E

Individual Research Grant

Research Grant Application no. 218/08

General application information

Role	Name	Academic Appointment	Department	Institute
PI.1	WEISS ANTHONY J.	Full professor	Electrical Engineering - Systems	Tel Aviv University

Research Title
Effective Exploitation of the Doppler Effect for Emitter Localization

Keywords
Geolocation, Emitter Localization, Doppler Effect

Requested Budget in US Dollars ($1 = 4.3 NIS)

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Name & Position ____ Date ____	Name & Position ____ Date ____
Signature & Stamp	Signature & Stamp

Part 2 – Scientific Abstract

The problem of emitter location attracts much interest in the Signal-Processing, Radar, Sonar, Bioengineering, Seismology and Astronomy literature. Emitter location techniques are currently used for many purposes such as emergency cellular phone location, law enforcement, radio spectrum monitoring, medical imaging, research of wildlife (fish, birds) migration, control of large herds of cows/sheep/horses, etc.

A well known technique for geolocation that is not used frequently enough is known as Differential Doppler (DD) or Differential Frequency of Arrival (DFOA). Differential Doppler localization is a position determination technique in which the signal of a stationary emitter is intercepted by moving receivers. The conventional method is a two-step procedure. At first, each receiver estimates the frequency of the observed signal at several interception intervals along its trajectory. Then the emitter's position is determined based on all frequency estimates. This is a suboptimal approach because each frequency estimate is performed separately and independently, although all estimates correspond to a common emitter position. Instead, a maximum likelihood method is proposed here for both known and unknown transmitted waveforms. The method directly determines the position using all the observations by a single grid search in the position space. Simulations show that the proposed technique outperforms the conventional method for weak signals.

The proposed research is aimed at further developing and adapting the proposed method for various applications.

Part 3 - Detailed description of the research program

3.1 Scientific Background

Passive position determination of a radiating stationary source is a problem that has been discussed in the literature since the Second World War. The position can be estimated from signal time of arrival, angle of arrival, received signal strength or Doppler frequency shifts [1]-[3]. A method that determines the emitter position from a set of Doppler frequency measurements is known as Frequency Difference Of Arrival (FDOA) or Differential Doppler (DD). Of coarse, DD can be implemented successfully only if there is a relative velocity between the receivers and transmitter. DD is based on the difference between the received frequencies at different receivers and thus eliminates the need to know the exact transmit frequency.

The problem of locating and tracking a moving source based on the received signal frequency at an array of stationary sensors has been discussed by Schultheiss and Weinstein [4], Weinstein [5], Wax [6] and Chan and Towers [7]. The dual problem of locating a stationary emitter by moving receivers has been discussed in [2]-[3]. The idea of using the Doppler Effect for localization found applications in radar, passive airborne location and satellite positioning. Becker [8] investigated radar localization by a single moving receiver based on bearing estimation, frequency estimation or the combination of both. The performance of each approach has been characterized by the Cramer-Rao Lower Bound (CRLB). He showed that combining both methods leads to a substantial performance gain. In [9] Becker extended the approach by considering the drift and frequency hopping of the transmitted radar. Fowler [10] extended the CRLB results to three dimensional emitter locations by a single moving receiver. He also discussed the location performance as a function of the emitter height information. Levanon [11] presented an error analysis of DD and compared its accuracy with an interferometer location system. Differential Doppler has also been used for emitter geolocation by satellites. The United States navy navigation satellite system (also known as TRANSIT) has been based on the Doppler effect [12]. Related papers have been contributed by Chung and Carter [13], Sonnenschein et al. [14] and Pattison and Chou [15]. Recently, Ho and Xu [16] presented a solution for locating a moving source from time and frequency difference of arrival. They proposed a weighted least squares minimization with no need for initial position guess. It has been shown that the position and velocity estimation accuracies attain the CRLB for Gaussian measurements noise.

The conventional DD localization approach is based on a two-step procedure: (1) Each receiver estimates the Doppler frequency of the received signal at several interception intervals along its trajectory. The measured frequency is a function of the transmitted frequency and the receiver-transmitter relative radial velocity; (2) The set of all frequency estimates are sent to a central processing unit where they are used to determine the position of the emitter.

Since DD is a two step procedure, it is a suboptimal approach. The reason is that the Doppler estimates are determined by each receiver in each interception interval separately without using the constraint that all estimates must correspond to the same transmitted frequency and the same position. Moreover, since the number of estimated frequencies is larger than the number of source coordinates, the problem is over parameterized, which in turn increases the estimation error. The objective of this study is to propose a position determination method that optimally estimates the emitter's position. The method solves the location problem using the data collected by all receivers at all interception intervals. The method can be applied to unknown signals and a priori known signals (for example, training or synchronization sequences [17]). Based on the maximum likelihood principle the emitter location is determined as the position that is most likely to explain all data. The proposed method requires only a single three-dimensional search or a two-dimensional search if the emitter's plane is known. Simulations indicate that the proposed method outperforms the two step methods under low signal to noise ratio conditions. Also in the presence of modeling errors the advocated method is superior.

The new technique requires higher computational load and the transmission of the raw data to a Central Processing Center (CPC) while the DD requires only the transmission of the estimated frequencies to the CPC.

3.2 Research Objectives and Expected Significance

The objective of this research is to provide methods, techniques and algorithms that will significantly improve the accuracy of location determination of emitting sources using the Doppler Effect. Applications include the following fields:

- Radio spectrum monitoring by the FCC and similar authorities in rural areas using airborne receivers.
- Law enforcement (localization of smugglers and other law-breaking entities).
- Homeland security.
- Localization of marine mammals for scientific research using hydrophones dragged by boats.
- Localization in disaster areas of buried individuals (earthquakes, snow avalanche) using airborne receivers.

3.3 Detailed Description of the Proposed Research

3.3.1 Working Hypothesis

Our hypothesis is that we can obtain considerably improved location accuracy using our proposed approach of using all observed signals together in order to obtain the position that best explains all the observed data. This approach differs considerably from the conventional approach that is based on two steps: in the first step all frequencies are measured. In the second step the position is estimated from the estimated frequencies.

3.3.2 Experimental Design and Methods

The proposed research consist of few parts. The first part is theoretical. We will analyze the proposed method analytically under the following conditions:

- Receiver location errors
- Local Oscillator errors
- Timing errors
- Various geometries and tracks.
- Closely spaced transmitters
- Deterministic, known and unknown signals

- Random signals

We will also examine various lower bounds in order to check the optimality of the solution. The bounds will include the Cramer-Rao bound, Barankin bound and the Weiss-Weinstein bound.

The second part of the research will examine real data. We expect to obtain real hydrophone data that include recording of marine mammals sounds (especially Dolphins.) Additionall, we will check our results in the laboratory using acoustic signals.

3.3.3 Preliminary Results

The preliminary results discussed here consider localization of stationary radio frequency transmitters by moving receivers. It is shown that advanced location methods based on a centralized approach leads to superior performance over conventional location methods.

