On the accuracy of an emitter localization method based on multipath exploitation in realistic scenarios

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ABSTRACT
This study aims to evaluate the accuracy of a method proposed for passive localization of radar emitters around irregular terrains with a single receiver in Electronic Support Measures systems. Previously, the authors targeted only the theoretical development of the localization method. In fact, this could be a serious concern in practice since there is no evidence regarding its accuracy under the real data gathered from realistic scenarios. Therefore, an accurate ray-tracing algorithm is adapted to enable the implementation of the method in practice. Then, realistic scenarios are determined based on the geographic information system map generated to collect high-resolution digital terrain elevation data, as well as realistic localization problems for radar emitters. Next, simulations are performed to test the localization method. Thus, the performance of the method is verified for practical implementation in the electronic warfare context for the first time. Lastly, the performance bounds of the method are discussed.

1. Introduction

Determining the position of the source of emissions (emitters) is a proliferating demand for both military and civilian applications. It is widely known that the position of an emitter can be determined by employing well-known localization methods or algorithms which basically use sensor measurements and different sources of information [1]. Conventional localization methods such as the angle of arrival (AOA), time difference of arrival (TDOA), and frequency difference of arrival (FDOA) utilize the received signals propagated through the direct paths from the source or emitter. In an AOA-based localization method, the bearings from the sensors to the emitter need to be measured [2]. In a TDOA-based localization method, the time differences of the received signals from the sensors are measured. Obviously, each time difference defines a hyperbola where the emitter could be located. The position of the emitter is then estimated by taking the intersection of the hyperbolas [3]. In an FDOA-based localization method, the aim is to estimate the position of the moving...
emitters. The FDOA-based methods can be applied together with the TDOA-based methods. In this case, it becomes possible to estimate the position and velocity of the emitter [4]. Moreover, the AOA-based methods can also be combined with the TDOA-based methods [5]. However, multipath scattering which is one of the most important concerns in practice should be taken into account as it adversely affects the performance of the localization methods. For this reason, several multipath mitigation techniques have been proposed so far to improve the localization accuracy [6–13].

Recently, on the other hand, researchers have sought ways to exploit the multipath phenomena in emitter localization. The studies proposed within this context can be grouped into two main categories: (a) multiple-sensor (receiver) localization systems [14–17] and (b) single receiver localization systems [17–25]. Today, multipath-assisted emitter localization using a single receiver localization system remains an interesting subject of investigation. The methods developed within this context bring some important advantages such as low-cost deployment and higher accuracy. These advantages have encouraged initiatives to seek opportunities for the development of various localization methods considering challenging operational conditions.

1.1. Related works

One of the existing studies in the literature is proposed in [17], which addresses a localization problem in the presence of a multipath where the emitted signal is exposed to reflection from a surface. The location of the emitting source is estimated by a particle-filtering algorithm, which processes AOA and TDOA measurements. In [18], a single receiver (base station) and signal reflections from the building walls are used to locate and track a moving agent. It is verified that an accurate localization in an indoor environment can be achieved by using tracking algorithms both with and without data association. The work proposed in [19] derives a time of arrival (TOA)-based algorithm to associate multipath reflections to their respective walls in urban sensing and through-the-wall (TTW) radar localization. A nonlinear least-squares (NLS) approach is also derived to reduce the propagation effects to achieve an accurate localization. Furthermore, the developed algorithm assumes a condition that all bounced multipath components are required to be resolvable. To relax this requirement, the work in [20] proposes an approach that uses embedded directivity in ultra-wideband antennas. More specifically, the given approach uses pulse shape dependency on the direction of arrival (DOA) of the radar return. Hence, it is shown that the availability of one single-bounce component along with the radar return is a sufficient condition for estimating the target position. In [21], a method to locate a source through multipath exploitation in urban settings is proposed. It is presented that source localization with a known waveform in a three-dimensional volume can be achieved with a minimum of five TOA measurements. Another work is presented by Giacometti et al. [22], which aims to exploit AOA and TDOA measurements in a radar emitter localization problem within a naval context given that there is no prior knowledge of the location of the reflectors. To solve this problem, a method based on an assignment algorithm is proposed. In [23], the direct and scattered waves received by two different antenna systems are analyzed to estimate the location of the target where the dominant object is considered to be an electromagnetic scatterer. The study presented in [24] proposes a method that combines the channel impulse response (CIR) estimation and a ray-tracing (RT) simulation tool. In
Table 1. Summary of the relevant works on the use of multipath in emitter localization by a single receiver.

