

Localization Algorithms in Passive Sensor Networks

by

Darya Ismailova

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Supervisory Committee

Dr. Wu-Sheng Lu, Supervisor
(Department of Electrical and Computer Engineering)

Dr. Pan Agathoklis, Departmental Member
(Department of Electrical and Computer Engineering)

Supervisory Committee

Dr. Wu-Sheng Lu, Supervisor
(Department of Electrical and Computer Engineering)

Dr. Pan Agathoklis, Departmental Member
(Department of Electrical and Computer Engineering)

ABSTRACT

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Chapter 1

Improved Least-Squares Methods for Source Localization: An Iterative Re-Weighting Approach

Locating a radiating source from range or range-difference measurements in a passive sensor network has recently attracted an increasing amount of research interest as it finds applications in a wide range of network-based wireless systems. Among the useful localization methods that have been documented over the years, least squares based algorithms constitute an important class of solution techniques as they are geometrically meaningful and often provide low complexity solution procedures with competitive estimation accuracy [1] - [14]. On the other hand, the error measure in a least squares (LS) formulation for the localization problem of interest is shown to be highly nonconvex, possessing multiple local solutions with degraded performance. There are many methods for continuous unconstrained optimization [25], however most of them are *local* methods that are iterative, hence extremely sensitive to where the iteration begins, and give no guarantee to yield global solutions when applied to non-convex objective functions. In the case of source localization, this inherent feature of local methods is particular problematic because the source location is assumed to be entirely unknown and can appear practically anywhere, thus the chances to secure a good initial point for a local algorithm are next to none. For these reasons, various “global” localization techniques were investigated that are either non-iterative or insensitive to initial iterate. One representative in the class of global localization methods is the convex-relaxation based algorithm for range measurements proposed

in [10], where the least squares model is relaxed to a semidefinite programming problem which is known to be convex [24], hence robust to where it starts. Another representative in this class is reference [14], where localization problems for range as well as range difference measurements are addressed by developing solution methods for *squared* range LS (SR-LS) and *squared* range difference LS (SRD-LS) problems. The methods proposed in [14] are non-iterative and the solutions obtained are proven to be the global minimizers of the respective SR-LS and SRD-LS problems, which are shown to be excellent estimates of the original LS solutions.

This chapter presents improved least squares methods that demonstrate improved localization performance when compared with the some best known results from the literature. The key new ingredient of the proposed algorithms is an iterative procedure where the SR-LS (SRD-LS) algorithm is iteratively applied to a weighted sum of squared terms where the weights are carefully designed so that the iterates produced quickly converge to a solution which, on comparing with the best known results, is found to be considerably closer to the original range-based (range-difference-based) LS solution.

1.1 Source Localization From Range Measurements

1.1.1 Problem Statement

The source localization problem considered here involves a given array of m sensors specified by $\{\mathbf{a}_1, \dots, \mathbf{a}_m\}$ where $\mathbf{a}_i \in R^n$ contains the n coordinates of the i th sensor in space R^n . Each sensor measures its distance to a radiating source $\mathbf{x} \in R^n$. Throughout it is assumed that only noisy copies of the distance data are available, hence the *range measurements* obey the model

$$r_i = \|\mathbf{x} - \mathbf{a}_i\| + \varepsilon_i, i = 1, \dots, m. \quad (1.1)$$

where ε_i denotes the unknown noise that has occurred when the i th sensor measures its distance to source \mathbf{x} . Let $\mathbf{r} = [r_1 \ r_2 \ \dots \ r_m]^T$ and $\boldsymbol{\varepsilon} = [\varepsilon_1 \ \varepsilon_2 \ \dots \ \varepsilon_m]^T$. The source localization problem can be stated as to estimate the exact source location \mathbf{x} from the noisy range measurements \mathbf{r} . In the rest of this section, a least-squares (LS) formulation of the localization problem and two most relevant state-of-the-art solution methods are briefly reviewed; and a new method based on iterative re-weighting of

squared range LS technique as well as a variant of the proposed method are then presented.