A stationary emitter and L moving synchronized receivers intercepting the transmitted narrow-band signal are considered. The emitter's position is denoted by the vector of coordinates $\mathbf{p}_0$. Each of the receivers intercepts the transmitted signal at K short intervals along its trajectory. Let $\mathbf{p}_{\ell,k}$ and $\mathbf{v}_{\ell,k}$ where $k = \{1, \ldots, K\}$ and $\ell = \{1, \ldots, L\}$ denote the position and velocity vectors of the ℓ-th receiver at the k-th interception interval, respectively. The complex signal observed by the ℓ-th receiver at the k-th interception interval at time t is

$$r_{\ell,k}(t) = b_{\ell,k} s_k(t) e^{j2\pi f_{\ell,k} t} + w_{\ell,k}(t) \quad ,0 \le t \le T \tag{1}$$

where T is the observation time interval, $b_{\ell,k}$ is an unknown complex scalar representing the path attenuation at the k-th interception interval observed by the ℓ-th receiver, $s_k(t)$ is the transmitted waveform during the k-th interception interval, $w_{\ell,k}(t)$ is a wide sense stationary additive white zero mean complex Gaussian noise and finally $f_{\ell,k}$ is the frequency observed by the ℓ-th receiver during the k-interception interval given by,

$$f_{\ell,k} \triangleq [f_c + \nu_k]\,[1 + \mu_{\ell,k}(\mathbf{p}_0)] \tag{2}$$

$$\mu_{\ell,k}(\mathbf{p}_0) \triangleq \frac{1}{c} \frac{\mathbf{v}_{\ell,k}^T[\mathbf{p}_0 - \mathbf{p}_{\ell,k}]}{\|\mathbf{p}_0 - \mathbf{p}_{\ell,k}\|} \tag{3}$$

where f_c is the nominal transmitted signal frequency, assumed known, ν_k is the unknown transmitted frequency shift due to the source instability, during the k-th interception interval and c is the signal's propagation speed.

Since $\mu_{\ell,k} \ll 1$ and $\nu_k \ll f_c$, Eq. (2) can be approximated as $f_{\ell,k} \cong \nu_k + f_c[1 + \mu_{\ell,k}(\mathbf{p}_0)]$ where the term $\nu_k \mu_{\ell,k}$, which is negligible with respect to (w.r.t.) all other terms, is omitted. Furthermore, as the nominal frequency, f_c, is known to the receivers, it is assumed that each receiver performs a down conversion of the intercepted signal by the nominal frequency. Hence, after down conversion the frequency is $\bar{f}_{\ell,k} = f_{\ell,k} - f_c$ and Eq. (2) can be replaced by

$$\bar{f}_{\ell,k} \cong \nu_k + f_c \mu_{\ell,k}(\mathbf{p}_0) \tag{4}$$

The transmitted frequency is assumed to be constant during the interception interval, T. The down converted signal is sampled at times $t_n = nT_s$ where $n = 0, \ldots, N-1$ and $T_s = T/(N-1)$. The signal at the k-th interception interval is given as $r_{\ell,k}[n] \triangleq r_{\ell,k}(nT_s)$. Then Eq. (1) can be written in a vector form as

$$\mathbf{r}_{\ell,k} = b_{\ell,k} \mathbf{A}_{\ell,k} \mathbf{C}_k \mathbf{s}_k + \mathbf{w}_{\ell,k} \tag{5}$$

where

$$\mathbf{r}_{\ell,k} \triangleq [r_{\ell,k}[0], \ldots, r_{\ell,k}[N-1]]^T \tag{6}$$

$$\mathbf{w}_{\ell,k} \triangleq [w_{\ell,k}[0], \ldots, w_{\ell,k}[N-1]]^T \tag{7}$$

$$\mathbf{s}_k \triangleq [s_k[0], \ldots, s_k[N-1]]^T \tag{8}$$

$$\mathbf{A}_{\ell,k} \triangleq \mathrm{diag}\left\{1, e^{j2\pi f_c \mu_{\ell,k} T_s}, \ldots, e^{j2\pi f_c \mu_{\ell,k}(N-1)T_s}\right\} \tag{9}$$

$$\mathbf{C}_k \triangleq \mathrm{diag}\left\{1, e^{j2\pi \nu_k T_s}, \ldots, e^{j2\pi \nu_k (N-1)T_s}\right\} \tag{10}$$

where $\mathrm{diag}\{x_1, \ldots, x_n\}$ denotes a diagonal matrix with $\{x_1, \ldots, x_n\}$ on the main diagonal.

It is to be noted that the matrix $\mathbf{A}_{\ell,k}$ is a function of the unknown emitter's position while the matrix $\mathbf{C}_k$ is a function of the unknown transmitted frequency. The noise vectors $\mathbf{w}_{\ell,k}$ are independent and normally distributed with zero mean and scaled identity covariance matrix, $\sigma_n^2 \mathbf{I}$.

To simplify the exhibition the vector of transmitted frequencies is defined by $\boldsymbol{\nu} \triangleq [\nu_1, \ldots, \nu_K]^T$, the vector of path attenuations is defined by $\mathbf{b} \triangleq [\mathbf{b}_1^T, \ldots, \mathbf{b}_K^T]^T$ where $\mathbf{b}_k \triangleq [b_{1,k}, \ldots, b_{L,k}]^T$, and finally, the vector of transmitted signals is defined by $\mathbf{s} \triangleq [\mathbf{s}_1^T, \ldots, \mathbf{s}_K^T]^T$. The parameter vector of the model in Eq. (5) is then given by $\boldsymbol{\psi} \triangleq \left[\mathbf{p}_0^T, \boldsymbol{\nu}^T, \mathbf{b}^T, \mathbf{s}^T\right]^T$. We consider $\mathbf{p}_0$ as the vector of interest and $\boldsymbol{\nu}$, $\mathbf{b}$ and $\mathbf{s}$ as the nuisance parameters.

The problem discussed in this article can be briefly stated as: Given the observation vectors $\{\mathbf{r}_{\ell,k}\}$ in Eq. (5), estimate the position of the emitter.

3.3.3.1 Conventional Location Algorithm

For the sake of clarity, the conventional FDOA method [2]- [3] is described. The signal frequency estimate performed by the ℓ-th receiver at the k-th interception interval is denoted by $\hat{f}_{\ell,k}$. Using Eq. (4), we can collect all the measurements associated with the k-th interception interval,

$$\hat{\mathbf{f}}_k \triangleq [\hat{f}_{1,k}, \cdots, \hat{f}_{L,k}]^T = \mathbf{1}\nu_k + f_c\mathbf{m}_k(\mathbf{p}_0) + \mathbf{e}_k \tag{11}$$

where $\mathbf{1}$ is a $L \times 1$ vector of ones, $\mathbf{m}_k \triangleq [\mu_{1,k}, \cdots, \mu_{L,k}]^T$ and $\mathbf{e}_k$ is the vector of errors reflecting the measurement errors and all other model errors. According to the least squares principle the position estimator is given by

$$\hat{\mathbf{p}}_0 = \underset{\mathbf{p}_g}{\operatorname{argmin}} \sum_{k=1}^{K} \|\hat{\mathbf{f}}_k - \mathbf{1}\nu_k - f_c\mathbf{m}_k(\mathbf{p}_g)\|^2 \tag{12}$$

It is well known that Eq. (12) can be minimized by choosing $\hat{\nu}_k = \frac{1}{L}\mathbf{1}^T[\hat{\mathbf{f}}_k - f_c\mathbf{m}_k(\mathbf{p}_g)]$. Substituting $\hat{\nu}_k$ back to Eq. (12) yields

$$\hat{\mathbf{p}}_0 = \underset{\mathbf{p}_g}{\operatorname{argmin}} \sum_{k=1}^{K} \|\mathbf{R}[\hat{\mathbf{f}}_k - f_c\mathbf{m}_k(\mathbf{p}_g)]\|^2 \tag{13}$$

where $\mathbf{R} = \mathbf{I} - \frac{1}{L}\mathbf{1}\mathbf{1}^T$ is a projection matrix.

