

Study of Parameters Influencing the Accuracy of the SDF Method Localization

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ABSTRACT: Modern military operations increasingly use unmanned aerial vehicles (UAVs) not only for observation and reconnaissance, but also for active localization of radio emission sources. One of the methods used for this purpose is the signal Doppler frequency method (SDF), based on the analysis of the frequency of the signal received by the moving sensor. The paper presents a theoretical analysis and simulation studies aimed at determining the effect of selected parameters on the accuracy of emitter localization using the SDF method. In particular, the factors such as data acquisition time, accuracy of Doppler frequency estimation, carrier frequency and the velocity of the moving sensor were considered. The aim of the work is to indicate which of these parameters are crucial for the quality of localization. We formulate conclusions that can support the development of the resistant to interference and more precise localization systems based on the SDF method. The presented approach can be used both in real armed conflicts and in work on autonomous electronic reconnaissance systems.

1 INTRODUCTION

In recent years, there has been a dynamic increase in the use of unmanned aerial vehicles (UAVs), commonly known as drones, in military operations. Their role on the battlefield continues to evolve—from reconnaissance tools that support command and observation to precise strike platforms with a high degree of autonomy. Conflicts such as the 2020 Nagorno-Karabakh war and the ongoing war in Ukraine clearly demonstrate how significantly drones are reshaping the nature of modern warfare [1], [2]. The growing availability of drone technology and the relatively low cost of production have made these systems increasingly attractive to both state actors and irregular armed groups.

The application of UAVs that we are investigating in several scientific research projects is the use of radio emitters for localization. The method that we use is the

SDF (signal Doppler frequency) method. It has both advantages and disadvantages. The aim of this article is to examine the influence of selected parameters on the accuracy of localization of radio emitters. The conclusions from the article will allow us to focus on the most important ones, which have the greatest impact on the localization errors. They show directions for further development of the method to improve its accuracy.

The rest of the paper is organized as follows. Section 2 describes the SDF method and her parameters, that influence the localization error. Simulation scenarios and obtained results are described in Section 3. The conclusions that are included in Section 4 concern the recommendations and directions for further research into the SDF method.

2 SDF METHOD

2.1 SDF Method principles

The SDF method is a frequency method for locating radio emitters. The basic parameter on which the localization algorithms operate is the Doppler frequency shift (DFS), which appears when the receiver or transmitter is set in motion [3]. This frequency can be expressed by the formula:

$$f_D = f_0 \frac{v}{c} \cos \gamma, \quad (1)$$

where: v – speed of change of position between the signal source and the receiver, f_0 – frequency of the emitted carrier wave, c – the speed of propagation of an electromagnetic wave in a medium, γ – angle between the direction of the velocity vector and the direction determined by the position of the signal source and receiver.

Assuming that we localize the stationary transmitter using a sensor placed on a moving platform, e.g. an unmanned aerial vehicle (UAV), we can estimate the coordinates $(\tilde{x}, \tilde{y})$ of the localized emitter in a two-dimensional plane using the equations [4]:

$$\tilde{x} \cong v \frac{t_1 A(t_1) - t_2 A(t_2)}{A(t_1) - A(t_2)} \quad (2)$$

$$\tilde{y} \cong \pm \sqrt{\left[\frac{v(t_1 - t_2) A(t_1) A(t_2)}{A(t_1) - A(t_2)} \right]^2 - z^2} \quad (3)$$

where:

$$A(t) = \frac{\sqrt{1 - F^2(t)}}{F(t)}, \quad F(t) \cong \frac{f_D(t)}{f_{D_{\max}}}, \quad f_{D_{\max}} = k f_0, \quad k = \frac{v}{c}, \quad f_{D_{\max}} -$$

maximum Doppler frequency, f_0 – carrier frequency of transmitted signal, z – constant height relative to the receiver, v – velocity of receiver.

2.2 Parameters affecting the localization error

Analyzing equation (1), we can see that the fundamental element influencing the Doppler frequency f_D value, apart from the carrier frequency f_0 is the angle between the direction of the velocity vector and the direction determined by the position of the signal source and receiver γ . How the UAV flight direction relative to the emitter location will affect the nature of the Doppler frequency f_D changes and the SDF method location error is presented, among others, in [5], [6]. Therefore, it is extremely important to select the correct UAV flight direction, which is worth noting here. For this reason, in further considerations including research on other parameters, many scenarios of UAV location relative to the emitter will be taken to develop optimal solutions into account. However, scenarios in which the Doppler frequency is extremely low or its value is almost constant, will not be considered.

