Development of a multipath mitigation method to enhance map accuracy

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Introduction

- Global Navigation Satellite Systems (GNSS) are widely used by civil users providing accurate and reliable positioning

- Yet, several issues can accumulate due to the environment that surrounds the user : GNSS signals can face environments that create Non-Line-Of-Sight (NLOS) and/or multipath effects

- The idea of the project is to deal with those issues in order to mitigate the positioning error and to enhance the positioning accuracy

Objectives

- Investigate the effects of multipath and NLOS effects on positioning for map production

- Identify the urban areas where these effects are more likely to happen

- Propose a method to identify these multipath and NLOS effects

- Implement a post-processing method to filter out signal component that lead to a lack of the positioning accuracy

- Present a synthesis of the results obtained : accuracy gained, benefits for the positioning exactness

- Have a critical view of our work

I- Trajectory comparison

1) **Provided data and reference trajectory**

- Data was collected by a research-survey Tomtom vehicle in some areas in the Netherlands.
- This vehicle is equipped by 2 receivers : a uBlox F9P with a frequency of 1 Hz and a Novatel receiver with a frequency of 1 kHz.
- Other data where provided by Tomtom such as : Map data, buildings data, digital surface model, location of the antennas on the top of the vehicle.
- Reference trajectory was chosen using the post-processed data from the Novatel receiver where the quality factor Q is lower than 2.

UTCDate (YMD)	UTCTime (HMS)	UTCTime (sec)	Week (week	GPSTime (sec)	Latitude (deg)	Longitude (deg)	H-Ell (m)	NS	Q	AccBdyX (m/s^2)
9/11/29	15:08:19.00	486499.00	2081	486517.00	52.0490078569	4.4625950405	41.911	11	1	0.000
9/11/29	15:08:20.00	486500.00	2081	486518.00	52.0489782133	4.4629850442	41.920	12	1	0.000
9/11/29	15:08:21.00	486501.00	2081	486519.00	52.0489500082	4.4633711034	41.916	12	1	0.000
9/11/29	15:08:22.00	486502.00	2081	486520.00	52.0489221848	4.4637529790	41.924	12	1	0.000
9/11/29	15:08:23.00	486503.00	2081	486521.00	52.0488943474	4.4641307993	41.919	12	1	0.000
9/11/29	15:08:24.00	486504.00	2081	486522.00	52.0488663628	4.4645055790	41.928	12	1	0.000

Figure 2: Post-processed Novatel data and the quality factor "Q"

I- Trajectory comparison

2) Post-processing of raw data

- 2 different services were chosen to carry out the post-processing of the data provided:

- Open source program RTKLIB using Differential GNSS (DGNSS)
- Canadian Geodetic Survey of Natural Resources (CSRS-PPP) which provides a PPP Kinematic service

- At the beginning, elevation mask in the settings will not be changed and will be let at 15° (RTKLIB DGNSS)

I- Trajectory comparison

3) Coordinate system

- World Geodetic System 84 (WGS 84) is the coordinate system used for the study
- Distance between the 2 antennas will be expressed in the car coordinate system (a rotated system with respect to the World coordinate system)
- The origin of the car coordinate system is assumed to be the same as the World coordinate system moving with the car

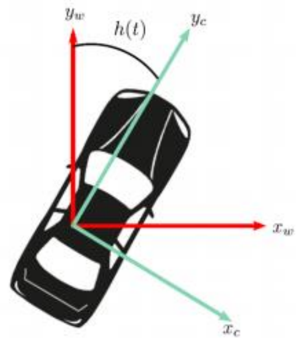


Figure 4: Representation of the two coordinates frames involved with the rotation angle $h(t)$ for each epoch, the car reference frame is presented by c subscript, and the World reference frame is presented by w subscript.

I- Trajectory comparison

4) Receivers setup on the research-survey vehicle

- In order to make comparison between data collected by the 2 receivers at the same location, the Novatel post-processed coordinates were compensated by a specific offset.
- This method was chosen so that the offset is converted to the World coordinate frame and is applied to the Novatel data (that is used as a reference)
- Since we will post-process several time the Ublox data, we decided to compensate the reference positions so we won't need to do several compensations → save processing time.