Note that the above equation does not depend on the unknown frequency offset ν_k. It is minimized by a grid search in the emitter space[1].

3.3.3.2 Direct Position Determination Approach

Consider the observation vectors in Eq. (5). The information on the emitter's position is embedded in each of the matrices $\mathbf{A}_{\ell,k}$. This position is common to all observations at

[1]Although this cost function has not been explicitly presented by Torrieri, he proposed the least squares estimator [2, Section VII, following Eq. (161)].

all interception intervals. Hence, we estimate the emitter position as the position that best explains all the data together. This is the main concept of the proposed Direct Position Determination (DPD) approach.

Due to its excellent asymptotic properties (consistency and efficiency) we focus on the Maximum Likelihood Estimator (MLE). The log-likelihood function of the observation vectors is given (up to an additive constant) by

$$L = -\frac{1}{\sigma_n^2}\sum_{k=1}^{K}\sum_{\ell=1}^{L}\|\mathbf{r}_{\ell,k} - b_{\ell,k}\mathbf{A}_{\ell,k}\mathbf{C}_k\mathbf{s}_k\|^2 \tag{14}$$

The path attenuation scalars that maximizes Eq. (14) are given by

$$\hat{b}_{\ell,k} = [(\mathbf{A}_{\ell,k}\mathbf{C}_k\mathbf{s}_k)^H\mathbf{A}_{\ell,k}\mathbf{C}_k\mathbf{s}_k]^{-1}(\mathbf{A}_{\ell,k}\mathbf{C}_k\mathbf{s}_k)^H\mathbf{r}_{\ell,k} = (\mathbf{A}_{\ell,k}\mathbf{C}_k\mathbf{s}_k)^H\mathbf{r}_{\ell,k} \tag{15}$$

where we assume without loss of generality that $\|\mathbf{s}_k\|^2 = 1$.

Substitution of Eq. (15) in Eq. (14) yields,

$$L \;=\; -\frac{1}{\sigma_n^2}\sum_{k=1}^{K}\sum_{\ell=1}^{L}\|\mathbf{r}_{\ell,k}\|^2 - |(\mathbf{A}_{\ell,k}\mathbf{C}_k\mathbf{s}_k)^H\mathbf{r}_{\ell,k}|^2 \tag{16}$$

Since $\|\mathbf{r}_{\ell,k}\|^2$ is independent of the parameters, instead of maximizing Eq. (16) we can now maximize the cost function L' given by

$$L' = \sum_{k=1}^{K}\sum_{\ell=1}^{L}|(\mathbf{A}_{\ell,k}\mathbf{C}_k\mathbf{s}_k)^H\mathbf{r}_{\ell,k}|^2 = \sum_{k=1}^{K}\mathbf{u}_k^H\mathbf{Q}_k\mathbf{u}_k \tag{17}$$

where $\mathbf{u}_k \triangleq \mathbf{C}_k\mathbf{s}_k$ and the $N \times N$ hermitian matrix $\mathbf{Q}_k$ is defined as

$$\mathbf{Q}_k \triangleq \mathbf{V}_k\mathbf{V}_k^H \;\;;\;\; \mathbf{V}_k \triangleq [\mathbf{A}_{1,k}^H\mathbf{r}_{1,k}, \cdots, \mathbf{A}_{L,k}^H\mathbf{r}_{L,k}] \tag{18}$$

Two cases are considered now: unknown and a priori known transmitted signals. The first is the common assumption when there is no prior information on the signals. However, the second is applicable to situations where the signals are a priori known to be training or synchronization sequences [17].

3.3.3.3 Unknown transmitted signals

When the transmitted signals are unknown, the cost function in Eq. (17) is maximized by maximizing each of the K quadratic forms w.r.t. $\mathbf{u}_k$. Thus, the vector $\mathbf{u}_k$ should be selected as the eigenvector corresponding to the largest eigenvalue of the matrix $\mathbf{Q}_k$ [20, Section 1f.2, page 62].

Therefore, the cost function in Eq. (17) reduces to

$$L_{us} \quad = \quad \sum_{k=1}^{K} \lambda_{max}\{\mathbf{Q}_k\} \tag{19}$$

where the right hand side of Eq. (19) denotes the largest eigenvalue of the matrix $\mathbf{Q}_k$.

The dimension of the matrix $\mathbf{Q}_k$ is $N \times N$ and, therefore, it increases with the number of data samples. Determining the eigenvalues of $\mathbf{Q}_k$ can in turn result in high computation effort. Instead, it is known that given a matrix $\mathbf{X}$, the non-zero eigenvalues of $\mathbf{X}\mathbf{X}^H$ and $\mathbf{X}^H\mathbf{X}$ are identical [20, Section 1c.3, pp. 42-43]. The $N \times N$ matrix $\mathbf{Q}_k$ in Eq. (19) can be therefore replaced with the $L \times L$ matrix $\bar{\mathbf{Q}}_k \triangleq \mathbf{V}_k^H \mathbf{V}_k$.

The estimated emitter's position $\hat{\mathbf{p}}_0$ is now determined by a simple grid search. For any grid point, $\mathbf{p}_g$, in the position space, evaluate Eq. (19) with $\mathbf{Q}_k$ replaced by $\bar{\mathbf{Q}}_k$, and obtain $L_{us}(\mathbf{p}_g)$. The estimated emitter's position $\hat{\mathbf{p}}_0$ is then given by

$$\hat{\mathbf{p}}_0 = \underset{\mathbf{p}_g}{\operatorname{argmax}}\{L_{us}(\mathbf{p}_g)\} \tag{20}$$

In words, the estimated position is the position that maximizes the the cost function L_{us}.

3.3.3.4 Known transmitted signals

Assuming that the transmitted signals are known Eq. (17) can also be rewritten as,

$$L' \quad = \quad \sum_{k=1}^{K} \sum_{\ell=1}^{L} |\mathbf{r}_{\ell,k}^H \mathbf{A}_{\ell,k} \mathbf{S}_k \mathbf{c}_k|^2 \tag{21}$$

where $\mathbf{S}_k \triangleq \text{diag}\{\mathbf{s}_k\}$ is a diagonal matrix whose main diagonal is the vector $\mathbf{s}_k$ and $\mathbf{c}_k \triangleq \text{diag}\{\mathbf{C}_k\}$ is a column vector equals to the main diagonal of the matrix $\mathbf{C}_k$. Define the $L \times N$ matrix $\mathbf{B}_k \triangleq \mathbf{V}_k^H \mathbf{S}_k$.

