How NLOS Signals affect GNSS relative positioning

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Abstract. Owing to the existence of non-line-of-sight (NLOS) signals in global navigation satellite system (GNSS) challenged environment, the accuracy of GNSS relative positioning is seriously damaged. This paper demonstrates the effects of NLOS measurement error on GNSS relative positioning for short-baseline in both theory and field test. The results show that the effects of NLOS signal in both pseudorange and carrier phase make the ambiguity unable to be successfully fixed. In addition, we have found that after removing the labelled NLOS observations, the positioning accuracy can be significantly improved. The more the available LOS satellites, the more the robustness against NLOS satellites of the ambiguity resolution. This implies that GNSS Multi-Frequency Multi-System technology might improve the performance of GNSS relative positioning because there would be sufficient LOS signals after the NLOS signals are removed.

1. Introduction

Global navigation satellite system (GNSS) relative positioning, for instance, Real Time Kinematic (RTK) has been widely used in various fields such as vehicle self-localization, geodetic survey, precision agriculture, autonomous refueling of Unmanned Aerial Vehicle (UAV). Different from the scene with good GNSS observation, in the GNSS challenge environment, including urban canyon, forest or mountain area, the sky visibility is limited, which cannot ensure the accuracy and reliability of GNSS positioning [1]. The existing research classify the signals in the restricted GNSS environment into three categories, which are LOS signals (only direct signals), NLOS signals (only reflected signals), and multipath signals (both direct and alternative path signals) [2]. Although both the NLOS signals and MP signals often arise together and are usually grouped together as MP effects, they are actually separate phenomena which may cause different observation errors [3]. Normally, the ranging errors caused by NLOS delay are greater than that caused by MP delay [4], which can introduce localization errors as much as 10 m [5].

In the published literatures, three well-known technologies are used to enhance the positioning performance in hash GNSS environments [6]. The first method focuses on distinguishing between LOS and NLOS signals. With using additional hardware, such as dual polarization antennas [7] and fish-eye camera [8], the NLOS signals can be identified effectively. In addition, the shadow matching method [9] which is based on offline 3D-maps, can be used to predict, identify and label NLOS satellites. However, in most cases, not all regions have high-precision 3D maps, and that are generally not open to the public. Without using auxiliary information, based on the features of the observations, such as C/N0, satellite elevation angle, and observation residuals are used for LOS/NLOS classification [10]. The second method tends to suppress, estimate and eliminate the ranging errors
caused by NLOS and multipath. At the level of signal receive, the vector tracking technology can reduce MP tracking errors and detect the injection of NLOS [11]. On the stage of observation processing, the code minus carrier (CMC) method is used to estimate code MP errors and the recursive least squares adaptive filtering algorithm is used to minimize the MP error [12]. In addition, the MP errors can be modeled as a Gauss-Markov process and the RTK performance can be improved by considering the time correlation of MP error [13]. The third method focuses on the constructive use of NLOS measurements, especially when the LOS measurements are insufficient for position estimation. Reasonable weighting of observations through robust estimation [14] or predict observation errors based on 3-D model [15] can be used to improve positioning performance.

Broadly speaking, GNSS observation errors caused by NLOS cannot be removed by differential techniques which may seriously damage the position accuracy. In this paper, some different features of received GNSS signals are introduced in Section II. After that the influence of NLOS measurement on GNSS relative positioning is analysed theoretically in Section III. The detailed field experiments set-up and results are shown in Section IV. Section V summarizes the conclusions and future work.

2. The Feature of Received GNSS Signals

Generally, the signal features can be extracted from the original measurement of GNSS receivers, which consists of measuring time, pseudorange, carrier phase, carrier noise ratio and doppler shift, etc. In this paper, the difference between NLOS and LOS signals are analysed based on the following signal features.