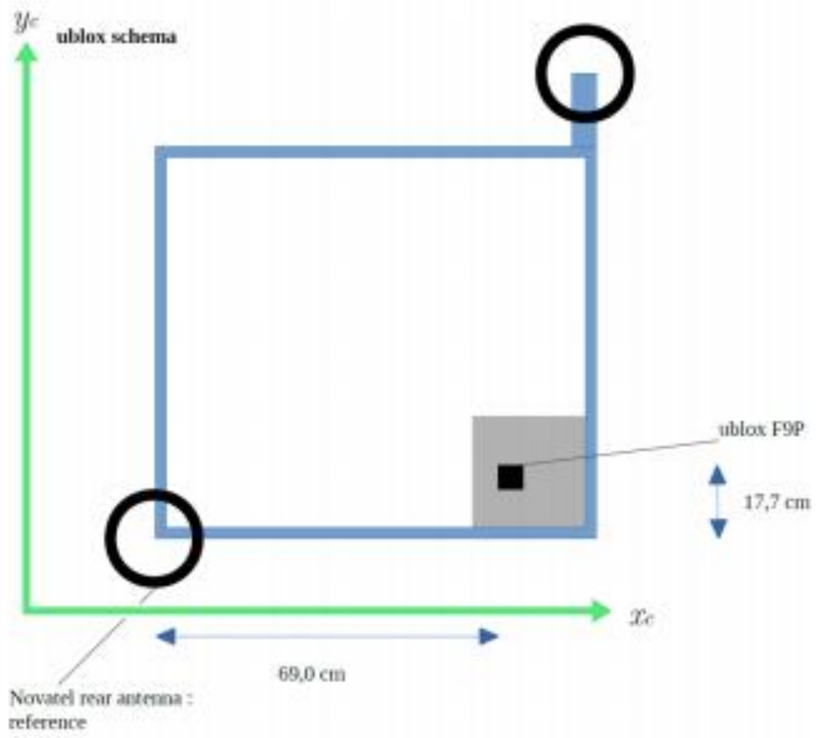


Figure 5: Setup of the Novatel and Ublox antennas on the TomTom research-survey vehicle frame.

I- Trajectory comparison

- **5) Conversion steps**
  - Rotation matrix $$\begin{bmatrix} dx \\ dy \end{bmatrix}^{world} = \begin{bmatrix} cos(\theta) & sin(\theta) \\ -sin(\theta) & cos(\theta) \end{bmatrix} \begin{bmatrix} dx \\ dy \end{bmatrix}^{car}$$
  - where dx^{car} = 0.690 m and dy^{car} = 0.177 m and **θ** is the heading angle at each epoch
  - Use the following relat

$$\varphi' = \varphi + (\frac{180}{\pi}) * (\frac{dy^{world}}{R_{earth}})$$

$$\lambda' = \lambda + (\frac{180}{\pi}) * (\frac{dx^{world}}{R_{earth} * cos(\varphi)})$$

With:

- $R_{earth} = 6371$ km (6).
- φ and λ are the latitude and longitude expressed in decimal degrees.
- φ' and λ' are the compensated latitude and longitude expressed in decimal degrees.

I- Trajectory comparison

6) Control of the exactness of the compensation

- Using a fictive point (coordinates ϕ=50° and λ = 5°) with 2 headings (0° and 90°) and then converting coordinates from WGS84 to the Netherlands local coordinates frame (EPSG:28992)

No rotation	East [m]	North [m]
Non-compensated	127232.455	223303.763
Compensated	127233.148	223303.937
Difference [m]	0.692	0.173

Table 1: Results of the coordinates difference after compensation (with no rotation)

Rotation	East [m]	North [m]
Non-compensated	127232.455	223303.763
Compensated	127232.629	223303.073
Difference [m]	0.174	-0.691

Table 2: Results of the coordinates difference after compensation (with a 90° rotation)

I- Trajectory comparison

7) Evaluation of the receiver’s accuracy

- We will compare the reference positions (provided by the Novatel) with the post-processed obtained by the uBlox within 3 scenarios :

- Scenario 1 : open environment in an open high highway with almost no obstructions (track 0)
- Scenario 2 : Urban environment, through the roads of Breda (track 0)
- Scenario 3 : Urban environment through the roads of Den Haag (track 9)

- Here, the comparison was done between the post-processed uBlox positions using RTKLIB (DGNSS) and PPP obtained with the Canadian CSRS service
- Novatel sampling frequency was adjusted to 1 Hz to compare positions with the same epochs.
- WGS84 coordinates were converted to East-North-Up format (ENU) in local coordinate system of the Netherlands.

