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Implementation of Doppler-Based Location Sensor on Unmanned Aerial Vehicle

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***Abstract*—The article presents the first implementation of the Signal Doppler Frequency (SDF) location method on an Unmanned Aerial Vehicle (UAV) named Autonomous System of Location radio EmmiteRs (ASLER), employing a DJI Matrice UAV as its mobile platform for the radio sensor. The system is used for position estimation, i.e., determining the location coordinates of localized radio emitters. Such functionality is the basis of radio reconnaissance, electronic warfare, or combat systems, and many radio navigation systems. The ASLER localization procedure is based on the Doppler localization method, also known as the SDF. Its distinctive feature is the use of a single moving platform for localization. In addition, the SDF allows simultaneous localization of multiple emission sources, which is an innovative distinction compared to other solutions of this class. ASLER is the first autonomous implementation of the SDF method on a flying platform. This paper illustrates the hardware and software implementation of location sensor, and results of the first empirical studies.**

***Keywords*—radio emitters; localization; Signal Dopler Frequency method; radio navigation; UAV**

I. INTRODUCTION

IN the contemporary dynamically evolving technical milieu, sophisticated localization systems assume a paramount role across diverse domains, encompassing both military and civilian applications. From search and rescue operations to situational monitoring, Unmanned Aerial Vehicles (UAVs, drones) emerge as innovative instruments facilitating target localization in challenging terrains, thereby contributing to the enhancement of measurement accuracy pertaining to localization parameters.

Numerous distinct localization methods exist, each possessing unique advantages and applications. Among them is the Angle of Arrival (AOA) measurement method, which utilizes directional information of the signal's arrival. In [1], an innovative Direct Position Determination (DPD) technique is introduced, representing a single-step localization approach without the need for intermediate parameter estimation. This method employs a moving sensor array, combining angular and Doppler information, enabling precise localization even under low Signal to Noise Ratio (SNR) conditions. In [2], the potential for target localization at a distance using a UAV platform is present-ed. A technique is introduced where a UAV, equipped with electro-optical devices and a laser rangefinder, performs angle and distance measurements for precise geolocation of a distant ground target. This method accounts for mounting errors between the navigation module and electro-optical device, with simulation results confirming localization accuracy at 10 meters when the UAV is positioned 4000 meters away from the target.

In the context of localization for multiple UAVs, article [3] proposes an algorithm based on Ultra-Wideband (UWB) signals and visual odometry information. This method processes data from visual motion measurement, constructing a graph to solve the problem of relative localization. Experimental results validate the effectiveness of the proposed algorithm. In the research work [4], an innovative approach to simultaneous localization of UAVs and Radio Frequency (RF) sources is introduced. The Simultaneous Localization of UAV and RF Sources (SLUS) method utilizes a Kalman filter, Received Signal Strength Indicator (RSSI), and AOA measurements to enhance the accuracy of RF source localization and prevent UAV navigation divergence. Simulations confirm the effectiveness of this technique.

In the case of passive radio emitter localization, article [5] introduces a method utilizing Time Difference of Arrival (TDOA) and Frequency Difference of Arrival (FDOA) measurements from moving UAVs. The proposed technique relies on the Cross Ambiguity Function (CAF) and grid optimization, enabling precise localization even in low SNR conditions. Conversely, in [6], the focus is on RF emitter localization using a Vertical Take-Off and Landing (VTOL) UAV platform. The study compares a standard two-step method based on AOA measurements with the DPD approach. Re-al-world experiments confirm the higher effectiveness of DPD techniques, especially in low SNR conditions.

In the context of multi-emitter localization, article [7] proposes a system structure based on UAV employing a Direction of Arrival (DOA) estimation algorithm, enhancing localization resolution and achieving two-dimensional DOA estimation (azimuth and elevation). Another example of multi-RF source localization is presented in article [8], where the authors suggest an approach based on Bayesian Compressive Sensing (BCS), utilizing Received Signal Strength (RSS) measurements collected by UAV. The Trajectory Planning-based Bayesian Compressive Sensing (TPBCS) algorithm dynamically plans UAV trajectories, optimizing localization results, and reducing computational costs in UAV path planning. Simulations confirm the effectiveness and robust-ness of the proposed approach.

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The conclusions drawn from these articles suggest that the diversity of localization methods, ranging from direct DPD algorithms to advanced techniques based on UWB, can be tailored to specific applications, terrain conditions, and environmental types. Each of these methods contributes innovative solutions, supported by simulations or experiments, facilitating the development of efficient localization systems for UAV platforms.

As an integral component of advancing localization methodologies, this study concentrates on pioneering strategies for location determination employing drones. The Autonomous System of Location radio EmmiteRs (ASLER) was developed as part of the ongoing research on the determinants of localization of radio emission sources based on Doppler Frequency Shift (DFS) estimation in a mobile measurement system. It is an autonomous Unmanned Aerial System (UAS), whose task is to detect and locate ground-based radio emitters and monitor the electromagnetic situation in a set airspace area. The purpose of the developed UAS is one of the essential tasks for reconnaissance and electronic warfare systems used in peacetime (e.g., for protection and search and rescue missions) and during military operations (i.e., detection of enemy radio objects). The project has developed a technology demonstrator at Technology Readiness Level (TRL) 5. Its part is a commercial UAV is its part. This drone has been retrofitted with an essential component of the system, i.e., a programmable radio sys-tem with an on-board computer providing localization functionality. The implemented localization procedure is based on the Signal Doppler Frequency (SDF) method. It was developed and is being expanded at the Military University of Technology (MUT) [9–11]. Implementing the localization algorithm, which works with a software-defined radio (SDR) platform and a Global Positioning System (GPS) receiver, provides accurate estimation of the location of radio emitters. It also allows analysis of the electro-magnetic situation. As part of the executed UAS with localization application, preliminary tests and field tests were realized.