2.1. Carrier Noise Ratio (C/N0)

Usually, the NLOS signal is reflected or refracted to the GNSS receiver, both of which will cause signal attenuation. Therefore, the NLOS signals have smaller C/N0 than LOS signals in most cases [16] [17]. The C/N0 is one of the most commonly used features to distinguish LOS and NLOS signals. The C/N0 is also related to the receiving antenna pattern, reflection surface textures and other factors, so it is not reliable to distinguish LOS and NLOS signals only by C/N0.

2.2. Satellite Elevation

In general, GNSS signals with high elevation are unlikely to be blocked by buildings or other obstacles. The probability of LOS is highly correlated with the satellite elevation [5]. Thus, the satellites elevation is also a useful feature in signal classification.

2.3. Pseudorange Rate Consistency (PRC)

The pseudorange rate is the trend of pseudorange measurement over time. The pseudorange rate derived from pseudorange measurement can be expressed as:

$$\Delta \rho_i^s (t) = \rho_i^s (t) - \rho_i^s (t-1)$$

(1)

where, \( \rho_i^s (t) \) and \( \rho_i^s (t-1) \) is the pseudorange measurement of satellite \( i \) for frequency \( f \) at epoch \( t \) and \( t-1 \). As we known, the pseudorange rate is also related with doppler shift and can be formulated as:

$$\dot{\rho}_i^s (t) = -\lambda_i D_i^f (t)$$

(2)

where, \( \lambda_i \) is the carrier wavelength and \( D_i^f \) is the doppler shift measurement for satellite \( i \) at frequency \( f \). The doppler shift is estimated form the frequency tracking loop, which is less affected by multipath and reflected signal than pseudorange measurement that is estimated form the code tracking loop. Therefore, the consistency between the pseudorange rate derived from pseudorange measurement and doppler shift measurement could reveal the influence of NLOS signals [18]. The pseudorange rate consistency is expressed as:

$$PCR = \dot{\rho}_i^s (t) - \Delta \rho_i^s (t)$$

(3)
2.4. Difference of C/N0 Between Reference and Rover Station (D_{C/N0})
In general, the C/N0 decreases with the decrease of satellite elevation. In the short baseline scenario, the satellite elevation of the reference station and the rover station is approximately the same. If the receiving antenna is the same, the difference of C/N0 between reference station and rover station can eliminate the influence caused by different satellite elevation. The difference of C/N0 is defined as:

\[ D_{C/N0} = C/N0_{ref} - C/N0_{rov} \]  

(4)

2.5. Double Difference Pseudorange Residual (DDP_Res)
The pseudorange residual is also an important feature related to satellite visibility [19]. As for GNSS relative positioning, the difference between NLOS and LOS signals can be reflected more by posteriori residuals of double difference pseudorange residual. The double difference pseudorange residual can be formulated by:

\[ DDP_{Res} = \nabla \Delta \rho - \nabla \Delta R \]  

(5)

where, \( \nabla \Delta \rho \) is the original double difference pseudorange measurement, \( \nabla \Delta R \) is the calculated double difference distance between satellites and stations.

2.6. Double Difference Carrier Phase Residual (DDC_Res)
In GNSS high precision positioning application scenarios, the accuracy of carrier phase is the key factor to determine the final positioning accuracy. Similar to the double difference pseudorange residuals, the double difference carrier phase residuals can better reflect the influence of NLOS signal on the positioning results. The double difference carrier phase residual can be formulated by:

\[ DDC_{Res} = \nabla \Delta \phi_f - \lambda_i^{\nu} \nabla \Delta R - \nabla \Delta N_f \]  

(6)

where, \( \nabla \Delta \phi_f \) is the original double difference carrier phase in cycle, \( \nabla \Delta N_f \) is the double difference integer ambiguity at frequency \( f \).

