Virtual Base Station Algorithm and Performance Assessment

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I. ABSTRACT

RTK (Real Time Kinematic) [1] is a positioning approach that provides centimeter level accuracy by using a reference station. When the rover and the base station are in proximity (short baseline), all common mode errors are eliminated by the double difference, allowing carrier phase ambiguity resolution [2]. In the medium and long baseline cases, the ionospheric and tropospheric delays are not completely eliminated by the double difference which make them critical factors for the positioning accuracy. Thus, the availability of base station limited the application of RTK, especially in certain regions where the closest base station can only be found over 50 km. Algorithms like RTK long baseline [3] and VBS (virtual base station) [4] emerged as an alternative. The virtual base station (VBS) algorithm processes the surrounding bases to generate a virtual one within a short distance of the moving rover. By doing so, the atmospheric errors will continue to be eliminated in the double-difference model and the RTK processing will be presumably assured all over the mainland continents. A performance assessment of the algorithm is conducted under various conditions, including high ionospheric activity, high baseline, harsh multipath environments and finally in a long trajectory. The results show that the developed VBS algorithm ensures centimeter-level accuracy even under the hardest conditions.

II. INTRODUCTION

Nowadays, algorithms like RTK (Real Time Kinematic) or PPP (Precise Point Position) [5] are developed to enhance the GNSS position performance up to centimeter level. Each of these algorithms aims to eliminate the effect of errors impacting GNSS signals using its own strategy in order to fix carrier-phase ambiguities. Ambiguity resolution allows us to take advantage of the high accuracy of the phase measurements which are more precise than code measurements by a factor of a 100, thus the positioning accuracy is substantially increased. The RTK is a positioning approach that provides centimeter level accuracy by using a reference station. When the rover and the base station baseline is small enough, all common mode errors such as receiver clock bias, orbit errors and atmospheric errors are eliminated by the double difference, allowing the ambiguity resolution. When the baseline is not small enough, the double difference will not eliminate all errors, especially the atmospheric errors which prevent the ambiguities resolution. This means that the distance between a rover and its reference station must be considerably short in order to work efficiently. The availability of base station limited the application of RTK, especially in certain regions where the closest base station can be found over 50 km. Algorithms like RTK long baseline and VBS emerged as an alternative. The RTK Long Baseline extended the range of traditional RTK, however the performance of this algorithm decreased from those showed by the conventional RTK-short-baseline, especially under harsh conditions because of the long convergence time of the estimated atmospheric residuals, which makes the instantaneous ambiguity resolution impossible. This convergence time limitation can be overcome by processing the surrounding bases to generate a virtual base station (VBS) within a short distance of the moving rover. By doing so, the atmospheric errors will continue to be eliminated in the double-difference model and the RTK processing will be presumably assured all over the mainland continents. Indeed, the generation of a VBS adds a level of robustness over the RTK long baseline. First, the availability of the system increases by providing a base where needed without the hardware infrastructure. Then, multiple far-located base stations are used to produce the virtual one, which means that if one of the bases of the network presents any type of anomalies it will be excluded by a RAIM [6] algorithm. As a result, the final virtual station would be previously validated removing potential errors in the RTK processing. The aim of the present paper is to develop a Virtual Base station algorithm, leveraging on the freely available base station data (more than 7000 worldwide) to deliver a centimeter accuracy in a post-processing environment. Finally, the algorithm performance will be evaluated under various conditions.

III. VIRTUAL BASE STATION CONCEPT

Virtual base station positioning algorithm is a network RTK technology based on multiple reference stations (Figure 1). By processing the surrounding bases. The VBS algorithm generates a virtual base in the vicinity of a rover receiver, which eliminates all baseline dependent errors such as troposphere, ionospheric and orbital errors, allowing carrier phase ambiguity resolution. To manage all types of rover trajectories including those where the rover travels over hundred kilometers (Figure 2), the VBS is generated epoch by epoch at rover position.

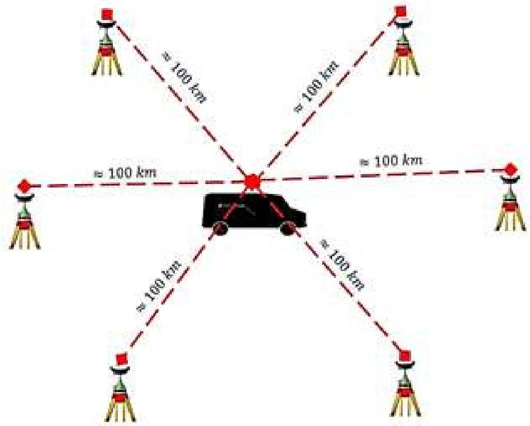


Figure 1: Virtual base station overview.

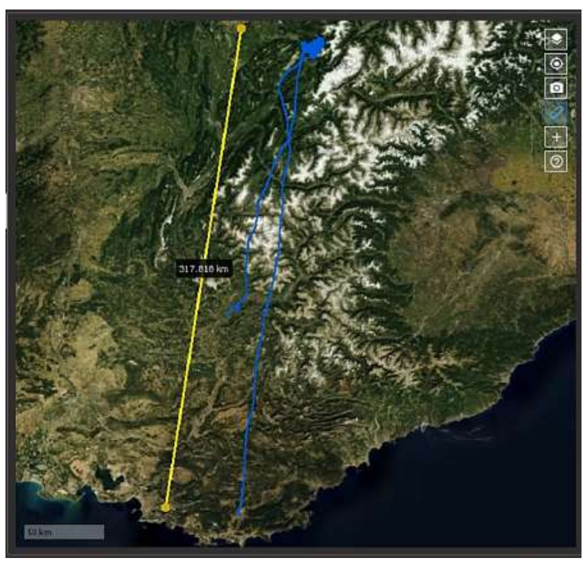


Figure 2: Exemple of a long-distance trajectory.