Now Eq. (21) can be written as

$$L' = \sum_{k=1}^{K} \|\mathbf{B}_k \mathbf{c}_k\|^2 = \sum_{k=1}^{K} \mathbf{c}_k^H \mathbf{B}_k^H \mathbf{B}_k \mathbf{c}_k \tag{22}$$

Recalling the definition of $\mathbf{c}_k$, and using Eq. (10), the last equation is a polynomial in $z \triangleq e^{j2\pi\nu_k T_s}$ and therefore for any given $\mathbf{B}_k$ the maximum of $\|\mathbf{B}_k\mathbf{c}_k\|^2$ w.r.t. ν_k can be obtained by the Fast Fourier Transform (FFT).

Define the $N \times N$ matrix $\mathbf{G} \triangleq \mathbf{B}_k^H\mathbf{B}_k$. Note that

$$\mathbf{c}_k^H\mathbf{B}_k^H\mathbf{B}_k\mathbf{c}_k = \sum_{i,j=1}^{N-1} \mathbf{G}_{i,j} z^{i-j} = \sum_{m=-N+1}^{N-1} \alpha_m z^m \tag{23}$$

where $\mathbf{G}_{i,j}$ is the (i,j)-th element of $\mathbf{G}$ and α_m is the sum of elements on the m-th diagonal of the $\mathbf{G}$. Since $\mathbf{G}$ is hermitian, $\alpha_m = \alpha_{-m}^*$. Let $\beta_0 = \alpha_0$ and $\beta_m = 2\alpha_m$ for $m = 1, \cdots, N-1$. We can rewrite Eq. (23) as

$$\mathbf{c}_k^H\mathbf{B}_k^H\mathbf{B}_k\mathbf{c}_k = \Re\left\{\sum_{m=0}^{N-1} \beta_m^* z^{-m}\right\} \tag{24}$$

Thus, in order to find ν_k that maximizes $\|\mathbf{B}_k\mathbf{c}_k\|^2$, compute the FFT of the sequence $\{\beta_n^*\}_{n=0}^{N-1}$ and take the real part of the result. The FFT length should satisfy $M \geq N$. If the largest FFT coefficient is the m_0-th coefficient, then $\hat{\nu}_k = \frac{m_0}{MT_s}$ if $m_0 < M/2$, and $\hat{\nu}_k = -\frac{M-m_0}{MT_s}$ if $m_0 \geq M/2$.

The emitter position estimate, $\hat{\mathbf{p}}_0$, is now determined by a simple grid search. For each grid point, $\mathbf{p}_g$, in the position space, evaluate the K matrices $\{\mathbf{B}_k\}$ and use FFT to find ν_k that maximizes the expression $\|\mathbf{B}_k\mathbf{c}_k\|^2$. The estimated emitter's position $\hat{\mathbf{p}}_0$ is then given by

$$\hat{\mathbf{p}}_0 = \underset{\mathbf{p}_g}{\operatorname{argmax}}\{\sum_{k=1}^{K} \max_{\nu_k}\{\mathbf{c}_k^H\mathbf{B}_k^H\mathbf{B}_k\mathbf{c}_k\}\} \tag{25}$$

Notice that in the conventional approach the Doppler frequencies at each of the LK interception intervals are estimated. However, in the direct approach, we only estimate the K transmitted frequencies associated with the K interception intervals. The k-th transmitted frequency is estimated by using the observations at all the receivers together.

3.3.3.5 Computation Load

In the first step of the conventional approach each of the L receivers estimates K frequencies along its trajectory. Frequency estimation may be performed by FFT which requires approximately $N\log_2 N$ complex multiplications (recall that N is the number of samples in each interception interval). Finding the absolute value of each FFT coefficient requires additional N complex multiplications. Since we have a total of LK interception intervals the total number of operations associated with frequency estimation is $LK(N\log_2 N + N)$.

In the second step, the cost function in Eq. (13) is evaluated. For a point in the grid, the number of operations needed is $K(8L + L^2)$. Thus, the total number of operations is dominated by, $N_g LK(8 + L + N\log_2 N + N) \cong N_g LKN\log_2 N$, where N_g is the number of grid points.

For known signals, the estimated position in our approach is determined by the maximum of Eq. (22) over all grid points. The number of multiplications required to evaluate $\mathbf{B}_k$ is $2NL$ since $\mathbf{A}_{k,\ell}$ and $\mathbf{S}_k$ are diagonal matrices. Since $\mathbf{B}_k$ is a $L \times N$ matrix, the number of multiplications required to evaluate the hermitian matrix $\mathbf{B}_k^H \mathbf{B}_k$ is approximately $0.5LN^2$. Therefore we need a total of $2NL + 0.5LN^2$ multiplications to evaluate $\mathbf{B}_k^H \mathbf{B}_k$. The scalar $\mathbf{c}_k \mathbf{B}_k^H \mathbf{B}_k \mathbf{c}_k$ is evaluated by FFT. The FFT requires approximately $N\log_2 N$ multiplications. The total number of operations, for N_g grid points, is therefore $N_g K(2NL + 0.5LN^2 + N\log_2 N) \cong 0.5N_g KLN^2$.

Thus, the ratio of multiplications in the proposed approach to the conventional approach, for known signals, is $\frac{0.5N}{\log_2 N}$. It is clear that the proposed approach requires considerable more operations.

For unknown signals the evaluation of $\mathbf{V}_k$ in Eq. (18) requires NL multiplications and the evaluation of the hermitian matrix $\bar{\mathbf{Q}}_k$ requires approximately additional $0.5NL^2$ multiplications. Finding the eigenvalues in Eq. (19), replacing $\mathbf{Q}_k$ with $\bar{\mathbf{Q}}_k$, requires L^3 multiplications. The total number of multiplications is $N_g K(L^3 + 0.5NL^2 + NL) \cong N_g KLN(0.5L + 1)$.

Thus, the ratio of multiplications in the proposed approach to the conventional approach, for unknown signals, is roughly $\frac{0.5L+1}{\log_2 N}$. In many practical cases the proposed approach requires less operations.

3.3.3.6 Simulation Results

In this section we examine the performance of the proposed method and compare it with the conventional Differential Doppler (DD) method and with the Cramér-Rao Lower Bound (CRLB) [19, Section 8.2.3] using Monte-Carlo computer simulations. We focus on the position Root Mean Square Error (RMSE) defined by RMSE $= \sqrt{\frac{1}{N_{exp}} \sum_{i=1}^{N_{exp}} \|\hat{\mathbf{p}}_0(i) - \mathbf{p}_0\|^2}$ where N_{exp} is the number of Monte-Carlo trials and $\hat{\mathbf{p}}_0(i)$ is the estimated emitter position at the i-th trial.