3. The Influence of NLOS Signals on GNSS Relative Positioning

3.1. The Principle of Relative Positioning and Ambiguity Resolution
The normal GNSS relative positioning method uses double difference (DD) pseudorange and carrier phase observations. The receiver and satellite dependent errors can be cancelled through differential technology. The differential atmospheric delays between receivers can be also ignored as well for short baselines. The linearized double difference observations can be formed as flow [19]:

\[ \begin{bmatrix} \nabla \Delta \phi_f \\ \nabla \Delta \rho \end{bmatrix} = \begin{bmatrix} \lambda_i^{\nu} B & A \\ B & 0 \end{bmatrix} \begin{bmatrix} b \\ \nabla \Delta N_f \end{bmatrix} + \begin{bmatrix} \nabla \Delta e_{\phi} \\ \nabla \Delta e_{\rho} \end{bmatrix} \]  

(7)

where \( \nabla \Delta \phi \) is the DD carrier phase vector, \( \nabla \Delta \rho \) is the DD pseudorange vector, \( B \) is the design matrix which contains the geometry of satellites and receivers, \( A \) is an unit matrix, \( b \) is the unknown vector of relative position, \( \nabla \Delta N \) is the unknown DD integer ambiguity vector, \( \nabla \Delta e_{\phi} \) and \( \nabla \Delta e_{\rho} \) are the DD pseudorange and carrier phase observation noise, respectively.

1) The 3D position solution \( \hat{b} \) and real-valued DD ambiguity vector \( \hat{N} \) are estimated, together with their covariance matrix \( Q_{\hat{b}}, Q_{\hat{N}} \) and \( Q_{\hat{b}\hat{N}} \).

2) The ambiguity resolution method, such as bootstrapping, LAMBDA [21], Integer Aperture estimation [22], is used to search for the optimal integer ambiguity solution \( \hat{N} : \)

\[ \hat{N} = \arg \min_N \| \hat{N} - N \|_{Q_{\hat{N}}}^2, N \in \mathbb{Z}^n \]  

(8)

where, \( \| \cdot \|_{Q_{\hat{N}}} = (\cdot)^T Q_{\hat{N}}^{-1} (\cdot) \).
4

The ambiguity validation test is performed in order to ensure the reliability of ambiguity resolution. In this study, the effective R-ratio test is used for ambiguity test, which can be expressed by the following formula:

\[
T = \frac{\left\| \hat{N}_2 - \hat{N} \right\|_{Q_b}^2}{\left\| \hat{N}_1 - \hat{N} \right\|_{Q_b}^2} \geq T_h
\]  

(9)

where \( T \) is the constructed test value, \( \hat{N}_1 \) and \( \hat{N}_2 \) are the optimal and suboptimal ambiguity candidates, \( T_h \) is a threshold value selected based on experience. In this study, the ratio test threshold was set to 3.

Once the optimal ambiguity candidate passes the test, it is then used to update the ‘float’ position \( \hat{b} \), so as to obtain a higher precision ‘fixed’ position \( \hat{b} \):

\[
\hat{b} = \hat{b} - Q_{\hat{b}}^{-1} \left( \hat{N} - \hat{N} \right)
\]  

(10)

3.2. The Influence of NLOS Signals on Ambiguity Resolution

Unlike multipath measurements, NLOS observations cannot be modelled as Gaussian distribution with mean value equals to zero. Assuming that all visible satellites of reference station are LOS signals, the number of satellites in common view is \( n \), and \( m \) satellites are labelled as NLOS signals in rover station. Suppose that the DD pseudorange errors and DD carrier phase errors are \( d_{\rho} = (0, ..., 0, d_{\rho}^{(m+1)}, ..., d_{\rho}^{n})^T \) and \( d_{\phi} = (0, ..., 0, d_{\phi}^{(m+1)}, ..., d_{\phi}^{n})^T \), respectively. The biases vector of float solution can be written as [19]:

\[
\Delta b = \left( G^T Q_{\phi}^{-1} G \right)^{-1} G^T Q_{\rho}^{-1} \left[ d_{\rho} \right]
\]

(11)

\[
G = \begin{bmatrix}
\lambda_{i,1} B \\
B & 0
\end{bmatrix}
\]

(12)

where, \( \Delta b \) and \( \Delta N \) are the position error vector and DD ambiguity error vector caused by DD errors, respectively. \( Q_{\phi} \) is the variance-covariance matrix which represents the stochastic properties of DD observations. Then we can obtain the affected part of float ambiguities:

\[
\Delta N = -\lambda_{i,1} H d_{\rho} + d_{\phi}
\]