The novelty presented in the research work is the implementation of the author's algorithms using the SDF method on the designer's integrated flying platform, the performance of the first practical tests proving the method's effectiveness using a UAV. Section 2 describes the concept of the UAS. Section 3 describes the project, including the implementation of the SDF on the SDR platform, the integration of a GPS receiver in the localization system, and the use of a digital map. Section 4 presents the experimental results for the selected measurement scenario. The article concludes with a summary.

II. ASLER Concept

A. ASLER Structure

The concept of the proposed localization system is based on a set of interconnected components and functionalities. The first is the B200mini Universal Software Radio Peripheral (USRP) SDR platform. Receiving the radio signal emitted by a localized transmitter (Tx) is the main task of this device. The SDR platform operates over a wide frequency range, allowing localization of emitters in the band from 70 MHz to 6 GHz. The received and processed signals in the form of in- and quadrature-phase (IQ) samples are transmitted via Universal Serial Bus (USB) to the second component, the Raspberry Pi 4B (RPi4) microcomputer. The GPS receiver is the third component of the system, which determines the position and speed of the moving UAV. In addition, the GPS is responsible for distributing the time scale, the reference standard signal for the entire system. The system uses a GPS located on a flying aircraft. It is connected to a microcomputer via a General-Purpose Input/Output (GPIO) interface. A functional diagram of the integrated localization system is shown in Fig. 1.

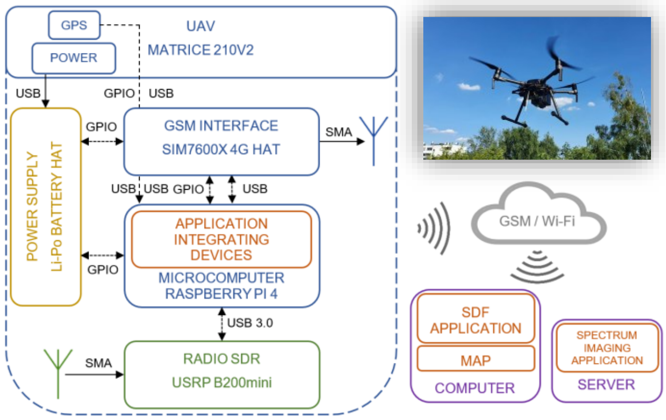

Fig. 1. ASLER scheme

A Global System for Mobile communication (GSM) overlay is attached to the microcomputer, responsible for communication with the mobile network and access to the Internet. This allows continuous access to the system and transmission of received radio data to the signal technical analysis station. A connection to a local Wi-Fi network router also provides the same functionality. The localization functionality of the UAS is provided by a dedicated application developed by the author, running on a microcomputer processing signals from the SDR and GPS. The whole system is placed on an autonomous and self-contained UAV. The UAV on-board power supply powers the ASLER components. To maintain continuous operation of the microcomputer and SDR, the system is equipped with an emergency power supply – a power overlay containing a lithium-polymer battery placed on the microcomputer. Data from the SDR are stored in memory, allowing offline signal analysis after the mission. Measurement results can also be sent anywhere in the world via the Internet to a designated server or another workstation.

B. SDF Method

The proposed radio emitter localization system uses the Doppler effect [9–12], based on the SDF method. This method is based on the analytical solution of the wave equation for a moving radio object, so it has high accuracy [10]. Changes in the DFS occurring in the signal received from the localized emitter provide a distinctive feature linking its position to the trajectory of the moving receiver (Rx), which is the basis of the SDF method. A unique feature of the proposed method is the ability to localize multiple radio emitters simultaneously [13]. This method belongs to a small group of localization techniques that allow the positioning of emitters using a single mobile platform. In contrast, other methods usually require two or three sensors (drones) working in parallel.

Its basis is a relationship describing the DFS as a function of the mutual location of the Tx and Rx [10,14,15]:

$$f_D(t) = f_{D\max} \frac{x_0 - vt}{\sqrt{(x_0 - vt)^2 + y_0^2 + z_0^2}} \tag{1}$$

where (x_0, y_0, z_0) is the actual position of the signal source relative to the Rx moving with velocity v along the x direction, $f_{D\max} = f_0 v / c$ is the maximum DFS, f_0 is the carrier frequency of the transmitted signal, while c is the light speed.

By transformation of Equation (1), we can estimate the coordinates of the radio emitter [14,16,17]:

$$\begin{cases} x = v \dfrac{t_1 A(t_1) - t_2 A(t_2)}{A(t_1) - A(t_2)} \\ y = \sqrt{\left[v \dfrac{(t_1 - t_2) A(t_1) A(t_2)}{A(t_1) - A(t_2)} \right]^2 - z^2} \end{cases} \tag{2}$$

where $A(t) = \sqrt{1 - F^2(t)} / F(t)$, $F(t) = f_D(t)/f_{D\max}$ is the normalized DFS, (x, y, z) is the estimated emitter position. Above, it is a version of the SDF method for locating emitters on a drone. In this case, the assumption is made that one of the coordinates is known, i.e., $z = z_0$. A three-dimensional version of the method is presented in [16,18]. On the other hand, an overview of the application of the SDF method for localization and navigation is included in [11,17]. An implementation of the SDF method on a SDR platform was presented in [15].

In the simplest case, the emitter can be localized using the SDF method if a DFS measurement is made at two interception intervals t_1 and t_2. an Rx localization system and placed on a moving UAS can locate stationary Tx. The exemplary measurement scenario conducted in [19] is presented in Fig. 2.

