Leveraging Digital Maps to Visualize Data in Doppler Effect-based Localization System Relying on GNSS

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Abstract — Abstract – This paper presents a localization solution exploiting the Doppler effect, digital maps and the Global Positioning System (GPS). To deploy such a system, the following steps must be completed: selecting a suitable GPS receiver, developing operating software, creating an app for displaying digital maps offline, choosing a software-defined RF receiver with a stable frequency reference, integrating the GPS receiver with the map and a radio within a software environment, and setting up a transmitter-receiver link. The second part of the research involves comprehensive tests of the integrated localization system and analyzing the empirical results obtained. The novel approach described in this article consists in the use of digital maps and GNSS data for dynamic visualization of transmitter location using the SDF method. The research was carried out in an NLOS environment.

Keywords* — *localization of radio sources, signal Doppler frequency method, UAV

1. Introduction

One of the key objectives of modern telecommunication systems, civilian rescue operations, and military electromagnetic reconnaissance campaigns is to search for, detect and determine the location of radio signal sources. Localization systems are used, inter alia, in mobile ad hoc networks, aircraft guidance as well as search and rescue (SAR) missions.

Enhancement of the existing localization methods and development of new techniques is of paramount importance for numerous civilian and military applications. Radio frequency (RF) transmitters may be localized based on the features of the received signal.

This work employs an innovative localization method utilizing the Doppler effect, i.e. the signal Doppler frequency (SDF) method, and presents the results obtained with the use of an integrated Doppler localization system. This objective was achieved by selecting a suitable GPS receiver, developing a supporting application and software displaying a digital map.

We also selected a software-defined radio platform with good frequency stability for the receiving path, as well as integrated the GPS receiver, the map, and the SDR into the programming environment. Then, we set up the transmitter-receiver link. In the second part of the research, tests of the integrated localization system were conducted and the results obtained were analyzed.

The novelty of the approach adopted consists in the first practical implementation of SDF method-based algorithms in an integrated measurement system, as well as in the fact that in-field measurements were conducted in non-line of sight (NLOS) conditions.

The structure of the article reflects the research conducted. Section 2 describes the localization method. In Section 3, the general concept of the integrated localization system is presented. Section 4 describes the signal processing steps taken by developed system. The implementation of the GPS receiver and the digital map in the localization system is outlined in Sections 5–6. In Sections 7–9, tests of the integrated system, empirical research, and results of in-field measurements are described. The work concludes with a summary provided in Section 10.

Recent articles related to the localization of radio sources focus on various localization methods, signal processing techniques, and real-world applications under various environmental conditions.

In article [1], received signal strength (RSS) information is explored to improve transmitter localization accuracy. The authors propose a direct position determination (DPD) method using RSS data in distributed receiver arrays with beamforming. The study aims to assess the potential of RSS data in transmitter localization applications and proposes an improved DPD method.

In [2], a single sensor localization method, utilizing time of arrival (TOA) with interpulse modulation, is presented. The presented model uses the nonlinear least squares (NLS) problem from the perspective of maximum likelihood (ML) estimation, achieving high estimation accuracy and surpassing outcomes of conventional methods. Paper [3] discusses various transmitter localization approaches using a single satellite reference, such as difference in received signal strength (DRSS), direction of arrival (DOA), TOA, and frequency of arrival (FOA) methods. The article also addresses challenges associated with passive synthetic aperture (PSA) techniques and proposes solutions to improve localization accuracy.

In article [4], an effective transmitter localization algorithm is proposed that uses frequency difference of arrival (FDOA), with its application divided into two steps. The authors discuss the limitations of traditional transmitter localization methods and present an innovative approach that enhances accuracy by reducing errors arising from FDOA initialization. Paper [5] describes a technique for localizing a passive transmitter using simultaneous measurements of time difference of arrival (TDOA) and FDOA from unmanned aerial vehicles (UAVs). The article describes numerous numerical experiments, proving the effectiveness of the proposed method.

The research presented in [6] describes a real-time localization testbed based on the TDOA method using software-defined radio (SDR) communication and using GPS-based synchronization. The system aims to achieve high accuracy thanks to updating frequencies for target tracking and employing Kalman filtering to improve the localization results.