An analysis of formulas (2) and (3) shows that the accuracy of localization is influenced by the accuracy of determination:

- Doppler frequency f_D ,
- carrier frequency of transmitted signal f_0 ,
- velocity of receiver v .

When spectrum analysis is used to estimate the Doppler frequency f_D , it can be expressed as [7]:

$$f_D(t) = f(t) - f_0, \quad (4)$$

where: $f(t)$ – instantaneous frequency of received signal.

In this case, the accuracy of the carrier frequency f_0 estimation of the emitted signal also affects the accuracy of the Doppler frequency f_D estimation. In the following article, it is assumed that the Doppler frequency f_D is estimated using methods which do not need information about the carrier frequency of the signal. Consequently, carrier frequency estimation error affects the accuracy of localization only in formulas (2) and (3).

Formulas (2) and (3) allow for estimating the coordinates (x, y) of the localized emitter in the case of measuring the Doppler frequency f_D at least at two moments of time t_1 and t_2 . Using a larger amount of data, e.g. a ten-element vector, will also affect the localization error. The fourth analyzed parameter will therefore be:

- the acquisition time t_A , reflecting the amount of data (Doppler frequency shifts f_D) used to determine the coordinates (x, y) of the emitter.

As with the UAV velocity v , information about the UAV location may also be subject to some error. The SDF method determines the position relative to the sensor position, and therefore it will also affect the error in the radio emission location. For this reason, it was decided to also examine the influence of

- the UAV's positioning accuracy.

In the case of performing localization procedures in real time, we rely only on a part of the Doppler curve, and we cannot select an arbitrary acquisition time t_A . However, it is necessary to determine when to perform localization procedures so that the result is not burdened with too large localization error Δr . The solution to this problem may be the last parameter studied in the publication, called:

- the range of Doppler frequency changes Δf_D .

3 SIMULATION STUDIES FOR TESTING THE IMPACT OF SELECTED PARAMETERS ON LOCALIZATION ACCURACY

3.1 Main assumptions for all scenarios

In order to investigate the influence of the parameters listed in Section 2.2 on the localization accuracy of the SDF method, a research scenario was adopted in which the localization sensor was mounted on the UAV and moved along the OX axis of the coordinate system shown in Figure 1.

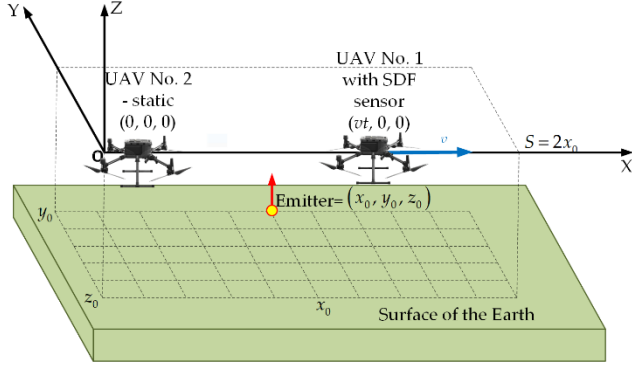


Figure 1. Spatial scenario for simulation studies.

Based on the arrangement of elements shown in Figure 1, the following assumptions were made:

- the emitter is located at point x_0, y_0, z_0 of the coordinate system,
- the localized emitter transmits a harmonic signal at the carrier frequency f_0 ,
- the carrier frequency f_0 of the emitted signal is determined by the sensor mounted on the non-moving UAV No. 2, which is placed at coordinates $(x_v, y_v, z_v) = (0, 0, 0)$ km,
- the Doppler frequency f_D is determined based on the signal samples received by both sensors,
- the carrier frequency f_0 estimation error of the signal does not affect the Doppler frequency f_D estimation error, and consequently, carrier frequency f_0 estimation error affects the accuracy of localization only in formulas (2) and (3),
- UAV No. 1 moves along the OX axis over a distance of S km with velocity v , at subsequent moments of time its position coordinates are $(x_v, y_v, z_v) = (vt, 0, 0)$ km,
- the localization sensor estimates parameters (f_0, f_D, v) every 1 s,
- to determine the emitter coordinates (x, y) data vectors (f_0, f_D, v) of length equal to the acquisition time t_A are taken,
- the localization error Δr is determined according to formula

$$\Delta r = \sqrt{(\tilde{x} - x_0)^2 + (\tilde{y} - y_0)^2} \quad (5)$$

where $x(t)$ and $y(t)$ are the coordinates estimated based on formulas (2) and (3).