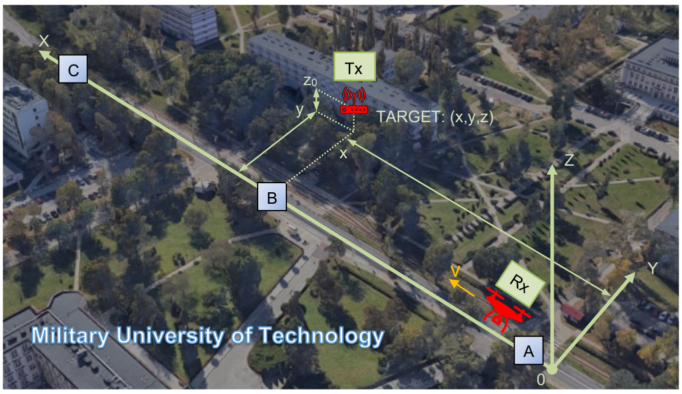

Fig. 2. Example measurement scenario [19]

SDR placed on a vehicle moves along a trajectory from point A to point C and localizes Tx emitting a radio signal. As the Rx moves toward the emitter, the DFS decreases from its maximum value to zero. Point B on the path is called the Point of the Closest Approach (PCA). In PCA, the frequency of the received signal coincides with the carrier frequency of the emitted signal. As the Rx moves away from point B, the DFS will decrease to a minimum value. As the Rx speed increases, the range of DFS changes will be larger. Fig. 3 demonstrates an example of Doppler curves versus time.

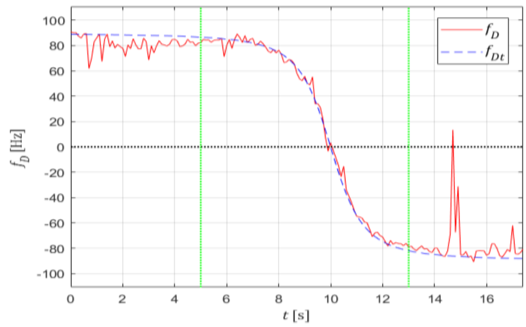

Fig. 3. Examples of theoretical (dashed blue line) and measured (solid red line) Doppler curves versus time. The green color indicates the area of the distinctive changes in the DFS

The course of the curve is the basis for estimating the coordinates of the emitter's position. The theoretical and empirical (i.e., obtained during one of the tests) curves are marked with dashed blue and solid red lines, respectively [15].

An integrated localization system on a UAV creates an autonomous UAS for locating radio emitters. An essential part of the ASLER functionalities is the author's dedicated microcomputer application supporting the SDR and GPS receiver. The implementation of SDF algorithms on the SDR allows for building electromagnetic situation awareness . It makes it possible to estimate the position coordinates of signal emission sources, i.e., localize them. The flight of the integrated system can also follow a designated and programmed route. The takeoff, flight, and return to the launch site is automatic. The aircraft's flight can take place at an altitude of a few to several hundred meters, at a speed of more than 50 km/h over a distance of up to several kilometers. During the flight, it is possible to perform real-time reconnaissance of the electromagnetic situation and record radio data (i.e., IQ samples), which allow analysis of the received signal in the post-processing "offline" mode. The performance of recon-naissance allows for the extraction of unique features of the received signal, estimation of the location of signal sources, and marking them on any map, for example, a topo-graphic military map. The developed autonomous UAS for localization of radio emitters is a developmental system, the functionalities of which can be extended in the future, e.g., localization/analysis of other types of emissions, ground analysis and command center, etc.

III. ASLER Project

The USRP B200mini model from Ettus Research [20] was used to implement the SDF method on a UAS. This is a SDR that can use so-called Cognitive Radio (CR) in the application [21–25]. When these two technologies are combined, such a device is sometimes called a cognitive programmable radio. A CR radio, unlike a typical programmable radio, can be programmed and configured dynamically, allowing it to select the best wireless channel found in the environment. The USRP B200mini is a radio with a lot of capabilities. Its main advantages is the device's small size. The radio con-sists of two tracks: receiving and transmitting. The receiving track will mainly be dis-cussed because it will be used later in the work. Based on the architecture, the radio's operation principle is considered. The received signal through the antenna is applied to the Rx signal input connector. Then, the signal is given to the RF Integrated Circuit (RFIC) module, where it is transferred to the baseband at the Intermediate Frequency (IF) and processed into digital form. The processed samples are then transferred from the intermediate frequency band to the fundamental band and filtered. This transformation is carried out using a Digital Down Converter (DDC). In the last phase, the samples are decimated and fed to a Field-Programmable Gate Array (FPGA) chip, where they undergo Digital Signal Processing (DSP).

The received Rx signal, after undergoing Band Pass Filter bandpass filtering to separate the bandwidth used in the application, is applied to the RFIC module. This module connects the RF input to the baseband section and integrated frequency synthesizers by providing a configurable digital interface to the processor. The operating range covers most licensed and unlicensed bands. The receiving subsystem includes independent Automatic Gain Control (AGC), quadrature equalization, and digital filtering. This will eliminate the need for these functions in the digital baseband. The filtered passband signal is amplified in a Low Noise Amplifier (LNA) and demodulated to the IF band. This is achieved using a programmable synthesizer, mixer and band-pass filter. After amplification, the signal transfers to the baseband, separating the synphase I and quadrature Q components. Two Analog to Digital Converters (ADCs) with high dynamic range digitize the received I and Q samples. The digital signal received at the output of the configurable decoding and Finite Impulse Response (FIR) filters appears in a 12-bit representation. Thus, it can be seen that the Rx circuit consists of several elements still made in analog technology [26]. Implementations of the SDF method using the USRP B200mini are detailed in [15] and [27].

One of the main components of ASLER is a microcomputer, which is the "heart" of the whole system. The computer platform of choice is the RPi4B [28]. The device con-sists of a single printed circuit board, a processor, 8 GB RAM (Read Access Memory), two USB 2.0 ports, two USB 3.0 ports, a Gigabit Ethernet interface, two micro High Definition Multimedia Interface (HDMI) ports, a USB-C power connector, and GPIO ports. The task of the microcomputer is to establish a connection and operate the selected programmable radio, read received data from it, save it to memory and upload it to the server, operate an overlay that provides GSM/Wi-Fi network connectivity, establish communication and read GPS data from the flying platform. The selected model has a RAM of 8 GB, which allows to dynamically allocate the received signal and then save it to static memory on a 32 GB micro Secure Digital (microSD) card. The base system for the Raspberry Pi is a free Debian-based Linux distribution called Raspbian. The software is installed as an image on a microSD card inserted into the micro-computer.