1.1.2 LS Formulations and Review of Related Work

Least squares approaches have proven effective for source localization problems [1]-[14]. For the localization problem at hand, the range-based least squares (R-LS) estimate refers to the solution of the problem

$$\underset{\mathbf{x}}{\text{minimize}} f(\mathbf{x}) \equiv \sum_{i=1}^m (r_i - \|\mathbf{x} - \mathbf{a}_i\|)^2 \quad (1.2)$$

The primary reason that justifies formulation (1.2) is its connection to the maximum-likelihood location estimation that determines \mathbf{x} by examining the probabilistic model of the error vector $\boldsymbol{\varepsilon}$. Assuming the errors ε_i are independent identically distributed (Gaussian) variables with zero mean and variance σ_i^2 , then $\boldsymbol{\varepsilon}$ obeys a Gaussian distribution with zero mean and covariance $\boldsymbol{\Sigma} = \text{diag}(\sigma_1^2, \dots, \sigma_m^2)$, and the maximum likelihood (ML) location estimator in this case is known to be

$$\mathbf{x}_{ML} = \arg \min_{\mathbf{x} \in R^n} (\mathbf{r} - \mathbf{g})^T \boldsymbol{\Sigma}^{-1} (\mathbf{r} - \mathbf{g}) \quad (1.3)$$

where $\mathbf{g} = [g_1 \ g_2 \ \dots \ g_m]^T$ with

$$g_i = \|\mathbf{x} - \mathbf{a}_i\| \quad (1.4)$$

It follows immediately that the ML solution in (1.3) is identical to the R-LS solution of problem (1.2) when covariance $\boldsymbol{\Sigma}$ is proportional to the identity matrix, i.e., $\sigma_1^2 = \dots = \sigma_m^2$. In the literature this is known as the equal noise power case. For notation simplicity the method described in this chapter focuses on the equal noise power case, however the method developed below is also applicable to the unequal noise power case by working on a weighted version of the objective in (1.2) with $\{\sigma_i^{-2}, i = 1, \dots, m\}$ as the weights.

Although there are many methods for continuous unconstrained optimization [25], most of them are *local* methods in the sense they are sensitive to the choice of initial point where the iteration of an optimization algorithm begins. Especially when applied to a nonconvex objective function which possesses a number of local minimizers, unless a chosen local method starts at an initial point that happens to be sufficiently close to the (unknown) global minimizer, the solution obtained by the method gives no

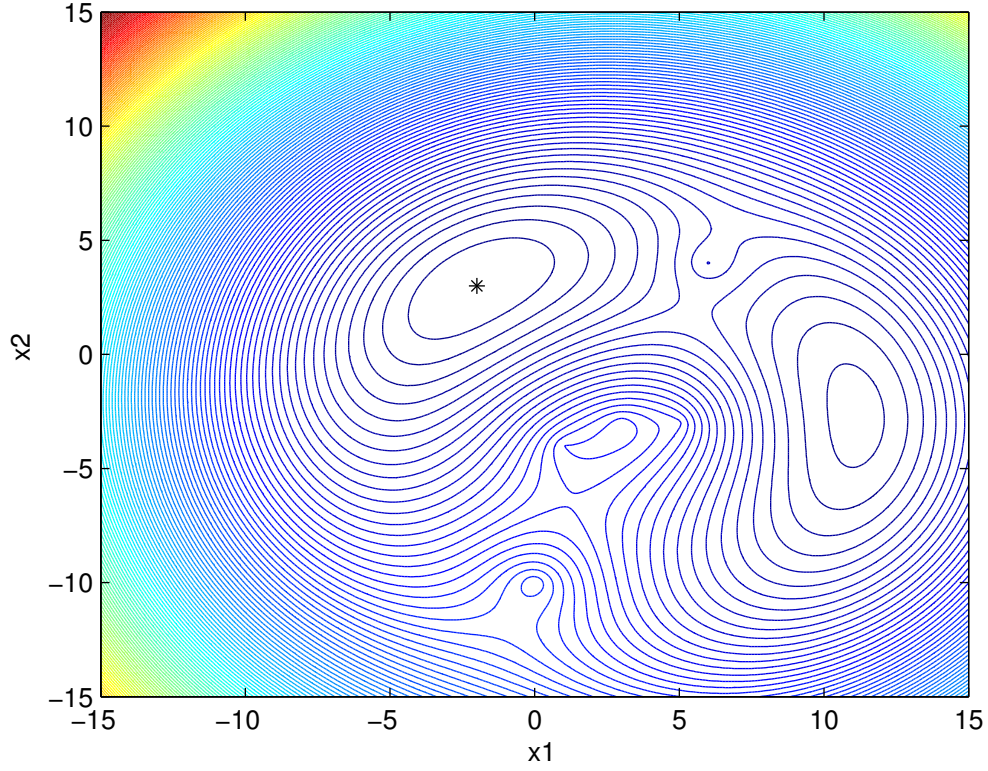


Figure 1.1: Contours of the R-LS objective over the region $\mathfrak{R} = \{-15 \leq x_1 \leq 15, -15 \leq x_2 \leq 15\}$