3.2 The influence of the acquisition time

A similar analysis of this parameter was performed in [8]. The authors of the article analyzed the acquisition time t_A for recorded signals burdened with large oscillations. In this chapter, we would like to present the trend of the localization error Δr in the case of the selection of the acquisition time t_A for ideal conditions.

3.2.1 Scenarios assumptions

The study was conducted taking the assumptions from Section 3.1 into account. Additionally, the following assumptions were made:

- $x_0, y_0, z_0 = \{(10, 40, -0.1), (10, 30, -0.1), (10, 20, -0.1), (10, 10, -0.1), (10, 5, -0.1), (10, 2, -0.1), (10, 1, -0.1), (5, 20, -0.1), (5, 15, -0.1), (5, 10, -0.1), (5, 5, -0.1), (5, 2.5, -0.1), (5, 1.25, -0.1),$

- $(5, 0.5, -0.1), (1.2, 4.8, -0.1), (1.2, 3.6, -0.1), (1.2, 2.4, -0.1), (1.2, 1.2, -0.1), (1.2, 0.6, -0.1), (1.2, 0.2, -0.1), (1.2, 0.1, -0.1)\}$ km,
- $f_0 = \{300, 600, 900, 1200, 1500, 1800, 2100, 2400, 2700, 3000\}$ MHz,
- $v = 15$ m/s,

- the selection of acquisition time t_A and its maximum value results from the selected scenarios. When the path $S = 2 \cdot x_0$ is 20 kilometers, at a speed of 15 m/s we need 1334 seconds to complete the entire route. When $S = 10$ kilometers we need 667 seconds and for $S = 2400$ meters it is 161 seconds. It was therefore decided to examine the acquisition time t_A values from 2 seconds to the total number of seconds needed to cover the entire route t_{Amax} , with a step of 1 s for all cases,
- the emitter position coordinates are determined for an analysis window of the acquisition time t_A length. Then, if the coordinate determination counter k is lower than the maximum number of localization procedure repetitions K defined as

$$K = t_{Amax} - t_A + 1, \quad (6)$$

the analysis window is shifted by one second and the coordinates are determined again. This procedure is repeated K times. For this reason, the first location result is obtained after a time equal to the acquisition time t_A .

- for each value of the acquisition time t_A , the mean value $\mu_{\Delta r}$ and deviation $\sigma_{\Delta r}$ of the localization error Δr is determined according to formulas

$$\mu_{\Delta r} = \frac{1}{K} \sum_{k=1}^K \Delta r_k, \quad (7)$$

$$\sigma_{\Delta r} = \sqrt{\frac{1}{K-1} \sum_{k=1}^K |\Delta r_k - \mu_{\Delta r}|^2}, \quad (8)$$

where $k=1, 2, \dots, K$, Δr_k is a localization error defined by Equation (5) for the k th estimation of emitter coordinates $(x(t), y(t))$.

3.2.2 Results

Table 1 presents the mean value $\mu_{\Delta r}$ and standard deviation $\sigma_{\Delta r}$ of the localization error for each value of the acquisition time t_A . Due to the different number of seconds needed to cover the entire route t_{Amax} depending on the length of the path S , the acquisition time t_A was expressed in percentage as:

$$t_A [\%] = \frac{t_A}{t_{Amax}} \cdot 100 \quad (9)$$

The course of the mean localization error as a function of acquisition time t_A for different path lengths is presented in Figure 2.

Table 1. The mean value $\mu_{\Delta r}$ and standard deviation $\sigma_{\Delta r}$ of the localization error for different path length S and different value of the acquisition time t_A .

	S=20 km		S=10 km		S=2.4 km	
t_A [%]	Localization error [m]					
	$\mu_{\Delta r}$	$\sigma_{\Delta r}$	$\mu_{\Delta r}$	$\sigma_{\Delta r}$	$\mu_{\Delta r}$	$\sigma_{\Delta r}$
10	1.471	3.356	0.684	1.612	0.160	0.321
20	1.114	2.316	0.524	1.119	0.124	0.225
30	0.836	1.499	0.396	0.723	0.096	0.148
40	0.632	0.881	0.304	0.428	0.075	0.090
50	0.500	0.454	0.243	0.222	0.062	0.051
60	0.440	0.231	0.216	0.116	0.056	0.031
70	0.442	0.198	0.216	0.101	0.056	0.027
80	0.466	0.213	0.228	0.108	0.059	0.029
90	0.491	0.220	0.240	0.111	0.063	0.031
100	0.530	0.245	0.258	0.123	0.069	0.037

