Increasing Accuracy of Combined GPS and GLONASS Positioning using Fuzzy Kalman Filter

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Abstract: In this paper, combined GPS and GLONASS positioning systems are discussed and some solutions have been proposed to improve the accuracy of navigation. Global Satellite Navigation System (GNSS) is able to provide position, velocity and time with respect to coordinated universal time. GNSS positioning is based on received satellite signals, so its performance is highly dependent on the quality of these received signals. The effect of noise and multi-path can often be large enough to produce significant errors in positioning. Satellite navigation is difficult in this situation. In such circumstances, GPS or GLONASS alone are often not able to ensure consistency and accuracy in positioning due to the absence (or low quality) of signals. The combination of these two systems is an appropriate solution to improve the situation. In positioning a receiver, one of the ways that is often used to reduce the error due to observation noise and calculation errors is Kalman Filter (KF) estimation. In this paper, some changes in the structure of the KF is applied to improve the accuracy of positioning. Process of updating KF's gain, is done in fuzzy form based on the parameters available in RINEX files, including the P code pseudo-range used as an input of the proposed fuzzy system. Simulation results show that applying a fuzzy KF based on P code pseudo-range on the available data sets, in terms of noise and blocking condition, reduces the positioning error respectively from 24 to 14 meters and 90 to 25 meters.

Keywords: Fuzzy, GLONASS, GNSS, GPS, Kalman Filter, Signal Blocking.

1 Introduction

Nowadays, positioning with GPS measurements has many civil and military applications. To take advantage of various available navigation constellations, research projects on combining GLONASS and GPS measurements is ongoing. Also, verification of this method is investigated by simulation of multi-constellation signals [1-3]. Considering the recent efforts to restore GLONASS to full operational mode, currently 24 active GLONASS satellites are available. The combination of GPS and GLONASS positioning has several advantages compared to the use of GPS alone. One of these benefits is increased availability of satellites. This advantage becomes important when part of the spectacle is blocked by obstacles [4]. In this case, signals of only few satellites are received. So, adding GLONASS signals to GPS signals significantly increases the probability of accurate positioning [5].

In future, by increasing the operational availability of other navigation constellations such as European Galileo and Chinese Compass, available signal range will be wider. Today, availability of the positioning signals from GPS and GLONASS satellites, provide users with possibility of producing observation codes and carrier phase [6, 7]. Nowadays, a lot of dual frequency receivers in the market are combined GPS/GLONASS receivers. To take advantage of the various GNSS systems, some researches have been done on combined measurements of GPS and GLONASS. The results show that the addition of GLONASS measurements to GPS satellites slightly increases the accuracy of positioning. GLONASS production errors and limited number of available GLONASS satellites are main reasons of slight effect of combining GPS and GLONASS signals [8-11].

This paper is the result of researches done on positioning of a static object by integration of GPS and GLONASS systems. In the integration process, positioning algorithm is based on an extended Kalman Filter (KF), as well as GPS and GLONASS status are updated separately. Since the accuracy of GLONASS

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satellites measurements is lower than GPS satellites, in the process of estimating position, for calculating gain of KF, different coefficients has been assigned to GPS and GLONASS [12]. To obtain these coefficients, different fuzzy systems related to satellites and observations status are proposed. Input parameters of these fuzzy systems are obtained from observation data of GPS and GLONASS satellites.

To assess the increase in accuracy of positioning with these proposed Fuzzy Kalman Filter (FKF), positioning was done for several RINEX data sets, in two different scenarios: noisy GPS signal condition and GPS signal blocking. The detailed results of tests and simulations for one of the proposed fuzzy systems in each scenario are shown. After receiving the raw data, available satellite coordinates are calculated and then receiver coordinate is obtained by positioning algorithms and KF estimator. In order to achieve better accuracy and data smoothing, fuzzy updating system is combined with KF. The traditional KF is transformed into a FKF. Fuzzy changes in KF structure results in a reduction in average error of positioning, from 24 to 14 meters, in noisy cases and from 90 to 25 meters in signal blocking condition.