Two receivers ($L = 2$) and one emitter in a plane are simulated. Each receiver intercepts the signal at five different intervals ($K = 5$) along its trajectory. The speed of each receiver is $v = 300$ [m/sec]. The first receiver intercepts the signal at the coordinates: $[2, 0]$, $[5, 0]$, $[6, 0]$, $[8, 0]$ and $[10, 0]$ (all measured in kilometers) with a velocity vector of $[v, 0]$ at all intervals. The second receiver intercepts the signal at the coordinates: $[9, 10]$, $[6, 10]$, $[5, 10]$, $[3, 10]$ and $[1, 10]$ with a velocity vector of $[-v, 0]$ at all intervals (see Fig. 1). When simulating known signals we used constant modulus signals. When simulating unknown signals we used random narrowband signals.

The emitter's position is randomly chosen within the squared area of 10×10 [Km x Km]. The signal carrier frequency is $f_c = 100$ [MHz]. The propagation speed is $c = 3 \times 10^8$ [m/sec]. The number of samples in each interception interval is $N = 300$. The vector of transmitted frequencies during the interception intervals is $\boldsymbol{\nu} = [0.8, 1.2, 2.5, 3.1, 4.2]^T$ [KHz]. The path-loss attenuation magnitude is selected at random using normal distribution with a mean of unity and standard deviation of 0.1. The attenuation phases are uniformly distributed on $[-\pi, \pi)$. To obtain statistical results, $N_{exp} = 100$ independent Monte-Carlo trials are performed. The Signal to Noise Ratio (SNR) is defined as SNR $\triangleq 10\log_{10}(P_t/\sigma_n^2)$ [dB] where P_t is the average power of the transmitted signal. Maximum likelihood has been used to estimate the frequencies in the conventional approach [18, Section 13.3].

First, DPD is compared with DD once for unknown signals and once for known signals. The position RMSE is displayed versus the SNR in Fig. 2 (unknown signals) and in Fig. 3 (known signals). It can be seen in both figures that for high SNR, DPD is equivalent to DD since both converge to the CRLB. However, DPD outperforms DD for low values of SNR.

Next, DD and DPD are compared when the SNR is 30 [dB] for all receivers at all interception intervals except for the SNR of the second receiver at the fifth interception interval. The SNR at this specific interval is changed from 30 [dB] to 0 [dB].

Fig. 4 shows the results. It can be seen that as the SNR at the fifth interval of the second receiver decreases, the performance of the two methods derogates. However, beyond a certain point, the performance of the DPD method improves in contrast with the conventional DD method. The DPD ignores the unreliable data and performs as if it does not exist.

3.3.4 Available Facilities for the research

Our laboratories are equipped with new personal computers. In addition we have powerful UNIX servers.

The Signal Processing Laboratory is supported by Texas Instruments and therefore we have access to the state of the art components and DSP controllers.

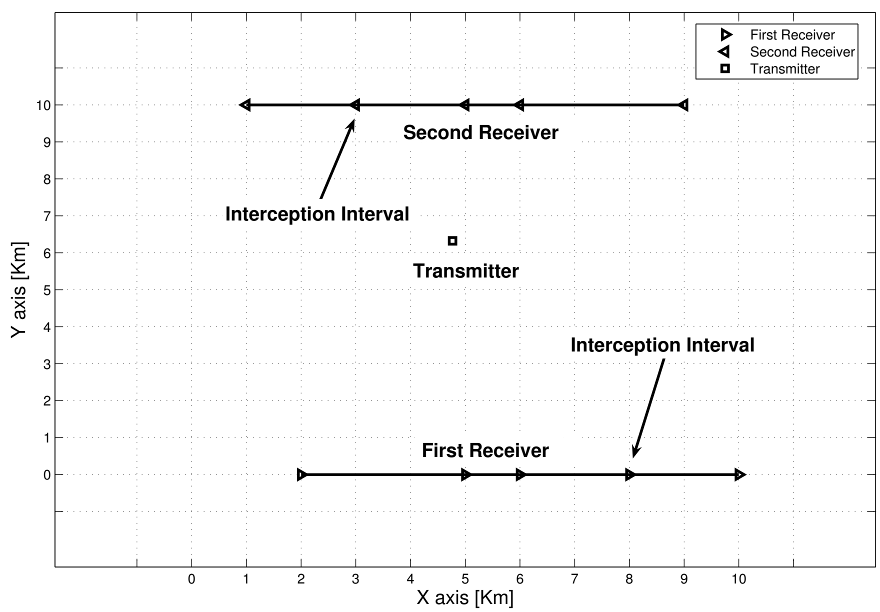

Figure 1: Receivers and Emitter Geometry.

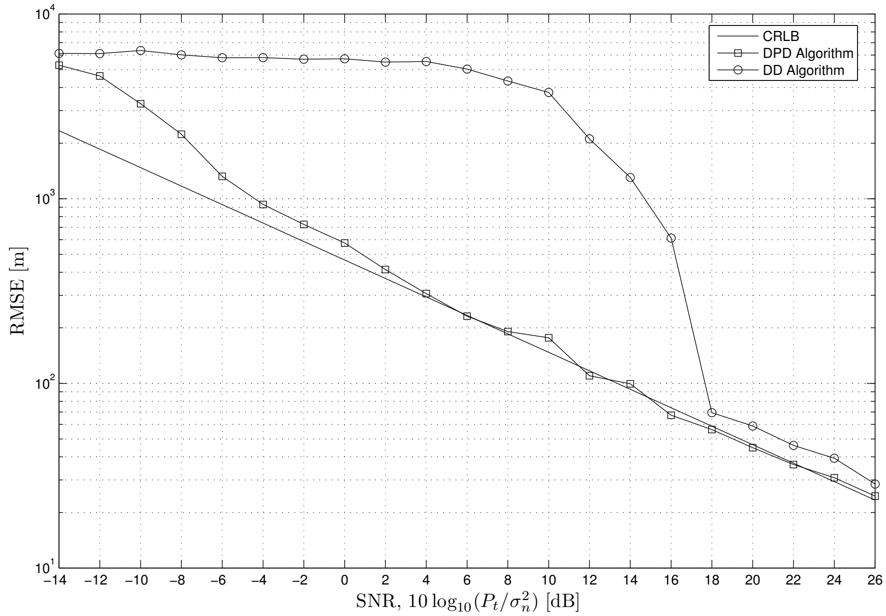

Figure 2: RMSE of the DPD method, the DD method and the CRLB versus the SNR with unknown transmitted signals.