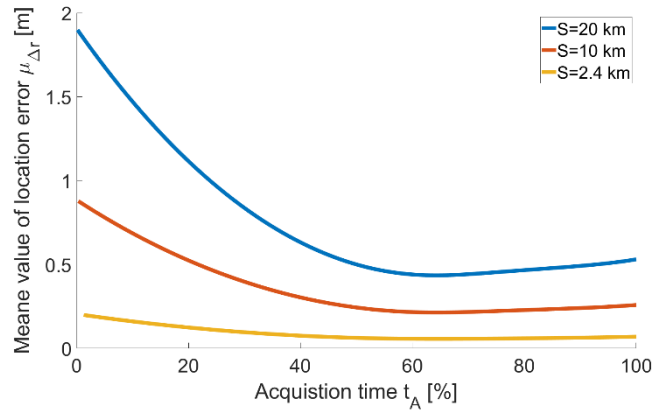


Figure 2. The mean value of localization error $\mu_{\Delta r}$ as a function of acquisition time t_A for different path lengths S .

Analyzing the above results, we can see that the lowest mean localization error $\mu_{\Delta r}$ is obtained in the case when the acquisition time t_A is about 65% of all seconds needed to cover the entire route t_{Amax} . However, this value is difficult to achieve, especially in the case of scenarios where there are more than 1300 of them. The measurement time to the first localization would reach more than 10 minutes. It can also be seen that with the increase in the length of the measurement path S , the difference between the localization errors for individual acquisition times t_A increases. However, the trend itself is identical. In ideal simulation conditions, we can see, however, that the selection of the acquisition time t_A does not have a critical significance in the localization error.

3.3 The influence of the range of Doppler frequency changes

As mentioned in Section 3.2, the accuracy of localization is influenced by the acquisition time t_A of the signal, i.e. the number of f_D values taken to calculate the emitter coordinates (x,y) . In general, the lowest localization error was obtained when the acquisition time t_A was about 60% of the entire Doppler curve. In real conditions, we do not always have the possibility to collect data that will allow for the analysis of the full Doppler curve and localization procedures must be performed on its part. In such a case, a decision must be made when to start determining the coordinates so as not to burden the result with too large a localization error Δr . For this purpose, another simulation study was conducted, in which it was decided to analyze the influence of the range of Doppler frequency changes

Bf_D on the localization error Δr . For assume that this parameter has a constant value, the acquisition time t_A is changed dynamically by appropriately adding and subtracting values from the f_D vector, to maintain a constant, previously determined the range of Doppler frequency changes Bf_D .

3.3.1 Scenarios assumptions

The study was conducted taking the assumptions from Section 3.1 into account. Additionally, the following assumptions were made:

- $x_0, y_0, z_0 = \{(10, 10, -0.1), (10, 5, -0.1), (10, 2, -0.1), (10, 1, -0.1), (1.2, 1.2, -0.1), (1.2, 0.6, -0.1), (1.2, 0.2, -0.1), (1.2, 0.1, -0.1)\}$ km,
- $f_0 = \{300, 600, 900, 1200, 1500, 1800, 2100, 2400, 2700, 3000\}$ MHz,
- $v = \{15, 20, 30\}$ m/s,
- the range of Doppler frequency changes was selected so that each scenario could meet the requirements for its value, it was therefore decided to test all possible Bf_D values in the range from 0.5 to 20 Hz with a step of 0.5 Hz,
- the acquisition time t_A is selected taking the range of Doppler frequency changes Bf_D into account,
- for each value of the range of Doppler frequency changes Bf_D , the mean value $\mu_{\Delta r}$ and deviation $\sigma_{\Delta r}$ of the localization error Δr is determined according to formula (7) and (8).

3.3.2 Results

Figure 3 presents courses of the mean value $\mu_{\Delta r}$ and standard deviation $\sigma_{\Delta r}$ of the localization error as a function of the range of Doppler frequency changes Bf_D .