| Reference | Signal information | Environment/application | Mechanism | Localization approach |
|-----------|--------------------|--------------------------|-----------|-----------------------|
| [17]      | TDOA & AOA         | Multipath environments   | Reflection | Particle-filtering algorithm |
| [18]      | TOA                | Office environment       | Specular reflection from the walls | Tracking algorithm both with and without data association |
| [19]      | TOA                | Urban sensing and TTW    | Specular reflection from the walls | TOA wall association algorithm & NLS |
| [20]      | TOA & DOA          | Urban sensing and TTW    | Specular reflection from the walls | A method using pulse shape dependency on DOA of the radar return |
| [21]      | TOA                | Urban settings           | Specular reflection from the walls | The Bancroft method-based algorithm |
| [22]      | TDOA & AOA         | Naval context            | Specular reflection from point reflectors | Assignment algorithm |
| [23]      | TDOA & DOA         | Scenarios with a large well-known object | Scattering from a cylinder | Electromagnetic modeling/analysis |
| [24]      | TDOA               | NLoS environments        | Diffraction and specular reflection from the walls | Combination of the RT simulation tool and the CIR estimation |
| [25]      | TOA & AOA          | ESM systems              | Diffuse scattering from irregular terrains | Weighted averaging method based on both a GIS-assisted RT algorithm and a TDOA technique |

As a summary, the relevant works are listed in Table 1. As can be deduced from Table 1, most of the works employ only specular reflection to exploit multipath propagation. Additionally, these works are mostly proposed to be used in indoor or urban applications.

On the other hand, only the work presented in [25] considers an advanced localization system within the context of electronic warfare (EW). In the work, a novel approach is proposed for passive localization of radar emitters around irregular terrains in electronic support measures (ESM) systems. Unlike the previous works, the approach involves diffuse scattering over irregular terrain in multipath exploitation. In the approach, the scattering regions over the irregular terrain, where the multipath signals are scattered, are used as virtual sensors. Moreover, the likelihood of the scattering regions being a source of multipath signals utilized. To do this, an RT algorithm along with the geographic information system (GIS) is used. Therefore, a weighted averaging method based on the use of both a GIS-assisted RT algorithm and a TDOA technique is employed to determine the location of the emitter. Here, it is evident that the identification of the likelihoods of the multipath scattered signals is indicative of the localization accuracy. Thus, it can be inferred that it is necessary to utilize an accurate RT algorithm to calculate the likelihood. However, the work does not provide any RT algorithm due to the fact that it only focuses on the theoretical development of the localization method. In this context, there might be serious concerns related to the performance of the proposed method under the real data gathered from realistic scenarios in practice. Hence, the proposed method needs not only to be enhanced by
1.2. Overview and contributions

This study is devoted to alleviating the concerns related to the performance of the localization method proposed in [25] under realistic scenarios. To this end, initially, an RT algorithm is adapted by using realistic obstruction models. To do this, realistic scenarios are constructed in some parts of the Aegean Sea. From each scenario, a GIS map is generated to collect the digital terrain elevation data (DTED). These data are then used in the RT algorithm to calculate the likelihood of the scattering regions being a source of multipath signals. Besides, the multipath scattering centers are determined and then assumed as virtual sensors to be used in an efficient TDOA-based localization method, namely improved two-step weighted least-squares (improved-TSWLS) [26]. To account for all virtual sensors along with the likelihood in the localization, a weighted averaging method is applied. Next, simulations are conducted to study the applicability and validity of the proposed method in realistic scenarios. Thus, the performance bounds of the method in realistic scenarios are also scrutinized and reported. Overall, the major contributions of the work can be listed as follows:

1. A radar emitter localization method based on improved-TSWLS is fully developed by adapting an accurate RT algorithm.
2. Scenarios are developed based on high-resolution real terrain data (GIS) as well as realistic localization problems for radar emitters.
3. The method is tested with simulations and its performance is verified for practical implementation in the EW context.

2. Basics of the localization method

The problem considered in this article is related to the operational challenges of ESM systems while locating the radar emitter’s position over and around the sea surface. Specifically, while discriminating the radar emitter, multipath signals that have similar radar parameters in the radar field of view cause difficulties for an ESM system. This, then, constitutes a serious problem that adversely affects the localization performance. To gain a concrete understanding of the problem, Figure 1 shows a simplified two-dimensional (2D) problem space (top-view), where the altitudes are ignored.

In Figure 1, \( \mathbf{u}^0 = [x^0, y^0, z^0]^T \) and \( \mathbf{s}_0^0 = [x_0^0, y_0^0, z_0^0]^T \) are the position of the radar emitter and ESM (intercept) receiver, respectively. The irregular terrains are depicted by the brown irregular shapes. For the sake of simplicity, only two propagation paths consisting of direct path \( (t_0) \) and multipath \( (t_1) \) are considered. Here, to solve the problem of emitter localization from a single receiver using direct and multipath pulses, a novel method is proposed [25]. The main purpose is to use multipath effects as an advantage in emitter localization. Basically, the proposed method is based on an idea that aims to use multipath scattering centers as virtual sensors for determining the emitter’s location. For this purpose, it employs an algorithm, the main steps of which are briefly described in the following. Figure 2 shows a flowchart of the algorithm.
2.1. Stage I

In this stage, the purpose is to estimate the multipath scattering centers. To this end, the AOA and TOA information provided by the ESM receiver is required for the direct and multipath pulses. Hence, it is necessary to estimate the probable region of the multipath scattering centers.