The advantage of the RPi platform is that its functionality can be extended. This is possible thanks to the GPIO expansion connector. This concept has allowed the development of overlays for microcomputers. The project uses an overlay that allows communication via a cellular network in 4G technology – SIM7600E 4G HAT from Waveshare [29]. This allows basic Internet services, as well as sending SMS and making phone calls. The Long Term Evolution (LTE) network provides high-speed data transmission. Fig. 4 shows the microcomputer and overlay used in the system.

Fig. 4. Connecting the SIM7600E 4G HAT overlay with a Raspberry PI microcomputer [30]

The main component of the overlay is Simcom's SIM7600E GSM module. It allows LTE communication at speeds of up to 150 Mbps for downloading and 50 Mbps for uploading. It also supports the technology of previous generations such as Universal Mobile Telecommunications System (UMTS) and General Packet Radio Service (GPRS). The overlay has a USB interface, Universal Asynchronous Receiver-Transmitter (UART) and Global Navigation Satellite System (GNSS) communication module for satellite localization. It is also possible to connect a microphone and headphones, making phone calls possible. Control is possible via Attention (AT) commands on the UART interface. The overlay includes a GSM and GPS antenna with SubMiniature version A (SMA) connectors, SMA-U.FL adapters, micro USB to USB cables, and a set of mounts allow mounting on a microcomputer. Preparing the overlay for operation involves inserting the operator's Subscriber Identity Module (SIM) card and connecting the GSM antenna to the MAIN connector and the GPS antenna to the GNSS connector. The two antennas can be connected using adapters.

Powering a microcomputer placed on a drone can be accomplished by attaching a suitable battery-powered cap and connecting a portable power bank to it, or using the power output from the drone. The challenge for a small power supply system is the need to provide significant power to the system being operated. This is due to the need to power the microcomputer, GSM overlay, and USRP B200mini programmable radio. The power source should be characterized by high current capacity while being light-weight. For this purpose, a Lithium-polymer Battery HAT overlay was used, which is integrated into the Raspberry Pi via the SW6106 power management chip.

The Matrice 210 V2 drone from Da-Jiang Innovations (DJI) [31] was used as the flying platform. It is an UAS with class-leading agility, speed, components for maxi-mum reliability, and new smart features that allow it to perform complex tasks. The system enables the use of one or two pendant cameras or one top-mounted camera. It is also possible to upgrade the drone with an Real Time Kinematic (RTK) GPS module – a technology for precise measurements using satellite navigation. This is currently the world's latest technology for the most accurate measurements of several centimeters. The Matrice 210 V2 drone was used in the construction of the ASLER system because it can carry a payload of up to 1.34 kg, develops a maximum speed of 81 km/h, performs autonomous flights, can directly read data (including GPS coordinates and speed) via the UART interface through the use of the on-board Software

Development Kit (SDK), and can power the attached systems through an external voltage output of 22V.

In the ASLER system, the drone is a vehicle transporting a localization sensor, consisting of a microcomputer chip and a SDR. The use of an on-board GPS receiver used by the aircraft allows it to acquire its navigation data (i.e., current position and speed) and the time scale pattern necessary for the localization system. In addition, drones can provide an alternative energy source for computers and radio systems. The two batteries have a total of 349.2 Wh of energy. This allows the drone to power the microcomputer chip, GSM overlay, and radio freely, whose maximum energy consumption is about 11 Wh. The drone's flight time with a load is limited to about 35 minutes on a single pair of batteries. However, the built system allows remote operation so that the drone can land in a designated place (e.g., on the roof of a building) and power the radio reconnaissance system, even for several hours. The operation of the entire radio reconnaissance system is limited only by energy consumption. If they are discharged, it is possible to quickly return to base, replace them, and continue the mission. Such a solution allows analysis of the radio spectrum in a preset geolocation. Due to the advanced technology of drones, it is also possible to plan missions and determine the route of flights, including landing. The role of the ship's operator can be limited to launching and sending the UAS to carry out tasks. The system automatically transmits received data to a data analysis center and saves it to offline memory. Fig. 5 depicts a schematic of the drone used and the pilot with a map.

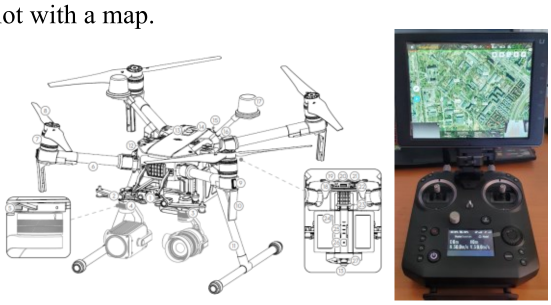

Fig. 5. Diagram of the Matrice 210 V2 [31] with remote control.

Fig. 6 depicts the system's operating algorithm.

In phase one, the mission for the UAS is planned. It is determined what the area of radio reconnaissance will be and in what frequency band the spectral analysis of radio signals will be carried out. Planning the route along which the UAS will be flown is possible. Otherwise, the operator can steer the aircraft independently and conduct a flight over the zone of his choice or land at the indicated point. In the next step, the system is activated by switching on the drone's power supply, the remote control to the craft and the connected DJI Pilot application. The drone connects to the remote control and the app, checking the correctness of the settings and the area of the flight being performed. When the craft is launched, the microcomputer , and the connected com-ponents (radio and GSM overlay) are also turned on. The microcomputer components are powered from an external source – the drone's voltage output. After the micro-computer is turned on, it connects to the GSM network and joins the selected network or the local Wi-Fi router.