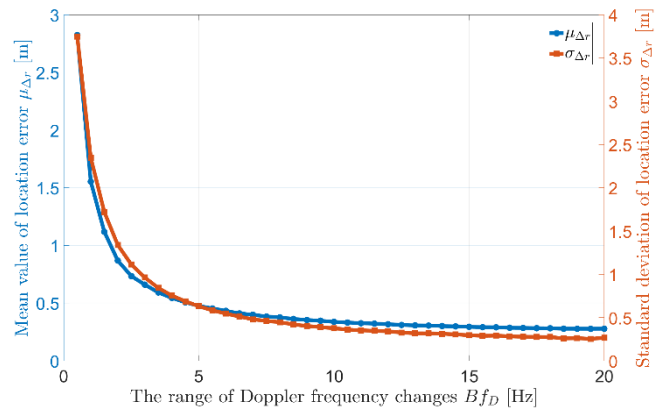


Figure 3. The mean value $\mu_{\Delta r}$ and standard deviation $\sigma_{\Delta r}$ of localization error as a function of the range of Doppler frequency changes Bf_D .

Analyzing the obtained results, it can be noticed that with small values of the range of Doppler frequency changes Bf_D , the mean localization error $\mu_{\Delta r}$ can reach almost 3 meters. By increasing the value of the tested parameter, localization error begins to decrease quickly. Assuming that the localization procedure is to be carried out as quickly as possible and the error cannot exceed 0.5 meters, localization can be done on data for which the range of Doppler frequency changes Bf_D equals 5 Hz. Further reduction of the value of this parameter obviously causes a decrease in the localization error and for $Bf_D = 20$ Hz, the mean localization error value $\mu_{\Delta r} = 0.278$ m. However, the parameter study was performed for ideal conditions

and in the case of real conditions, where the Doppler frequency will oscillate, among others due to the frequency stability of the SDR platform used [9], it will be necessary to previously determine the value of this parameter for the target solution.

3.4 The influence of the Doppler frequency estimation error

The approximate analysis was carried out in [10]. The ideal Doppler frequency courses as a function of time were obtained using the following equation

$$f_D(x, t) = \frac{k}{1-k^2} \left(k + \frac{x_0 - vt}{\sqrt{(x_0 - vt)^2 + (1-k^2)(y_0^2 + z_0^2)}} \right) f_0,$$

where $\mathbf{x}=(x_0, y_0, z_0)$.

In our consideration it was assumed, that the estimated f_D values oscillate and the oscillations follow a normal distribution $N(\mu_{fD}, \sigma_{fD})$.

3.4.1 Scenarios assumptions

The study was conducted taking into account the assumptions from section 3.1. Additionally, the following assumptions were made:

- $x_0, y_0, z_0 = (1.5, 1.0, -0.1)$ km,
- Doppler frequency f_D oscillations have a normal distribution $N(\mu_{fD}, \sigma_{fD}) = N(0, 0.001), N(0, 0.01), N(0, 0.1), N(0, 1), N(0, 10)$,
- $f_0 = 1200$ MHz,
- $v = 15$ m/s,
- the acquisition time $t_A = 30$ s,
- the mean value $\mu_{\Delta r}$ and standard deviation $\sigma_{\Delta r}$ of the localization error Δr is determined according to formula (7) and (8).

3.4.2 Results

Figure 4 shows the Doppler curves for all the scenarios studied. Table 2 and Figure 5 show the localization error for the given scenarios.

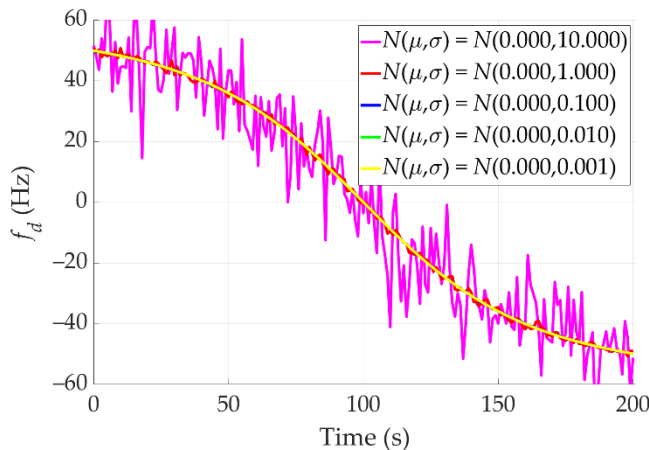


Figure 4. The Doppler curves for all the scenarios.

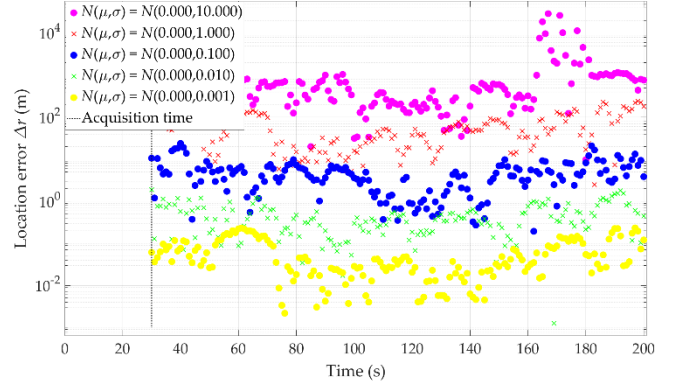


Figure 5. Localization error as a function of time for all distributions of Doppler frequency f_D oscillations.

