Pseudolites as UAV Navigation Support

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Abstract: *The augmentations of the Global Navigation Satellite Systems (GNSS) are widely used. Pseudolites make it possible for users to augment navigation systems considering specific local needs of users. Urban canyons, rough terrain, radio signal disturbances are only some of the problems that can make GNSS satellite signal unavailable or disturbed. The navigation of Unmanned Aerial Vehicles (UAV) has specific requirements on GNSS navigation that can be solved by a network of pseudolites. Pseudolites augmentations were analyzed in the UAV test flight area. Dilutions of Precision (GDOP, PDOP, HDOP, VDOP and TDOP) were used to analyze the quality of pseudolites and GNSS radio-navigation network geometry. The scenarios considering the UAV navigation using ground-based pseudolites and satellite based GPS, GLONASS and Galileo are analyzed.*

Key words: *augmentation, DOP, GNSS, pseudolites, radio-navigation network, UAV*

1. Introduction

The availability, accuracy and reliability of GNSS positioning systems are not guaranteed all the time and at every point on or near the Earth's surface. In some cases, the number of visible satellites may not be sufficient to determine the user's position reliably. Urban canyons, valleys, deep open-cut mines, near-shore applications, rough terrain and radio signal disturbances are only some of the problems that can make satellite signal unavailable or disturbed to the extent that accuracy and reliability become highly questionable [Morley 1997] [Saka et al. 2004]. To solve these problems, the augmentations of GNSS are used. The purpose of the GNSS augmentation system is to reduce or eliminate influences that deteriorate the quality of position, navigation and timing services [Gorski, Gerten 2007]. Pseudolite augmentation can be used to improve availability and accuracy of GNSS based positioning or they can be implemented as an independent radio-navigation network [Wang 2002]. Some of the benefits are: greater positioning accuracy, improved reliability, availability, signal continuity, integrity monitoring and a reduction of integer ambiguity resolution time [Wang 2005]. Optimizing pseudolites, satellites and UAV receiver geometry is a core problem in building a pseudolite positioning network [McKay, Pachter 1997].

UAV mission planning involves knowledge from many fields as: navigation and positioning, geodesy, flight, regulations, safety measures and other [Santamaria et al. 2008]. UAV navigation has specific navigation requirements in which pseudolite augmentation of the existing GNSSes can improve UAV navigation or can be used as an independent radio-navigation network.

2. Pseudolites

Pseudolites (PLs) are pseudo-transmitters that can be used to build radio-navigation networks to perform real-time dynamic positioning. Pseudolites provide signals to GNSS users so that they can improve radio-navigation network geometry and positioning accuracy [Stewart 1997]. PLs typically transmit pseudo range and carrier phase signals at GNSS frequency bands. Normally, standard GNSS receivers with minor firmware modifications can track PL signals. Pseudolites are mainly used in the places where real-time positioning at centimetre-level is required. Locata is a ground based system of transmitters that can be operationally used to design a network for local needs and determine a position with centimetre accuracy in real time [Novaković et al. 2010]. In an indoor space where the GNSS signals are not available, a set of pseudolites can be used to replace the whole GNSS constellation. Optimally located pseudolite and reference receiver can significantly improve the geometric strength of positioning solutions and reduce the effects of nonlinearity and pseudolite errors [Parkinson, Fitzgibbon 1986].

Basically, three kinds of pseudolite navigation systems can be developed [Dai et al. 2001]:

- GNSS augmentation with pseudolites,
- independent pseudolite network,
- inverted pseudolite-based positioning system; e. g. mobile pseudolite monitored by GNSS.

PLs have specific error sources. Some of the challenging issues are pseudolites geometry design, multipath, tropospheric delay, clock synchronisation, location-dependent errors, pseudolite biases and near-far problem. The near-far problem is caused by the variation in the received signal power of the pseudolites when the distance between the receiver and the transmitters changes. A pseudolite in the vicinity of a receiver may overwhelm the signals from other pseudolites/satellites and jam the receiver. However, on the other hand, if some of the pseudolites reside too far, their signal level may be too weak to allow the receiver to detect them.

PLs geometry design is important for pseudolite augmented positioning systems [Yongqi, Xiufeng 2006]. Although various functions are suggested in the literature, the most often used is the GDOP that is used as a precision indicator in GNSS applications. In this work, Dilutions of Precision (GDOP, PDOP, HDOP, VDOP and TDOP) are used as quality indicators of radio-navigation network geometry. DOP is estimated from the network design matrix.