(13)

\[
H = B \left( B^T W_{n-1} B \right)^{-1} B^T W_{n-1}
\]

(14)

where, \( W_{n-1} \) is a constant matrix which is related to number of satellites in view.

\[
W_{n-1} = \left[ I_{n-1} - \frac{1}{n} E_{n-1} \right]
\]

(15)

where, \( I_{n-1} \) is an \( n-1 \) dimensional matrix with all entries are equal to 1, \( E_{n-1} \) is an \( n \) dimensional unit matrix.

According to [19], the bias-affected Z-transformation bootstrapped success rate can be expressed as:

\[
P_{\phi}(z_{\phi} = z) = \prod_{i=1}^{n} \left[ \Phi \left( \frac{1 + 2c_i Z^T \hat{N} \Delta N}{2c_i D D_i} \right) + \Phi \left( \frac{1 - 2c_i Z^T \hat{N} \Delta N}{2c_i D D_i} \right) - 1 \right]
\]

(16)

where, \( c_i \) denotes the \( 1 \times n \) vector with its \( i \)-th element equals to 1 while other entries equal to 0, matrix \( L_i \) and \( D_i \) can be obtained from the triangular factor of \( Z^T Q_{\phi} Z = L_i D_i L_i^T \), \( Z \) is the transformation matrix.

From (13), (16), it can be seen that the success rate of ambiguity resolution is reduced due to the influence of pseudorange and carrier phase error caused by NLOS observation. The influence of pseudorange error on ambiguity is also related to satellite geometry.
4. Field Test and Analysis of Results

4.1. Data Collection

In order to analyze the influence of NLOS signals on GNSS relative positioning, a static filed test had been carried out in National University of Defense Technology in July 2020. A rover station and a reference station are set up on the building roof of our laboratory. GNSS receiver is NovAtel ProPak6 with an antenna (NovAtel GPS-703-GGG) for high precise positioning. The reference station is in an open sky environment, while the rover antenna was about 2.5m next to buildings which makes the occurrence of NLOS signal obvious. Fig. 1 shows the outline of the rooftop with the allocation of the GNSS antenna and obstacles.

![Fig.1 The outline of the rooftop](image1)

![Fig.2 The sky plot overlapped with building boundaries and GPS satellites trajectory](image2)

The field testing in July 2nd, 2020 is selected for analysing the influence of NLOS signals on GNSS relative positioning. We developed the post-processing software for GNSS relative positioning base on RTKLIB. Two hours of double-frequency (L1/L2) GPS data were collected, and then processed in only single epoch mode. As shown in Fig. 2, the trajectory of visible satellites during the field test is projected onto a hemisphere along with the boundaries of surrounding building. Different colors in Fig. 2 show the L1 C/N0 of rover receiver. The triangle indicates the position of each satellite observed for the first time, while the circle represents where it was last observed. Fig. 3 shows the labelled LOS and NLOS signals according to the building boundaries. It is obvious that satellites with PRN number of 10 and 20 are of higher potential to be blocked because their elevation decrease over time, and there are relatively high buildings towards their azimuth direction.
4.2. Feature Analysis of GNSS measurements

The analysis of the differences between LOS and NLOS signals can not only provide help for signal classification, but also enable us to better understand the influence of GNSS measurement on positioning.

As discussed earlier, additional features such as satellite elevation and PRC, could be used to improve the classified accuracy of the traditional single feature based on C/N0. Fig. 4 shows the relationship between the C/N0 and satellite elevation of the labelled NLOS and LOS signals. It can be seen from Fig. 4 that the C/N0 values of most NLOS signals are less than 40 dB/Hz. At the same elevation angle, the C/N0 of NLOS signal is lower than that of LOS signal.

Fig. 5 shows the relationship between the C/N0 and PCR of the labelled signals. The PCR of LOS signals range from -0.2m to 0.2m with a standard deviation close to 0.03m. The PCR of NLOS signals largely range from -5 to 5m at L1 frequency, which is smaller than that of L2 frequency.