guaranty about its global minimality. Unfortunately, the objective function in (1.2) is highly nonconvex, possessing many local minimizers even for small-scale systems. As an example, consider an instance of the source localization problem in the plane $n = 2$ with five sensors $m = 5$ located at $(\cdot), (\cdot), (\cdot), (\cdot)$ and (\cdot) with the signal emitting source at $(-2, 3)$. Figure (1.1) describes a contour plot of the R-LS objective function in (1.2).

Reference [10] addresses problem (1.2) by a convex relaxation technique where (1.2) is modified to a convex problem known as semidefinite programming (SDP) [24]. A key step in this procedure is to use (1.4) with g_i as new variables, which leads (1.2) to the constrained problem

$$\underset{\mathbf{x}, \mathbf{g}}{\text{minimize}} \sum_{i=1}^m (r_i - g_i)^2 \quad (1.5a)$$

$$\text{subject to: } g_i^2 = \|\mathbf{x} - \mathbf{a}_i\|^2, \quad i = 1, \dots, m. \quad (1.5b)$$

By further defining matrix variables

$$\mathbf{G} = \begin{bmatrix} \mathbf{g} \\ 1 \end{bmatrix} \begin{bmatrix} \mathbf{g}^T & 1 \end{bmatrix} \text{ and } \mathbf{X} = \begin{bmatrix} \mathbf{x} \\ 1 \end{bmatrix} \begin{bmatrix} \mathbf{x}^T & 1 \end{bmatrix} \quad (1.6)$$

and neglecting the rank constraints on \mathbf{G} and \mathbf{X} , (1.5) can be reformulated in term of variables \mathbf{G} and \mathbf{X} as

$$\underset{\mathbf{X}, \mathbf{G}}{\text{minimize}} \sum_{i=1}^m (G_{ii} - 2r_i G_{m+1,i} + r_i^2) \quad (1.7a)$$

$$\text{subject to: } G_{ii} = \text{Tr}(\mathbf{C}_i \mathbf{X}), i = 1, \dots, m \quad (1.7b)$$

$$\mathbf{G} \succeq 0, \mathbf{X} \succeq 0 \quad (1.7c)$$

$$G_{m+1,m+1} = G_{n+1,n+1} = 1 \quad (1.7d)$$

where

$$\mathbf{C}_i = \begin{pmatrix} \mathbf{I}_{n \times n} & -\mathbf{a}_i \\ -\mathbf{a}_i^T & \|\mathbf{a}_i\|^2 \end{pmatrix} \quad i = 1, \dots, m \quad (1.8)$$

which is a standard SDP problem that can be solved efficiently [24, 25]. Note that because (1.7) is a convex problem, global minimality of the solution is ensured regardless of the initial point used. On the other hand, however, because (1.7) is an approximation of the original problem in (1.2), the solution of (1.7) is only an approximate solution of problem (1.2). In what follows the solutions obtained by this SDP-relaxation based method will be referred to as SDR-LS solutions.

A rather different approach is recently proposed in [14] where the localization problem (1.2) is tackled by developing techniques that find global solution of the *squared range based LS* (SR-LS) problem

$$\underset{\mathbf{x}}{\text{minimize}} \sum_{i=1}^m (\|\mathbf{x} - \mathbf{a}_i\|^2 - r_i^2)^2 \quad (1.9)$$

By writing the objective in (1.9) as $(\alpha - 2\mathbf{a}_i^T \mathbf{x} + \|\mathbf{a}_i\|^2 - r_i^2)^2$ with $\alpha = \|\mathbf{x}\|^2$, it becomes a convex quadratic objective if one treats α as an additional variable and $\alpha = \|\mathbf{x}\|^2$ as a constraint. In this way, (1.9) is converted to the following constrained