I- Trajectory comparison

7) Evaluation of the receiver's accuracy

- Results

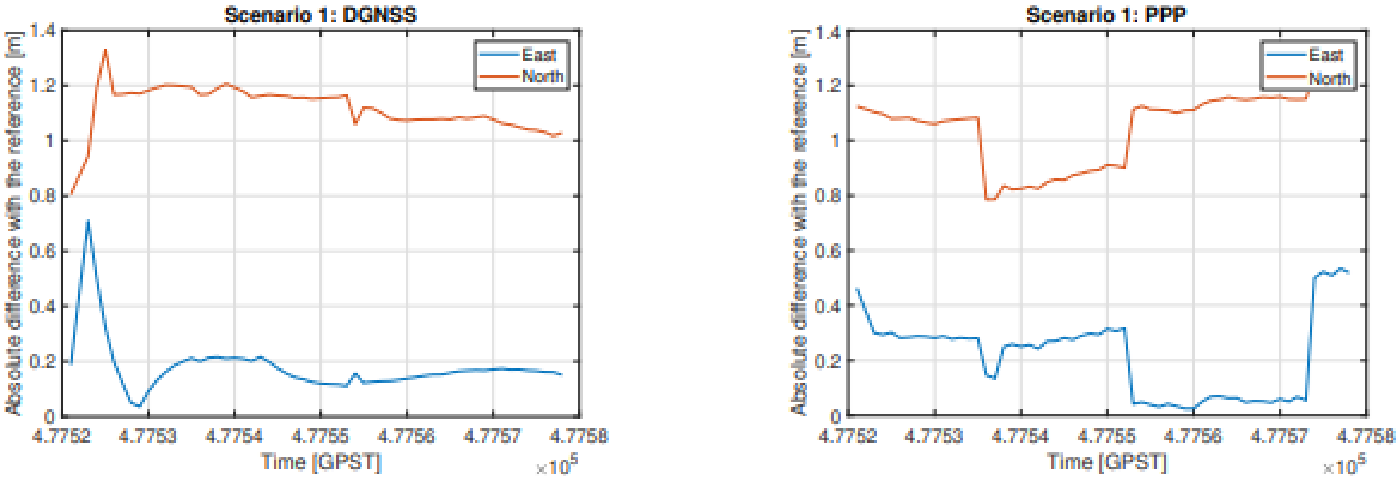


Figure 7: Differences in East and North coordinates with reference using DGNSS and PPP Kinematic as a function of time (Scenario 1)

I- Trajectory comparison

7) Evaluation of the receiver’s accuracy

- Results

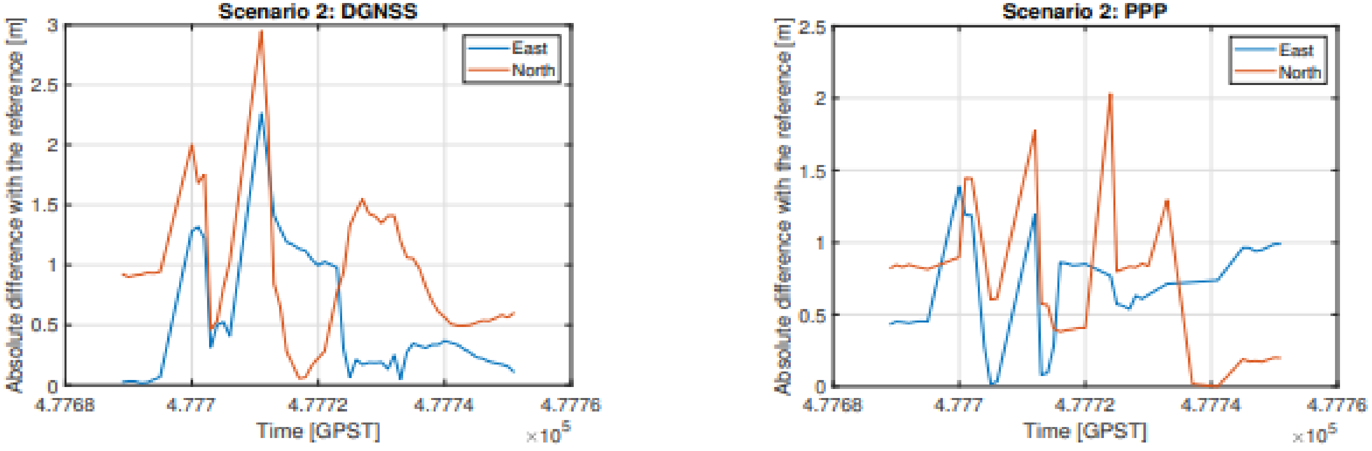
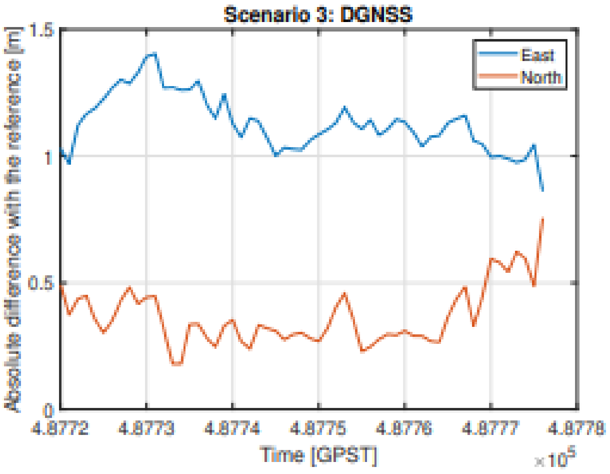