Fig. 6 shows the contrast between C/N0 and DC/N0 at L1 frequency. The DC/N0 of LOS signals is mainly vary from -5 dB/Hz to 5 dB/Hz, while that of NLOS signals is from 5dB/Hz to 20dB/Hz. It is obvious that the C/N0 between NLOS and LOS signals have a larger overlap than that of DC/N0. Therefore, considering the C/N0 of reference station can be better than using that of rover station to distinguish NLOS and LOS signals.
Fig. 5 Relationship between PCR and C/N0 of the labelled signals

Fig. 6 The histogram of C/N0 and D_{C/N0} for different signals at L1 frequency

Fig. 7 The double difference pseudorange residual of satellites (reference satellite: PRN 32); (a) the DDP_Res of NLOS at L1 frequency; (b) the DDP_Res of LOS at L1 frequency; (c) the DDP_Res of NLOS at L2 frequency; (d) the DDP_Res of LOS at L2 frequency
Fig. 7 The double difference pseudorange residual of different satellites at different frequency is presented in Fig. 7. It is obvious that the pseudorange residual of LOS signals changes smoothly with time with the mean value close to zero. However, the pseudorange residual of NLOS signals fluctuate greatly and there are frequent jumps for both L1 and L2 frequency. Fig. 8 shows the double difference carrier phase residual. The carrier phase residual of LOS signal mainly ranges from -0.1 cycle to 0.1 cycle, which can be modelled as a Gaussian distribution with zero mean and standard deviation of 0.03 cycle. However, the carrier phase residual of NLOS signals fluctuate greatly and there is an obvious trend term which may regard as non-zero bias for both L1 and L2 frequency. As discussed before, the non-zero bias of double difference carrier phase may decrease the ambiguity fixed rate.

Fig. 9 The double difference integer ambiguity of labelled NLOS signals (reference satellite: PRN 32); (a) The double difference ambiguity of PRN 10, PRN 20 and PRN 31 at L1 frequency; (b) The double difference ambiguity of PRN 10, PRN 20 and PRN 31 at L2 frequency

The double difference integer ambiguity of labelled NLOS signals is presented in Fig. 9. It can be seen that when the state of signal changes, whether from LOS to NLOS (PRN 10 and PRN 20) or from NLOS to LOS (PRN 31), the double difference integer ambiguity will remain unchanged for a period of time. However, shown in Fig. 8, during this period, for the signal whose state changes to NLOS, the double difference carrier phase residuals gradually increase for signals with state changing to NLOS, and gradually decrease for signals with state changed to LOS.
4.3. Results and analysis of GNSS relative positioning

To analysis the effects in GNSS relative positioning of NLOS signals, the integer ambiguity fixed rate and positioning error has been calculated. The processing parameters stay the same for all two computation scenarios, two frequency GPS using both pseudorange and carrier phase observations, with elevation cutoff of 15 degree. The two chosen computation scenarios are

1) Original: all the original GPS observations are taken.
2) LOS only: solely labelled LOS observations are taken.

The error of the estimated relative positioning is shown in Fig. 10, Fig. 11 and TABLE I. The table also list the success rate of ambiguity fixing (SRAF).

![Fig. 10](image)

Fig. 10 The error of relative positioning for two computation scenarios;
(a) The horizontal error; (b) The Vertical error

![Fig. 10](image)

Fig. 10 The CDF of 3D error for two computation scenarios

As shown in Fig. 10, in most cases (such as, epoch 2350~2550, epoch 2600~2800, epoch 5250~5550), when the marked NLOS signals are removed in the relative positioning process, the positioning accuracy of the corresponding period will be greatly improved due to the successful fixing of the integer ambiguity. Combined with Fig. 8, it can be seen that the main reason of the ambiguity fixing may be that the NLOS signals with large carrier phase residual are eliminated. However, there are some cases where the integer ambiguity cannot be successfully fixed after removing the labelled NLOS signal, such as epoch 4100~4150. Combined with Fig. 3 and Fig. 8, it can be seen that during
epoch 4100–4150, the state of PRN 10 changes from LOS to NLOS, and the double difference carrier phase residual is smaller than 0.05 cycle. When PRN 10 is eliminated, the number of available satellites is reduced from 6 to 5.