The basic three principles of virtual base stations are detailed in the following section:

1. Network and master base definition

The choice of the network is critical to generate a reliable VBS (at least 4 reference stations are required). The larger the number of well-distributed bases, the better and more reliable the generated corrections are. According to the atmospheric conditions, the network baseline can be medium (20km to 50km), large (50km, 100km) or even very large (> 100 km). For more network robustness, a RAIM algorithm can be used to exclude any bases that present anomalies. Once the network is defined, a master base is selected according different criteria, such as common number of constellations with the rover, baseline, number of cycle slip detected, etc.

2. Atmospheric effect and estimation

The VBS algorithm requires running a RTK long baseline between the master base and each base of the network (Figure 3) to estimate the atmospheric residual. The Earth's atmosphere can be divided in two major parts for GNSS applications, troposphere, and ionosphere. The troposphere delay is the non-dispersive lowest region of Earth's atmosphere ranging from 0 to 50km, while ionosphere is a dispersive layer that surround the earth, stretching from a height of about 50 km to more than 1000 km [7].

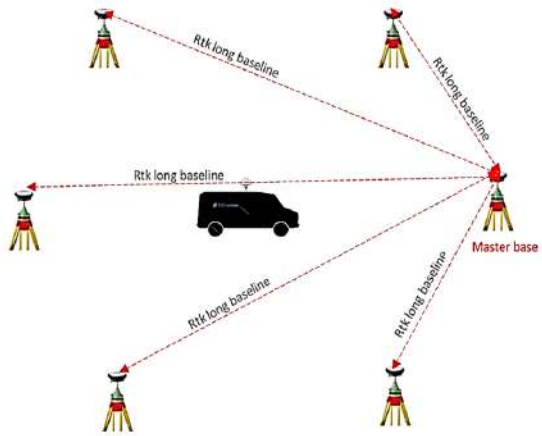


Figure 3: Atmospheric residual estimation.

The following equations are the mathematical model of the pseudorange (1) and the carrier phase measurement (2) between a single receiver (subscript r) and a single satellite (superscript s) on the frequency i:

$$P^s_{r,i} = (\rho^s_r + \xi r, i^s) + (dt_r - dt^s) + \gamma_i I^s_r + T^s_r + (d_{r,i} - d^s_i) \tag{1}$$

$$\Phi^s_{r,i} = (\rho^s_r + \zeta r, i^s) + (dt_r - dt^s) - \gamma_i I^s_r + T^s_r + (\delta_{r,i} - \delta^s_i) + \lambda_i N^s_{r,i} + \lambda_i \omega^s_r \tag{2}$$

The use of precise ephemeris and the double difference eliminate all these errors except the ionospheric and tropospheric residual that need to be estimated according to the following model:

$$P^{ps}_{qr,i} = \rho^{ps}_{qr} + \gamma_i I^{ps}_{qr} + T^{ps}_{qr} \tag{3}$$

$$\Phi^{ps}_{qr,i} = \rho^{ps}_{qr} - \gamma_i I^{ps}_{qr} + T^{ps}_{qr} + \lambda_i N^{ps}_{qr,i} \tag{4}$$

Where

- ρ^{ps}_{qr}: Double difference of the geometric distance.
- T^{ps}_{qr}: Double difference of the tropospheric delay.
- I^{ps}_{qr}: Double difference of the ionospheric delay.
- $N^{ps}_{qr,i}$: Double difference of ambiguities.
- γ_i: Ionospheric factor that vary with the inverse square of the signal frequency f_i.

The following state model is used by the extended Kalman model:

$$X = \begin{bmatrix} p_x & p_y & p_z & T_r & T_q & I^{p1}_{qr} & N^{p1}_{qr,i} & \dots & I^{pn}_{qr} & N^{pn}_{qr,i} \end{bmatrix}^T \tag{5}$$

3. Atmospheric Residual Interpolation

In this step, assuming that all atmospheric residuals are estimated between the master base and each base of the network, an interpolation of all these residuals is needed at the VBS position. Some efficient interpolation algorithms have been developed [8], such as Ordinary Kriging (OKR), Least Square Collocation Method (LSC), Linear Combination Model (LCM), Linear interpolation Method (LIM), etc. Multiple algorithms have been tested, LSC has proved to outperform the others. Least Square Collocation Method (LSC) is a distance weighted interpolation method (Figure 4). The backbone of this method is the so-called covariance function, which considers the correlation effect between the bases.