3. Quality of radio-navigation network geometry and positioning accuracy

In analogy with GPS, PL carrier phase observable can be given as

$$\varphi_r^{PL} = \rho_r^{PL} + N_r^{PL}\tau + c\delta t^{PL} - c\delta t_r + \delta_{pos} + \delta_{trop}^{PL} + \delta_{mp}^{PL} + \delta_n^{PL}, \qquad (1)$$

where ρ_r^{PL} is the geometric distance between a pseudolite PL and receiver r, δt^{PL} PL clock error, δt_r receiver clock error, δ_{pos} PL location error, δ_{trop}^{PL} tropospheric delay, δ_{mp}^{PL} PL signal multipath, δ_n^{PL} observation noise, τ signal wavelength, N_r^{PL} integer ambiguity, and c is the speed of light. Related positioning accuracy considering the radio-navigation network (PLs and GNSS satellites) can be expressed with the equation

$$\Delta\vec{x} = (G^T G)^{-1} G^T \cdot \Delta\vec{\rho}_c. \qquad (2)$$

Here $\Delta\vec{x}$ is the positioning error vector, G is the geometry matrix and $\vec{\rho}_c$ is the vector of corrected pseudo range errors. In the expression (2), $(G^T G)^{-1}$ is the Dilution of Precision (DOP) matrix and $G^T \cdot \Delta\vec{\rho}_c$ is the user range error.

$$(G^T G)^{-1} = \begin{bmatrix} q_{XX} & q_{XY} & q_{XZ} & q_{Xt} \\ q_{XY} & q_{YY} & q_{YZ} & q_{Yt} \\ q_{XZ} & q_{YZ} & q_{ZZ} & q_{Zt} \\ q_{Xt} & q_{Yt} & q_{Zt} & q_{tt} \end{bmatrix}. \qquad (3)$$

Diagonal elements of matrix (3) are used to calculate Geometric DOP (GDOP), Position DOP (PDOP), Horizontal DOP (HDOP), Vertical DOP (VDOP) and Time DOP (TDOP) as follows:

$$\begin{aligned} GDOP &= \sqrt{q_{XX} + q_{YY} + q_{ZZ} + q_{tt}}, \\ PDOP &= \sqrt{q_{XX} + q_{YY} + q_{ZZ}}, \\ HDOP &= \sqrt{q_{XX} + q_{YY}}, \\ VDOP &= \sqrt{q_{ZZ}}, \\ TDOP &= \sqrt{q_{tt}}. \end{aligned} \qquad (4)$$

DOP is a measure of the quality of network geometry. DOP can be interpreted as the reciprocal volume of a tetrahedron (in the case of four satellites) which is defined by the peak that represents the receiver antenna and receiver sites that are actually the connections between receiver and transmitter [Matišić 2014]. If the value of DOP is a small scalar value, the volume of the body is bigger and geometry is good. If the value of DOP is a large scalar value, the volume of the body is smaller and thus geometry is bad.

Positioning accuracy measures the uncertainty of a positioning solution based on one-way range measurements from GNSS satellites and/or PLs. If four or more of transmitters are in view of a UAV receiver, a navigation solution consisting of the position of the receiver and the offset between the receiver clock and the GNSS clock can be computed.

4. Influence of PLs and UAV receiver range uncertainties on positioning accuracy

PLs of different qualities can be found in the market. Numerical tests were made to judge how PL noise can influence positioning accuracy. Computations were done for a test area around Sv. Nikola church near the town Nin [figure 4.1]. The test area is mostly a flat terrain and covers an area of 113 km^2. A flight path of the UAV was simulated at an altitude of 300 m above MSL. Then, a grid of resolution, Lat/Long 0.002 deg was created. The number of computational grid points was 1458. The simulation started on 17th Mar. 2016 at 11:00:00.000 UTC and it took as long as the UAV's flight time.

To make simultaneous satellite and ground-based PLs measurements, two antennas are needed on the UAV because of different directions of the satellite and PLs transmitting signals. Phase correction of antennas offset should be calculated. In order to calculate the correction, the antennas offset vector in the UAV's body frame needs to be determined. Because of changing the position of UAV, the line of sight vector between UAV and PL should also be considered in the calculation [Lee et al. 2002]. The accuracy of the correction is primarily affected by the antenna offset measurement and attitude error.