This paper structured as follows. In the second part, RINEX files and their data fields are presented. In the third section, a brief description of KF is presented. In the fourth part, fuzzy updating systems for KF gain is proposed to increase the accuracy of positioning. In the fifth part the results of applying the proposed fuzzy system on the raw data from a number of recoded data sets in RINEX files are provided. Finally, a comparison is done between the results of these tests and the results of positioning using the classical KF.

2 RINEX

RINEX is a data interchange format for raw satellite navigation systems. This format allows users to post process the received data by using other data that is unknown for main receiver, to produce more accurate result. For example, by creating a better modeling of atmospheric conditions at the time of measurement, by using RINEX stored data, measurement error can be reduced significantly [13-15]. Usually, the output of a navigation receiver includes location, velocity and other relevant physical quantities. However, this value is calculated based on a set of measurements from one or more satellite constellation. RINEX is a standard format that provides management and access to measurements made by receiver [16].

RINEX format is designed to be adaptable with new types of measurements and new navigation systems. There are different versions of this format. The most commonly used version is 2/11. This version is capable of presenting pseudo-range, carrier phase and Doppler measurements for GPS satellite system (including L2C and L5 signals of new GPS generation), GLONASS, Galileo and Beidou simultaneously [17].

RINEX includes seven ASCII files [18]: Observation file, GPS navigation file, metrological file, GLONASS file, GEO navigation file, clock data of satellite and receiver file, and SBAS broadcast data file.

In this study, observation, GPS navigation and GLONASS navigation files are used for positioning. The data sets used in this paper has been downloaded from Internet: http://www.filewatcher.com/b/ftp/prissy.unavco.org/pub/rinex/obs/2013/001-0.html.

This information is raw data received from satellites for calculating position of a static object. To create a noisy condition, deliberate errors are added to the data, and then the data is analyzed based on the noise. Simulation results show that using FKF in these data sets, in noisy condition, reduced the average error of positioning.

3 Position Estimator

In the measurement model of noise, it is assumed that the average of white noise is zero and its distribution is Gaussian. KF uses sets obtained from prediction and update steps, to get an optimal estimate of the state vector, in order to achieve minimum variance [19]. An important feature of KF is that it needs a small amount of memory as it stores just the last calculations. New information is used to update previous calculations. Recursive relations of KF use state equations and measurement in the form of Eq. (1) [20].

$$x_{k+1} = \varphi_k x_k + w_k \tag{1}$$

where x_k represents the state vector at the time t_k, φ_k shows the transition matrix from x_k to x_{k+1} and w_k is the process error vector. Measurement equation in KF is shown in Eq. (2):

$$Z_k = H_k x_k + V_k \tag{2}$$

where Z_k represent measured vector at time t_k, H_k is the perfect correlation matrix (without noise) between the measurement vector and state vector at time t_k. V_k is measurement error. KF gain is calculated using Eq. (3):

$$K_k = P_k^- H_k^T \left(H_k P_k^- H_k^T + R_k \right)^{-1} \tag{3}$$

in which P_k^- represents the error covariance matrix, in case of the optimum estimated state vector, and it is used as a known parameter in the positioning equations. R_k is noise covariance. Estimation of Z_k measurement vector is updated by Eq. (4):

$$\hat{x}_k = \hat{x}_k^- + K_k \left(Z_k - H_k \hat{x}_k^- \right) \tag{4}$$

where $\hat{x}_k$ represents the estimation of x_k after updating with current measurement Z_k and $\hat{x}_k^-$ is the estimation of x_k before updating with current measurement Z_k. Covariance matrix for the optimum estimation is calculated using Eq. (5):

$$P_k = \left(I - K_k H_k\right) P_k^- \quad (5)$$

In this paper, the problem of positioning a stationary object has been considered. x_k is including state variables x_k, y_k, z_k, Δt_k (at the moment of k) in positioning calculations as state variables dimension is meters, and Δt_k is time measured in seconds. It should be multiplied by the velocity of light. Other measurements are also in meters and should be multiplied by unit to convert to state variables. Thus, in this case we have:

$$H_k = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & C \end{bmatrix} \quad (6)$$

where C is light speed (about 300000 m/s). Since this positioning is performed on a stationary object in this paper, the transfer matrix φ_k is a diagonal 4*4 matrix (according to Eq. (7)):