LS problem after necessary variable changes:

$$\underset{\mathbf{y} \in R^{n+1}}{\text{minimize}} \|\mathbf{A}\mathbf{y} - \mathbf{b}\|^2 \quad (1.10a)$$

$$\text{subject to: } \mathbf{y}^T \mathbf{D} \mathbf{y} + 2\mathbf{f}^T \mathbf{y} = 0 \quad (1.10b)$$

where $\mathbf{y} = [\mathbf{x}^T \|\mathbf{x}\|^2]^T$ and

$$\mathbf{A} = \begin{pmatrix} -2\mathbf{a}_1^T & 1 \\ \vdots & \vdots \\ -2\mathbf{a}_m^T & 1 \end{pmatrix}, \mathbf{b} = \begin{pmatrix} r_1^2 - \|\mathbf{a}_1\|^2 \\ \vdots \\ r_m^2 - \|\mathbf{a}_m\|^2 \end{pmatrix} \quad (1.11)$$

$$\mathbf{D} = \begin{pmatrix} \mathbf{I}_{n \times n} & \mathbf{0}_{n \times n} \\ \mathbf{0}_{n \times n} & 0 \end{pmatrix}, \mathbf{f} = \begin{pmatrix} \mathbf{0} \\ -0.5 \end{pmatrix}$$

This problem conversion, made in [14], turns out to be crucial as problem (1.10), which remains to be nonconvex because of the nonlinear equality constraint (1.10b), falls into the class of generalized trust region subproblems (GTRS) [17, 18] whose global solutions can be computed by exploring the KKT conditions which are both necessary and sufficient optimality conditions in the case of GTRS [17].

Few remarks are now in order. First, an unconstrained version of (1.10) may be obtained by neglecting the constraint in (1.10b) as

$$\underset{\mathbf{y} \in R^{n+1}}{\text{minimize}} \|\mathbf{A}\mathbf{y} - \mathbf{b}\|^2 \quad (1.12)$$

whose solution, called *unconstrained squared-range-based LS* (USR-LS) estimate, is given by

$$\mathbf{y}^* = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{b} \quad (1.13)$$

It is demonstrated by numerical experiments [14] that the SR-LS solution outperforms the USR-LS and, in many cases, SDR solutions. Second, the SR-LS solution, although it solves (1.9) exactly, lacks the statistical interpretation of the ML formulation. The SR-LS remains to be an approximate solution for the original problem in (1.2) and, as it was demonstrated by the numerical results in [15], provides less accurate estimates of the true source location, than the ML approach. The method, described in detail below, tries to reduce the gap between the two solutions.

1.1.3 An Iterative Re-Weighting Approach

Iterative re-weighting least squares method is a popular technique used for solving problems involving the sums of norms *{cite}*. The method has found many applications, such as in robust regression *{cite}*, sparse recovery *{cite}*, but the most relevant application for the current case is for solving the Fermat-Weber location problem. The Fermat-Weber problem has a long history and has been extensively studied in the field of optimization and location theory *{cite}*. This problem can be stated as: given m points $\mathbf{a}_1, \mathbf{a}_2, \dots, \mathbf{a}_m \in R^n$ called *ancors* and nonnegative weights $\omega_1, \omega_2, \dots, \omega_m > 0$, find $\mathbf{x} \in R^n$ that minimizes the weighted sum of Euclidian distances between \mathbf{x} and m ancors:

$$\underset{\mathbf{x} \in R^n}{\text{minimize}} \sum_{i=1}^m \omega_i \|\mathbf{x} - \mathbf{a}_i\|.$$

Fermat-Weber problem is much easier to analyze and solve than the ML problem (1.2) since it is a well-structured nonsmooth convex minimization problem, however the similarities of these problems has been noted in the literature [15]. The standard fixed point (SFP) algorithm proposed in [15] is a gradient method with a fixed step size. However, being a gradient method, it has chances to converge to local minimum. The sequential weighted least squares algorithm (SWLS) proposed in [15] is also an iterative method where each iteration involves solving a nonlinear least squares problem similar to (1.9). As discussed in [15] the SWLS method is superior over SFP in terms of convergence rate and a wider region of convergence to the global minimum. However, it still does have a chance to converge to a local minimum in case of certain sensor setup even if an initial point \mathbf{x}_0 is constructed by following a procedure developed specifically for this purpose. The method presented below is different from the above described approaches in a sense that it does not require an initial point and the solution produced is guranteed to converge to a *global* solution.