The positioning accuracy was calculated for the grid points using different PL range uncertainties. The first calculation involved a range uncertainty of 1 mm for all seven PLs, and the second used 2 mm, respectively. The differences of average values of the positioning accuracy for the whole test area was 1.2 cm and the biggest differences of positioning accuracy in the test area was 2.7 cm. This simulation is showing that one millimeter change of PL range uncertainty caused more than a ten times bigger difference in positioning accuracy. That indicates that PL noise and quality can significantly reduce UAV positioning accuracy.

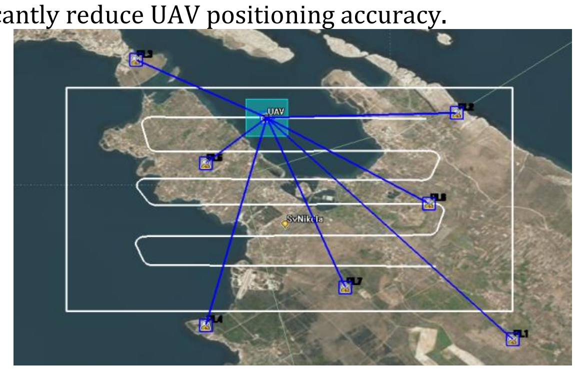

Figure 4.1 PLs and UAV in the test area

To judge the influence of a UAV GNSS receiver's quality on the positioning accuracy, it was calculated for the grid test area grid with different UAV receiver range uncertainties. In the first solution, the UAV receiver range uncertainty was 1 mm and in the second solution, it was 2 mm. The differences between average position accuracies is 9 mm, but the differences can reach up to 20 mm. This simulation is showing that one millimetre change of the UAV receiver range uncertainty caused a little bit less than ten times the difference in positioning accuracy. That indicates that a poor UAV receiver can cause significant lower positioning accuracy.

The results of all previous calculations are indicating that the influence of UAV receiver quality on the positioning accuracy is a little bit lower than the influence of the transmitters (PLs) quality.

5. UAV positioning network quality considering PLs and other GNSS systems

The quality of UAV navigation depends on radio-navigation network geometry (PLs and GNSS). Dilution of Precision (DOP) matrix (2) contains derivations of observables and combined PLs and GNSS networks were treated using the same equations [Rzepecka et al. 2005] [Cobb 1997]. To judge the influence of PLs, GPS, GLONASS and Galileo on UAV positioning, different radio-navigation networks were simulated. Calculation and analysis for the following radio-navigation networks were made: PLs, GPS, GPS+PLs, GLONASS, GLONASS+PLs, Galileo+PLs and PLs+GPS+GLOANS+Galileo. DOP values were computed for the test area using expressions from (4) in AGI STK 11. GNSS satellite positions were predicted for the simulation time. To visually display position accuracy of the UAV, a range of colours from red to green is displayed on the grid. Red indicates the best DOP values, and green the poorer results.

5.1. Quality of PLs radio-navigation network

Radio-navigation network geometry was calculated using seven PLs [figure 5.1]. They are ground distributed to cover the UAV flight area and were placed considering the terrain constraints.

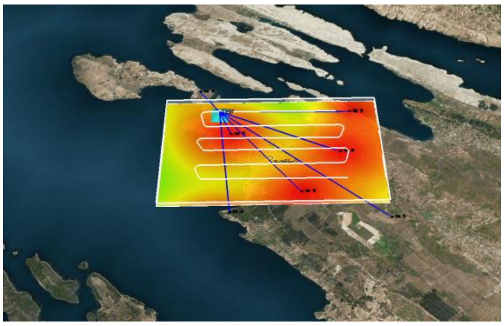

Figure 5.1 PLs radio-navigation network

In table 5.1, DOP values of the PLs radio-navigation network geometry are given.

Table 5.1 DOPs of PLs radio-navigation network

	Min	Max	Average
GDOP	1.68	32.22	14.41
HDOP	0.79	4.13	1.37
PDOP	1.59	32.09	14.33
TDOP	0.55	4.23	1.41
VDOP	1.28	31.98	14.23

5.2. Quality of PLs and GPS radio-navigation network

In this analysis there is a GPS network augmented by 7 PLs given. During the simulation time, 12 GPS satellites were visible from the test site [figure 5.2]. The DOPs of the joined PLs and GPS network are given in the table 5.2.