Table 2. The mean value $\mu_{\Delta r}$ and standard deviation $\sigma_{\Delta r}$ of the localization error for different distributions of Doppler frequency f_D oscillations.

$N(\mu_{fD}, \sigma_{fD})$ [Hz]	Localization error [m]	
	$\mu_{\Delta r}$	$\sigma_{\Delta r}$
$N(0, 10)$	857.08	1471.41
$N(0, 1)$	38.06	31.82
$N(0, 0.1)$	5.07	4.30
$N(0, 0.01)$	0.58	0.54
$N(0, 0.001)$	0.05	0.05

Analyzing the obtained results, it can be seen that even small oscillations of the estimated Doppler frequency f_D lead to significant errors. In the case of $\sigma_{fD} = 1$ Hz, a satisfactory localization error can be obtained. As can be seen, $\sigma_{fD} = 10$ Hz disqualifies the SDF method from practical use without prior filtering of Doppler frequency curves.

3.5 The influence of the carrier frequency estimation error

As mentioned in Section 2.2 in the following article, it is assumed that the Doppler frequency f_D is estimated using methods which do not need information about the carrier frequency of the signal. Consequently, carrier frequency estimation error affects the accuracy of localization only in formulas (2) and (3).

3.5.1 Scenarios assumptions

The study was conducted taking the assumptions from Section 3.1 into account. Additionally, the following assumptions were made:

- $x_0, y_0, z_0 = (1.5, 1.0, -0.1)$ km,
- Doppler frequency f_D is estimated without error,
- carrier frequency of transmitted signal $f_0 = 1200$ MHz,
- $v = 15$ m/s,
- the acquisition time $t_A = 30$ s,
- carrier frequency f_0 is estimated with error $\Delta f_0 = \{0.01, 0.1, 1, 10, 100\}$ MHz which is added to real value of carrier frequency of transmitted signal f_0 ,
- the mean value $\mu_{\Delta r}$ and standard deviation $\sigma_{\Delta r}$ of the localization error Δr is determined according to formula (7) and (8).

3.5.2 Results

Table 3 and Figure 6 show the localization error for the given scenarios.

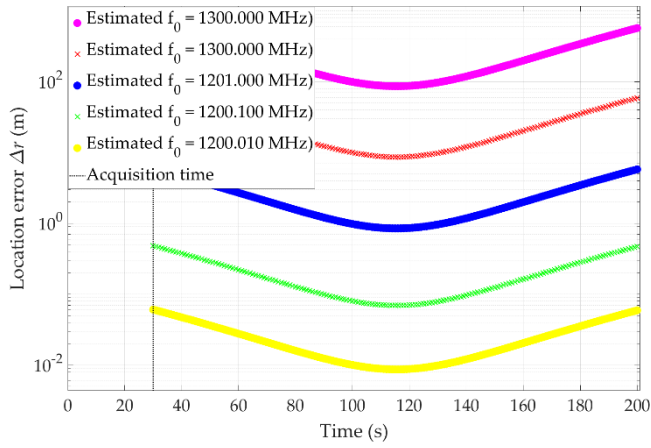


Figure 6. Localization error as a function of time for different estimated carrier frequency ($f_0=1200$ MHz) .

Table 3. The mean value $\mu_{\Delta r}$ and standard deviation $\sigma_{\Delta r}$ of the localization error for different errors of carrier frequency estimation.

Estimated f_0 [MHz]	Localization error [m]	
	$\mu_{\Delta r}$	$\sigma_{\Delta r}$
1300.00	238.03	145.09
1210.00	24.30	14.97
1201.00	2.39	1.48
1200.10	0.20	0.12
1200.01	0.02	0.02

Analyzing the above results, we can see that even a carrier frequency estimation error Δf_0 of 1 and 10 MHz does not disqualify the SDF method from use. The localization error does not exceed 2.5 and 25 meters in this case, respectively. Only at $\Delta f_0=100$ MHz does the localization error reach hundreds of meters, which would not allow for correct localization for a given scenario.