Fig. 11 shows the cumulative distribution function (CDF) of 3D position error. When all observations are taken into consideration in the process, the 3D position error smaller than 1 m accounts for about 60%, while the value improved to about 80% after the labelled NLOS signals are eliminated.

Table 1 The statistic result of relative positioning

|         | Horizontal (m) | Vertical (m) | 3D Position (m) | SRAF   |
|---------|----------------|--------------|-----------------|--------|
| Original| 1.029          | 1.745        | 2.025           | 42.06% |
| LOS Only| 0.572          | 1.278        | 1.400           | 76.88% |

Table 1 shows the position error of relative positioning. The SRAF of the LOS only scenario is 76.88%, which is 34% higher than the Original scenario. The position errors in horizontal and vertical directions are reduced from 1.029 m, 1.745 m to 0.572 m, 1.278 m, respectively. Compared with the Original scenario, after the labelled NLOS signals are eliminated, the 3D position accuracy is improved by 30.86%, which conforms that when the NLOS signals are labelled correctly and eliminated reasonably, the relative positioning accuracy will be greatly improved.

5. Conclusion
In this contribution, we have shown the effect of NLOS signals on GNSS relative positioning. First, some features related to satellite visibility have been discussed. Then, the influence of pseudorange and carrier phase error of NLOS observation on ambiguity resolution is analysed theoretically. The field test results show that the difference of C/N0 between reference and rover station can distinguish LOS and NLOS signals better than single C/N0. The double difference residual can well reflect the influence of NLOS signals on GNSS relative positioning. The more the LOS satellites, the robust the relative position resolution against NLOS signals. The ambiguity can be resolved after removing the NLOS satellites. This implies that GNSS Multi-Frequency Multi-System technology might improve the performance of RTK because there would be sufficient LOS signals after the NLOS signals are removed.

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References
[1] Kbayer, N., and Sahmoudi, M.: ‘Performances Analysis of GNSS NLOS Bias Correction in Urban Environment Using a Three-Dimensional City Model and GNSS Simulator’, in IEEE Transactions on Aerospace and Electronic Systems, vol. 54, no. 4, pp. 1799-1814, Aug. 2018, doi: 10.1109/TAES.2018.2801658
[2] Ollander, S., Bode, F. and Baum, M.: ‘Multi-Frequency GNSS Signal Fusion for Minimization of Multipath and Non-Line-of-Sight Errors: A Survey’, 2018 15th Workshop on Positioning, Navigation and Communications (WPNC), Bremen, 2018, pp. 1-6, doi: 10.1109/WPNC.2018.8555856
[3] Groves, P.: ‘Multipath vs. NLOS signals. How does non-line-of-sight reception differ from multipath interference’, Inside GNSS Mag., vol. 8, pp. 40–42, 2013
[4] Abolfathi Momtaz, A., Behnia, F., Amiri, R., and Marvasti, F.: ‘NLOS Identification in Range-Based Source Localization: Statistical Approach’, in IEEE Sensors Journal, vol. 18, no. 9, pp. 3745-3751, 1 May1, 2018, doi: 10.1109/JSEN.2018.2810257
[5] Hsu, L.: ‘Analysis and modeling GPS NLOS effect in highly urbanized area’, *GPS Solut* 22, 7 (2018), doi:10.1007/s10291-017-0667-9

[6] M. Adjrad and P. D. Groves, “Intelligent Urban Positioning: Integration of Shadow Matching with 3D-Mapping-Aided GNSS Ranging,” Journal of Navigation, vol. 71, no. 1, pp. 1–20, 2018.