Figure 8: Differences in East and North coordinates with reference using DGNSS and PPP Kinematic as a function of time (Scenario 2)

I- Trajectory comparison

7) Evaluation of the receiver's accuracy

- Results



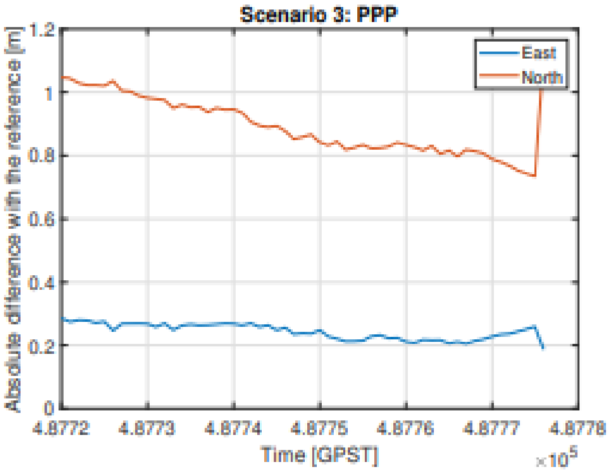


Figure 9: Differences in East and North coordinates with reference using DGNSS and PPP Kinematic as a function of time (Scenario 3)

I- Trajectory comparison

7) Evaluation of the receiver's accuracy

- Results : Numerical synthesis

Scenario 1	dE (DGNSS)	dN (DGNSS)	dE (PPP Kinematic)	dN (PPP Kinematic)
Max [m]	0.71	1.33	0.50	1.25
Min [m]	0.04	0.80	0.03	0.78
Mean [m]	0.18	1.12	0.19	1.03
Median [m]	0.16	1.15	0.26	1.08
Standard deviation [m]	0.10	0.08	0.13	0.13

Table 3: Summary of the results (Scenario 1)

I- Trajectory comparison

7) Evaluation of the receiver’s accuracy

- Results : Numerical synthesis

Scenario 2	dE (DGNSS)	dN (DGNSS)	dE (PPP Kinematic)	dN (PPP Kinematic)
Max [m]	2.26	2.95	1.39	2.03
Min [m]	0.02	0.05	0.02	0.00
Mean [m]	0.52	0.90	0.67	0.70
Median [m]	0.31	0.83	0.68	0.81
Standard deviation [m]	0.53	0.56	0.34	0.46

Table 4: Summary of the results (Scenario 2)

I- Trajectory comparison

7) Evaluation of the receiver's accuracy

- Results : Numerical synthesis

Scenario 3	dE (DGNSS)	dN (DGNSS)	dE (PPP Kinematic)	dN (PPP Kinematic)
Max [m]	1.40	0.76	0.29	1.11
Min [m]	0.86	0.18	0.19	0.73
Mean [m]	1.13	0.37	0.24	0.89
Median [m]	1.13	0.33	0.25	0.87
Standard deviation [m]	0.11	0.12	0.02	0.09

Table 5: Summary of the results (Scenario 3)

I- Trajectory comparison

7) Evaluation of the receiver's accuracy

- Results : impact of multipath on both tracks : track 0 that gathers scenario 1 and 2, track 9 that refers to scenario 3