Other important works include articles [7] and [8]. These papers focus on the challenge of precise localization and UAV navigation using cooperative localization that exploits inexpensive ultra-wideband (UWB) transmitters. The accuracy of the proposed system is evaluated through simulations and field tests, as well as through comparisons with GNSS data in urban environments. Paper [8] proposes a novel localization and mapping system based on UWB technology that enables real-time motion tracking in an unknown environment. Experiments confirm that the proposed system offers a localization precision level of less than 1 m from the actual trajectory of the object tracked.

The Doppler effect has been widely utilized for the localization of dynamic objects due the simple nature of the process of capturing frequency shifts caused by the relative motion between the transmitter and receiver. This makes the approach in question particularly suitable for scenarios where the tracked objects are in motion, such as in aircraft guidance, SAR operations, and military reconnaissance. However, existing methods often face challenges in complex environments, where multipath propagation and NLOS conditions degrade their accuracy. Many approaches rely on using multiple receivers, precise synchronization, or exploit other techniques, such as RSS, TOA, or FDOA.

Unfortunately, they are susceptible to errors in dynamic and obstructed environment scenarios. The proposed solution, based on the SDF method, fills these gaps by providing localization services with only a single mobile receiver, without requiring external synchronization or relying on received signal strength. This approach offers improved accuracy in NLOS conditions and dynamic environments – an issue which has not been fully addressed in previous research.

Furthermore, by integrating a GPS receiver and digital maps, the proposed solution enhances the ability of Doppler-based methods to provide quasi-real-time accurate localization in challenging scenarios. The comparison with existing methods shows that the proposed approach not only simplifies the hardware, but also improves the accuracy and reliability of the localization process, especially in real-world conditions with signal interference and obstacles affecting the radio link.

2. Proposed Localization Method

The radio source localization system is based on the SDF method [9], [10]. It utilizes the Doppler effect and allows to localize radio transmitters. The Doppler frequency shift (DFS) f_D phenomena are observed in the received signal when at least one of the elements transmitting the signal is in motion. The method is based on the functional relationship between DFS and the location of transmitter and receiver positions and allows to localize multiple radio emitters [11]. It belongs to a narrow group of transmitter position localization methods that rely on a single mobile platform. The advantage of the proposed solution is that external time synchronization of the received signal is not required and received signal strength indicator is not considered.

The SDF method is based on the analytical solution of the wave equation presented in [12], [13]. It refers to a moving signal source that causes the f_D frequency shift that is dependent on time t, velocity v of the moving transmitter or receiver, and their relative positioning x_0, y_0, z_0 [10], [11]:

$$f_D(x_0, y_0, z_0, t) = f_{Dmax} \frac{x_0 - vt}{\sqrt{x_0 - vt}^2 + \sqrt{y_0^2 + z_0^2}} , \quad (1)$$

where $f_{Dmax} = \frac{f_0 v}{c}$ is the maximum Doppler frequency, v is the velocity of the moving receiver (or transmitter) along the x axis, c is the velocity of the electromagnetic wave in the given medium, f_0 stands for the carrier frequency of the emitted signal, x_0, y_0, z_0 are the x, y, z coordinates of the position relative to the receiver at time $t = 0$. By some manipulations of Eq. (1), the estimators of the coordinates of the position of the localized signal source are obtained. These coordinates define the SDF method [12], [14]:

$$\begin{aligned} x &\cong v \frac{t_1 A_1 - t_2 A_2}{A(t_1) - A(t_2)} \\ y &\cong \pm \sqrt{\left[\frac{v(t_1 - t_2) A(t_1) A(t_2)}{A(t_1) - A(t_2)} \right]^2 - z_0^2} \end{aligned} , \quad (2)$$

where

$$A(t) = \frac{\sqrt{1 - F^2(t)}}{|F(t)|} , \; F(t) \cong \frac{f_D(t)}{f_{Dmax}} . \quad (3)$$

Equations (2) and (3) describe two-dimensional localization (2D), i.e., they assume that coordinate $z = z_0$ is known.

The three-dimensional version of the SDF method is widely presented in the literature, among others, in [15]. Here, the 2D SDF method was utilized, where RF source localization is possible if the Doppler frequency measurement is performed at two moments in time, namely t_1 and t_2. The concept utilizes a system receiver (Rx) placed in a moving vehicle, allowing to determine stationary coordinates of signal sources, i.e. transmitter (Tx), as shown in Eq. (2).