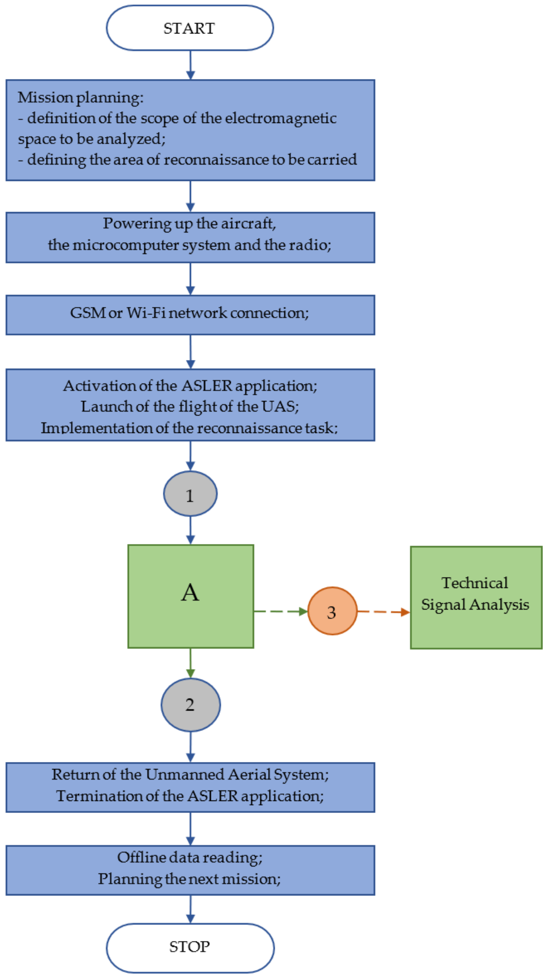

Fig. 6. Algorithm of operation of the ASLER system

The next step is to log into the microcomputer and set the flight parameters. It is possible to automate the process so that when the drone is powered up, the system immediately starts measurements on the pre-set parameters. When the system is ready to carry out the task, the operator sends the UAS, which independently starts the take-off, performs a flight with signal recording, and returns to the place where the flight started. In the course of the flight, the developed application installed on the micro-computer is the main program that performs the task of reading data from the radio, recording it and retrieving information from the drone's GPS.

During the execution of the mission by the UAV, the operator at the signal technical analysis station reads the received data recorded by the system and observes the instantaneous power density spectrum of the received signal. The technical analysis of the signal and the determination of the position of localized emitters can be carried out almost in real-time. The only delay is related to the transmission of the recorded data. In the event of loss of communication with the GSM / Wi-Fi network, the system carries out the planned mission to completion and the data is saved on the microSD card of the microcomputer, from where, in offline mode they can be read after the drone returns to base or after GSM/Wi-Fi communication is re-established. Signal processing using the SDF method is implemented in the Matlab programming environment [32].

The application installed on the microcomputer developed in the C++ programming language. Its compilation was possible due to the compilation of an appropriate list of directives and instructions in the CMakeList.txt file. The list includes information on the minimal version of the *cmake* compiler, indicates the name of the project, informs about the Armv7 microprocessor architecture used, sets compiler parameters, indicates the location of header files placed on the system, sets files and programs to compile, finds the USRP Hardware Driver (UHD) package, links the DJI and UHD libraries to the compiled program.

In a radio emitter localization system, a map is used to visualize the Rx's current position and the radio signal source's estimated position. A digital map is an electronic version of a map that combines graphic elements with information describing a selected area of the Earth's surface. Most digital maps are usually used in online mode. That is, they are hosted on servers. To view them the user must have access to the Internet or a server with map data. The ongoing project assumes that the localization system can occur in areas with no GSM or Internet access. Such areas are, for example, bodies of water or airspace. For this purpose, a digital map that works in offline was created. This mode involves uploading a digital map of a given area to the application and using it without connecting to the corresponding server. For the purposes of the system under development and the empirical research performed, it represents the MUT area. A diagram of the application's operation is shown in block A in the main algorithm, and its detailed operation is illustrated in Fig. 7.

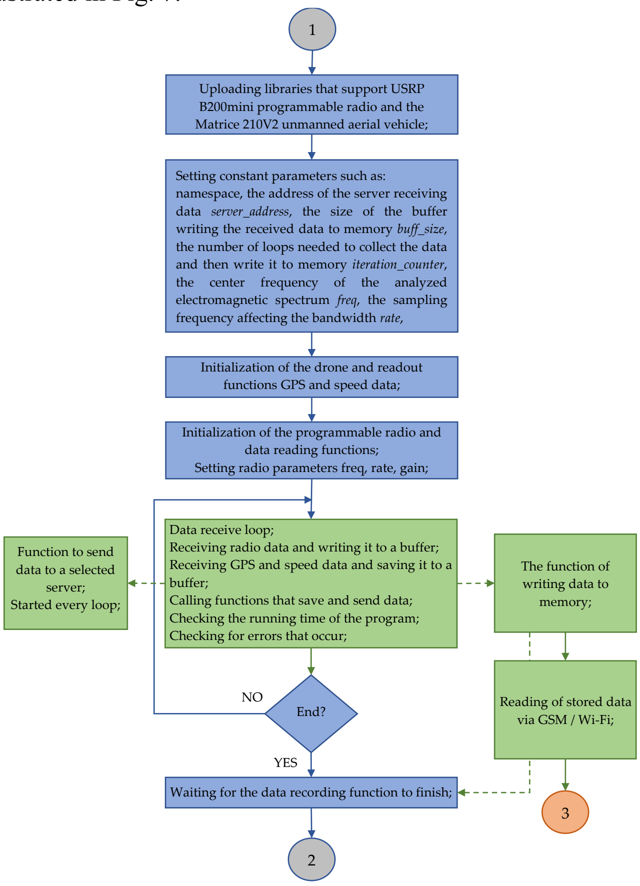

Fig. 7. Block A of the algorithm for the operation of the ASLER system

Geoportal [33] was used to create the digital map. The National Geoportal is an access point to Poland's national infrastructure resources for spatial information. Topographic maps and aerial photographs can be found there, among other things. Maps can be accessed using Web Map Service (WMS) and Web Map Tile Service (WMTS) viewing services. WMS and WMTS are international standard that specifies how to make geographic data available on the Internet through rasterized map fragments called tiles. Unlike WMS, the WMTS service returns to the user preprepared graphics stored on servers in an appropriate structure. This speeds up the operation of the service since WMS generates graphic files each time a request is invoked.