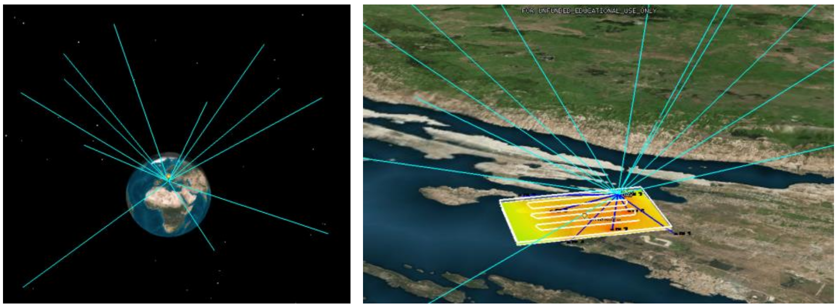

Figure 5.2 PLs and GPS radio-navigation network

Table 5.2 DOPs of PLs and GPS radio-navigation network

	Min	Max	Average
GDOP	0.84	1.13	0.98
HDOP	0.54	0.65	0.58
PDOP	0.79	1.05	0.92
TDOP	0.28	0.42	0.34
VDOP	0.56	0.83	0.71

In the table 5.3 there are the differences between GPS only solution and joined PLs and GPS solution given. All DOP values are indicating better results in the joined PLs and GPS solution. It means that higher positioning quality was achieved by using PLs augmentation.

Table 5.3 Differences between joining PLs and GPS solution and GPS only

	Min	Max	Average
GDOP	-0.68	-0.38	-0.54
HDOP	-0.27	-0.16	-0.23
PDOP	-0.58	-0.32	-0.45
TDOP	-0.37	-0.22	-0.30
VDOP	-0.54	-0.28	-0.39

5.3. Quality of PLs and Galileo radio-navigation network

Galileo system has six operational satellites. However, only three were available in the test area during the simulation time. The results are given in table 5.4.

Table 5.4 DOPs of PLs and Galileo radio-navigation network

	Min	Max	Average
GDOP	1.33	7.04	3.57
HDOP	0.71	1.97	0.97
PDOP	1.26	6.79	3.50
TDOP	0.38	1.51	0.61
VDOP	0.95	6.28	3.26

5.4. Quality of PLs and GLONASS radio-navigation network

Eight GLONASS satellites were visible during the time of UAV flight simulating over the test area [figure 5.3]. In table 5.5 DOPs of the PLs and GLONASS radio-navigation network are given.

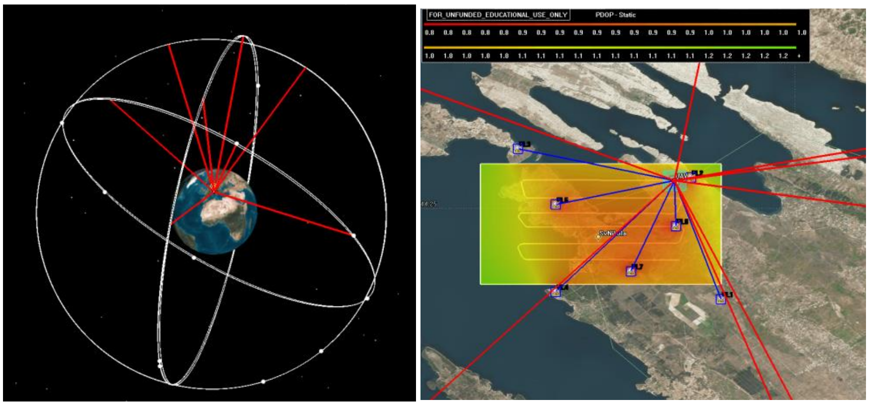

Figure 5.3 PLs and GLONASS radio-navigation network

Table 5.5 DOPs of PLs and GLONASS radio-navigation network

	Min	Max	Average
GDOP	0.88	1.28	1.06
HDOP	0.56	0.72	0.61
PDOP	0.83	1.18	1.00
TDOP	0.28	0.49	0.36
VDOP	0.59	0.93	0.78

In table 5.6, the differences between only GLONASS solution and joined PLs and GLONASS radio-navigation networks are given. All differences indicate that the joined solution is better than the only GLOSNASS solution. PLs augmentation is improving GLONASS positioning.

Table 5.6 Differences between PLs and GLONASS solution and only GLONASS solution

	Min	Max	Average
GDOP	-0.93	-0.54	-0.75
HDOP	-0.37	-0.21	-0.31
PDOP	-0.80	-0.46	-0.64
TDOP	-0.49	-0.28	-0.41
VDOP	-0.74	-0.41	-0.55

5.5. Quality of PL, GPS, GLONASS and Galileo radio-navigation network

The simulation of combined PLs, GPS, GLONASS and Galileo network is made for the test area [figure 5.4]. The results are given in table 5.7.