The SDF method is used in a wide range of applications, such as electronic reconnaissance, navigation, maritime rescue operations, and emergency management scenarios. Moreover, by relying on SDF, one may also determine the positions of signal sources transmitting binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK) modulated signals [15]. To achieve this, the property of phase shift keying

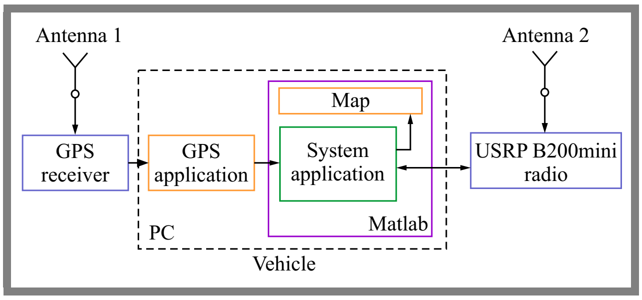

Fig. 1. Diagram of the localization system developed.

(PSK) emission is exploited, resulting in a peak in the signal spectrum raised to a power equal to the modulation depth.

In practice, software and hardware must be integrated into a single system in order to find specific applications of localization methods. The best solution is to utilize software defined radio (SDR) platforms [12] enabling easy and fast implementation of localization algorithms, as well as their testing and further modifications.

3. Integrated Localization System Concept

The localization system developed is made up of several components (Fig. 1). The USRP B200mini radio platform [14] receives the RF signal from the transmitter to be localized. The samples received, in the form of IQ components (in-phase/quadrature-phase), are transmitted via the USB port to a PC computer. The second component of the setup is the GPS receiver. The purpose of this device is to determine the position of the moving receiver, calculate its velocity, and provide time serving as a reference value for the entire system. The GPS receiver is also connected to the PC via a USB port and its operation is ensured by a dedicated application written in the C language.

An offline map is another part of the system, allowing to visualize the position of the moving receiver and the estimated position of the transmitter. The entire system is installed in a vehicle.

A PC-based application that integrates all of the listed components, including radio control, digital map handling, reading of stored data from the GPS receiver, and estimation of the signal source location using the SDF method, has been implemented in the Matlab environment.

4. Signal Processing in the Developed System

In [16], a signal processing method was presented, serving as a foundation for implementing the SDF method. The proposed system extracts the carrier frequency of the target signal from the received spectrum, which appears to change due to the movement of the object. The utilization of SDR radio allows to analyze the selected frequency band, transform it into a digital form, and transmit such data to the PC and the Matlab software. The data buffering and processing diagram is shown in Fig. 2.

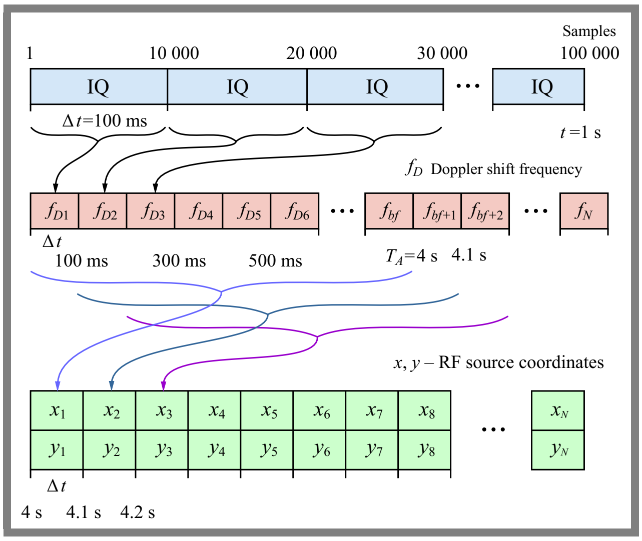

Fig. 2. Processing the received signal and estimating the coordinates of the RF signal source in the system.

The DFS value is determined from each received frame containing 10 000 IQ samples. While one frame lasts for 100 ms and the buffer depth is set to 40 values, the first position of the localized transmitter could be determined after 4 s. Then, after collecting 40 subsequent frames, Tx coordinates x, y are calculated.