$$\varphi_k = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

4 Fuzzy Kalman Filter

Accuracy of GPS positioning system is higher than GLONASS navigation system [21]. In this paper, the difference in positioning accuracy of the two systems in navigation calculations is considered as a principle in application of combined GPS and GLONASS applications. Navigation calculations in this study are based on pseudo-range observations. In location estimation with KF, in each epoch, the difference between the calculated distance from satellite to receiver and observed distance is obtained and after updating the gain of KF, the position of receiver is estimated [22]. Based on the accuracy difference in GLONASS and GPS observations, a weighting factor is assigned to the gain of KF in KF's structure. If the estimation process involves data from GPS satellites, the weight factor is always equal to one; and if pseudo-range data is received from the GLONASS satellite, the weight factor will be less than one.

In this study, 30 sets of data has been used that each of them contains the recorded positioning information of a stationary object for 24 hours. Statistical analysis was performed on 10 data sets, and the results were tested on the remaining 20 data sets. The effect of various parameters on the positioning error of a static object in integration of GPS and GLONASS were evaluated. Results showed that the following parameters had similar and predictable behavior in all 10 datasets: (a) the ratio of signal to noise power in L1 band, (b) the ratio of signal to noise power in L2 band, (c) carrier phase in L1 band, (d) carrier phase in L2 band, (e) elevation angle, and (f) the difference of P code and C/A code pseudo-range.

This behavior was tested on the remaining 20 data sets and similar results were found. Based on the behavior of positioning error with respect to the each of the 6 parameters above, independent fuzzy systems were designed and proposed, corresponding to each of the parameters. In each fuzzy system, the number of parts of the input and output membership functions and fuzzy rules and number of them are specified based on changes in positioning error behavior with respect to the parameters.

Various tests showed that using complex membership functions had little effect on the final results; with one difference that using sophisticated membership functions increases the computational load, processing volume and the probability of processing error. Hence, in design of the proposed fuzzy systems, triangular functions were considered, which have the lowest implementation cost in computational load, processing, memory, speed and complexity. Below, the blocks of proposed fuzzy systems are presented and one of these systems (based on the difference of P code and C/A code pseudo-range) will be discussed. The fuzzy system block diagram is shown in Fig. 1.

In Fig. 2, the membership function of fuzzy system's input (the difference of P code and C/A code pseudo-range) is shown.

Description of indices used in the Fig. 2, are shown in Table 1. In Fig .3, the membership function of fuzzy system's output (the coefficients of GLONASS observations) is shown.

Fuzzy rules used in the fuzzy systems are as follows:

First rule: If the input (the difference of P code and C/A code pseudo-range) is *Very Low*, Then the output (the coefficients of GLONASS observations) is *Very High*.

Second rule: If the input (the difference of P code and C/A code pseudo-range) is *Low*, Then the output (the coefficients of GLONASS observations) is *High*.

Third rule: If the input (the difference of P code and C/A code pseudo-range) is *Moderate*, Then the output (the coefficients of GLONASS observations) is *Moderate*.

Fourth rule: If the input (the difference of P code and C/A code pseudo-range) is *High*, Then the output (the coefficients of GLONASS observations) is *Low*.

Fifth rule: If the input (the difference of P code and C/A code pseudo-range) is *Very High*, Then the output (the coefficients of GLONASS observations) is *Very Low*.

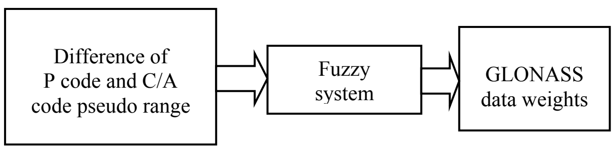

Fig. 1 Proposed fuzzy system block diagram.