In the first step of this stage, the outer boundaries of the probable region of the multipath scattering centers are determined. It is important to note that the scatterers should be determined in the same radar cell, which is one of the most important requirements to be satisfied. Here, the radar cell size ($r_c$) corresponds to the projection on the ground, since a 2D problem is considered.

In the second step, the inner boundaries of the probable region of the multipath scattering centers are determined. This is achieved by satisfying another requirement that the pulses received from the direct path and multipath should not be overlapped in time scale. To avoid such an overlapping, the difference in TOA measurements (or TDOA) between the directly received and multipath pulses must be greater than the pulse width of the radar emitter. Therefore, it becomes possible to determine a minimum distance from the receiver to the inner boundary of the probable region of virtual sensors. Yet, notice that this distance can be determined if and only if the TDOA measurements are expressed in terms of range differences (RDs).

In the third stage, the width of the probable region of the multipath scattering centers is specified by the AOA of radar pulses with an error margin ($\gamma$) as shown in Figure 1.
incorporating the information achieved in all those steps, the probable region of multipath scattering centers over the rough surface can easily be determined.

On the other hand, since the probable region of multipath scattering centers are considered as irregular terrains in practice, it is expected that the multipath pulses are exposed to diffuse scattering. Hence, the local region from which the multipath pulses are scattered could be a multipath scattering center. Thus, in the last step, segmentation is applied as shown in Figure 1 to split up the probable region of the multipath scattering centers so that
each of the segments can be considered as multipath scattering centers \((\mathbf{sc}_{ij}, \; i = 1, \ldots, N_j \text{ and } j = 1, \ldots, M)\), where \(N_j\) denotes the number of the scattering centers in the \(j\)th probable region of virtual sensors and \(M\) denotes the number of probable regions of virtual sensors.

Among these, however, further processing is required to determine the proper segments that can be utilized in the localization. In fact, this can be achieved by calculating the likelihood of the segments from which the multipath scattering takes place. The details are discussed in the following stage.

### 2.2. Stage II

In this stage, it is aimed to calculate the likelihood of the scattering centers being a source of the multipath scattering, \(p(\mathbf{sc}_{ij})\), by utilizing an RT algorithm. It is important to note that the work presented in [25] lacks providing an RT algorithm. It only proposes the conceptual structure of the algorithm. Therefore, this study attempts to fill this gap by providing an accurate RT algorithm. In the following, the theoretical background of the algorithm is presented, and then the adaptation of the algorithm to the localization problem is described, which is followed by the calculation of the likelihood of the scattering centers.

### 2.2.1. Background information

Computational electromagnetics for high frequency can be categorized into the field-and current-based groups [27]. The latter employs Physical Optics for short-wavelength approximation. The field-based methods, on the other hand, rely on Geometric Optics. The field-based methods are well suited for the typical radar frequencies of the problem space. In the implementation of these methods, the RT methods are generally used [28]. The RT methods can be divided into two main categories, namely the image method and the ray launching method. The image method is based on symmetry with respect to the segments. The image method controls whether the rays are blocked by the segments or not. However, the computational complexity is the main drawback of the image method when there is a large number of segments to be considered. It should be noted that the authors have already studied and extensively published on the various aspects of RT algorithms [29–31]. Hence, when the localization problem presented in this study is considered, using the ray launching method could be a good option rather than the image method for wireless propagation prediction. Therefore, in this study, the ray launching method is used due to its advantages over the image method.

Basically, the ray launching method can be applied in three steps: (1) ray initiation, (2) RT, and (3) ray interception [32]. In the ray initiation step, the rays are launched with the same differential angle intervals. In the RT step, the rays are controlled to determine whether the rays are blocked by an obstacle or not. If the rays are blocked by an obstacle, they are reflected by this obstacle with the same angle of incidence. Here, the number of reflections is determined by the user. If there is no reflection from the obstacles for the first ray, then it is passed to the second ray. After tracing all of the rays, the rays are intercepted at the receiver position.

On the other hand, the directed, reflected, or diffracted wave can be measured at the receiver in practice. In this case, the electric field of the direct wave can be expressed
as [33]

\[ E_{\text{dir}} = \frac{1}{r_0} e^{-jk r_0}, \tag{1} \]

where \( r_0 \) is the distance between the transmitter and receiver, and \( k \) is the wavenumber. Besides, the electric field of the reflected waves can be expressed as

\[ E_{\text{ref}} = R \frac{1}{r} e^{-jk r}, \tag{2} \]

where \( r \) is the total distance of the transmitter, ground, and the receiving point, while \( R \) is the reflection coefficient. Moreover, according to the uniform theory of diffraction model, the electric field of the diffracted waves can be expressed as [34]