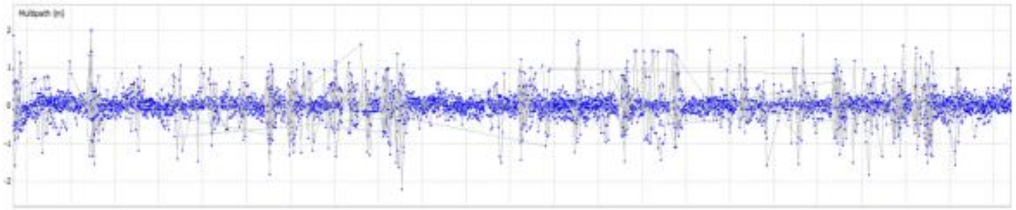


Figure 10: Multipath effects on the Track 0

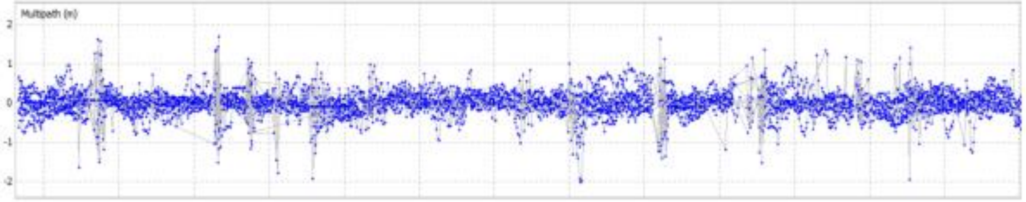


Figure 11: Multipath effects on the Track 9

II- Comparison of tracking

- We will compare the number of tracked satellites for the GPS and GLONASS constellations (used when post-processing the Novatel data)

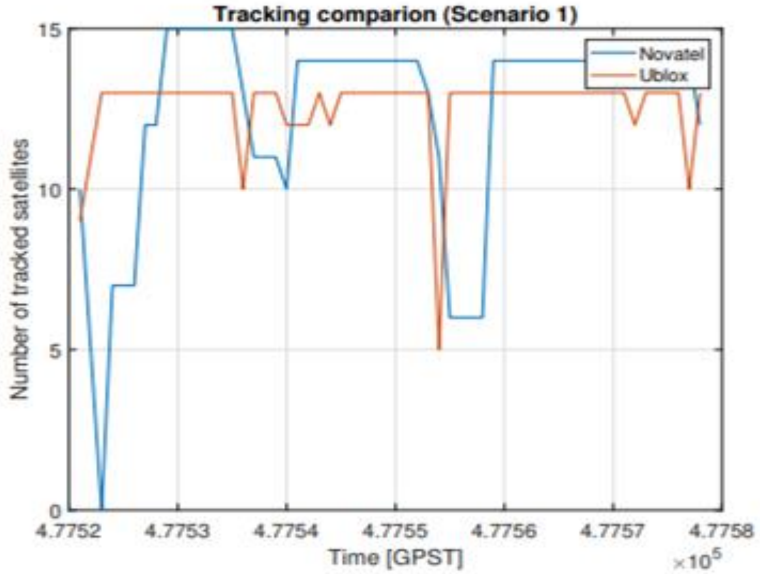


Figure 12: Comparison of the number of tracked satellites (Scenario 1)

II- Comparison of tracking

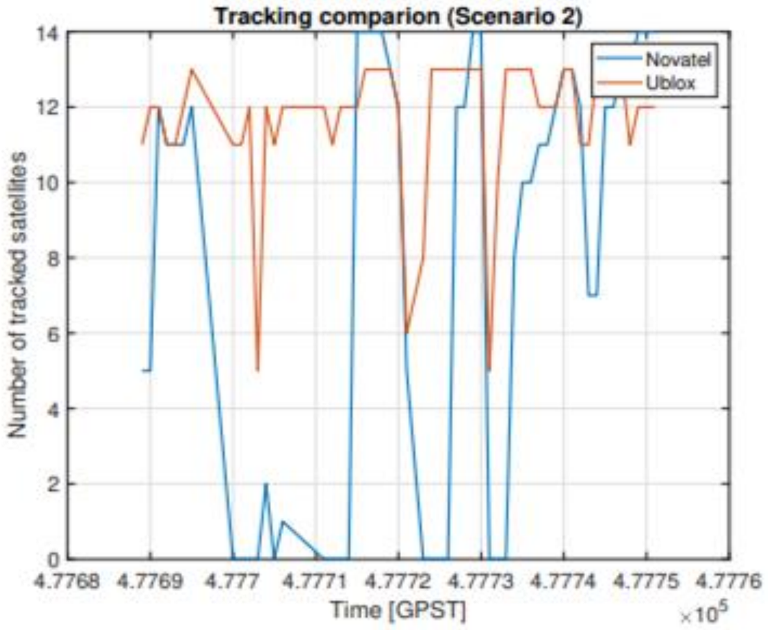


Figure 13: Comparison of the number of tracked satellites (Scenario 2)