Absolute errors x, y and relative errors Δ_r, δ_r of the estimated location may be determined based on the known coordinates x, y [17], as the position calculations are carried out in a local Cartesian coordinate system which is then transformed into a geocentric coordinate system using the Universal Transverse Mercator (UTM) approach. The position of the GPS receiver serves as the reference for mapping the positions onto a geographically projected map.

$$\Delta_r = \sqrt{(\Delta_x)^2 + (\Delta_y)^2} = \sqrt{|x_0 - x|^2 + |y_0 - y|^2} \,, \qquad (4)$$

$$\delta_r = \frac{\Delta_r}{\sqrt{x_0^2 + y_0^2}} \times 100 \ [\%] \,. \qquad (5)$$

5. Implementation of a GPS Receiver

The PhidgetGPS 1040 platform was chosen for the implementation of the GPS receiver in the proposed localization system [18]. This receiver can determine the position, velocity, and the direction of movement with the circular error probable (CEP) specified by the manufacturer at 2.5 m. The percentage probability for this metric, however, is not provided.

In the context of GPS navigation, a 50% probability is most commonly used for CEP, meaning that in 50% of cases, the position measurement should fall within a 2.5-meter radius of the actual position.

Figure 3 shows the PhidgetGPS receiver module used and an antenna adapted for receiving L-band signals.

The application supporting the PhidgetGPS module was developed in the Embarcadero Technologies RAD Studio pro-

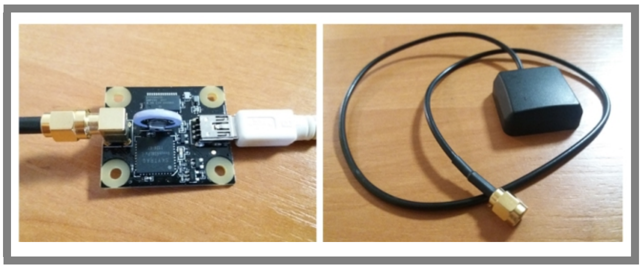

Fig. 3. PhidgetGPS 1040 receiver and external antenna.

gramming environment [19]. The software operates independently in Windows 10, using the latest version of the Phidget22 libraries [20]. The main task of the developed application is to determine and record the current position and velocity of the localization system equipped with a GPS receiver. The application allows data related to coordinates, date, time, altitude above sea level, and velocity of the receiver to be retrieved, and then the information obtained may be saved into a text file.

Alternatively, a second measurement mode may be activated in which a specified number of measurements (e.g., 200) is performed at specified time intervals (minimum 0.1 s). The collected data are also saved into a text file.

6. Implementation of a Digital Map in a Location-based System

The current position and the estimated position of the source being localized are visualized on the digital map. Most digital maps are available for use online. Hence, to view them, Internet access is needed. In the project in question, it is assumed that the localization system may operate in areas without cellular network coverage.

To address this issue, an offline digital map was created and uploaded to the application. This map was created using [21], serving as a library of various resources, including topographic maps and aerial photos. A topographic map was chosen to better visualize the positions of the localized transmitters and receivers with metadata that allow the addition of georeferencing information.

Thanks to such an approach, the map created using the software in question contains an image of the designated area along with information about geographic coordinates, reference system parameters, projection details, etc.

7. Testing the Integrated Localization System

A block diagram of the data processing algorithm used in the SDF method is presented in Fig. 4. Block B covers the operation of the GPS receiver and the recording of system positions throughout the measurement campaign. In the next step, Matlab program is run, and data on the number of measurements to be performed are loaded. The present values determine execution time, with one measurement corresponding to one DFS lasting 0.1 s, for a sampling frequency of $F_S = 100$ kHz and the number of samples in a frame $N_S = 10\,000$.

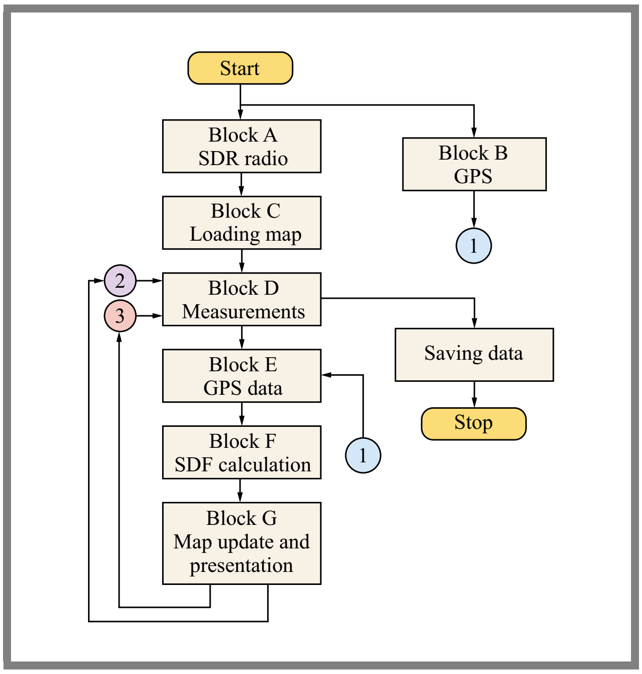

Fig. 4. Block diagram presenting operation of the proposed system and integration of its components.