[7] Egea-Roca, D., Tripiana-Caballero, A., López-Salcedo, J.A., et al.: ‘GNSS Measurement Exclusion and Weighting with a Dual Polarized Antenna: The FANTASTIC project,’ 2018 8th International Conference on Localization and GNSS (ICL-GNSS), Guimaraes, 2018, pp. 1-6, doi: 10.1109/ICL-GNSS.2018.8440897

[8] Areeyapinun, T., and Kitani, T.: ‘A prototype of a precision forecasting system for real-time navigation with RTK-GNSS’, in Proc. of the 11th International workshop on Informatics (IWIN2017), pp. 193–200, Informatics Society, 2017

[9] Groves, P.: ‘Shadow Matching: A New GNSS Positioning Technique for Urban Canyons’, *Journal of Navigation*, vol. 64, no. 3, pp. 417–430, Jul. 2011

[10] Yozevitch, R., Ben Moshe, B., and Weissman, A.: ‘A Robust GNSS LOS/NLOS Signal Classifier,’ *Navigation*, vol. 64, no. 3, pp. 429-442, 2016, doi: 10.1002/navi.166

[11] Hsu, L., Jan, S., Groves, P.D. *et al.: ‘Multipath mitigation and NLOS detection using vector tracking in urban environments’, GPS Solut* 19, 249–262 (2015), doi:10.1007/s10291-014-0384-6

[12] Yedukondalu, K., Sarma, A.D., and Kumar, A.: ‘Mitigation of GPS multipath error using recursive least squares adaptive filtering’, 2010 IEEE Asia Pacific Conference on Circuits and Systems, Kuala Lumpur, 2010, pp. 104-107, doi: 10.1109/APCCAS.2010.5775022

[13] Henkel, P., and Sperl, A.: ‘Real-time kinematic positioning for unmanned air vehicles’, 2016 IEEE Aerospace Conference, Big Sky, MT, 2016, pp. 1-7, doi: 10.1109/AERO.2016.7500933

[14] Lesouple, J., Robert, Y., Sahmoudi, M., Tourneret, J., and Vigneau, W.: ‘Multipath Mitigation for GNSS Positioning in an Urban Environment Using Sparse Estimation’, in *IEEE Transactions on Intelligent Transportation Systems*, vol. 20, no. 4, pp. 1316-1328, April 2019, doi: 10.1109/TITS.2018.2848461.

[15] Ahmad, Khairol Amali & Sahmoudi, Mohamed & Macabiau, Christophe & Bourdeau, Aude & Moura, Grégory. (2013). Reliable GNSS Positioning in Mixed LOS/NLOS Environments Using a 3D Model

[16] Sun, Rui., Wang, G., Zhang, W., et al. ‘A gradient boosting decision tree based GPS signal reception classification algorithm’, Applied Soft Computing 86 (2019):105942.

[17] L. Wang, P.D. Groves, and M. K. Zieba, ‘Smartphone shadow matching for better cross-street GNSS positioning in urban environments’, *Journal of Navigation*, vol.68, pp.411-433, 2015.

[18] Xu H, Angrisano A, Gaglione S, et al. ‘Machine Learning based LOS/NLOS Classifier and Robust Estimator for GNSS Shadow Matching’, Satellite Navigation, 2020.

[19] Hsu,L., Tokura,H., Kubo,N., et al. ‘Multiple Faulty GNSS Measurement Exclusion Based on Consistency Check in Urban Canyons’, IEEE Sensors Journal, 2017, PP(99):1-1.

[20] Ye X , Xiao W , Liu W , et al. ‘Influence of pseudorange biases on single epoch GNSS integer ambiguity resolution’, IEEE Access, 2020, PP(99):1-1.

[21] Teunissen, P.J.G. ‘The least-squares ambiguity decorrelation adjustment: a method for fast GPS integer ambiguity estimation’,Journal of Geodesy, 1995,70(1-2), pp.65-82.

[22] Teunissen, P.J.G. ‘Integer aperture bootstrapping: a new GNSS ambiguity estimator with controllable fail-rate’, Journal of Geodesy, 2005, 79(6/7):389-397.