Weighted squared range-based least squares formulation

We now consider a weighted SR-LS (WSR-LS) problem, namely,

$$\underset{\mathbf{x}}{\text{minimize}} \sum_{i=1}^m w_i (\|\mathbf{x} - \mathbf{a}_i\|^2 - r_i^2)^2 \quad (1.14)$$

Following [14], it is rather straightforward to convert (1.14) into a GTRS similar to (1.10) as

$$\underset{\mathbf{y} \in \mathbb{R}^{n+1}}{\text{minimize}} \|\Gamma(\mathbf{A}\mathbf{y} - \mathbf{b})\|^2 \quad (1.15a)$$

$$\text{subject to: } \mathbf{y}^T \mathbf{D}\mathbf{y} + 2\mathbf{f}^T \mathbf{y} = 0 \quad (1.15b)$$

where $\Gamma = \text{diag}(\sqrt{w_1}, \dots, \sqrt{w_m})$. Clearly, problem (1.15) can be written as

$$\underset{\mathbf{y} \in \mathbb{R}^{n+1}}{\text{minimize}} \|\mathbf{A}_w \mathbf{y} - \mathbf{b}_w\|^2 \quad (1.16a)$$

$$\text{subject to: } \mathbf{y}^T \mathbf{D}\mathbf{y} + 2\mathbf{f}^T \mathbf{y} = 0 \quad (1.16b)$$

where $\mathbf{A}_w = \Gamma \mathbf{A}$ and $\mathbf{b}_w = \Gamma \mathbf{b}$. On comparing (1.16) with (1.10), if $S(\mathbf{A}, \mathbf{b}, \mathbf{D}, \mathbf{f})$ denotes a solver that produces the global solution of problem (1.10) for a given data set $\{\mathbf{A}, \mathbf{b}, \mathbf{D}, \mathbf{f}\}$, then the same solver produces the global solution of the weighted problem (1.14) as long as it is applied to the data set $\{\mathbf{A}_w, \mathbf{b}_w, \mathbf{D}, \mathbf{f}\}$. We stress that the weights $\{w_i, i = 1, \dots, m\}$ in (1.14) are *fixed* nonnegative constants.

Moving the SR-LS solution towards R-LS solution via iterative re-weighting

The main idea here is to use the weights $\{w_i, i = 1, \dots, m\}$ to tune the objective in (1.14) toward the objective in (1.2) so that the solution obtained by minimizing such a WSR-LS objective is expected to be closer toward that of the problem (1.2). To substantiate the idea, we compare the i th term of the objective in (1.14) with its counterpart in (1.2), namely,

$$\underbrace{w_i (\|\mathbf{x} - \mathbf{a}_i\|^2 - r_i^2)^2}_{\text{in (15)}} \leftrightarrow \underbrace{(\|\mathbf{x} - \mathbf{a}_i\| - r_i)^2}_{\text{in (2)}} \quad (1.17)$$

and write the term in (1.14) as

$$\begin{aligned} w_i (\|\mathbf{x} - \mathbf{a}_i\|^2 - r_i^2)^2 = \\ w_i (\|\mathbf{x} - \mathbf{a}_i\| + r_i)^2 \underbrace{(\|\mathbf{x} - \mathbf{a}_i\| - r_i)^2}_{\text{same as in (2)}} \end{aligned} \quad (1.18)$$

It follows that the objective in (1.14) would be the same as in (1.2) if the weight w_i were assigned to $1/(\|\mathbf{x} - \mathbf{a}_i\| + r_i)^2$. Evidently, weight assignments as such cannot

be realized because w_i 's must be fixed constants for (1.14) to be a globally solvable WSR-LS problem. A natural remedy to deal with this technical difficulty is to employ an iterative procedure whose k th iteration generates a global solution \mathbf{x}_k of a WSR-LS sub-problem of the form

$$\underset{\mathbf{x}}{\text{minimize}} \sum_{i=1}^m w_i^{(k)} (\|\mathbf{x} - \mathbf{a}_i\|^2 - r_i^2)^2 \quad (1.19)$$

where for $k \geq 2$ the weights $\{w_i^{(k)}, i = 1, \dots, m\}$ are assigned using the previous iterate \mathbf{x}_{k-1} as

$$w_i^{(k)} = \frac{1}{(\|\mathbf{x}_{k-1} - \mathbf{a}_i\| + r_i)^2} \quad (1.20)$$