II- Comparison of tracking

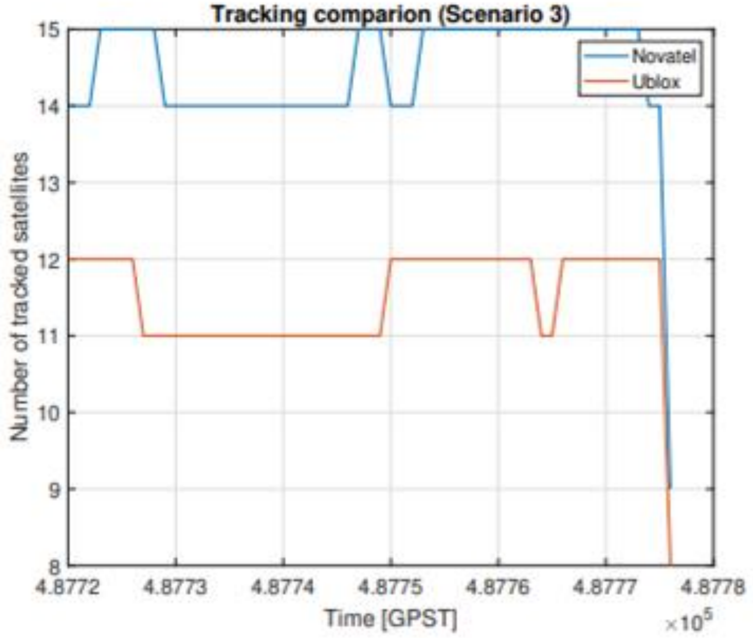


Figure 14: Comparison of the number of tracked satellites (Scenario 3)

III- Skyplot analysis and building mask

1) **Computation of the ECEF coordinates for each satellite** (from ephemeris parameters)

- ☐ Time elapsed since t_{oe} $\quad t_i = t - t_{oe}$
- ☐ Mean anomaly at t_i $\quad M_i = M_0 + \left(\sqrt{GM/a^3} + \Delta n\right)t_i$
- ☐ Eccentric a. (iterative!) $\quad E_i = M_i + e\sin(E_i)$
- ☐ True anomaly $\quad f_i = \arctan\left(\dfrac{\sqrt{1-e^2}\sin E_i}{\cos E_i - e}\right)$

- ☐ Argument of perigee with true anomaly

$$\varphi_i = \omega + f_i + C_{\omega c}\cos 2(\omega + f_i) + C_{\omega s}\sin 2(\omega + f_i)$$

- ☐ Radial distance

$$r_i = a(1 - e\cos E_i) + C_{rc}\cos 2(\omega + f_i) + C_{rs}\sin 2(\omega + f_i)$$

- ☐ Inclination

$$i_i = i_o + idot \cdot t_i + C_{ic}\cos 2(\omega + f_i) + C_{is}\sin 2(\omega + f_i)$$

- ☐ Longitude of the ascending node

ECI: $\Omega_i = \Omega_0 + (\dot{\Omega})t_i \qquad$ ECEF: $\Omega_i = \Omega_0 + (\dot{\Omega} - \omega_e)t_i - \omega_e t_{oe}$

- ☐ Geocentric coordinates

$$x_i^e = \begin{bmatrix} x \\ y \\ y \end{bmatrix}_i^e = r_i \begin{bmatrix} \cos\varphi_i\cos\Omega_i - \sin\varphi_i\cos i_i\sin\Omega_i \\ \cos\varphi_i\sin\Omega_i + \sin\varphi_i\cos i_i\cos\Omega_i \\ \sin\varphi_i\sin i_i \end{bmatrix}$$

Figure 15: Calculation of the ECEF coordinates for each satellite (6)

III- Skyplot analysis and building mask

2) Computation of the coordinate differences in the ENU coordinate frame

$$\mathbf{d_e} = \mathbf{s_e} - \mathbf{a_e} \qquad \mathbf{d_l} = \mathbf{R} \cdot \mathbf{d_e}$$

With the rotation matrix $\mathbf{R}$:

$$\mathbf{R} = \begin{bmatrix}\mathbf{e} & \mathbf{n} & \mathbf{u}\end{bmatrix} = \begin{bmatrix} -sin(\varphi) & -sin(\varphi)cos(\lambda) & cos(\varphi)cos(\lambda) \\ cos(\lambda) & -sin(\varphi)sin(\lambda) & cos(\varphi)sin(\lambda) \\ 0 & cos(\varphi) & sin(\varphi) \end{bmatrix}$$

With :

- $\mathbf{d_e}$ is the vector containing coordinates differences in the ECEF (e) frame expressed in meters.
- $\mathbf{d_l}$ is the vector containing coordinates differences in the ENU (l) frame expressed in meters.
- $\mathbf{s_e}$ is the vector containing the satellites coordinates in the (e) frame.
- $\mathbf{a_e}$ is the vector containing the coordinates of the receiver's antenna in the (e) frame (available at the output when using RTKLIB).
- φ and the λ are the latitude and longitude of the receiver's antenna expressed in decimal degrees.