3.6 The influence of the UAV's velocity fluctuations

3.6.1 Scenarios assumptions

The study was conducted taking the assumptions from Section 3.1 into account. Additionally, the following assumptions were made:

- $x_0, y_0, z_0 = (1.5, 1.0, -0.1)$ km,
- Doppler frequency f_D is estimated without error,
- carrier frequency of transmitted signal $f_0=1200$ MHz and is estimated without error,
- the acquisition time $t_A=30$ s,
- velocity v is estimated. Oscillations have a normal distribution $N(\mu_v, \sigma_v) = N(0, 0.001)$, $N(0, 0.01)$, $N(0, 0.1)$, $N(0, 1)$ and they are added to constant velocity $v=15$ m/s,
- the mean value $\mu_{\Delta r}$ and standard deviation $\sigma_{\Delta r}$ of the localization error Δr is determined according to formula (7) and (8).

3.6.2 Results

Figure 7 shows the UAV velocity courses as a function of time for all the scenarios studied. Table 4 and Figure 8 show the localization error for the given scenarios.

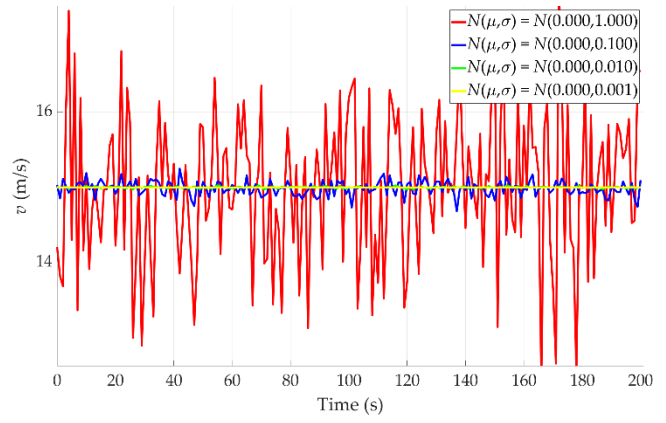


Figure 7. The UAV velocity courses as a function of time for all the scenarios studied.

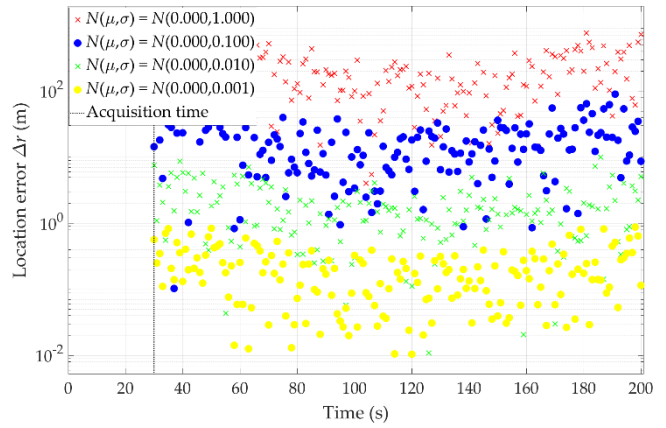


Figure 8. Localization error as a function of time for all distributions of velocity v oscillations.

Table 4. The mean value $\mu_{\Delta r}$ and standard deviation $\sigma_{\Delta r}$ of the localization error for different velocity v estimation error.

$N(\mu_v, \sigma_v)$ [m/s]	Localization error [m]	
	$\mu_{\Delta r}$	$\sigma_{\Delta r}$
$N(0, 1)$	229.59	214.56
$N(0, 0.1)$	22.59	19.52
$N(0, 0.01)$	2.42	2.33
$N(0, 0.001)$	0.22	0.21

Analyzing the above results, we can see that an error in determining the UAV speed of about 1 m/s results in localization errors of several hundred meters. Therefore, it is necessary to estimate this parameter as accurately as possible. The distribution of the UAV speed estimation error for which the localization error is acceptable is $N(0, 0.1)$.

3.7 The influence of the UAV's positioning accuracy

3.7.1 Scenarios assumptions

The study was conducted taking the assumptions from Section 3.1 into account. Additionally, the following assumptions were made:

- $x_0, y_0, z_0 = (1.5, 1.0, -0.1)$ km,
- Doppler frequency f_D is estimated without error,
- carrier frequency of transmitted signal $f_0=1200$ MHz and is estimated without error,
- the acquisition time $t_A=30$ s,
- the determination of its own position by the UAV is performed with an error whose values have a normal distribution $N(\mu_p, \sigma_p) = N(0, 0.1)$, $N(0, 1)$, $N(0, 2)$, $N(0, 5)$, $N(0, 10)$ m,

- the velocity is obtained from the UAV and is equal to $v=15$ m/s
- the mean value $\mu_{\Delta r}$ and standard deviation $\sigma_{\Delta r}$ of the localization error Δr is determined according to formula (7) and (8).