The buffer size indicates how many measured DFS values are to be used to calculate the x, y coordinates of the transmitter being localized.

Upon startup of the application, the program will check if the SDR radio is connected to the PC (block A) and will configure it according to the specified preset values. Block C illustrates the loading of the offline map.

During the measurement loop, the sampled signal is divided into 10 frames. On the basis of spectral analysis, f_d is determined from each frame and stored in the $freq\_Doppler$ buffer. Subsequently, current GPS information containing data on the receiver's position, velocity, and reference time is retrieved. All data are stored in a local database.

The next step is to check if the required number of DFS has already been reached, based on which the transmitter's coordinates could be determined. If not, the software skips the location estimation step and moves on to determine the receiver's position on the map, checking the program termination conditions.

Once the required number of DFS values has been obtained, the program calculates the estimated coordinates of the RF transmitter located using the SDF method. For this purpose, information is used about the current velocity of the moving receiver, the transmitter's carrier frequency and the time at which the DFS were measured. Additionally, the known real coordinates of the located transmitter are introduced as variables, while the difference between the calculated coordinates x_0, y_0, z_0 and the real coordinates x, y, z allows to determine the localization error.

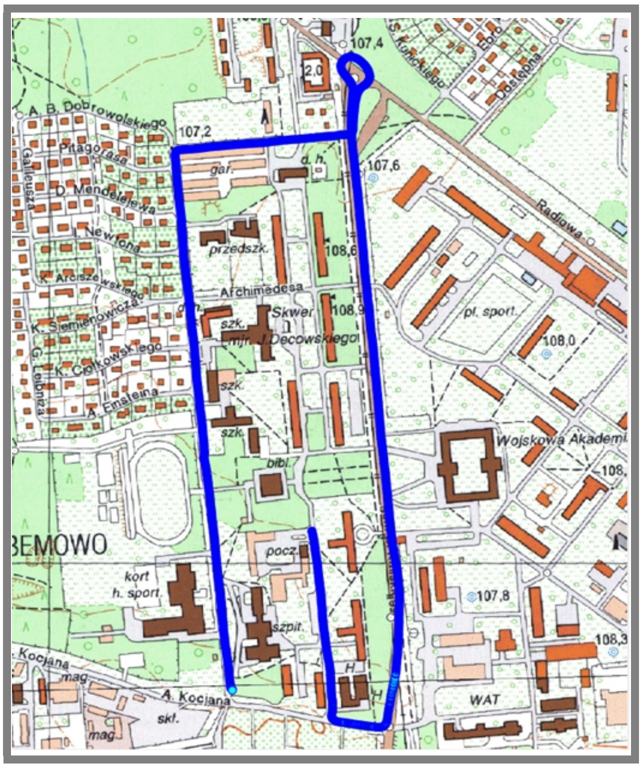

Fig. 5. Route of the vehicle with a GPS receiver on board.

8. Empirical Studies

The GPS system was validated by driving a vehicle in the selected area shown on the map (Fig. 5).

The difference between the coordinates determined by the GPS receiver and its actual position did not exceed 1 m. Position accuracy falls within the manufacturer specified circular error probability of 2.5 m. Figure 6 shows the velocity of the receiver during the measurements, while Fig. 7 depicts the receiving part of the measurement setup. Two antennas were installed on the vehicle's roof: one for GPS and the other for receiving signals from the transmitter. Inside the vehicle, the radio was connected to the antenna by means of a cable, and a laptop with the radio and GPS receiver was connected via a USB port.

The transmission part includes a Rhode & Schwarz SMIQ2 signal generator, an Amplifier Research 5S1G4M4 signal amplifier, a standard source of rubidium frequency (FS725) from Stanford Research Systems, and a Katherin 738449 transmitting antenna. The generator works at 1832 MHz, which, according to Eq. (3), allows to achieve a DFS of up to 100 Hz, while maintaining a vehicle speed of approximately 60 kph. The transmitter setup is shown in Fig. 8.