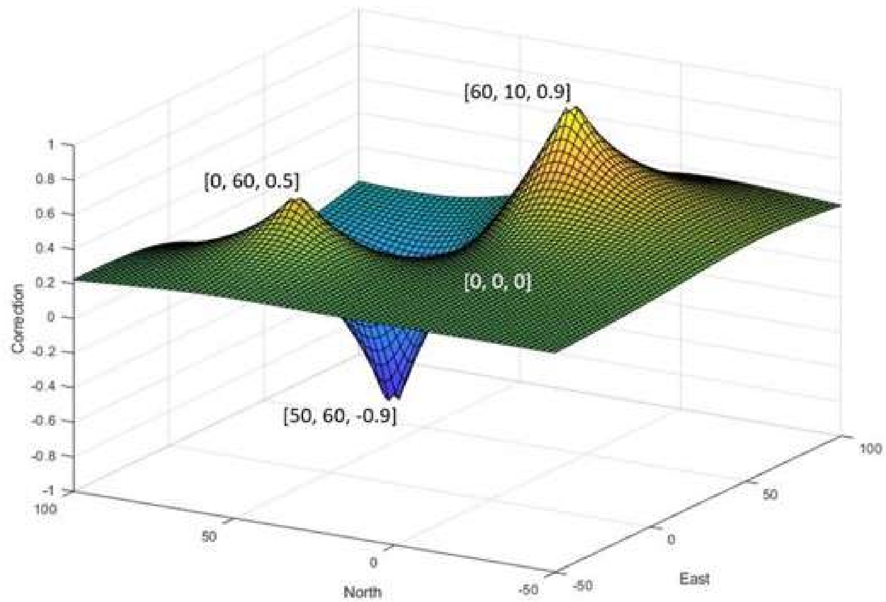


Figure 4: Distance weighted interpolation surface.

A practical interpolator is suggested by Van der Marel [9] is:

$$\bar{V_{1x}} = \begin{pmatrix} c_{x1} & c_{x2} & \dots & c_{xn} \end{pmatrix} \cdot \begin{pmatrix} c_{11} & c_{12} & \dots & c_{1n} \\ c_{21} & c_{22} & \dots & c_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ c_{n1} & c_{n2} & \dots & c_{nn} \end{pmatrix} \cdot \begin{pmatrix} \hat{V_{11}} \\ \hat{V_{12}} \\ \vdots \\ \hat{V_{1n}} \end{pmatrix} \tag{6}$$

Where:

$$c_{kt}^s = l_{max} - l_{kt}^s \tag{7}$$

$$l_{max} = \infty \tag{8}$$

- c_{kt}^s: spatial covariance function between the reference station (k) and (t).
- c_{xt}^s: spatial covariance function between the reference station (k) and the VRS.
- $\hat{V_{1n}}$: the estimated atmospheric residual between the master base (1) and the base (n).
- l_{kt}^s: baseline between the reference station (k) adn (t)

Note that in the case of ionosphere interpolation, the spatial covariance function must be calculated at the pierce point which is located around 300km of altitude.

IV. BIASES ANALYSIS

The quality of the VRS is closely related to the correction of the biases. In fact, a bad correction of the biases leads inevitably to bad estimation of atmospheric residuals, therefore a bad VRS. These biases can be attributed to several different sources:

1. Orbital errors

Information about orbital parameters and clocks, called broadcasted ephemeris, which have a precision about 5 meters, are transmitted in the navigation message. In a relatively short-baseline RTK, the double difference eliminates all common errors including those caused by the broadcasted ephemeris. When the baseline becomes important these errors are not completely eliminated. They represent one of the largest error sources, alongside the troposphere and ionosphere delays. The broadcast ephemeris errors become even more important when dealing with the GLONASS constellation. To overcome this limitation, precise ephemeris and clocks provided by some organizations such as IGS (http://www.igs.org/) are used. By convention, the satellite position provided in the precise files is referred to the spacecraft center-of-mass, meaning that two more errors must be accounted, the phase center offset (PCO) and the phase center variations (PCV) [10].

2. Antenna PCO and PCV

a) Satellite

The commonly used broadcasted ephemeris provides the position of the satellite antenna for direct use within the position computation. However, as mentioned earlier, the precise ephemeris is referred to the satellite center of mass. The offset between these two points is known as phase center offset, and it must be considered and corrected in order to succeed in the VBS generation. In precise applications such as RTK long baseline, the correction of the satellite PCO's is not enough to ensure the highest precision. In this case the assumption that there is a common electrical phase center as a single point for all signals is no longer possible, since variations that depend on the azimuth, the elevation and the frequency are still present. These variations are known as phase center variations and they account for the individual measurement residuals that are left after the PCO correction. Both the PCO and PCV for all existing satellites are described inside the antenna exchange (ANTEX) format. The PCO is represented as a 3D vector on the satellite body frame. To apply this correction into the measurement a coordinate frame rotation and a projection onto the positive line-of-sight vector is needed. On the other hand, the PCV is a scalar value that may depend on the frequency, the elevation, and the azimuth.

b) Receiver

In the case of the receiver antennas, the mean electrical phase center differs from the ARP by a frequency dependent PCO and a PCV. This receiver effects can also be removed from the observation modeling, and their value has been computed by calibration method and added to the ANTEX file. The complete correction $\zeta_{r,i}^{s}$ of the satellite and receiver PCO and PCV is:

$$\zeta_{r,i}^{s} = \zeta_{PCO,i}^{s} + \zeta_{PCO,r,i} + \zeta_{PCV,i}^{s} + \zeta_{PCV,r,r} \tag{9}$$

3. Receiver Code and Phase Biases

As aforementioned, to obtain a VBS, RTK long baseline algorithm must be done between the master base and each base of the network. The data of these bases do not necessarily come from the same provider, each base has its own manufacturer, model, and firmware version. All these possibilities of heterogeneity create biases that must be managed to get a reliable VBS. The biases which must be considered are:

a) GLONASS Biases

It is assumed that the receiver hardware delays are the same for satellites belonging to the same constellation for the same signal. This assumption holds true for GNSS' using code division multiple access (CDMA) to distinguish between signals transmitted by different satellites. It is, however, not true for GLONASS biases, as this constellation employs frequency division multiple access (FDMA) instead of CDMA. Because of the FDMA strategy, the receiver hardware bias will vary depending on the tracked satellite. These GLONASS related biases affect both code and phase measurement which are known as:

GLONASS Code-Phase Alignment

As explained in the RINEX 3 [11] documentation, the code and the phase measurement are not measured at the same time, consequently some biases are created. The created bias is generally constant and remains the same by design. The value of the bias can be retrieved either from the header of the RINEX file or from the 1230 RTCM message. Once the value of the bias is obtained, it is possible to apply it by using the following equation:

$$L_{aligned} = L_{measured} + \frac{GCPB}{\lambda} \tag{10}$$

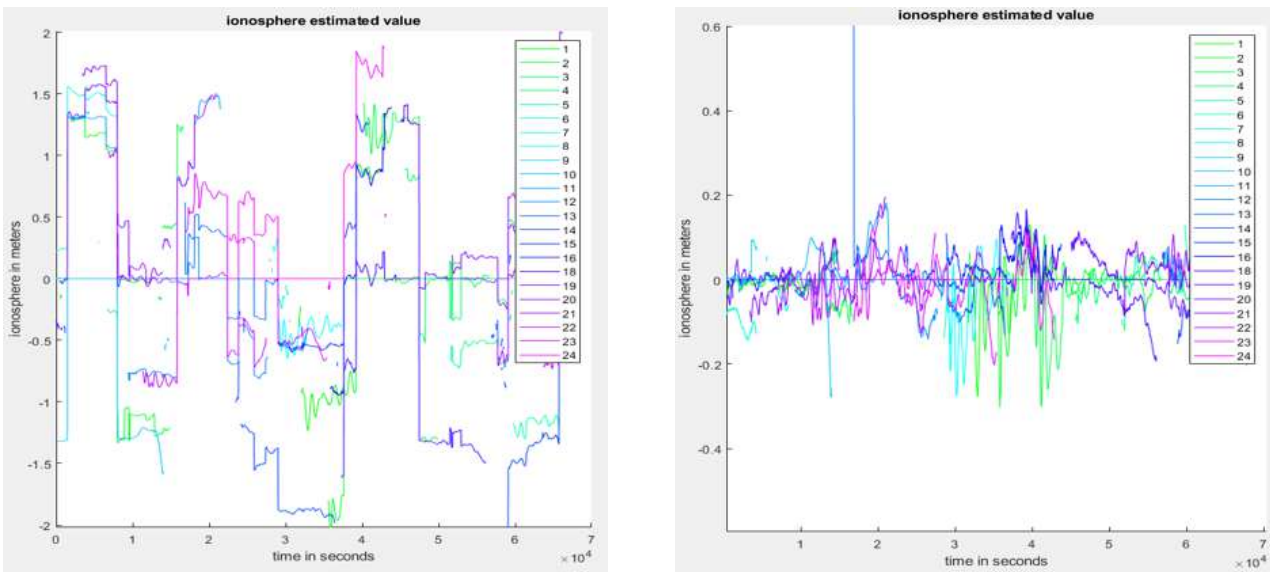
Where:

- $L_{aligned}$: Aligned phase in cycles.
- $L_{measured}$: Measured phase in cycles.
- GCPB: The retrieved GLONASS code phase bias in meter.
- λ: Wavelength of the aligned phase in meter.

GLONASS IFCB

In RTK long baseline algorithm, the unbiased double difference of range is fundamental. It allows the convergence of the ionosphere state to a consistent value while the double difference of phase helps the converge the ambiguities. Therefore, the ambiguity resolution is closely related to the consistency of the estimated ionosphere. Because of the FDMA strategy, the GLONASS range double difference is biased by an inter-frequency code bias (IFCB).

In case of RTK long baseline where the 2 receivers are heterogeneous, it is impossible to estimate a consistent ionosphere without eliminating the IFCB. Many methods were developed[12] to estimate it. (Figure 5a) illustrates the result of estimated ionosphere without IFCB estimation while (Figure 5b) illustrates the result considering IFCB estimation. The estimated values without IFCB estimation are biased which makes the generation of a consistent VBS impossible.



(a) Estimated ionosphere without GLONASS IFCB corrections.

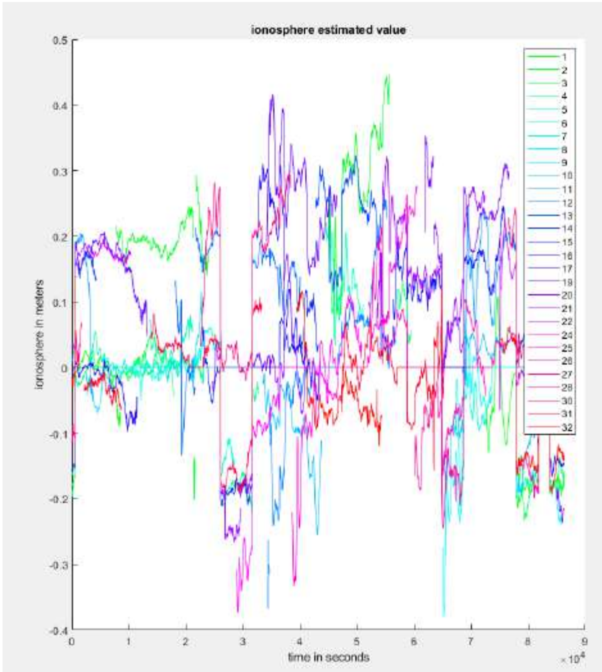
(b) Estimated ionosphere with GLONASS IFCB corrections.