III- Skyplot analysis and building mask

3) Computation of the Azimuth and Elevation angles

$$Elevation = asin(\frac{(d_l(3))}{\|\mathbf{d_l}\|}) \qquad Azimuth = atan2(\frac{(d_l(1))}{\|\mathbf{d_l}\|}, \frac{(d_l(2))}{\|\mathbf{d_l}\|})$$

With:

- Atan2 returns the arc tangent of the two numbers x and y. It is similar to calculating the arc tangent of y/x, except that the signs of both arguments are used to determine the quadrant of the result
- $d_l(1)$, $d_l(2)$ and $d_l(3)$ are the coordinates differences in the East, North and Up respectively.

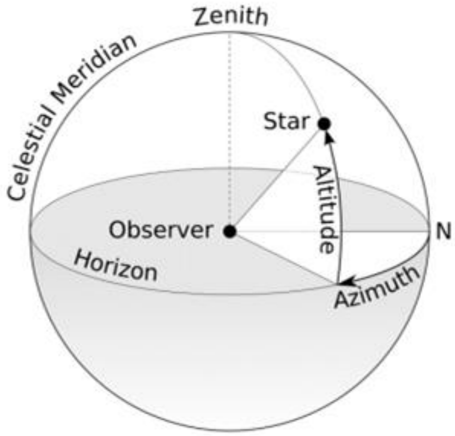


Figure 16: Azimuth and elevation (altitude) angles of satellites relative to the receiver (17)

III- Skyplot analysis and building mask

4) Satellites skyplots

For scenario 2, with an elevation mask of 15° for the epoch 11/29/2019 at 12h 41min 29 sec UTC