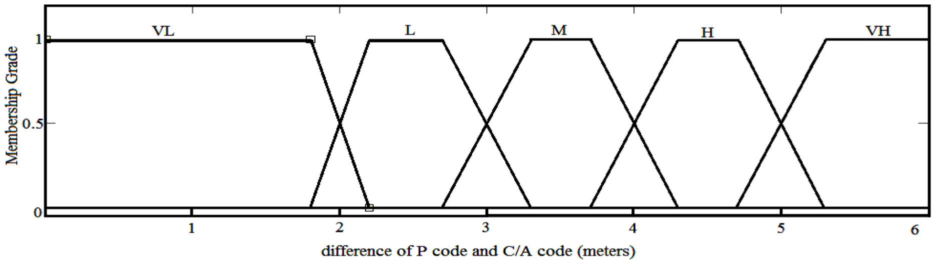

Fig. 2 Membership function of fuzzy system's input.

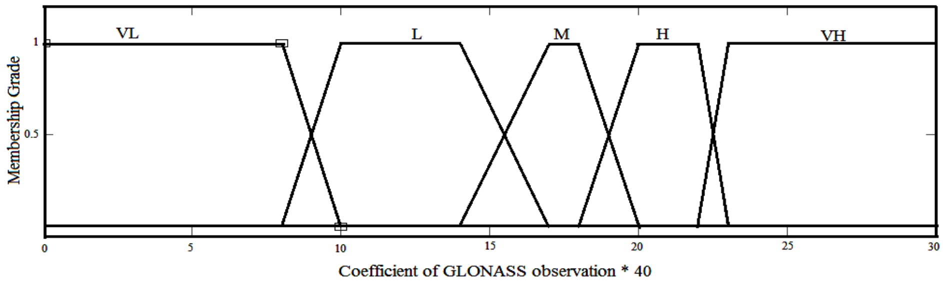

Fig. 3 Membership function of fuzzy system's output.

Table 1 Description of indices used in input membership function.

Indic	Description
VL	Very Low
L	Low
M	Moderate
H	High
VH	Very High

Based on the results of the designed fuzzy system, weighting coefficients of observed pseudo-range of GLONASS satellites in KF estimation process, based on the difference of P code and C/A code pseudo-range (ΔP), is obtained and shown in Fig. 4. Figs. 5-8 show variation of weight coefficient according to other parameters.

5 Simulation Results

In this paper, the software that is developed by author in C++ Builder environment is used for simulations. Actually, the research is done based on real data recorded in RINEX mixed observation and navigation files, the location of specified receivers are obtained in X, Y and Z. Proposed fuzzy systems are imposed on 30 data sets in both scenarios of noise and blocking, and 6 sets of data were presented randomly in each scenario. Since these data have been recorded in noisy and blocking environments, positioning error of conventional methods was higher than normal. In these calculations, classical KF and FKF based on proposed fuzzy systems are used. The results show that the accuracy of positioning in combined fuzzy systems is higher than combined common systems. Root Mean Square (RMS) values of calculation error resulting from the use of KF and FKF (from the listed parameters) for noisy case are presented in Table 2. The last row of Table 2 shows the average positioning error of test data set. As you can see, the positioning error using FKF is lower than the classical KF (about 14 compared to about 24 meters). In Figs. 9 to 11, the calculation error in X, Y and Z for the states of the classical KF and FKF (in use of ΔP) are shown in meters.

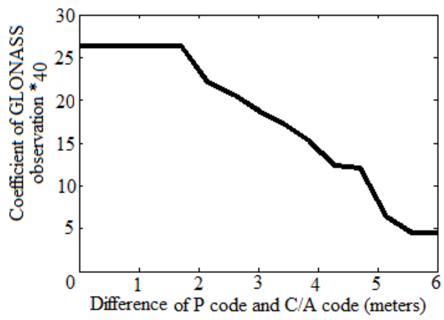

Fig. 4 Variation of the weight coefficient according to ΔP.

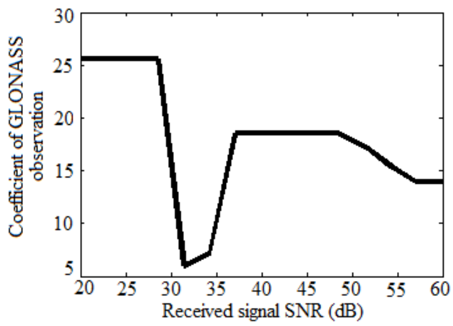

Fig. 5 Variation of the weight coefficient according to the ratio of signal to noise power in L1 or L2 band.

