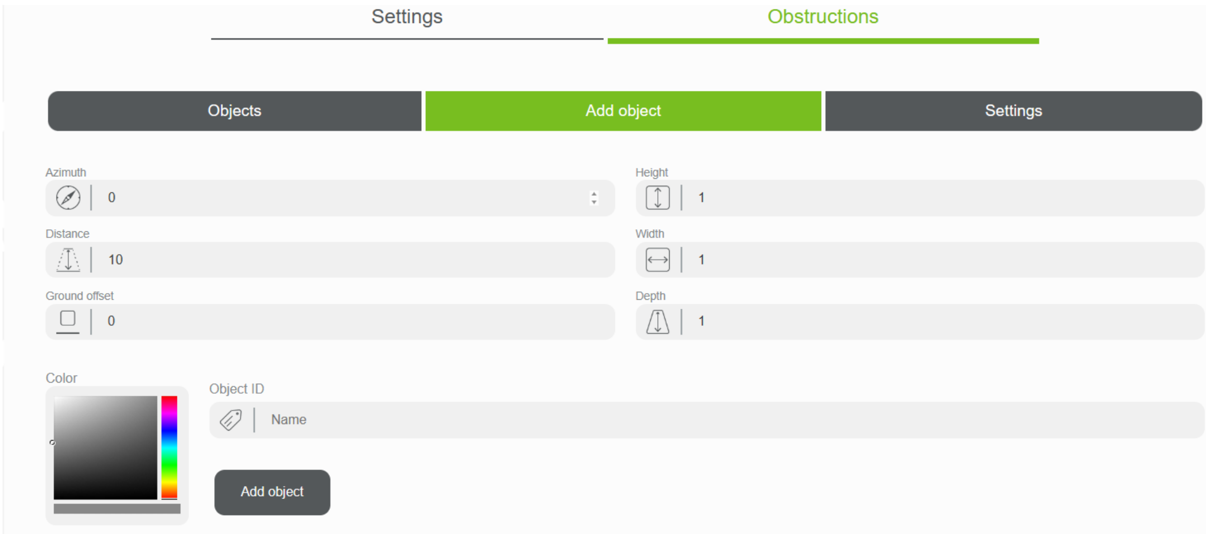


Figure 6: Tools to create the obstructions

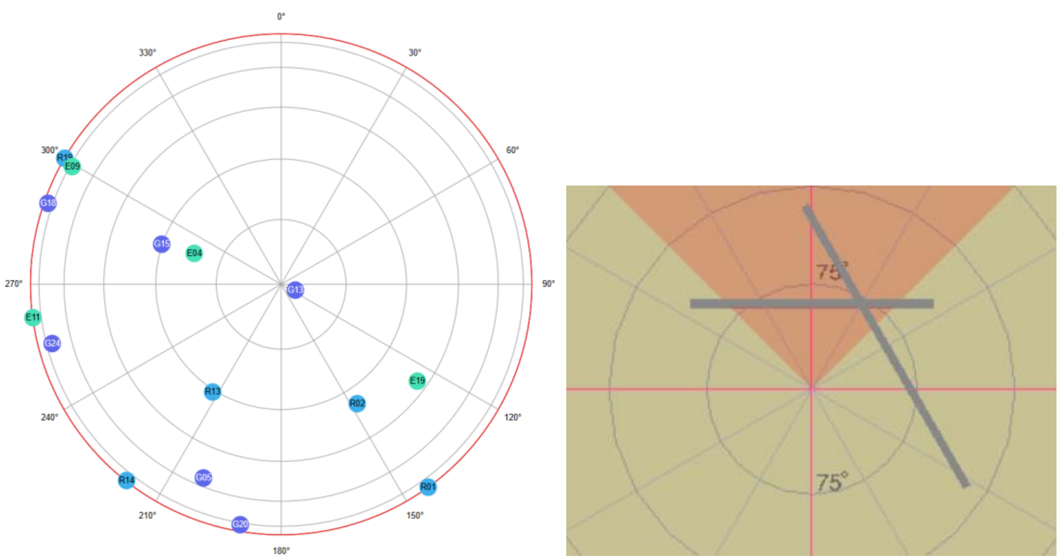


Figure 7: Skyplot view with obstructions

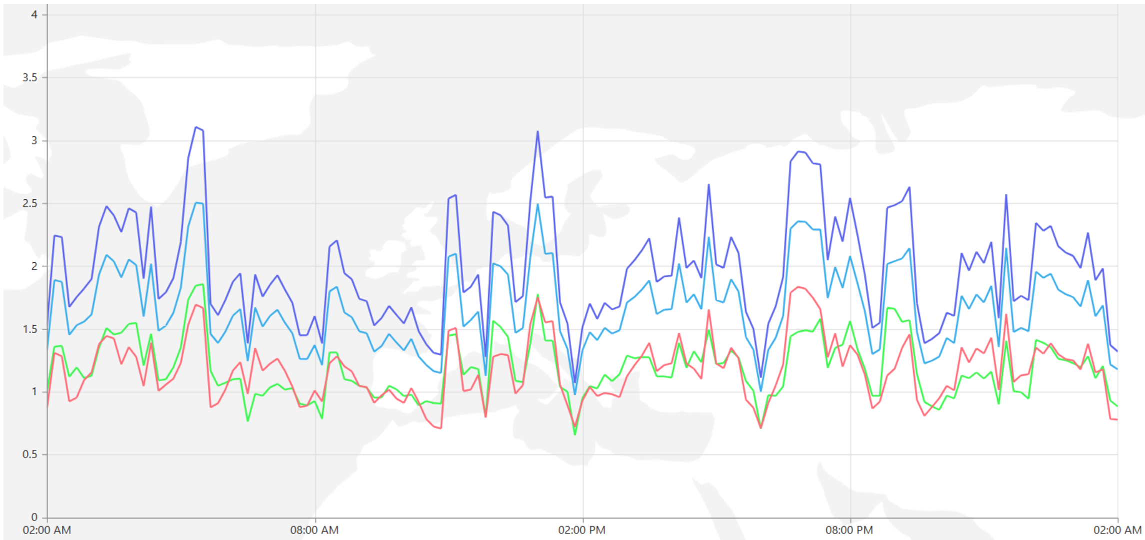


Figure 8: DoP values in the case of obstructed areas

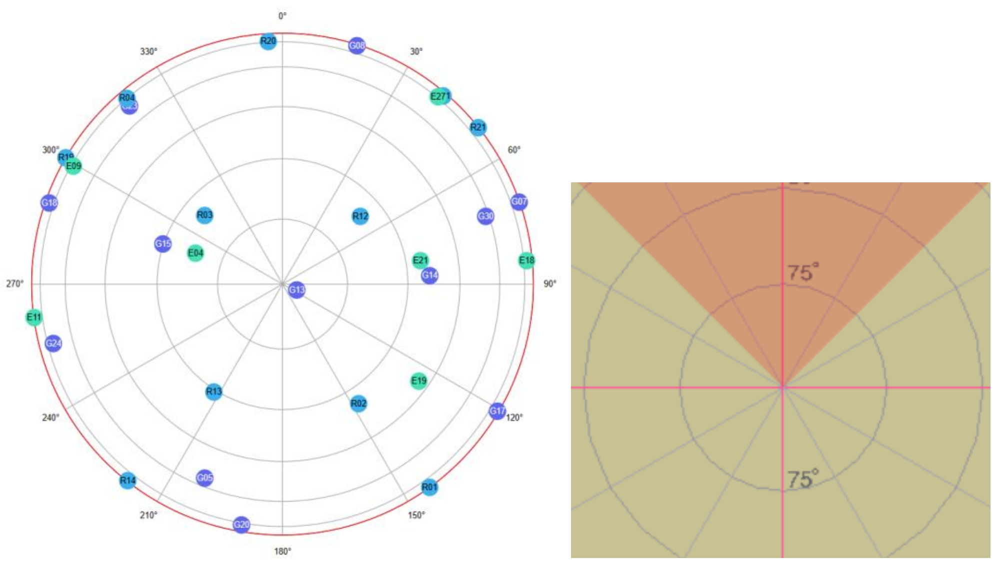


Figure 9: Skyplot view without obstructions

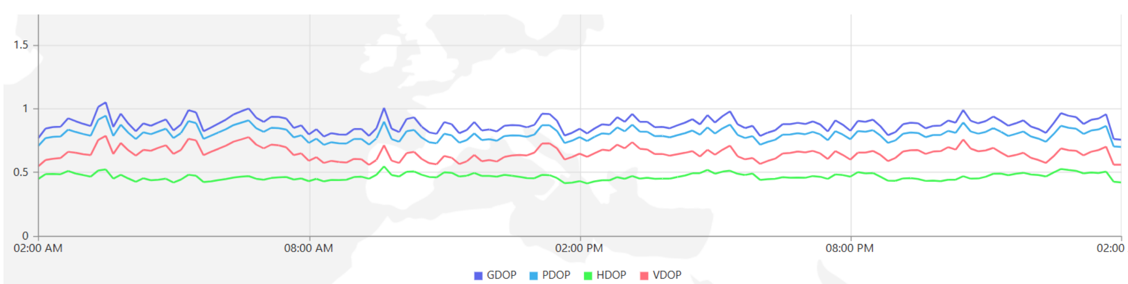


Figure 10: DoP values in the case of open sky areas

5. Time planning

Thesis planning

Research on thesis subject	19th-24th of April
P1	24th of April
Study literature review	28th of April – 12th of June
Thinking of how to prepare the use case	
Study the existing visibility algorithms	
Understand how DoP values work	
Research the workflow of GNSS planning tools	
P2	19th of June 2023
Prepare the use case – use GNSS mission planning tools	20th of June – 10th of September
Data acquisition – including satellite orbit data	
Point cloud data manipulation	
Implement existing visualization method	
P3	Beginning – middle of September
Begin thesis writing	15th of September – 27th of November