The user who wants to display the map connects to the WMS server. Metadata describing the list of layers, formats, coordinate systems, etc., is then downloaded. After selecting the appropriate layer, a request is sent to the server for a specific map section with a given dimension and location. This type of service allows online viewing of maps using the appropriate program.

Qgis software [34] was used to create an offline map. It allows to manage geo-graphic data and, more importantly, create your maps. The application needs to define the area of the Earth's surface using geographic coordinates. Then select a layer, its coverage, and approximation. To best depict the position of the localized emitters and the Rx, a topographic map was selected. After selecting the appropriate parameters, the program downloads tiles from Geoportal servers using WMS and WMTS services. An example map is presented in Fig. 8.

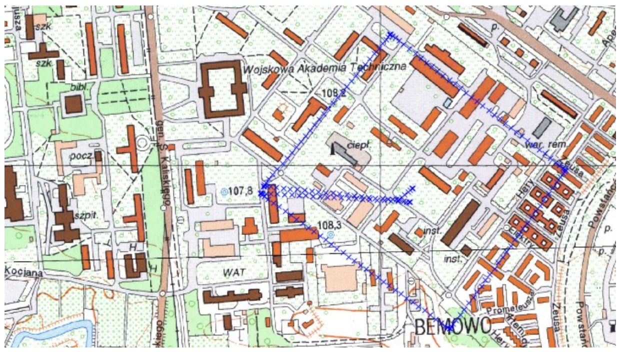

Fig. 8. An extract from the created offline topographic digital map for the MUT area (blue crosses indicate the flight path of the UAV)

The map prepared in this way can be saved in various formats. The project uses the open GeoTIFF metadata format, which allows adding georeferenced information. Thus, the map created in the program contains an image of the given area and information on geographic coordinates, datum parameters, mapping, and others. The created offline tactical map, which covers the region of the performed empirical research, is opened and edited in the interactive Matlab environment.

IV. Measurement Scenario

A typical search mission using the ASLER system involves flying a UAS along a predetermined movement trajectory (i.e., a survey route), on which a radio signal from the localized signal source is recorded. The recorded signal is subjected to spectral analysis, which allows the DFS to be determined. The change in this parameter, along with additional data on the speed and position of the UAV, is then used in the SDF method to estimate the position of the localized radio emitter. The flight of the UAV must be at such a distance from the localized object to ensure reception of its signal above the sensitivity of the used SDR receiver.

Verification of the correctness of the system's operation was realized by performing UAV flights along the indicated routes in the selected geographical area. The error of coordinates determined by the GPS receiver concerning its actual position did not exceed 1m. The position accuracy is within the manufacturer's three meter circular error [31]. The purpose of the measurements was to verify the correct cooperation of the microcomputer system with the programmable radio and the drone, to check the correctness of localization of the aircraft, to receive the signal from the sought Tx and determine the spectrum from it, and then to read the frequency shift and estimate the coordinates of the localized source.

A measuring station was constructed in order to carry out empirical test studies. Its schematic diagram is depicted in Fig. 9. In the research, the mobile receiving part of the measurement stand is the developed autonomous localization system, while the transmitting part is a localized radio emitter.

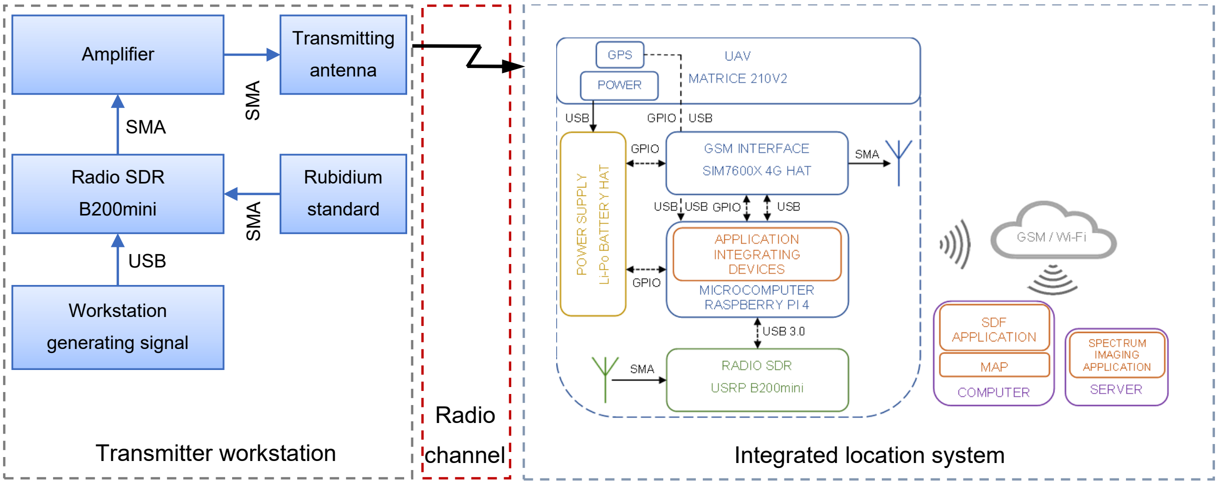

Fig. 9. Scheme of the integrated location system and Tx.