3.7.2 Results

Figure 9 shows an example of a UAV route used in research with and without UAV location error. Table 5 show the localization error for the given scenarios.

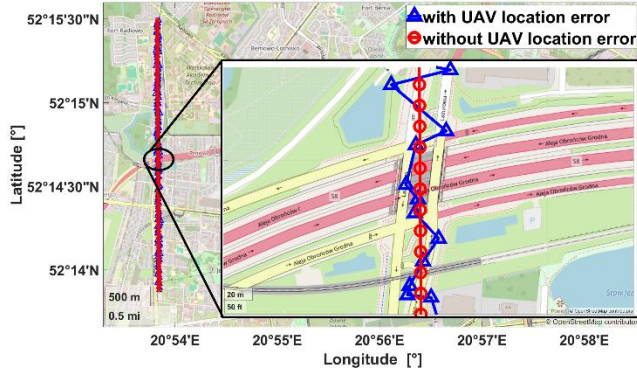


Figure 9. Example of a UAV route used in research with and without UAV location error.

Table 5. The mean value $\mu_{\Delta r}$ and standard deviation $\sigma_{\Delta r}$ of the localization error for different UAV location errors.

$N(\mu_P, \sigma_P)$ [m]	Localization error [m]	
	$\mu_{\Delta r}$	$\sigma_{\Delta r}$
$N(0, 0.1)$	0.41	0.25
$N(0, 1)$	3.64	2.72
$N(0, 2)$	7.39	4.98
$N(0, 5)$	18.33	13.89
$N(0, 10)$	37.49	26.61

Analyzing the above results, we can see that an error in determining the UAV location also has a significant impact on accuracy of radio emissions localization. However, it does not affect that significantly as, for example, the Doppler frequency f_D . Considering the accuracy of available GNSS receivers, whose worst-case location error is about 3-5 meters, will still allow for obtaining effective location for which the location error of the SDF method will increase by only a few meters.

4 CONCLUSIONS

The aim of the article was to examine the influence of parameters on the accuracy of localization of emission sources using the SDF method. For this purpose, a theoretical analysis of the SDF method and a series of simulation studies were conducted.

Analyzing the obtained results, it can be seen that in ideal conditions and taking all research assumptions into account, the carrier frequency f_0 estimation error has the smallest impact on the accuracy of localization. In its case, even an estimation error reaching tens of megahertz allows for effective determination of the position of the signal source. The selection of the acquisition time t_A has a slightly greater influence. In extreme cases, for ideal conditions, its change allows for a reduction of the localization error Δr by several meters, which is not a significant value. The selection of this parameter may become more important in the

case of an additional error in the estimation of the Doppler frequency f_D . However, the analysis conducted in the article concerned ideal conditions and only the change of the acquisition time t_A value. A much greater influence in the case of localization is the precise determination of the velocity of the localization sensor carrier, in our case UAV. In this case, an incorrect determination of the speed differing from the actual value by only 1 m/s can result in localization errors reaching hundreds of meters for the analyzed scenario. Also, the influence of the UAV's positioning accuracy is important in SDF method location error. The scenarios tested show that the use of commercial GNSS receivers with an error of several meters should still allow for effective localization, and the impact on the SDF method location error should be of the order of several meters. However, the greatest impact on the localization error can be observed in the case of the Doppler frequency f_D estimation. In the assumed scenario, its value varied in the range from about 60 Hz to -60 Hz. Errors in the estimation of this parameter reaching tens of hertz completely disqualify the method from practical use. Frequency estimation with an error of single hertz, on the other hand, translates into a localization error of several dozen meters, which, however, for a given scenario allows for the correct localization of the signal source.

To sum up, in the case of the SDF method, the greatest impact is played by the Doppler frequency f_D estimation. Its determination is also the biggest problem in the case of practical implementation, especially when we are dealing with modulated signals and non-line-of-sight (NLOS) conditions. Future research will therefore focus on the most faithful recovery of the Doppler frequency f_D value using different frequency estimators.

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ABBREVIATIONS

DFS	Doppler frequency shift
GNSS	global navigation satellite system
NLOS	non-line-of-sight
SDF	signal Doppler frequency
UAV	unmanned aerial vehicle

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