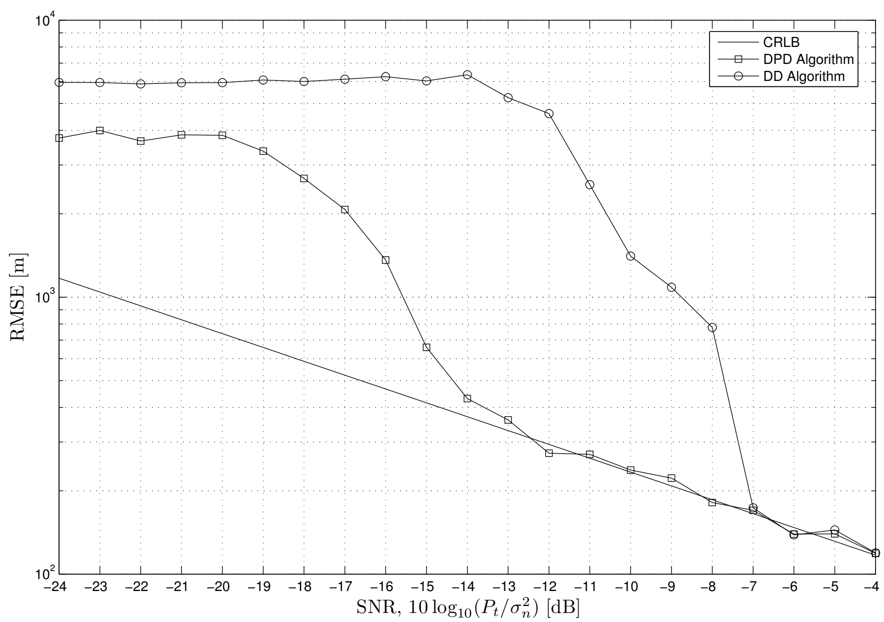

Figure 3: RMSE of the DPD method, the DD method and the CRLB versus the SNR with known transmitted signals.

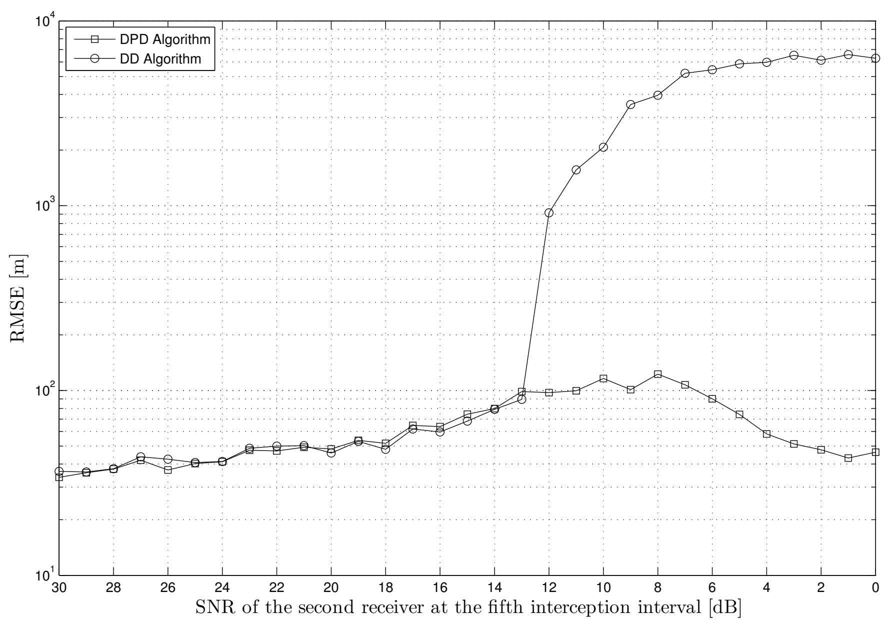

Figure 4: RMSE of the DPD method and the DD method versus the SNR of the second receiver at the fifth interception interval.

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Time schedule and work-plan

Objective	Beginning	End
Theoretical analysis of model errors	10/2008	3/2009
Developments of error lower bounds	4/2009	7/2009
Exploration of various geometries and tracks	8/2009	12/2009
Development of simulation tools	1/2010	6/2010
Comparison of simulations and bounds	7/2010	10/2010
Experiments with real data	11/2010	5/2011
Algorithms improvements based on results with real data	6/2011	9/2011

Budget details

A. Personnel

Name (last, first)	Role in project	% time devoted	Salaries (in $)		
			1st year	2nd year	3rd year
WEISS ANTHONY J.	PI	20	0	0	0
To be named	RA (Ph.D. student level c)	100	17,700	17,700	17,700
To be named	RA (M.Sc. Student level b)	100	15,300	15,300	15,300
To be named	RA (M.Sc. Student level a)	100	11,400	11,400	11,400
Total Personnel			**44,400**	**44,400**	**44,400**

B. Supplies, Materials & Services

Item	Requested sums (in $)		
	1st year	2nd year	3rd year
Computer + Office + MATLAB + Antivirus + ACROBAT	4,000	0	0
Students´ travel for conferences	1,000	1,000	1,000
Total supplies, materials & services	**5,000**	**1,000**	**1,000**

C. Miscellaneous

	Requested sums (in $)		
	1st year	2nd year	3rd year
Photocopies and office supplies	100	100	100
Publication charges in scientific journals	200	200	200
Professional literature	300	300	300
Communication services	100	100	100
Memberships in scientific associations	200	200	200
Total miscellaneous	**900**	**900**	**900**

Budget Summary

	Requested sums (in $)		
	1st year	2nd year	3rd year
Personnel, materials, supplies, services & miscellaneous	50,300	46,300	46,300
Overhead	7,545	6,945	6,945
Equipment (no overhead on this item):	0		
Total budget	**57,845**	**53,245**	**53,245**

Budget Justification:

The computer and software will be used for developing algorithms, computer simulations, data analysis, reports, scientific publications.

The research assitants will be involved in all research stages. The three students will cooperate and help each other. The theoretical tasks are not easy for students. Collection of real data is a time consuming task that will keep the research assitants busy for the full period.

Curriculum Vitae

Name: WEISS ANTHONY J.

A. Academic Background

Date (from-to)	Institute	Degree	Area of specialization
1969-1973	Technion, Haifa	B.Sc.	Electrical Enginering
1979-1982	Tel Aviv Unversity	M.Sc.	Electrical Enginering
1982-1985	Tel Aviv Unversity	Ph.D.	Electrical Enginering

B. Previous Employment

Date (from-to)	Institute	Title	Research area
1983-present	Tel Aviv University	Full Professor	Signal Processing
2006-present	Tel Aviv University	EE School - Head	Signal Processing
1996-1999	Tel Aviv University	Department - Head	Signal Processing
1996-1999	Tel Aviv University	IEEE Israel - Head	Signal Processing
1973-1983	IDF	Engineer	Communications

C. Grants and Awards Received Within The Past Five Years

Research Topics	Funding Organization	Total (in $)
Emitter Localization via New Methods	Israel Science Found.	150000
Comments	2004 to 2007	
Generation of full picture of Emitters Location	Institute for Future Defense Technologies Research Named for the Medvedi, Shwartzman and Gensler	30000
Comments	2005-2006	
Simultaneous Position Determination	Mnistry of Defense	15000
Comments	2005-2006	
Statistical Mechanics and Graphical Models for Communications	Adavanced Communication Center	10000
Comments	2005-2006	

List of Publications - Anthony J. Weiss

Articles

1. A.J. Weiss, and E. Weinstein, “Composite Bound on the Attainable Mean Square Error in Passive Time Delay Estimation,” *IEEE, Transactions on Information Theory,* Vol. IT-28, No. 6, pp. 977-979, November 1982.