Fig. 10 illustrates the transmitting part of the test bench. It includes the following components: transmitting antenna - OMNI-A105 (2011-05-31-0821), power amplifier - ZHL-30W-252 (SC224501949), signal generating workstation - laptop with Matlab environment, Tx - USRP B200mini radio, frequency standard - Stanford Re-search Systems (FS725), power supply - NDN (DF1730SL).

Fig. 10. Scheme of the integrated location system and Tx

The transmitting station generates a sinusoidal signal at 2800.1 MHz. It is created in an application in the Matlab environment and then transmitted to the radio's input, which converts the received samples into a radio wave. The signal is amplified and radiated through an antenna. The emitted signal should be of such power that it can be distinguished in the spectrum, i.e., the characteristic signal bar should be above the noise level. A rubidium standard with a frequency of 10 MHz ensures stable signal generator operation. Fig. 11 presents an example of a measurement scenario.

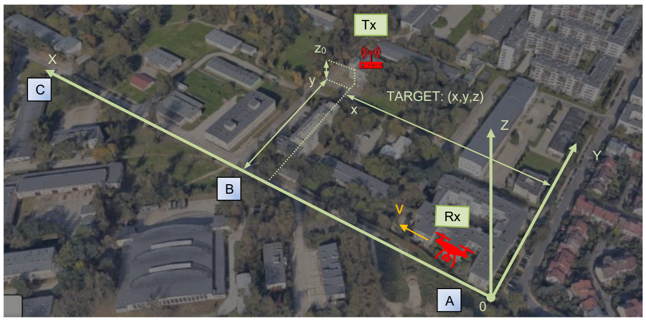

Fig. 11. Example route of measurement scenario

Empirical studies were performed on the basis of several post-measurement scenarios. The main variation in the measurements carried out concerned the flight paths of the UAS. The following part of the paper presents the measurement results of overflights obtained in different measurement scenarios.

The task of the UAS, on which the localization system was placed, was to move along a designated route between points A - C and C - A. In flying the drone along the selected trajectory section, the Rx received the signal emitted by the Tx. Based on the analysis of the received signal and the UAS's current position obtained using the on-board GPS, the integrated localization system estimated the target/source coordinates. The flight including the measurement, was carried out several times at an average flight speed of about 15m/s.

V. Exemplary Results

Fig. 12 illustrates an example of the power density spectrum of the received signal. Its characteristic feature is a prominent bar representing the presence of a harmonic signal emitted by the localized source. This fact confirms the presence of a radio emitter in the region where the measurement was carried out.

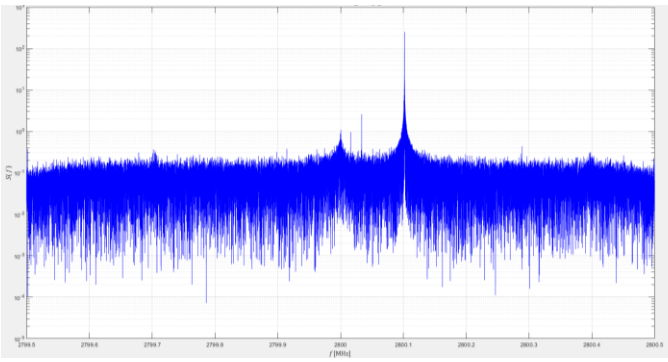

Fig. 12. Example spectrum of received signal with characteristic presence of harmonic emission of detected source

Fig. 13 illustrates a graph of changes in the recorded speed of the moving UAS as a function of time and a graph of the obtained DFS.

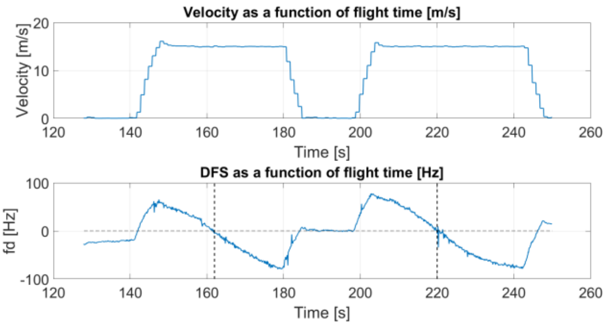

Fig. 13. Example waveform of velocity change and estimated DFS as a function of flight time with indicated measurement window delimited by dashed vertical lines

This shift results from a technical analysis of the signal recorded from the flight. The dashed line has been marked with the 0 Hz shift level. This takes place when the UAS passes the localized Tx at the PCA point. The characteristic increase and decrease in frequency on the waveform rests on the given flights along the localized emitter (between local points A and C).

Fig. 14–15 present the resulting emitter coordinates plotted on the map. Each mark shown on the map corresponds to the analysis of a particular window – a select-ed range of received data. Consequently, after analyzing the entire received signal, a characteristic parabola is formed on the map, at the apex of which is the probable lo-cation of the wanted Tx.

Discrete DFS values were derived from signals collected during observed flyovers. The SDF method determined the signal source's estimated coordinates in the local coordinate system (x, y, z). The analysis included calculating the error (Δr) in locating the signal source [9]:

$$\Delta r = \sqrt{|x - x_0|^2 + |x - y_0|^2 + |x - z_0|^2} \tag{3}$$

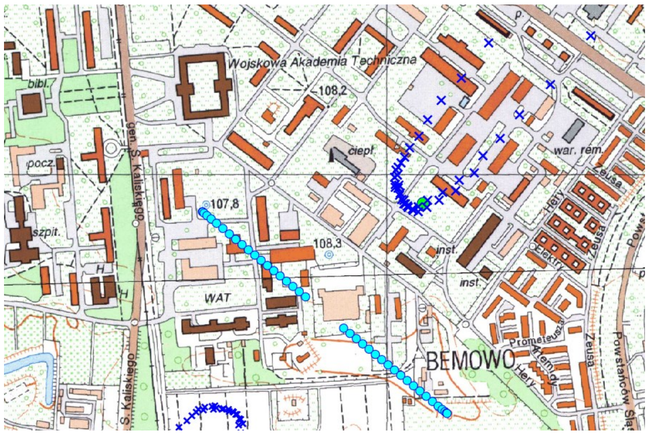

Figure 14. The result of sample measurement no. 1 - a topographic map with estimated coordinates of the localized source. The blue circles represent the UAS flight segment. Crosses indicate the estimated location of the Tx