\[ E_{\text{dif}} = E_{\text{in}} D A(r) e^{-jk r}, \tag{3} \]

where \( E_{\text{in}} \) is the incoming field, \( A \) is the spreading factor, and \( D \) is the diffraction coefficient which can be expressed as [35]

\[ D(\alpha) = -\frac{e^{-j\pi/4}}{2\sqrt{2\pi} \cos(\alpha/2)} F[x], \tag{4} \]

where \( \alpha \) is the diffraction angle and \( F[x] \) is the transition function given as [36]

\[ F[x] = 2 j \sqrt{x} e^{-jx} \int_{\sqrt{x}}^{\infty} e^{-ju^2} du, \tag{5} \]

where \( x = 2kL \cos^2(\alpha/2) \) and \( L \) is the distance parameter given as

\[ L = \frac{r_0 r_1}{r_0 + r_1}. \tag{6} \]

### 2.2.2. Implementation of the RT algorithm

To use the RT algorithm in the proposed localization method, it is strictly necessary that the scattering centers are electromagnetically visible to both the radar emitter and the receiver. In this context, the probable region of the radar emitter needs to be defined properly. To do this, the distance between the radar emitter and the receiver is estimated by utilizing both the peak transmitting power of the radar emitter and the received power as well as the erroneous AOA of the radar pulses measured by the receiver (\( \gamma_i \)). Because of the inherent imperfections at the radar emitter or the receiver, the estimated distance is expected to be erroneous which corresponds to the width of the region in perpendicular to the direction to the receiver. Next, as shown in Figure 1, the region needs to be split up to segments so that the center of each segment can be assumed as the nominal position of the radar emitter, \( \mathbf{u}_k = [x_k, y_k, z_k], k = 1, \ldots, K \), where \( K \) is the number of segments of the probable region of the radar emitter. This may then provide an opportunity to construct the links between the scattering center and the nominal position of the radar emitter. To do that, the center of each scattering center needs to be determined, \( \mathbf{s}^o_{ij} = [x^o_{ij}, y^o_{ij}, z^o_{ij}] \). In this way, the links between the scattering center and the receiver can also be constructed. After constructing the links, it becomes possible to implement the RT algorithm to estimate how the obstacles might cause path loss (PL) for the particular links.
To implement the RT algorithm, firstly, the area where the localization method is expected to be employed is determined in a 3D map. Here, the algorithm requires the use of the DTED by GIS. The DTED is a raster topographic data that provides basic quantitative data for the systems requiring terrain elevation, slope, and surface information. Here, choosing a higher level of DTED tiling scheme is crucial to gathering precise terrain data. Then, for constructing the links between the nominal positions of the radar emitter and the center of each scattering center, and for the links between the center of each scattering center and the receiver, a 2D terrain profile is extracted from a 3D map. After that, the terrain profile is redefined with the line segmentation to apply the RT algorithm. Figure 3 shows a typical 2D terrain profile and line segmentation.

Next, for the links between the nominal positions of the radar emitter and the center of each scattering center, the transmitting and receiving points are deployed at the nominal positions of the radar emitter and the center of each scattering center, respectively. Similarly, for the links between the center of each scattering center and the receiver, the transmitting and receiving points are deployed at the center of each scattering center and the receiver, respectively. On both links, all the direct, the reflected, and the diffracted waves are determined by the RT algorithm. Thus, the electric field and the coverage map for a 2D profile are calculated with all the direct, reflected, and diffracted ray contributions. In this way, it is also possible to estimate the PL for each link. As an example, a coverage map for a 2D terrain profile is shown in Figure 4.

As can be seen in Figure 4, the coverage map is obtained by all the direct, diffracted, and reflected waves. The diffracted waves can be explicitly observed behind the obstacle where the electric fields sharply reduce. It is worth noting that the obstructions are expected to fall inside the Fresnel zone generated between the nominal position of the radar emitter and the receiver. Moreover, because of the considerations discussed in Stage I regarding the determination of the probable region of the multipath scattering centers, the obstructions are also expected to fall inside the vertical plane containing the nominal position of the radar emitter and the receiver. It is also important to note that the reflecting surface on the obstacle is assumed to be locally flat (line segment). In this case, specular reflection also known as the Fresnel approximation is expected to be obtained. Besides, the diffraction
is also expected to be obtained owing to the presence of edge- or wedge-shaped obstacles between the transmitter and the receiver. Therefore, both the reflected and diffracted waves from the obstructions are measurable at the receiver.