while for $k = 1$ all weights $\{w_i^{(1)}, i = 1, \dots, m\}$ are set to unity. Clearly the weights given by (1.20) are realizable. More importantly, when the iterates produced by solving (1.19) (namely \mathbf{x}_k for $k = 1, 2, \dots$) converge, in the k th iteration with k sufficiently large, the objective function of (1.19) in a small vicinity of its solution \mathbf{x}_k is approximately equal to

$$\begin{aligned} & \sum_{i=1}^m w_i^{(k)} (\|\mathbf{x} - \mathbf{a}_i\|^2 - r_i^2)^2 \\ & \approx \sum_{i=1}^m w_i^{(k)} (\|\mathbf{x}_k - \mathbf{a}_i\|^2 - r_i^2)^2 \\ & = \sum_{i=1}^m w_i^{(k)} (\|\mathbf{x}_k - \mathbf{a}_i\| + r_i)^2 (\|\mathbf{x}_k - \mathbf{a}_i\| - r_i)^2 \\ & \approx \sum_{i=1}^m w_i^{(k)} (\|\mathbf{x}_{k-1} - \mathbf{a}_i\| + r_i)^2 (\|\mathbf{x}_k - \mathbf{a}_i\| - r_i)^2 \\ & = \sum_{i=1}^m (\|\mathbf{x}_k - \mathbf{a}_i\| - r_i)^2 \approx \sum_{i=1}^m (\|\mathbf{x} - \mathbf{a}_i\| - r_i)^2 \end{aligned}$$

In words, with the weights from (1.20), the limiting point of the iterates produced by iteratively solving WSR-LS problem (1.19) is expected to be close to the global solution of problem (1.2).

The algorithmic steps of the proposed localization method are outlined as follows.

Algorithm 1

1) Input data: Sensor locations $\{\mathbf{a}_i, i = 1, \dots, m\}$, range measurements $\{r_i, i = 1, \dots, m\}$, maximum number of iterations k_{max} and convergence tolerance ζ .

2) Generate data set $\{\mathbf{A}, \mathbf{b}, \mathbf{d}, \mathbf{f}\}$ as

$$\mathbf{A} = \begin{pmatrix} -2\mathbf{a}_1^T & 1 \\ \vdots & \vdots \\ -2\mathbf{a}_m^T & 1 \end{pmatrix}, \mathbf{b} = \begin{pmatrix} r_1^T - \|\mathbf{a}_1\|^T \\ \vdots \\ r_m^T - \|\mathbf{a}_m\|^T \end{pmatrix}$$

$$\mathbf{D} = \begin{pmatrix} \mathbf{I}_{n \times n} & \mathbf{0}_{n \times n} \\ \mathbf{0}_{n \times n} & 0 \end{pmatrix}, \mathbf{f} = \begin{pmatrix} \mathbf{0} \\ -0.5 \end{pmatrix}.$$

Set $k = 1, w_i^{(1)} = 1$ for $i = 1, \dots, m$.

3) Set $\mathbf{\Gamma}_k = \text{diag}(\sqrt{w_1^{(k)}}, \dots, \sqrt{w_m^{(k)}})$, $\mathbf{A}_w = \mathbf{\Gamma}_k \mathbf{A}$ and $\mathbf{b}_w = \mathbf{\Gamma}_k \mathbf{b}$.

4) Solve the WSR-LS problem

$$\underset{\mathbf{x}}{\text{minimize}} \sum_{i=1}^m w_i^{(k)} (\|\mathbf{x} - \mathbf{a}_i\|^2 - r_i^2)^2$$

via (1.16)

$$\underset{\mathbf{y} \in \mathbb{R}^{n+1}}{\text{minimize}} \|\mathbf{A}_w \mathbf{y} - \mathbf{b}_w\|^2$$

subject to: $\mathbf{y}^T \mathbf{D} \mathbf{y} + 2\mathbf{f}^T \mathbf{y} = 0$

to obtain its global solution \mathbf{x}_k .

5) If $k = k_{max}$ or $\|\mathbf{x}_k - \mathbf{x}_{k-1}\| < \zeta$, terminate and output \mathbf{x}_k as the solution; otherwise, set $k = k + 1$, update weights $\{w_i^{(k)}, i = 1, \dots, m\}$ using

$$w_i^{(k)} = \frac{1}{(\|\mathbf{x}_{k-1} - \mathbf{a}_i\| + r_i)^2}$$

and repeat from Step 3).