TABLE I
AVERAGED LOCATION ERROR RESULTS FOR 3 MEASUREMENT SCENARIOS

Scenario 1 Δr [m]	**Scenario 2** Δr [m]	**Scenario 3** Δr [m]
4.62	5.72	4.48
8.24	14.73	16.43
7.51	3.28	6.85

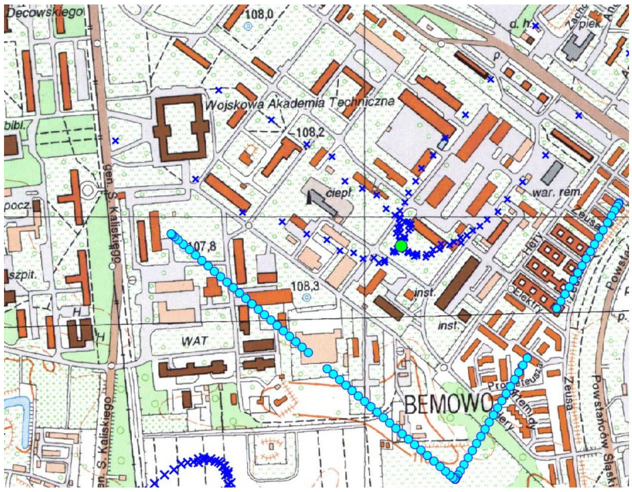

Figure 15. The result of sample measurement no. 2

The research was conducted in three different measurement scenarios. In each scenario, a total of five flights were performed. Subsequently, circular location errors were computed based on the known actual position of the signal emission source and measurements obtained through the modified SDF method. These results are presented in Table I.

VI. Conclusion

X The research has successfully achieved its objectives, marked by the implementation of the author's algorithms through the SDF method on a customized integrated flying platform. The conducted studies include the execution of initial practical tests, confirming the method's efficacy when applied to a UAV. This accomplishment underscores the technical advancements and contributions made through the conducted research, providing valuable insights for the field and demonstrating the practical applicability of the proposed algorithms on the integrated flying platform.

Practical tests were realized for a transmitted harmonic signal. The average accuracy from all measurements was 8.72 m Δr. This result was obtained for a measurement platform about 250 m away from the target. Based on the literature review conducted, the presented localization method does not deviate significantly in measurement accuracy from other existing methods.

One of the most significant advantages of the system lies in its modularity, allowing for the independent development of its individual components. If new and improved components become available, they can be seamlessly integrated into the existing system, allowing for an upgrade in response to technological advancements. The application supporting the individual components has been written in an open-license system, while the code itself can be flexibly adapted to other hardware resources. The system was built to be easily transported using other aircraft: helicopters, reconnaissance aircraft or other drones. Other advantages of the UAS are the ability to fly at distances of up to 8 km, the ability to carry out autonomous operations, the development of speeds of up to 20 m/s, resistance to strong wind gusts and adverse weather conditions (after isolation of the microcomputer system), rapid replacement of batteries and continuation of the mission, the ability to capture the drone by an additional operator (increasing the flight range by two times), possibility of several hours of spectrum recording with the expansion of memory resources or online data transmission, development of data transmission through the aircraft's radio device (independence from the GSM network), expansion of the radio data transmission system using a portable programmable radio.

The constructed ASLER system is still under development. Localization of modulated signals using the SDF method implemented on a single UAV is presented in [35]. A two-stage overlapping algorithm for SDF location methods is presented in [36]. The future research work using UAS will be devoted to studies related to the accuracy of localization by the SDF method under the variable speed of the moving survey platform.

Abbreviations

ADC	Analog to Digital Converters
AGC	Automatic Gain Control
AOA	Angle of Arrival
ASLER	Autonomous System of Location radio EmmiteRs
AT	via Attention
BCS	Bayesian Compressive Sensing
CAF	Cross Ambiguity Function
CR	Cognitive Radio
DDC	Digital Down Converter
DFS	Doppler Frequency Shift
DJI	Da-Jiang Innovations
DOA	Direction of Arrival
DPD	Direct Position Determination
DSP	Digital Signal Processing
FDOA	Frequency Difference of Arrival
FIR	Finite Impulse Response
FPGA	Field-Programmable Gate Array
GNSS	Global Navigation Satellite System
GPIO	General Purpose Input/Output
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile communication
HDMI	High Definition Multimedia Interface
IF	Intermediate Frequency
IQ	in- and quadrature-phase
LNA	Low Noise Amplifier
LTE	Long Term Evolution
microSD	micro Secure Digital
MUT	Military University of Technology
PCA	Point of the Closest Approach
RF	Radio Frequency
RFIC	RF Integrated Circuit
RPi4	Raspberry Pi 4B
RSS	Received Signal Strength
RTK	Real Time Kinematic
Rx	Receiver
SDF	Signal Doppler Frequency
SDK	Software Development Kit
SIM	Subscriber Identity Module
SLUS	Simultaneous Localization of UAV and RF Sources
SNR	Signal-to-Noise Ratio
TDOA	Time Difference of Arrival
TPBCS	Trajectory Planning-based Bayesian Compressive Sensing
TRL	Technology Readiness Level
Tx	Transmitter
UART	Universal Asynchronous Receiver-Transmitter
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UMTS	Universal Mobile Telecommunications System
USB	Universal Serial Bus
UWB	Ultra-Wideband
VTOL	Vertical Take-Off and Landing
WMS	Web Map Service
WMTS	Web Map Tile Service

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