2.2.3. Calculating the likelihood of the scattering centers

Calculating the likelihood of the scattering centers, \( p(\mathbf{s}_{ij}) \), has a key role in the implementation of the proposed localization method. To calculate the likelihood, total PL (or PG) should be accounted for. This is because there may be different propagation mechanisms for each of the segments in practice. For the considered localization problem, the PL for a particular link consists of the free-space PL (FSPL), the reduction in the received electric field due to reflection (\( PL_r \)), and the loss due to diffraction (\( PL_d \)) provided by the R algorithm. If there is no obstruction between the transmitter and the receiver, the FSPL is used to calculate the field strength as expressed in Equation (1). Moreover, the electric field of single or multiple reflected waves from the line segments can be calculated by Equation (2). Furthermore, there is diffraction from the sharp surfaces, and the field strength of the diffracted waves is obtained by Equation (3). Basically, the PL for a fundamental link can be then expressed as

\[
PL[dB] = FSPL + PL_r + PL_d. \tag{7}
\]

As expected, there might be multiple reflected or diffracted waves reaching the receiver. The developed RT algorithm determines multiple reflections and diffraction rays up to 6 times (e.g. reflection-diffraction-reflection-diffraction), although the radar emitter localization problem requires only a few.

It is important to note that the factors used for calculating the PL can be varied according to the localization scenario. In some cases, the diffracted signals become unmeasurable due to the position of the obstacles. Then, the PL simply consists of the FSPL and \( PL_R \).

Evidently, the PL needs to be estimated for all the scattering centers in each probable region of virtual sensors. From a general perspective, the PG value of the \( i \)th scattering center in the \( j \)th probable region of scattering centers (\( PL_{ij} \)) can be estimated by

\[
PG_{ij} = 1/PL_{ij}, \tag{8}
\]
where

$$\text{PL}_{ij} = \text{PL}_{u\text{sc}ij} + \text{PL}_{\text{sc}ij\text{s}0},$$

(9)

where $\text{PL}_{ij}$ is the total PL of the link between the nominal position of the radar emitter and the center of each scattering center ($\text{PL}_{u\text{sc}ij}$) and the link between the center of each scattering center and the receiver ($\text{PL}_{\text{sc}ij\text{s}0}$).

Therefore, the estimated losses can be used to calculate the $p(\text{sc}_{ij})$ as follows:

$$p(\text{sc}_{ij}) = \frac{\text{PG}_{ij}}{\sum_{i=1}^{N_j} \text{PG}_{ij}}.$$  

(10)

### 2.3. Stage III

In the third stage, the purpose is to estimate the position of the radar emitter. The steps required to achieve this goal are straightforward. In the first step, the center of each scattering center determined in Stage I is considered the nominal position of the virtual sensors. The single-sensor localization problem then becomes a multiple-sensor localization problem, which can be solved by conventional techniques using TDOA measurements. However, as the multipath scattering involves diffuse components over the irregular terrain, uncertainty is expected in the location of the scattering centers. In this case, the erroneous virtual sensor positions need to be taken into account. For this reason, it is necessary to employ an efficient source localization technique using TDOA measurements in the presence of sensor position errors. From the comparison results provided in [37], the improved-TSWLS technique presented in [26] could be a good choice to employ in the proposed localization method due to its efficiency at high sensor position errors. In the following section, an adaptation of the improved-TSWLS technique to the proposed method is briefly described. This is followed by another section presenting the weighting averaging method used to obtain the final estimate of the radar emitter.

#### 2.3.1. Adaptation of improved-TSWLS technique

To comprehend the adaptation of the improved-TSWLS technique to the proposed method, we should consider the problem space as illustrated in Figure 1. In the figure, assume that there is only one virtual sensor in each of the probable regions of scattering centers, and there is only one nominal position of the radar emitter ($k = 1$), for the sake of simplicity. In this case, by considering 3D, there are $M$ virtual sensors at locations $\mathbf{s}^0_j = [x^0_j, y^0_j, z^0_j]^T$, where $j = 0, \ldots, M$, and the receiver, $\mathbf{s}^0_0$, to locate the radar emitter, $\mathbf{u}^0$. Here, the case that $j = 0$ can be considered as the position of the receiver while the other values correspond to the positions of virtual sensors. To account for the uncertainty in the location of the scattering centers, the virtual sensor positions need to be considered noisy. Therefore, a sensor position vector can be defined as $\mathbf{s} = [\mathbf{s}^0_0, \mathbf{s}^0_1, \ldots, \mathbf{s}^0_M]^T = \mathbf{s}^0 + \Delta \mathbf{s}$, where $\mathbf{s}^0 = [\mathbf{s}^0_0, \mathbf{s}^0_1, \ldots, \mathbf{s}^0_M]^T$, and $\Delta \mathbf{s}$ is the sensor position error vector, $\Delta \mathbf{s} = [\Delta \mathbf{s}_0^T, \Delta \mathbf{s}_1^T, \ldots, \Delta \mathbf{s}_M^T]^T$, which is assumed to be a zero-mean random variable and Gaussian distributed with the covariance matrix, $\mathbf{Q}_s = E[\Delta \mathbf{s} \Delta \mathbf{s}^T]$. Since the position of $\mathbf{s}^0_0$ is exactly known, the value of $\Delta \mathbf{s}_0$ should be approximate to zero.