From the steps in Algorithm 1, it follows that the complexity of the algorithm is practically equal to the complexity of the WSR-LS solver involved in Step 4 times the number of iterations, k . The algorithm converges with a small number of iterations, typically a $k \leq 6$ suffices. For simplicity, the solutions obtained from Algorithm 1 are called IRWSR-LS solutions. Technical details on how to solve (1.20) can be found in

Appendix 1.

A variant of Algorithm 1

As argued above, the IRWSR-LS solution from Algorithm 1 is expected to be an improved approximation of the global solution of R-LS problem in (1.2). However a small gap between the two solutions is inevitable owing to the approximate nature of the re-weighting strategy. This section presents a variant of Algorithm 1 that closes this gap by taking the IRWSR-LS solution as an initial point to run a good local unconstrained optimization algorithm for problem (1.2). The rationale behind this two-step approach is that the initial point produced in the first step by Algorithm 1 is highly likely within a sufficiently small vicinity of the exact global solution of problem (1.2), hence a good local method will lead it to the exact solution in a small number of iterations. We remark that such a “hybrid” approach is also expected to work with other “global” methods including the SDR-LS and SR-LS methods, but with a difference that employing an IRWSR-LS solution in the first step improves the closeness of the initial point, hence increases the likelihood of securing the exact global solution of problem (1.2) by a local method in the second step.

The well-known Newton algorithm [25] is chosen as a local method because of its fast convergence and low complexity. We note that, unlike in a general scenario where the Newton algorithm is often considered numerically expensive because it requires to compute the inverse of the Hessian matrix, computing such an inverse is not costly in the present case because the dimension of the unknown vector \mathbf{x} is extremely low: $n = 2$ or 3 . Moreover, the Hessian matrix involved can be efficiently evaluated by a closed-form formula, as shown below.

To evaluate the Hessian of the objective $f(\mathbf{x})$ in (1.2), we assume $\mathbf{x} \neq \mathbf{a}_i$ for $i = 1, \dots, m$, so that $f(\mathbf{x})$ is a smooth function of \mathbf{x} . The assumption simply means that the radiating source is away from the sensor at least by a certain distance, which appears to be reasonable for a practical localization problem. Under this circumstance, the gradient and Hessian of $f(\mathbf{x})$ are found to be

$$\mathbf{g}(\mathbf{x}) = \sum_{i=1}^m \left(1 - \frac{r_i}{\|\mathbf{x} - \mathbf{a}_i\|} \right) (\mathbf{x} - \mathbf{a}_i)$$

and

$$\mathbf{H}(\mathbf{x}) = 2(\tau \mathbf{I} + \mathbf{H}_1(\mathbf{x}))$$

respectively, where

$$\tau = m - \sum_{i=1}^m \frac{r_i}{\|\mathbf{x} - \mathbf{a}_i\|}$$

and

$$\mathbf{H}_1(\mathbf{x}) = \sum_{i=1}^m \frac{r_i(\mathbf{x} - \mathbf{a}_i)(\mathbf{x} - \mathbf{a}_i)^T}{\|\mathbf{x} - \mathbf{a}_i\|^3}.$$

To apply the Newton algorithm, the positive definiteness of the Hessian $\mathbf{H}(\mathbf{x})$ needs to be examined and, in case $\mathbf{H}(\mathbf{x})$ is not positive definite, to be modified to ensure its positive definiteness. To this end, the eigen-decomposition of $\mathbf{H}(\mathbf{x})$, namely,

$$\mathbf{H}(\mathbf{x}) = \mathbf{U}\mathbf{\Lambda}\mathbf{U}^T$$

may be performed, where \mathbf{U} is orthogonal and $\mathbf{\Lambda} = \text{diag}(\tau + \lambda_1, \dots, \tau + \lambda_n)$ with $\{\lambda_i, i = 1, \dots, n\}$ being eigenvalues of $\mathbf{H}_1(\mathbf{x})$. Let l_{min} be the smallest eigenvalue of $\mathbf{H}(\mathbf{x})$, namely $l_{min} = \min(\tau + \lambda_1, \dots, \tau + \lambda_n)$. If $l_{min} > 0$, then $\mathbf{H}(\mathbf{x})$ is positive definite and the Newton algorithm is carried out without modification; if $l_{min} \leq 0$, then the algorithm uses a slightly modified Hessian given by