2. A.J. Weiss, and E. Weinstein, “Fundamental Limitations in Passive Time Delay Estimation, Part I: Narrow-band Systems,” *IEEE Transactions on Acoustics, Speech, and Signal-Processing,* Vol. ASSP-31, No. 2, pp. 472-485, April 1983.

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6. A.J. Weiss, “Composite Bound on Arrival Time Estimation Errors,” *IEEE Transactions on Aerospace and Electronic Systems,* Vol. AES-22, No. 6, pp. 751-756, November 1986.

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10. E. Weinstein, and A.J. Weiss, “A General Class of Lower Bounds in Parameter Estimation,” *IEEE Transactions on Information Theory,* Vol. IT-34, No. 2, pp. 338-342, March 1988.

11. A.J. Weiss, A.S. Willsky, and B.C. Levy, “Eigenstructure Approach for Array Processing with Unknown Intensity Coefficients,” *IEEE Transactions on Acoustics, Speech, and Signal-Processing,* Vol. ASSP-36, No. 10, pp. 1613-1617, October 1988.

12. A.J. Weiss, A.S. Willsky, and B.C. Levy, “Nonuniform Array Processing via the Polynomial Approach,” *IEEE Transactions on Aerospace and Electronic Systems,* Vol. AES-25, No. 1, pp. 48-55, January 1989.

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15. A.J. Weiss, and B. Friedlander, “Eigenstructure Methods for Direction Finding with Sensor Gain and Phase Uncertainties,” *Circuits Systems and Signal Processing,* Vol.9, No. 3, pp. 271-300, 1990.

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72. E. Bashan, A.J. Weiss, and Y. Bar-Shalom, "Estimation Near 'Zero Information' Points: Angle-of-Arrival Near the Endfire," *IEEE Transaction on Aerospace and Electronics System,* Accepted for publication, July 2006.

73. A. Amar, and A.J. Weiss, "Fundamental Limitations on the Number of Resolvable Emitters in Geolocation Systems," *IEEE Transactions on Signal-Processing,* Accepted for publications July 22, 2006.

74. I. Rosenhouse and A.J. Weiss, "Combined Analog and Digital Error Correction Codes For Analog Information Sources". *IEEE Transactions on Communications,* Accepted for publications January 29, 2007.

75. A. Amar, and A.J. Weiss, "A Decoupled Algorithm for Geolocation of Multiple Emitters," *Signal-Processing,* Accepted for publications March 22, 2007.

76. A.J. Weiss, and J.S. Picard, "Improvement of Location Accuracy by Adding Nodes to Ad-Hoc Networks," *Springer, Wireless Personal Communications,* Accepted Mar. 28, 2007.

77. A.J. Weiss, and J.S. Picard, "Network Localization with Biased Range Measurements," *IEEE Transactions on Wireless Communications,* Accepted June 11, 2007.

Submitted for Publication

1. S. Zruia, E. Weinstein, and A.J. Weiss, "Blind Diversity Combining and Equalization in Multiuser Environment,"*IEEE Transactions on Information Theory.*

2. A.J. Weiss, and J.S. Picard, "Maximum Likelihood Position Estimation of Network Nodes Using Range Measurements," *IEEE Transactions on Signal-Processing,* Submitted September, 2007.

3. J.S. Picard, and A.J. Weiss, "Localization of Networks Using Various Ranging Bias Models" *Elsevier, Wireless Communications and Mobile Computing* Submitted Jan. 29, 2007.

4. I. Rosenhouse and A.J. Weiss, "On Consistency in Estimating Chaotic Sequences," *IEEE Transactions on Signal Processing,* Submitted for publications April, 2007.

5. Ori Shental, Noam Shental, Shlomo Shamai (Shitz), Ido Kanter, Anthony J. Weiss, and Yair Weiss, "Discrete-Valued Input Two-Dimensional Gaussian Channels with Memory: Estimation and Information Rates via Graphical Models and Statistical Mechanics, " *IEEE Transactions on Information Theory.*

6. A. Amar, and A.J. Weiss, "Fundamental Resolution Limits of Closely Spaced Random Signals," *IET Radar, Sonar & Navigation.*

7. A. Amar, and A.J. Weiss, "Fundamental Limitations on the Resolution of Deterministic Signals," *IEEE Transactions on Signal Processing.*

8. A. Amar, and A.J. Weiss, "A Novel Approach to Differential Doppler Localization," *IEEE Transactions on Signal Processing.*

Chapters In Books

1. B. Friedlander and A. J. Weiss, "Self Calibration for High Resolution Array Processing." A chapter in *Advances in Spectrum Analysis and Array Processing* by Simon Haykin (editor), Prentice Hall, 1991.

2. The following papers were selected to appear in: G. C. Carter (editor), *Coherence and Time Delay Estimation*, IEEE PRESS, 1993.

   - A.J. Weiss, and E. Weinstein, "Composite Bound on the Attainable Mean Square Error in Passive Time Delay Estimation," *IEEE, Transactions on Information Theory,* Vol. IT-28, No. 6, pp. 977-979, November 1982.
   - E. Weinstein, and A.J. Weiss, "Fundamental Limitations in Passive Time Delay Estimation, Part II: Wide-band Systems," *IEEE Transactions on Acoustics, Speech, and Signal-Processing,* Vol. ASSP-32, No. 5, pp. 1064-1078, October 1984.
   - J.P. Ianniello, E. Weinstein, and A.J. Weiss, "Comparison of the Ziv-Zakai Lower Bound with Correlator Performance," *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal-Processing,* (ICASSP), Boston, MA, pp. 875-878, April 1983.

3. A.J. Weiss, and A. Amar "Direct Position Determination of Multiple Radio Transmitters," Chapter 11 in *Advances in Direction Finding,* Editor Sathish Chandran, Artech House, 2006.

Current ISF application No.: 218/08
PI Name: Anthony J. Weiss
Research title: Effective Exploitation of the Doppler Effect for Emitter Localization

Objectives, results, achievements & list of publications of a Recent ISF grant

Recent ISF grant No. 1232/04

Research title: Emitter Localization via New Methods

Objectives

The objective of this research is to provide methods, techniques and algorithms that will significantly improve the accuracy of location determination of emitting sources. Applications include the following field:
1) Emergency cellular phone location (E911),
2) Radio spectrum monitoring by the FCC and similar authorities
3) Law enforcement (localization of smugglers and other law-breaking entities)
4) Homeland security,
5) Localization of fish/birds for research purposes
6) Agriculture (localization of sheep, horses, cows in large fields)
7) Seismology (location of earthquake centers, underground oil reservoirs)
8) Astronomy
9) Localization in disaster areas of buried individuals (earthquakes, snow avalanche)

Summary of Results

Extension of the Direct Position Determination (DPD) Algorithm to multiple Signals

We proposed a technique that uses exactly the same data as the common Angle of Arrival (AOA) methods but the position determination is direct. The proposed method can handle more than *M-1* co-channel simultaneous signals. Although there are many stray parameters only two-dimensional search is required for a planar geometry. The technique provides a natural solution to the measurements-sources association problem that is encountered in AOA based location systems. In addition to new algorithms we provided analytical performance analysis, Cramér-Rao bounds and Monte-Carlo simulations. We demonstrated that the proposed approach frequently outperforms the traditional AOA methods for unknown as well as known signal waveforms. For full details see [1].