To employ the improved-TSWLS technique, $\mathbf{s}^0_0$ is assigned to be the reference sensor. In this case, the TDOAs are expressed as

$$\Delta t_{j+1,0} = (t_{j+1} - t_0),$$  

(11)
where $t_0$ and $t_{j+1}$ are the TOA to the reference sensor and the $j$th sensor, respectively. Then, the TDOAs can be converted to the RDs by

$$r_{j+1,0}^0 = c \Delta t_{j+1,0} = c(t_{j+1} - t_0) = r_{j+1}^0 - r_0^0,$$

where $c$ is the speed of light, $r_{j+1}^0$ denotes the Euclidian distance between the emitter and the $j$th sensor, and $r_0^0$ is the Euclidian distance between the emitter and $s_0^0$.

Moreover, the TDOA or RD measurement vector can be defined as $r = [r_{1,0}, r_{2,0}, \ldots, r_{M,0}]^T = r^0 + \Delta r$, where $r^0 = [r_{1,0}^0, r_{2,0}^0, \ldots, r_{M,0}^0]^T$, and $\Delta r$ is the measurement error vector, $\Delta r = [\Delta r_{1,0}, \Delta r_{3,0}, \ldots, \Delta r_{M,0}]$, which is assumed to be a zero-mean random variable and Gaussian distributed with the covariance matrix, $Q_t = E[\Delta r \Delta r^T]$.

In the improved-TSWLS technique, basically, there are two stages to locate the emitter. In the first stage, by introducing nuisance parameters, a nonlinear measurement equation is linearized and then solved. To this end, firstly an unknown vector, $\mu_1$, which contains the preliminary estimates of the radar emitter and the distance between the emitter and the receiver, is defined. Then, the weighted least-squares estimate of vector $\mu_1$ is

$$\mu_1 = (G_1^TW_1G_1)^{-1}G_1^TW_1h_1,$$

where

$$G_1 = -2 \begin{bmatrix}
(s_1 - s_0)^T & r_{1,0} \\
\vdots & \vdots \\
(s_M - s_0)^T & r_{M,0}
\end{bmatrix}, \quad h_1 = \begin{bmatrix}
r_{1,0}^2 - s_1^T s_1 + s_0^T s_0 \\
\vdots \\
r_{M,0}^2 - s_M^T s_M + s_0^T s_0
\end{bmatrix},$$

and

$$W_1 = (B_1Q_tD_1^T + D_1Q_sD_1^T)^{-1},$$

where

$$B_1 = 2\text{diag}[r_{1,0}^0, \ldots, r_{M,0}^0],$$

where $\text{diag}[\cdot]$ denotes the diagonal matrix.

In (13), the first three elements of $\mu_1$ ($\mu_1(1:3)$) correspond to a preliminary estimate of the radar emitter. Additionally, $\mu_1(4)$ is the last element of $\mu_1$, which is the preliminary estimate of the distance between the emitter and the receiver.

In the second stage, the localization error of the first stage is estimated, and then it is subtracted from the output of the first stage. For this purpose, the second stage begins with updating (13) as

$$\mu_2 = (G_2^TW_2G_2)^{-1}G_2^TW_2h_2,$$

where

$$G_2 = \begin{bmatrix}
I_{(3,3)} & -((\mu_1(1:3) - s_0)/(\mu_1(1:3) - s_0))
\end{bmatrix}, \quad h_2 = \begin{bmatrix}
0_{(3,1)} \\
\mu_1(4) - (\mu_1(1:3) - s_0)
\end{bmatrix},$$

and

$$W_2 = B_2(G_1^TW_1G_1)^{-1}B_2^T,$$
where

$$B_2 = \begin{bmatrix} -I_{(3,3)} & 0_{(3,1)} \\ 0_{(3,1)^T} & 1 \end{bmatrix}.$$  

(20)

Here, $I_{(3,3)}$ is a $3 \times 3$ identity matrix while $0_{(3 \times 1)}$ is a $3 \times 1$ zero vector. Hence, the emitter location is estimated by

$$\hat{u} = \mu_1 (1 : 3) - \mu_2.$$  

(21)

2.3.2. Weighting averaging method

In practice, there might be numerous virtual sensors in each of probable regions of scattering centers, and there might be several nominal positions of the radar emitter in the probable region of the radar emitter. Then, the localization problem becomes complicated, and further approaches are required to solve the problem. For this purpose, as a first step, virtual sensor groups are created by considering all the combinations of virtual sensors selected from $M$ probable regions of the scattering centers to employ the improved-TSWLS technique. In this way, scattering center groups are also created. Thus, it becomes possible to calculate the likelihoods of the scattering center groups ($p_t, t = 1, \ldots, T$, where $T$ is the number of the combinations of scattering centers or virtual sensors) by considering the reliability of a series system [38]. Next, for each of the virtual sensor groups, the nominal position of the radar emitter is estimated by employing an improved-TSWLS technique

$$\hat{u}_{k,t} = [\hat{u}_{k,1} \hat{u}_{k,2} \cdots \hat{u}_{k,T}] \text{ for } k = 1, \ldots, K,$$  

(22)

where $K$ is the number of segments of the probable region of the radar emitter.