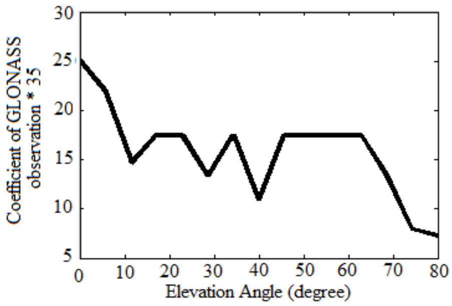

Fig. 6 Variation of the weight coefficient according to elevation angle.

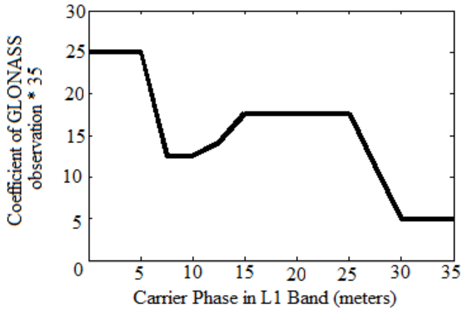

Fig. 7 Variation of the weight coefficient according to carrier phase in L1 band.

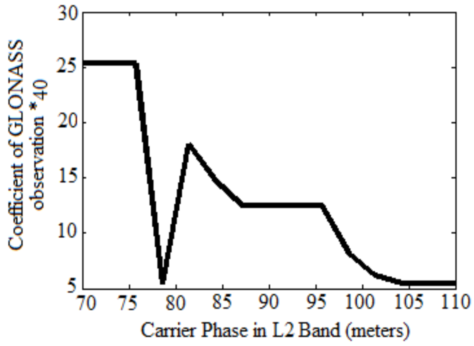

Fig. 8 Variation of the weight coefficient according to carrier phase in L2 band.

RMS values of calculation error resulting from the use of KF and FKF (from the listed parameters) for signal blocking case are presented in Table 3. The last row of Table 3 shows the average positioning error of test data set. As you can see, the positioning error using FKF is lower than the classical KF (about 25 compared to about 90 meters). In Figs. 12 to 14 the calculation error in X, Y and Z for the states of the classical KF and FKF (in use of ΔP) are shown in meters.

Table 2 Comparison of results of FKF and classical KF to get the positioning error (in meters) for noisy case.

No.	Classic KF	Fuzzy KF				
	GPS+GLONASS	GPS+GLONASS				
		SNR	ELV	PHL1	PHL2	ΔP
1	22.235	13.257	14.251	12.954	14.254	13.724
2	26.458	14.125	15.325	13.812	14.741	15.246
3	24.874	13.745	14.874	13.652	14.135	14.284
4	23.145	12.945	12.954	13.154	13.406	13.307
5	22.840	15.235	12.178	13.670	14.254	15.023
6	26.456	14.752	13.871	15.324	14.486	13.941
Average error (in meter)	**24.335**	**14.010**	**13.909**	**13.761**	**14.213**	**14.254**

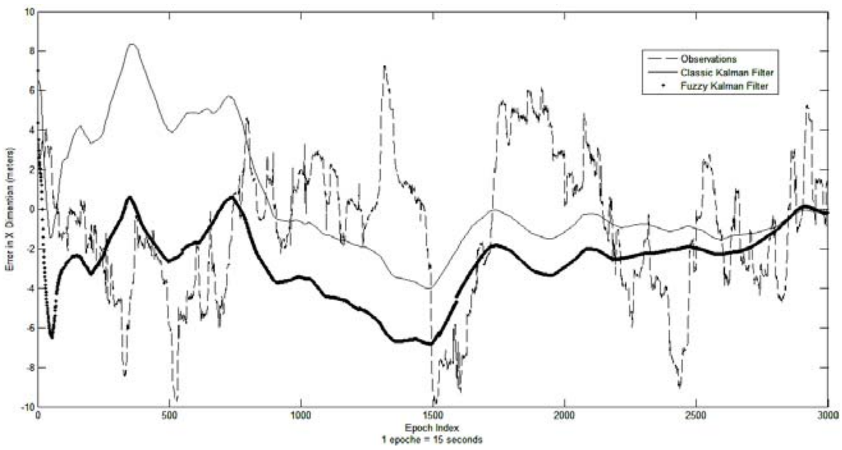

Fig. 9 Comparison of positioning error in extreme noise (X component).