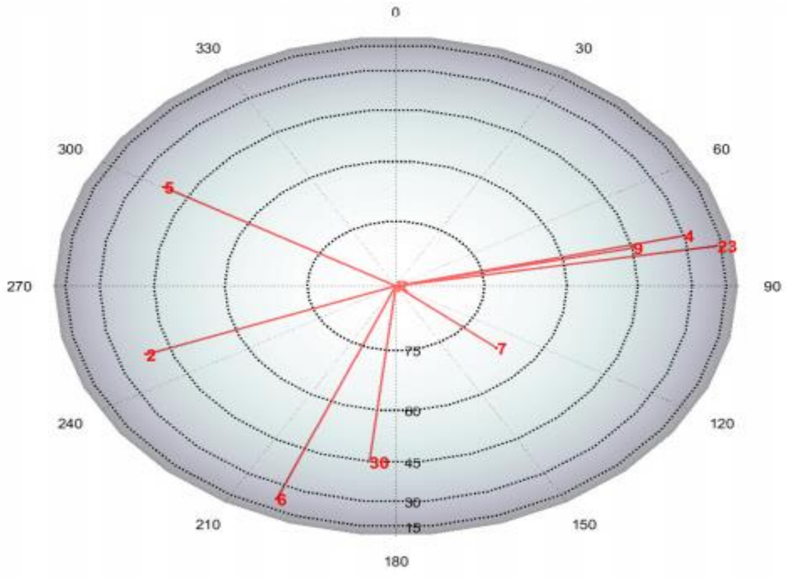


Figure 17: Skyplot of the GPS satellites for the Scenario 2

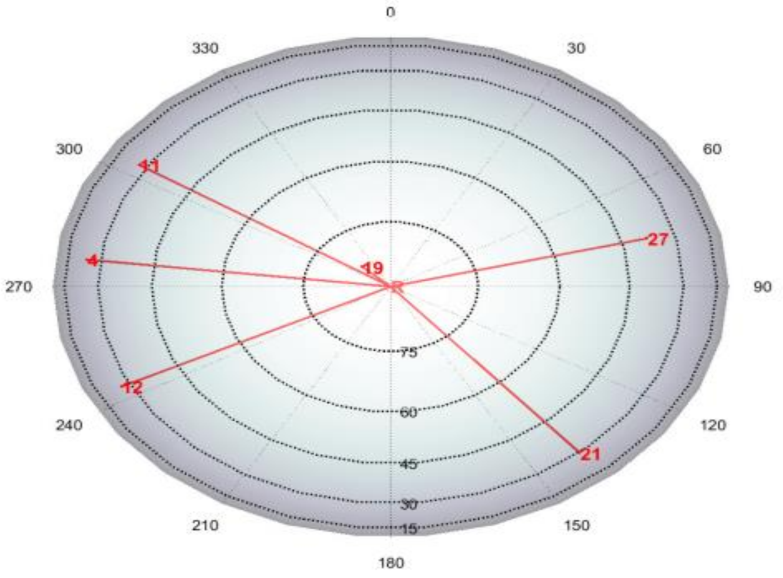


Figure 18: Skyplot of the Galileo satellites for the Scenario 2

III- Skyplot analysis and building mask

4) Satellites skyplots

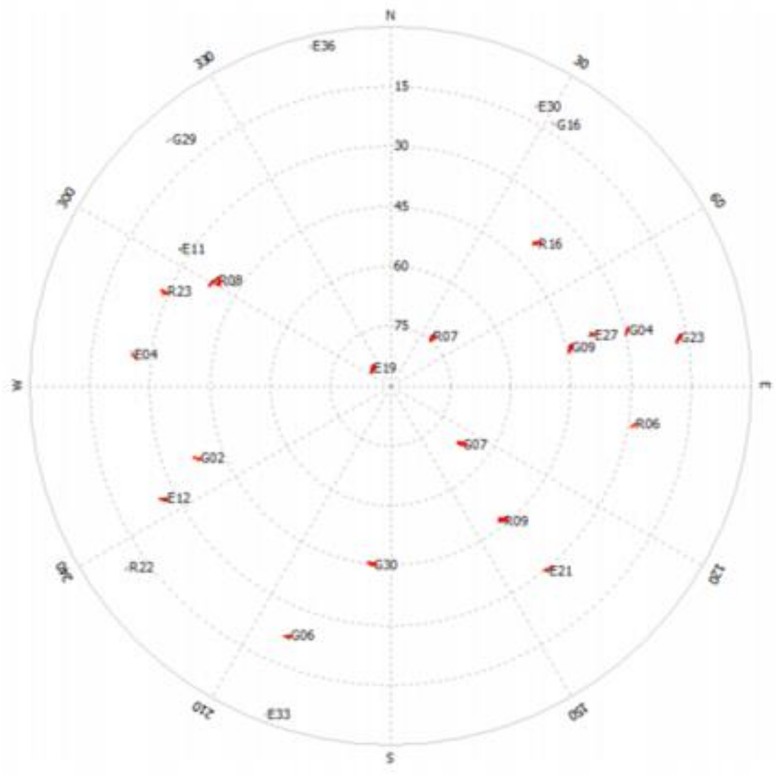


Figure 19: RTKLIB Skyplot of the GPS, Galileo and Glonass satellites for the Scenario 2 (red are valid satellites and grey are non-valid relative to the elevation mask condition)

III- Skyplot analysis and building mask

5) Building mask and elevation of surrounding objects

We chose a point where the difference with the reference coordinates is the highest :

- dE(DGNSS) = 2.26 m
- dN(DGNSS) = 2.95 m

Here, the elevation angle is approximately 30°

Figure 20: Antenna position when the differences with the reference position is maximal (Breda highways, at 12:41:51 UTC) (21)

Figure 21: Calculation of the elevation angle of the surrounding objects relative to the Ublox antenna position (21)

IV- Post-processing adjustments to enhance the accuracy of the solution

1) Accuracy gained (for the previous point)

Point with max difference (30° elevation mask)		Point with max difference (15° elevation mask)	
dE (DGNSS) [m]	1.14	dE (DGNSS) [m]	2.26
dN (DGNSS) [m]	0.37	dN (DGNSS) [m]	2.95

Table 6: Comparison of the accuracy under two different elevation mask conditions for the point with the maximum difference (absolute)

IV- Post-processing adjustments to enhance the accuracy of the solution

2) Generalizing the post-processing for scenario 2

Scenario 2 (30° elevation mask)	dE (DGNSS)	dN (DGNSS)
Max [m]	1.69	2.16
Min [m]	0.01	0.08
Mean [m]	0.33	0.92
Median [m]	0.17	0.93
Standard deviation [m]	0.39	0.53

Table 7: Summary of the results under a 30° elevation mask (Scenario 2)

Scenario 2 (15° elevation mask)	dE (DGNSS)	dN (DGNSS)
Max [m]	2.26	2.95
Min [m]	0.02	0.05
Mean [m]	0.52	0.90
Median [m]	0.31	0.83
Standard deviation [m]	0.53	0.56

Table 8: Summary of the results under a 15° elevation mask (Scenario 2)

Conclusion

- Many steps should be accomplished before proceeding to find a solution that enhances the positioning accuracy (compensate the Novatel positions by the offsets, post-processing row data, using appropriate coordinate system, controlling the exactness of the compensation, and then forward, the accuracy of the receiver).

- Then, we can proceed to track the satellites and analyze the skyplots in order to build elevation masks depending on the surrounding environment of the antenna.

- Finally, we finish our process by post-processing the tracks depending on relevant building mask that lead us to reach a gain in maximum difference accuracy between approximately 60 to 80 cm for the urban environment scenario 2 (compared to the data processed with a default elevation mask of 15°).

Thank you for your attention and for your precious help during this project

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