Figure 5: GLONASS IFCB

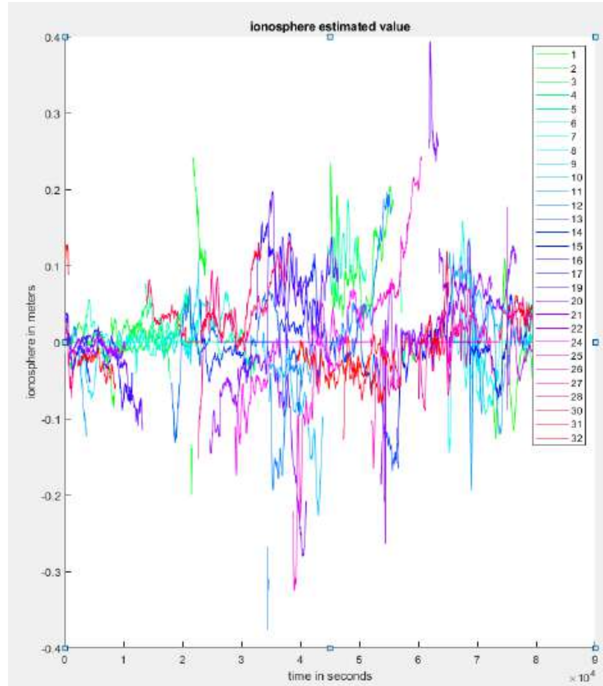
b) RINEX 2 limitations

Until now, the developed VBS algorithm is a post-processing algorithm, which use the reference stations data that comes from many different organisms and providers. Most of the time, the data is provided in RINEX 2.11 format. This format has been used widely in the geodetic community, including the international GNSS service (IGS) for more than 15 years. This format was initially developed for GPS data and was later adapted to be compatible with the Russian GLONASS system. The modernization of GPS, with additional signals like L5, L2C and the emergence of the new GNSS constellations is not properly handled, with in particular, the impossibility to know exactly which signal is tracked. Although this problem is known and easily tackled with the newer RINEX 3.x versions, the “de facto” standard for base stations data is still the good old 2.11 format. This means that during the RINEX 2.11 file encoding/decoding process, some important information about the nature of the signals is lost. This may sometimes generate unaligned phase measurements (breaking RINEX convention).

Unaligned phase measurements can cause invalid ionospheric estimation as shown in the (Figure 6a). Our algorithm detects any unaligned phase measurement and compensate it to provide a consistent ionospheric estimation.



(a) Unaligned ionosphere estimation.



(b) Aligned ionosphere estimation.

Figure 6: RINEX limitations

V. EXPERIMENTAL RESULTS AND ANALYSIS

1. Post-Processing Tool Used For Assessment

The performance assessment was done using Qinertia post-processing software (Figure 7). This tool integrates the developed RTK/VBS algorithms. It is a very convenient tool which is designed to be very user-friendly and intuitive.

Qinertia provides many features:

- Virtual base station.
- Tight coupling INS/GNSS fusion.
- + 7,000 ase stations always up to date.
- All processing: INS/GNSS and GNSS only.
- Open to third-party IMUs.
- The fastest processing and advanced tools for assessment.
- Modern & intuitive interface.
- Multi-constellation support (GPS, GLONASS, Galileo, BEIDOU, QZSS).
- Seamless integration of odometer and dual antenna GNSS receivers.

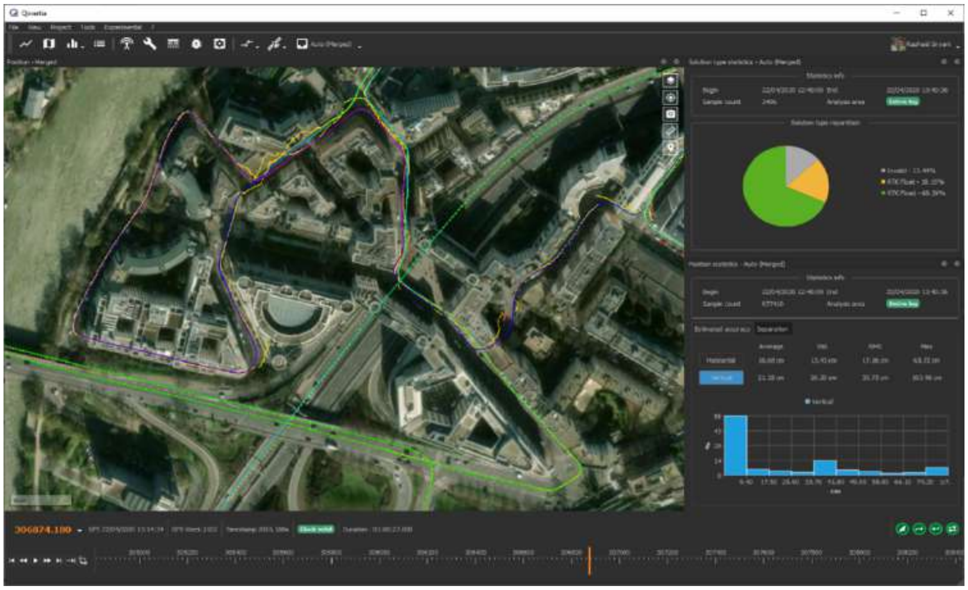


Figure 7: Qinertia overview.