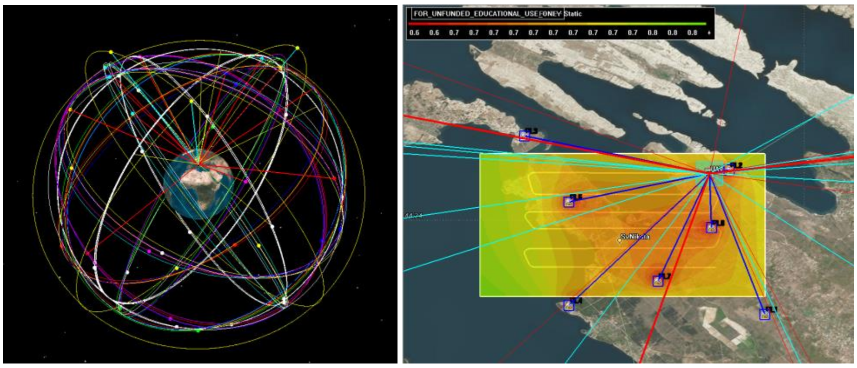

Figure 5.4 PLs, GPS, GLONASS and Galileo radio-navigation network

Table 5.7 DOPs of PLs, GPS, GLONASS and Galileo radio-navigation network

	Min	Max	Average
GDOP	0.68	0.83	0.76
HDOP	0.43	0.47	0.44
PDOP	0.64	0.77	0.71
TDOP	0.24	0.32	0.28
VDOP	0.47	0.60	0.55

Combined PLs, GPS, GLONASS and Galileo network is giving the best results.

6. Conclusion

PLs can be used as GNSS augmentation or as independent radio-navigation network to support UAV navigation. UAV flight has specific requests on radio-navigation networks, and optimizing its geometry is one of the primary problems.

The simulation calculations in the test area are indicating that PLs and UAV receiver range uncertainties are significantly lowering the positioning accuracy. Using lower quality PLs and UAV GNSS receivers will result in significantly lower positioning accuracy.

DOPs as indicators of geometry quality of radio-navigation network are analyzed in the UAV flight test area. UAV flight simulations were made using PLs, GPS, GLONASS and Galileo radio-navigation networks in several combinations. PLs as the augmentation of GPS and GLONASS are improving the quality of network geometry and positioning accuracy. Galileo system has six satellites, but only three were visible in the test area during the simulation time. Without PLs augmentation, the only Galileo navigation would not be possible. In all simulations, geometry quality of radio-navigation networks was improved with PL augmentation.

Pseudolites have a big potential in solving local positioning and navigation problems and in improving the existing positioning and navigation systems. However, pseudolites also have limitations and specific error sources that should be reduced to make pseudolites widely used.

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Podrška navigacije bespilotnih zrakoplova pseudolitima

Sažetak. *Proširenja globalnih navigacijskih satelitskih sustava (GNSS) se obimno koriste u praksi. Pseudoliti daju korisnicima mogućnost da prilagode navigacijski sustav s obzirom na svoje specifične potrebe. Urbani kanjoni, razveden neravni teren te poremećaji radio signala, samo su neki od problema koji mogu učiniti GNSS satelitski signal ne dostupnim ili poremećenim. Navigacija bespilotnih letjelica (Unmanned Aerial Vehicle, UAV) ima specifične zahtjeve na GNSS navigaciju, a koji mogu biti zadovoljeni ili njihov utjecaj ublažen mrežom pseudolita. Pseudoliti se mogu koristiti za proširenje postojećih GNSS sustava ili se mogu koristiti za izradu neovisnih radio-navigacijskih mreža. Kvaliteta geometrije mreže pseudolita ima važnu ulogu u točnosti pozicioniranja. Kao indikatori kvalitete radio-navigacijske mreže u ovom radu su korišteni Dilutions of Precision (GDOP, HDOP, PDOP, VDOP i TDOP). Za testno područje leta UAV-a je analizirana kvaliteta geometrije radio-navigacijskih mreža i njihovo proširenje pseudolitima. Geometrija samostalne radio-navigacijske mreže je također analizirana.*

Ključne riječi: *GNSS proširenja, DOP, GNSS, pseudoliti, radio navigacijska mreža, UAV*