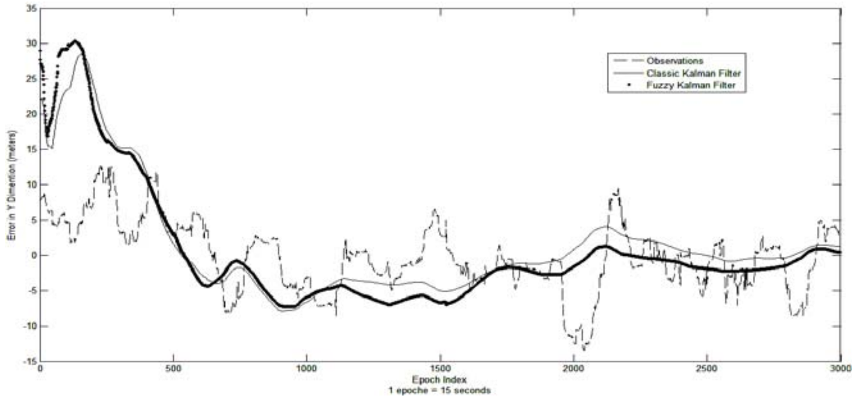

Fig. 10 Comparison of positioning error in extreme noise (Y component).

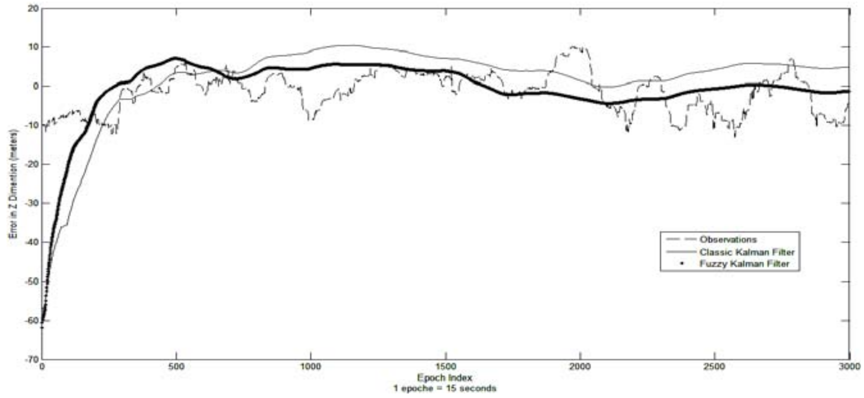

Fig. 11 Comparison of positioning error in extreme noise (Z component).

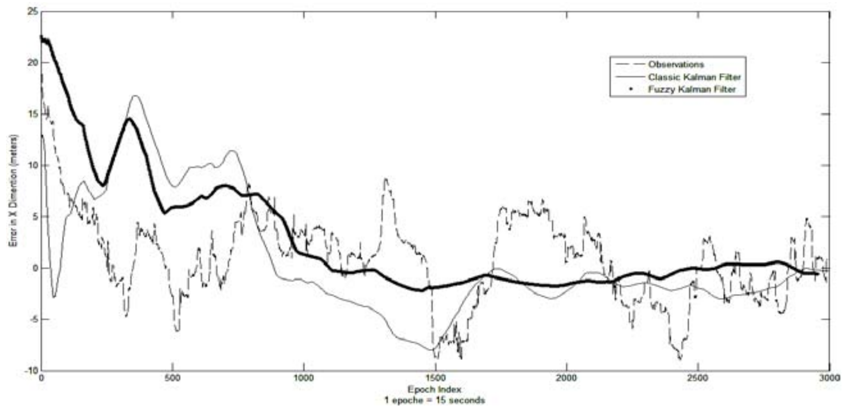

Fig. 12 Comparison of positioning error in signal blocking (X component).

Table 3 Comparison of results of FKF and classical KF to get the positioning error (in meters) for signal blocking case.