2. Results and Analysis

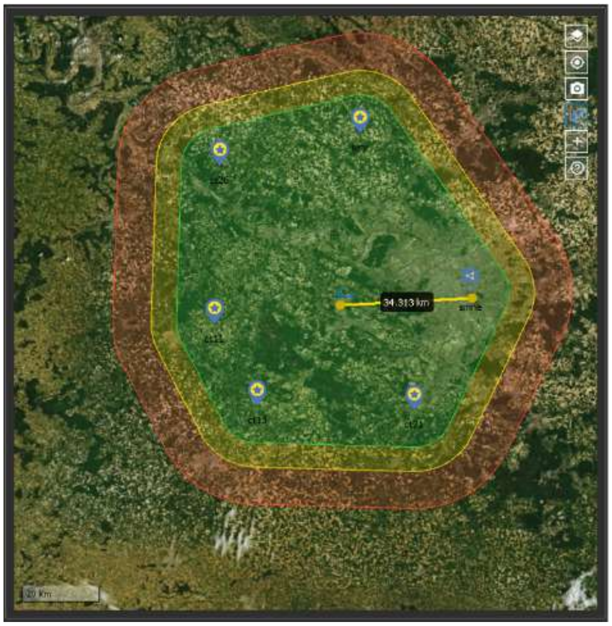
During our test campaign, to properly assess the performance of the developed VBS algorithm under real conditions, we tested it on several applications (automotive, marine, airplane, etc.) under different atmospheric conditions. The SBG RTK short baseline which has a very good performance, therefore it is taken as a reference to assess the developed VBS algorithm. To process RTK short baseline references, a base physically present near the rover is used. Here are the obtained results.

a) Automotive Open Sky Application

The first scenario consists of an automotive open sky environment with challenging ionospheric conditions. The data were gathered during the spring 2015 at midday, a period known for its high ionospheric activity. To compare the performance of the VBS algorithm, a RTK short baseline was processed using a reference base station located at 1km from the rover. In this case, the reference has a 100 % fix rate. In addition, a standard RTK was processed using the master base of the VBS network as a reference station to point out the advantages of the VBS algorithm. Two different network configurations were proposed to highlight the impact of the network's baseline. (Figures 8a and 8b) present the network overview with a medium and large baseline, respectively. The details of each network are presented in (Table 1).

Table 1: VBS networks details of the automotive open sky application

Test	Num Bases	Min baseline (km)	Max baseline (km)	Receivers
Network 1	6	34	47	Trimble
Network 2	6	47	71	Trimble



(a) VBS network 1 overview.

(b) VBS network 2 overview.

Figure 8: Automotive open sky

(Figure 9) and (Table 2) show the obtained performance with the network1 regarding to the reference, there is 1 to 2cm error and a fix rate of 99%. In this case the VBS's performance is almost identical to the RTK short baseline reference. At the same time, errors ranging from 10cm to 15cm and a fix rate of 0% are obtained when the master base is used for a short baseline, which highlights the precision of the developed VBS algorithm and its interest in this kind of scenarios.

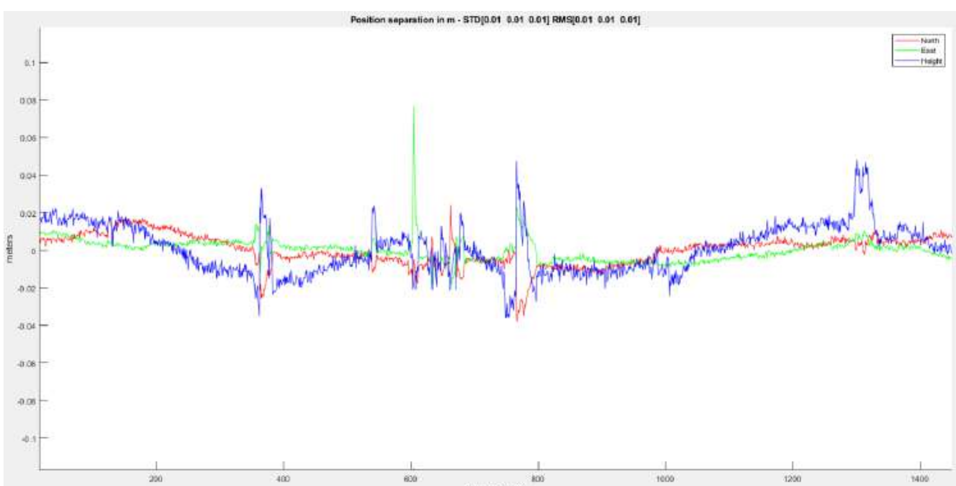


Figure 9: Network 1 performance compared to the reference.

Table 2: Network 1 RMS performance to the reference.

Error RMS (m)				
	N	E	D	Fix rate (%)
RTK Reference	-	-	-	100
VBS	0.02	0.01	0.01	99
RTK (w. master base)	0.1	0.13	0.15	0

The second network had a more challenging configuration with a larger distance between the rover and the bases of the network. Additionally, the high ionospheric activity demanded a high-end correction of the biases mentioned in the previous sections. Despite these harsh conditions, the VBS produced a cm error position (Figure 10) with a fix rate of 85% (Table 3), which proves the robustness of the algorithm while highlighting the relation between performance and network size. In Addition, the RTK using the master base of the network obtains very poor performance with a dm position error and a fix rate of 0% (Table 3). The VBS clearly outperforms this method in this scenario.