Thus, to estimate the position of the emitter, the weighted averaging method is used as follows:

$$\bar{u}_k = \sum_{t=1}^{T} p_t \times \hat{u}_{k,t},$$  

(23)

and, the averaging of all estimated positions gives the final estimate of the emitter position ($\bar{u}$)

$$\bar{u} = \left( \sum_{k=1}^{K} \bar{u}_k \right) / K.$$  

(24)

As a final note, although the proposed localization method is based on the use of the TDOA method, it differs from the conventional localization methods which require multiple sensors (receivers), or, to be more precise, wireless sensor networks. The proposed localization method uses virtual sensors which are determined from the multipath scattering centers, and a single receiver that receives both direct and scattered signals to analyze them for estimating the position of the emitter. Thus, unlike the conventional methods, in the proposed method, communication links between the sensors (or between the emitter and sensors) need to be established for the implementation of the RT algorithm, as discussed earlier.
3. Simulations

This section presents the results of simulations conducted to examine the applicability and validity of the localization method under realistic scenarios. For creating the scenarios, a part of the Aegean Sea is chosen from the 3D map as shown in Figure 5(a, b).

After determining a particular region over the Aegean Sea, the GIS map was generated to use the DTED data (Figure 5(c)). Three different simulation experiments containing various scenarios were then created by varying the receiver position around the scatterers. The receiver was deployed behind the scatterers in the first experiment, while it was deployed at the center of the scatterers in the second experiment. In the last experiment, it was deployed in front of the scatterers. As an example, Figure 6 shows the deployment of the receiver (rectangle), the emitter (triangle), and virtual sensors (circles) for a fixed radar beamwidth.

In each experiment, the radar parameters were set to simulate the localization geometry as depicted in Figure 1. The first important parameter here is the pulse width (τ) of the radar emitter. In the experiments, it was considered to be 1 μs. The beamwidth (θ) of the radar emitter which is another important parameter was envisaged to be 10°, 15°, and 20°. In addition, it was considered that \( s_0 \) is able to measure five different AOA information of radar pulses with an error margin (\( \gamma = 3° \)). In this case, four probable regions of scattering centers were assumed to be obtained (\( M = 4 \)) after excluding the AOA of the direct pulse.

In each experiment, the AOA of the multipath pulses was defined according to the position
of the scatterers randomly selected within the radar cell. Only the AOA of the direct pulse was fixed in each scenario ($\gamma_0 = 90^\circ$).

In the segmentation of the probable regions of the scattering centers obtained for each scenario, a particular DTED format level was used. Practically, the used DTED format level corresponds to $22.5\,\text{m} \times 22.5\,\text{m}$ segment size. It should be noted that the localization method is expected to be more accurate when the small-sized segments are used. The reason for achieving better accuracy is stemmed from the lower uncertainty in virtual sensor positions that appear when the small-sized segments are used in the segmentation. Therefore, based on the size of the segments, virtual sensor position noise power was determined by utilizing the basic three-sigma rule in statistics as $6\,\text{dB}$ to be used in the TDOA technique. Moreover, the distance between the receiver and the radar emitter ($r_0^2$) was envisaged to be 30, 40, and 50 km, respectively. Here, the maximum distance was limited to 50 km to avoid signal loss due to the earth’s curvature. Furthermore, the possible region of the radar emitter was determined and then split up into nine segments ($K = 9$) so that the center of each segment could be assigned as a nominal position of the radar emitter ($u_k$, $k = 1, \ldots, K$).

For each scenario, on the other hand, the likelihood of the scattering centers was estimated by the RT algorithm introduced in Section 2.2. From each probable region of the virtual sensors, top-five scattering centers that have maximum likelihood were selected to be used in the localization algorithm. It should be also noted that both the radar emitter and the receiver were assumed to be deployed at naval ships, and their antenna height was assumed to be 60 m. Additionally, according to the position of the scattering centers on the GIS 3D map, the heights of the virtual sensors were varied between 300 m and 450 m.

Simulations were then performed to evaluate the performance of the localization method. To examine the accuracy of the localization algorithm, mean square error (MSE) of the radar emitter location estimate was obtained by $\text{MSE}(\hat{u}) = \frac{1}{L} \sum_{v=1}^{L} (\hat{u}_v - u^o)^2$, where $\hat{u}_v$ is the estimated position of $u^o$ in the $v$th ensemble run, and $L$ is the number of ensemble runs [26,39]. In the simulations, the MSEs of the location estimates were obtained at $10^3$ ensemble runs. Further, the results were compared with the MSEs obtained from the improved-TSWLS method to validate the accuracy of the proposed algorithm. Since it is not possible to directly employ the improved-TSWLS method to solve the localization problem in consideration, the localization geometry obtained for each scenario was relaxed. To do this, the center of each probable region of the scattering centers was assigned as a sensor position to be used in the improved-TSWLS method.