Finalise the implementation of the method	
P4	4 – 15th of December
Final thesis draft	15th of December 2023 – 8th January 2024
Thesis presentation	
P5	15th – 19th of January 2024

6. Tools and datasets used

6.1 Tools

Algorithms for data analysis and visibility will be written using python programming language. Some of the python packages that will be used for this research might be:

- Numpy
- Matplotlib
- Laspy
- Open3d
- PDAL

The FME software package will be used in order to cut the data only to the proportion that is needed for the project to carry the visibility analysis. In order to show the level of visibility for each point of the data, a map will be created using GIS software such as QGIS or ArcGIS.

For the data acquisition part, additional GNSS hardware and software will be used. In the first phase, the smartphone application NMEA Tools will be used to gather satellite data on a Samsung Galaxy S20 FE. If the smartphone application proves to not be successful, another hardware tool will be used. To start with an idea on how the satellite visibility analysis should work, the GNSS mission planning tool Home - Mission planning (gnssmissionplanning.com) from Navmatix will be researched and used for comparison with the results. More advanced commercial GNSS mission planning software might also be used in the future

6.2 Data

Parts of the AHN4 point cloud set will be used for the visibility analysis in 3D environment AHN4 - Download kaartbladen | ArcGIS Hub. The area of interest will be Delft as a number of locations will be assessed regarding satellite visibility. A tile of the AHN4 set is 8 GB of memory. The output files from the data acquisition part will also be considered data. What type of data will they contain and how it will be arranged depends on the type of hardware that will be used to gather the data. For a better understanding of satellite trajectories in time, TLE files could be used CelesTrak: Current GP Element Sets, although something with more defined ephemerids data might be needed for a better prediction.

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