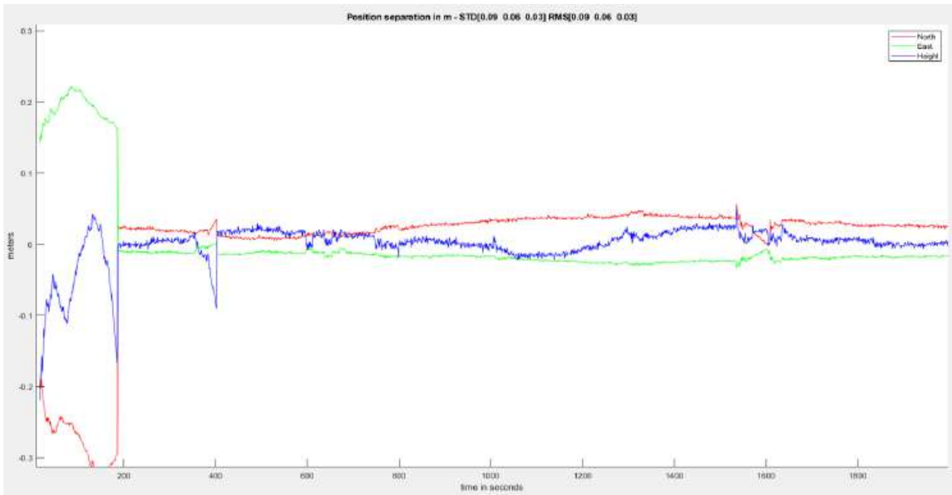


Figure 10: Network 2 performance compared to the reference.

Table 3: Network 2 RMS performance to the reference.

Error RMS (m)				
	N	E	D	Fix rate (%)
RTK Reference	-	-	-	100
VBS	0.09	0.06	0.03	85
RTK (w. master base)	0.15	0.24	0.25	0

b) Automotive Urban Canyon Application

Another challenging application is the urban canyon. In this case the ionospheric activity is considered lower, but the conventional RTK may suffer from long convergence time and bad ambiguity resolution because of a baseline of 76.7km. The reference was generated with an RTK processing with a baseline of 17 km to the reference station. In this harsh environment, with many GNSS multipath effects and masks, even the reference trajectory cannot fix all the time (85% fix rate).

The network configuration is detailed in (Table 4):

Table 4: VBS networks details of the automotive urban canyon application

Test	Num Bases	Min baseline (km)	Max baseline (km)	Receivers
Automotive 3	6	76.7	130	Trimble, Ashtech, Spectra, Lecia

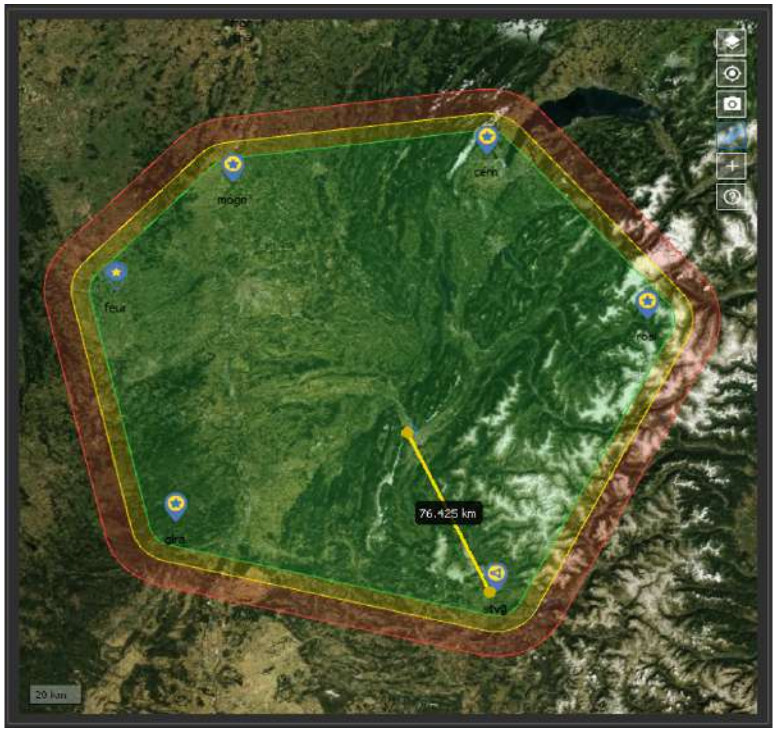


Figure 11: VBS network overview of the urban canyon automotive application.

(Figure 12) and (Table 5) show the obtained performance regarding to the reference. Concerning the seen gaps (Figure 12), they correspond to the moment when it was impossible to calculate a position because of the loss of GNSS signal. The VBS performance is excellent with an error of 1cm to 2cm and a fix rate of 87 % which is even better than what was obtained with the reference. On the other hand, errors ranging from 19 cm to 46 cm and a fix rate of 40 % were obtained when the master base is used in a single baseline RTK setup. This test highlights the fact that in lower ionospheric conditions, the VBS algorithm provides excellent performance even if the size of the network is very large (76 to 130 km).