For the first experiment, the estimation accuracy of the improved-TSWLS and the proposed localization method is shown in Figure 7. From the results, it can be seen that the proposed method is expected to be inaccurate when the receiver is deployed behind the scatterers. It is also clear that the improved-TSWLS method provides mostly inaccurate results. Nonetheless, one of the important findings is that the localization accuracy of the proposed method tends to increase when the parameter $\theta$ is increased. Therefore, if the receiver is deployed behind the scatterers, the proposed method will probably provide a relatively accurate localization given that the targeted radar emitter has a wider beamwidth.

Figure 8 shows the localization accuracy of the improved-TSWLS and the proposed method for the second experiment. Here, the results obtained by the improved-TSWLS method suggest that a typical TDOA method based on wireless sensor networks could be inefficient for the given localization scenario. However, especially when compared with
Figure 7. The estimation accuracy of the improved-TSWLS and the proposed method when the receiver is behind the scatterers.

Figure 8. The estimation accuracy of the improved-TSWLS and the proposed method when the receiver is at the center of the scatterers.

In the previous experiment, the efficiency and the robustness of the proposed method can be explicitly observed from the results. For all cases in terms of the range and beamwidth, the proposed method provides accurate results where the maximum value of the estimation error is about 50 dB, which corresponds to approximately 320 m in distance.

In Figure 9, the localization accuracy of the improved-TSWLS and the proposed method for the last experiment is given. It can be observed from the figure that the results are inconsistent when $\theta \leq 10^\circ$. In other words, similar to the results obtained in the previous experiments, the localization accuracy of the proposed method tends to increase when the parameter $\theta$ is increased. Thus, the proposed method is expected to be efficient to locate...
4. Discussions

The achieved results from the simulations verify that the proposed localization method is mostly implementable in the EW context except for some specific localization scenarios. More precisely, although the overall accuracy of the localization method in realistic scenarios is acceptable, the performance of the method still depends on the position of the virtual sensors. The reason is due to the fact that TDOA-based methods are highly affected by the location geometry. Particularly, under the poor geometry, the localization accuracy is expected to be degraded. Theoretically, this can be attributed to the case of large geometric dilution of precision (GDOP) which is a metric that is used to evaluate the geometric effect of sensor configurations on the localization accuracy [40]. That is, the localization performance of the system is considered to be worse when there is a large GDOP value. Within this context, the GDOP effect can be easily observed in the simulation results presented in the previous section. Based on the results, the worst accuracy is obtained when the receiver is placed at the center of the virtual sensors. On the other hand, the best accuracy is achieved when the receiver is placed at the center of the virtual sensors. Thus, better localization accuracy can be linked with the virtual sensor layout that yields a lower value of GDOP. This finding is consistent with the previous studies that examined the GDOP value for various layouts [41,42]. Moreover, the range between the emitter and the receiver is also an important factor that adversely affects the GDOP. Its effects can be clearly observed in the simulation results. Particularly, in each experiment, it is observed that the proposed method provides better localization accuracy in short-range scenarios.

Furthermore, the localization accuracy of the proposed method could be low when the targeted radar emitter has a narrow beamwidth ($\theta \leq 10^\circ$). This is due to the fact that narrower probable regions of the multipath scattering centers are expected to be obtained.
when the radar emitter has a narrow beam width. In this case, virtual sensor positions are expected to be very close to each other. This then leads to poor location geometry, so-called large GDOP. Hence, to achieve higher accuracy in the localization systems, it is necessary to acquire a good geometric layout between the emitter and sensors. At this point, the GDOP can be used as a criterion for selecting proper virtual sensor groups. This can be achieved if the virtual sensor groups providing minimum GDOP are used. In fact, this constitutes a part of an ongoing project, and the authors are currently focused on improving the accuracy of the proposed localization method for the case of narrower radar beamwidth in real operational scenarios in the EW context.

5. Conclusion

In this study, the accuracy of an emitter localization method based on multipath exploitation recently proposed by the authors is evaluated in realistic scenarios. Overall, according to the results, it is concluded that the accuracy of the method is acceptable in realistic scenarios and the method is mostly implementable in the EW context. Particularly, better localization accuracy is expected when the receiver is placed at the center of the scatterers. Besides, the method is expected to provide better localization accuracy in short-range scenarios. Moreover, results show that better localization accuracy is expected when the radar emitter has a wide beamwidth ($\theta > 10^\circ$).

On the other hand, the method is expected to exhibit relatively poor performance when the receiver is placed behind the scatterers, and when the radar emitter has a narrow beamwidth ($\theta \leq 10^\circ$). Currently, the authors are extensively seeking new approaches to improve the accuracy of the method for such specific localization scenarios.

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