Effects of Model Errors on the Proposed Algorithm

The performance of the Direct Position Determination (DPD) approach in the presence of model errors is examined. We analyzed the performance of DPD in the presence of model errors caused by multipath, calibration errors, mutual coupling, etc. The analysis is general enough to encapsulate various sources of errors. Monte-Carlo simulations are used to validate the analysis. We show that in many cases of interest DPD should be selected as the preferred method of localization. For full details see [2].

Limitations on the Number of Resolvable Emitters

We derived conditions for unique geolocation of multiple radio-frequency emitters. These conditions determine upper bounds on the Resolution Capacity (RC) of the system, which is defined as the maximum number of emitters that can be uniquely located. Our derivations extend previously published results in the field of geolocation based on Angle-of-Arrival estimation. We show that with no prior information, the RC is upper bounded by the total number of antenna elements in the system, ML, where M is the number of elements in each array and L is the number of arrays (stations). In contrast, the RC of geolocation based on Angle-of-Arrival (AOA) is upper bounded by M. In addition, with some prior information on the signals, the resolution capacity is upper bounded using uniform linear arrays by (ML)^{2}-L(M-1)^2. We corroborate our results by examining the condition number of the Fisher Information Matrix. Our results lead to the inevitable conclusion that geolocation using AOA is suboptimal and new methods should be developed that can exploit the information collected by all the antenna arrays together. For full details see [3].

Location of Ad-hoc Wireless Networks

Given a network of stations with incomplete and possibly imprecise inter-station distance measurements it is required to find the relative stations position. Due to its asymptotic properties Maximum Likelihood estimation is discussed. Although the problem is quadratic, the proposed solution is based on solving a linear set of equations. For precise measurements we obtain explicitly the exact solution with a small number of operations. For noisy measurements the method provides an excellent initial point for the application of the Gerchberg-Saxton iterations. Proof of convergence is provided. The case of planar geometry is coached using complex numbers which reveals a strong relation to the celebrated problem of phase retrieval. Numerical examples are provided to corroborate the results. For full details see [4].

Grant Related Publications

Published Articles

1. A.J. Weiss, and A. Amar, ``Direct Position Determination of Multiple Radio Signals," *EURASIP Journal on Applied Signal Processing*, 2005:1, pp. 37-49, January 2005.

2. A. Amar and A.J. Weiss, ``Direct Position Determination in the Presence of Model Errors - Known Waveforms," *Digital Signal Processing*, Elsevier, Vol. 16, No. 1, pp. 52-83, January, 2006.

3. A. Amar, and A.J. Weiss, ``Fundamental Limitations on the Number of Resolvable Emitters in Geolocation Systems," *IEEE Transactions on Signal Processing,* Vol. 55, No. 5, pp. 2193-2202, May 2007.

4. A. Amar, and A.J. Weiss, ``A Decoupled Algorithm for Geolocation of Multiple Emitters," *IEEE Transactions on Signal-Processing*, Vol. 87, No. 10, pp. 2348-2359, Oct. 2007.

Accepted Articles

5. A.J. Weiss, and J.S. Picard, ``Network Localization with Biased Range Measurements," *IEEE Transactions on Wireless Communications*, Accepted for publications.

6. A.J. Weiss, and J.S. Picard, ``Improvement of Location Accuracy by Adding Nodes to Ad-Hoc Networks," *Springer, Wireless Personal Communications*, Accepted for publications.

Submitted Articles

7. A.J. Weiss, and J.S. Picard, "Maximum Likelihood Position Estimation of Network Nodes Using Range Measurements," *IEEE Transactions on Signal Processing*.

8. J.S. Picard, and A.J. Weiss, "Localization of Networks Using Various Ranging Bias Models" Elsevier, Wireless Communications and Mobile Computing.

9. A. Amar, and A.J. Weiss, "Fundamental Resolution Limits of Closely Spaced Random Signals", submitted to IET Radar, Sonar & Navigation.

10. A. Amar, and A.J. Weiss, "Fundamental Limitations on the Resolution of Deterministic Signals", submitted to IEEE Transactions on Signal Processing.

11. A. Amar, and A.J. Weiss, "A Novel Approach to Differential Doppler Localization", submitted to IEEE Transactions on Signal Processing.

Conference Papers

12. A. Amar, and A.J. Weiss, "On unique passive geolocation of multiple radio-frequency emitters," Proceedings of the Eighth International Symposium on Signal Processing and Its Applications, Sydney, Australia, 2005.

13. O. Landau, and A. J. Weiss, "On Maximum Likelihood Estimation in the Presence of Vanishing Information Measure," Proceeding of IEEE International Conference on Acoustics, Speech, and Signal Processing, ICASSP, Toulouse, France, May 14-19, 2006.

14. A. J. Weiss, and J. Picard, "Maximum Likelihood Positioning of Network Nodes Using Range Measurements," Proceeding of the third International Symposium on Wireless Communication Systems (ISWCS), Valencia, Spain, September 2006.

15. A. Amar, and A. J. Weiss," Efficient Position Determination of Multiple Emitters, " Proceeding of 24th IEEE Convention of Electrical and Electronics Engineers in Israel, Eilat, Israel, November, 2006.

16. O. Bar Shalom, and A. J. Weiss, ``Direct Position Determination of OFDM Signals," The VIII IEEE Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Marina Congress Center, Helsinki, Finland, June 17- 20, 2007.

17. A. Amar, and A. J. Weiss, ``Resolution of Closely Spaced Deterministic Signals with Given Success Rate," IEEE International Symposium on Information Theory (ISIT), Nice, France, June 2007.

18. A. Amar, and A. J. Weiss, ``Resolution Limits Of Closely Spaced Random Signals Given The Desired Success Rate," Advanced Video and Signal based Surveillance (AVSS), London, United Kingdom, 5-7 September 2007.

19. A. Amar, and A. J. Weiss, ``Limits on the Resolution of Closely Spaced Multipath Signals," 5th International Symposium on Image and Signal Processing and Analysis (ISPA 2007), September 27-29, 2007, Istanbul, Turkey.

20. A.J. Weiss, and J. S. Picard, ``Maximum Likelihood Localization of Wireless Networks using Biased Range Measurements,'' 7th International Symposium on Communications and Information Technologies, Sydney, Australia, October 16-19, 2007.

21. A.J. Weiss, and J. S. Picard, ``Localization Enhancement by Additional Nodes in Wireless Networks,'' 7th International Symposium on Communications and Information Technologies, Sydney, Australia, October 16-19, 2007.