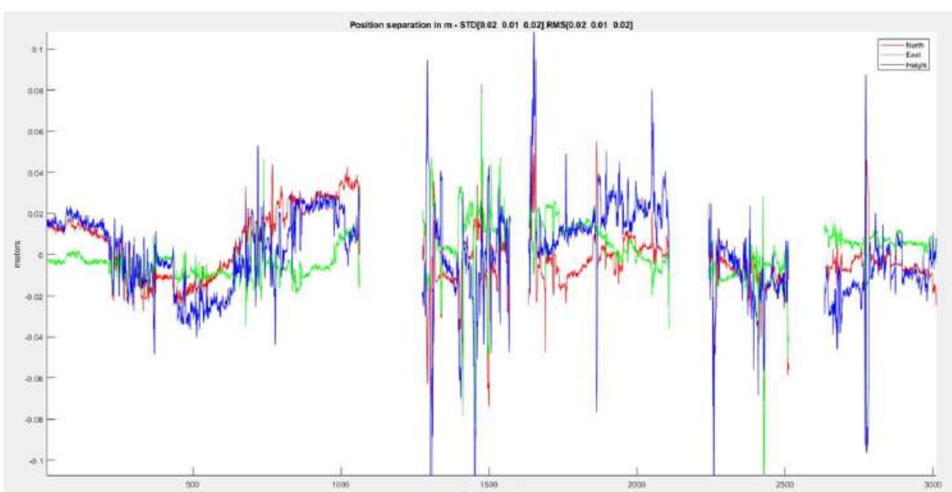


Figure 12: Automotive urban canyon: VBS performance compared to the reference.

Table 5: Automotive urban canyon: VBS RMS performance compared to the reference.

Error RMS (m)				
	N	E	D	Fix rate (%)
RTK Reference	-	-	-	85
VBS	0.02	0.01	0.02	87
RTK (w. master base)	0.19	0.19	0.46	40

c) Airplane Application

A very interesting scenario for the VBS algorithm is an airplane application where a very long trajectory is traveled (figure 16). Under these conditions, a standard RTK algorithm is unable to keep a consistent position estimation because the reference station needs to be switched very frequently. In this case, the data has been fragmented in several segments to use an RTK short baseline processing to generate multiple references. The baseline of the fragments goes from 1km to 17km and the fix rate of the obtained is 100%. Once again, a standard RTK processing between the rover and the VBS master base was generated to compare and highlight the VBS advantages under hard conditions. The network configuration is detailed in (Table 6):

Table 6: VBS networks details of an airplane application.

Test	Num Bases	Min baseline (km)	Max baseline (km)	Receivers
Airplane	9	14	417	Trimble, Ashtech, Spectra, Topcon

Despite of the huge size of the network and the airplane that travels over 330 km, the VBS provides excellent performance with 99% fixed solutions while the RTK short baseline using the master base provides only 44%. Regarding the errors on each segment, except segment 2, the VBS produces centimetric errors while those of traditional single base RTK are decimetric. In segment 2, the VBS and the single base RTK have almost the same performances because the master base is close to the rover which make the RTK short baseline work very well. This test highlights that the algorithm is able to cover very large distance with a single master base – as long as we have auxiliary bases along the trajectory, while maintaining a centimeter level accuracy. The advantage of this process is to enable continuous position output without any jump.

Figure 13: VBS network overview of the airplane application.

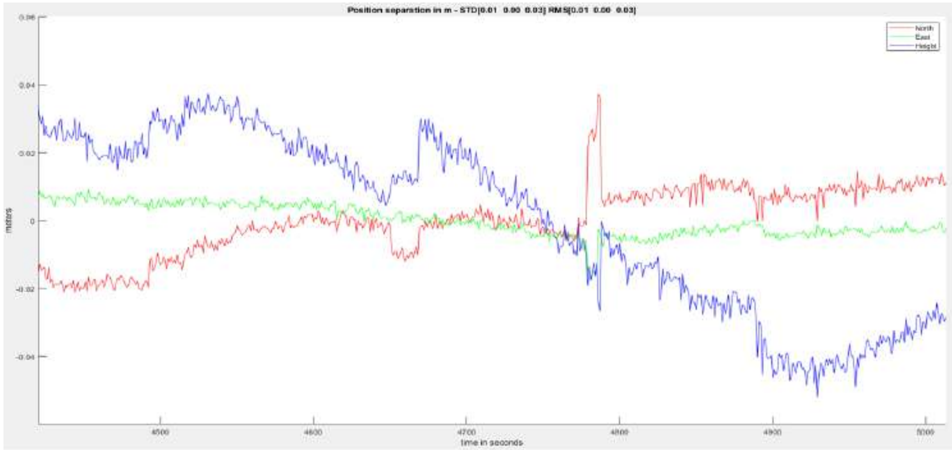


Figure 14: Airplane application: VBS segment 1 performance compared to the reference.

Table 7: Global test performance of airplane application.

Global Test	Fix rate (%)
VBS	99
RTK (w. master base)	44

Table 8: Segment 1 test performance of airplane application.

Error RMS (m)				
Segment 1	N	E	D	Fix rate (%)
VBS	0.01	0.01	0.03	99
RTK (w. master base)	0.08	0.05	0.22	10

Table 9: Segment 2 test performance of airplane application.

Error RMS (m)				
Segment 2	N	E	D	Fix rate (%)
VBS	0.01	0.01	0.03	100
RTK (w. master base)	0.01	0.01	0.02	100

Table 10: Segment 3 test performance of airplane application.

Error RMS (m)				
Segment 3	N	E	D	Fix rate (%)
VBS	0.01	0.02	0.05	99
RTK (w. master base)	0.09	0.03	0.13	31

VI. CONCLUSION

In this paper, we presented a Virtual base station algorithm with its performance assessment. The proposed algorithm greatly extends the range of PPK applications, providing a centimeter level accuracy, and relying only on freely available base station data. The algorithm can work well with typical baselines of 50 to 100km, and even more in low ionospheric conditions. The algorithm proves to be very versatile, covering either typical use cases, and up to more complex scenarios like very long trajectories or corridor mapping. The next steps in our development will be to challenge the algorithm in even more difficult ionospheric conditions.

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