No.	Classic KF	Fuzzy KF				
	GPS+GLONASS	GPS+GLONASS				
		SNR	ELV	PHL1	PHL2	ΔP
1	82.997	20.279	19.638	19.790	19.875	20.097
2	95.738	23.468	24.099	23.422	23.149	24.110
3	101.650	34.741	35.379	34.238	33.499	35.149
4	86.258	22.475	22.619	22.459	23.115	22.195
5	73.215	19.253	19.618	19.241	18.508	19.679
6	95.824	21.196	20.319	20.013	20.188	20.625
Average error [m]	**89.280**	**23.569**	**23.612**	**23.194**	**23.056**	**23.643**

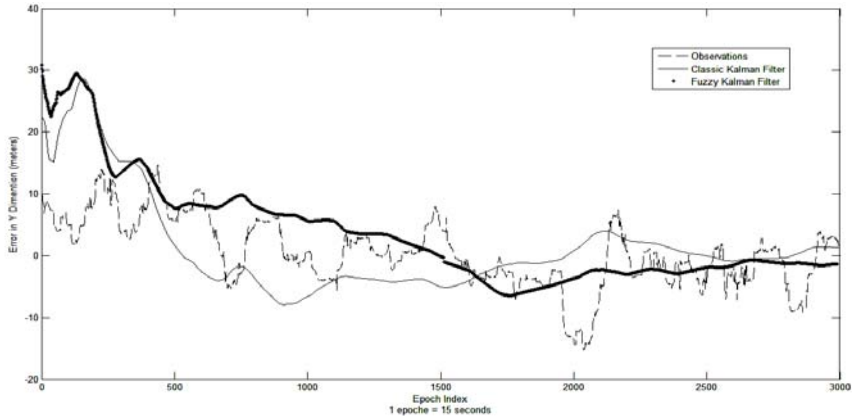

Fig. 13 Comparison of positioning error in signal blocking (Y component).

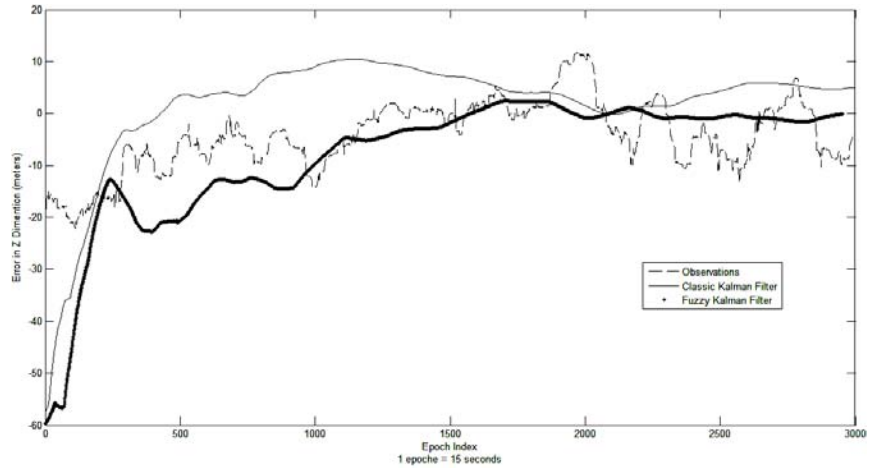

Fig. 14 Comparison of positioning error in signal blocking (Z component).

6 Conclusion

In this paper, we assumed two environments in one of them GPS satellites data are received with noise by receivers and the other one GPS data has been blocked. In these circumstances, positioning with the GPS information has been accompanied by a significant error. Calculations on a number of data sets have demonstrated an average error of about 35 meters for noisy case and about 120 meters for signal blocking condition. One solution proposed in these situations in literature is using the GLONASS satellites raw data combined with GPS data. Calculations and simulations on real combined data show that this method leads to positioning error of about 24 and 90 meters respectively in noisy and signal blocking cases. The method adopted in this paper is using fuzzy systems in the structure of KF to estimate the position. In this case, in the integration process, the various weighting coefficients are considered for GLONASS satellites raw data and a weighting factor equal to one is considered for GPS data. These coefficients are obtained based on various fuzzy inputs. Using this method, with the proposed fuzzy systems, leads to a reduction of positioning error to about 14 meters in noisy case and about 25 meters in signal blocking condition.

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