The generator signal is fed to the RF amplifier and amplified to an output power of 5 W. It is then radiated through the antenna. Such a high power value was selected to make sure that the signal is distinguishable in the spectrum and above the noise level. The rubidium frequency standard at 10 MHz acts as a reference value for the generator.

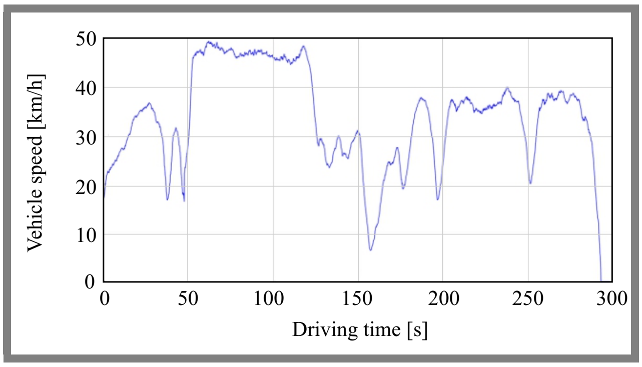

Fig. 6. Speed of the GPS receiver during the measurement campaign.

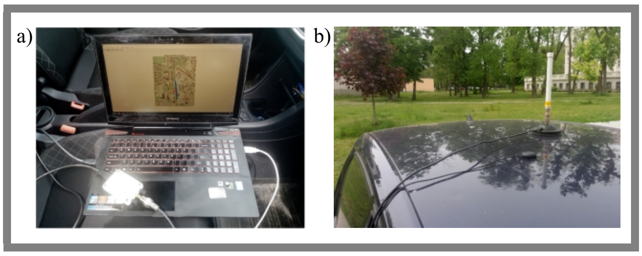

Fig. 7. Diagram of the integrated locator and transmitter system.

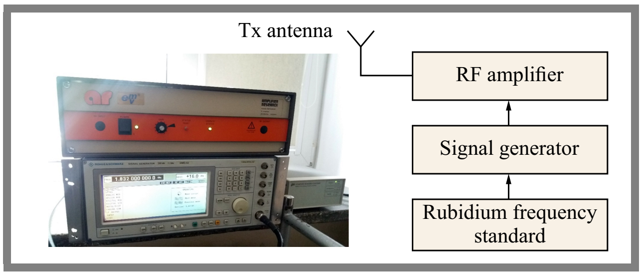

Fig. 8. Transmitter with a generator, amplifier, and rubidium frequency standard a) and diagram of setup b).

Empirical studies were conducted based on the selected measurement scenario shown in Fig. 9. The plan was to travel along the road between points A–C and C–A. While the car was moving along the selected route, Rx received the signal from Tx. On the basis of the analysis of the received signal and the determination of the position using GPS, the developed localization system estimated the target coordinates. The in-motion test was repeated several times during the night with the vehicle traveling at approximately 60 kph.

9. Results of Empirical Studies

Figure 10 shows the measurement results of the estimated positions of the Tx location, marked in red. Each point was determined based on consecutive sets of 40 DFS. One may notice that the highest density of points is observed near the Tx location.

Using information about the actual position of the localized source, we verified the accuracy of the determined coordinates using Eq. (4). Table 1 presents the determined localization errors, with lowest error value equaling 1.46 m only.

Such results demonstrate that the developed method allows to determine the coordinates of an RF source with accuracy similar to that of other proposals. The best result is achieved when the receiver passes the transmitter at the closest approach

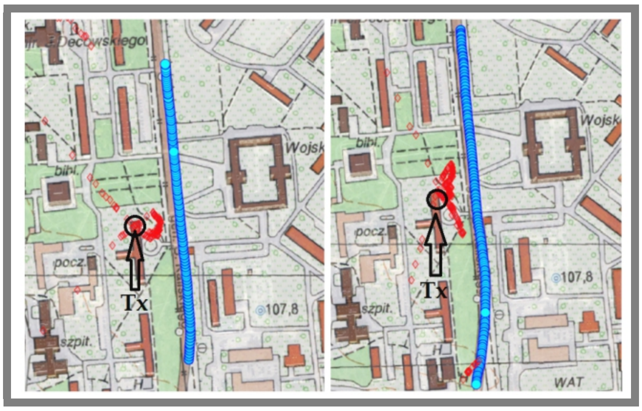

Fig. 9. Route taken by the vehicle during the tests.

(PCA) point. The lowest error is obtained for the section of the route where characteristic rapid changes in DFS occur (Fig. 11). DFS values were determined every 0.1 s, which explains the visible discrete variations. Similarly, the estimated T_x position (values x and y) was also evaluated sequentially, every 0.1 s for consecutive DFS measurements, spaced apart by the signal acquisition time of $T_A = 4$ s. This is why many estimated x_n, y_n values are marked red on the map.

The NLOS environment in which the measurements were performed had the most negative impact on location accuracy. The impact of interference present in the measurement environment is shown in Fig. 11, where a high frequency of rapid changes is visible. The error, defined as the difference between consecutive estimated DFS exceeding $\frac{f_{Dmax}}{2}$, is obtained directly from the complex NLOS environment, with large trees, a building, a tram power line, and other smaller objects affecting the measurements. Such errors were not observed during measurements conducted using UAVs, where a LOS environment was expected between Tx and Rx, hence the transmission was not obstructed.

However, in this experiment, the aim was to test whether the proposed method would succeed in a highly urbanized area. The low-cost SDR used in the system provides short-term frequency stability at a level of 10^{-7} [22], which directly contributed to low error values, appearing as frequency jumps of only 20 Hz, due to atomic frequency standard utilized in Tx.

10. Summary

The aim of this research was to integrate a GPS receiver and a digital map with a Doppler-based RF source localization system. The tests confirmed the functionality of the hardware platform and the dedicated PC-based application.

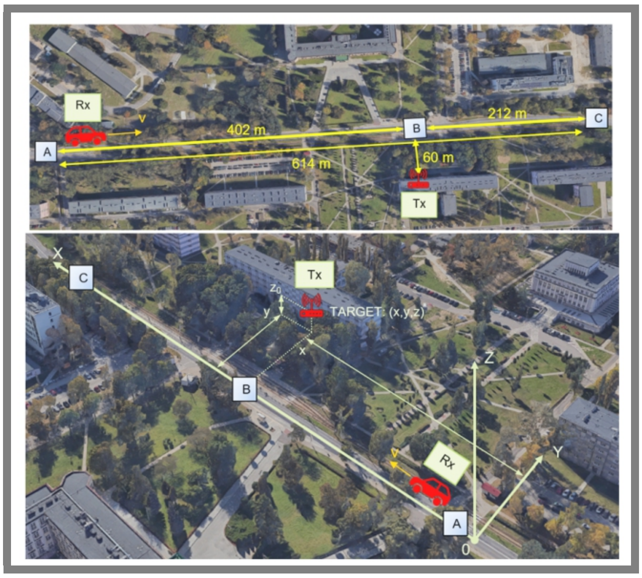

Fig. 10. Map with the path of the receiver (blue) and the estimated coordinates of the transmitter (red).

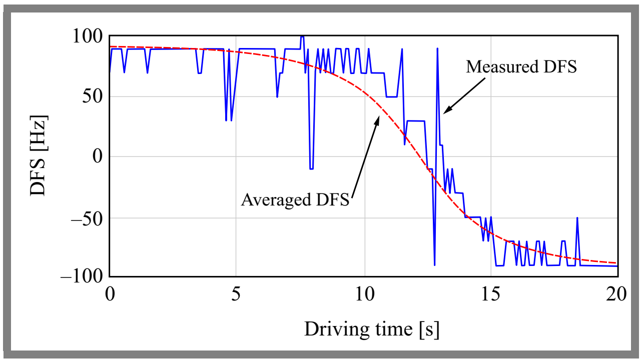

Fig. 11. Measured DFS (blue) and its averaged value (red) for the selected route.

The tests involving the integrated localization system demonstrated its accuracy and effectiveness. The position of the receiver was determined, on the map, with a very high level of precision, while the error in the estimated coordinates of the localized transmitter amounted to a few meters only. Empirical studies were conducted in an urban environment where obstacles existing between the transmitting and receiving antennas caused multipath propagation. Nevertheless, coordinates showing the location of the RF source were determined successfully.

Tab. 1. Location errors Δ_r obtained during the measurements.

Measurement no.	1	2	3	4	5
Δ_r [m]	3.25	2.99	8.88	1.46	9.50

The modular design and compact size of the hardware setup are additional advantages of the proposed solution.

To further improve accuracy, a higher-precision GPS receiver should be utilized and the localization system should be mounted on a flying object, such as a drone. This would help reduce the impact of NLOS environments on the received signals, allowing to extend the research to cover 3D localization methods.

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