$$\tilde{\mathbf{H}}(\mathbf{x}) = \mathbf{U}\tilde{\mathbf{\Lambda}}\mathbf{U}^T$$

where $\tilde{\mathbf{\Lambda}} = \text{diag}(\tilde{\lambda}_1, \dots, \tilde{\lambda}_n)$

$$\tilde{\lambda}_i = \begin{cases} \tau + \lambda_i & \text{if } \tau + \lambda_i > 0 \\ \delta & \text{if } \tau + \lambda_i \leq 0 \end{cases} \quad i = 1, \dots, m$$

and δ a small positive constant. Obviously, $\tilde{\mathbf{H}}(\mathbf{x})$ is guaranteed to be positive definite. In what follows, solutions obtained by the proposed two-step method are called *hybrid* IRWSR-LS solutions.

1.1.4 Numerical Results

Performance of the proposed algorithms was evaluated and compared with existing state-of-the-art methods by Monte Carlo simulations with a set-up similar to that of [?]. SR-LS and SRD-LS solutions were used as performance benchmarks for Algorithm 1 and 2, respectively. In both cases the system consisted of m sensors $\{\mathbf{a}_i, i = 1, 2, \dots, m\}$ randomly placed in the planar region in R^2 , and a radiating

Table 1.1: Averaged MSE for SR-LS and IRWSR-LS methods

σ	SR - LS	IRWSR-LS	Improvement, %
1e-03	1.897294e-06	1.123411e-06	40.8
1e-02	1.779870e-04	1.081470e-04	39.2
1e-01	1.831870e-02	1.128165e-02	38.4
1e+0	2.415438e+00	1.877930e+00	22.3

source \mathbf{x}_s , located randomly in the region $\{\mathbf{x} = [x_1; x_2], -10 \leq x_1, x_2 \leq 10\}$. The coordinates of the source and sensors were generated for each dimension following a uniform distribution. Measurement noise $\{\varepsilon_i, i = 1, \dots, m\}$ was modelled as independent and identically distributed (i.i.d) random variables with zero mean and variance σ^2 . Accuracy of source location estimation was evaluated in terms of mean squared error in the form $MSE = E\{\|\mathbf{x}^* - \mathbf{x}_s\|^2\}$ where \mathbf{x}_s denotes the exact source location and \mathbf{x}^* is its estimation obtained by SR-LS(SRD-LS) and IRWSR-LS(IRWSRD-LS) methods, respectively. Table 1.1 and 1.2 provide comparisons of these methods with SR-LS(SRD-LS), where each entry was averaged MSE over 10,000 Monte Carlo runs of the method. The last column in each table represents relative improvement of the proposed methods over SR-LS(SRD-LS) solutions in percentage.

Employing a set-up similar to that in [?], the simulation studies of Algorithm 1 considered $m = 5$ sensors placed in the region $[-15; 15] \times [-15; 15]$, with σ being one of four possible levels $\{10^{-3}, 10^{-2}, 10^{-1}, 1\}$. The range measurements $\{r_i, i = 1, 2, \dots, 5\}$ were calculated using (??) and Step 4 of Algorithm 1 was implemented using the SR-LS algorithm proposed in [?]. It is observed that IRWSR-LS solutions offer considerable improvement over SR-LS solutions.

1.2 Source Localization From Range-Difference Measurements

1.2.1 Problem Formulation

Another type of source localization problem that has attracted considerable attention is that of localizing a radiating source using range-difference measurements [13, 14]. In practice, range-difference measurements may be obtained by comparing the signal

as it is received at the $m + 1$ sensors taken in pairs. As usual, these sensors are denoted as $\{\mathbf{a}_0, \mathbf{a}_1, \dots, \mathbf{a}_m\} \in R^n$ with \mathbf{a}_0 be placed at the origin and used as a *reference sensor*. The range-difference measurements are obtained as

$$d_i = \|\mathbf{x} - \mathbf{a}_i\| - \|\mathbf{x} - \mathbf{a}_0\| = \|\mathbf{x} - \mathbf{a}_i\| - \|\mathbf{x}\|, i = 1, \dots, m \quad (1.21)$$

and the problem here is to estimate the location of a radiating source \mathbf{x} based on measurements d_i 's. Therefore, the standard range-difference LS (RD-LS) problem is formulated as

$$\underset{\mathbf{x} \in R^n}{\text{minimize}} F(\mathbf{x}) = \sum_{i=1}^m (d_i + \|\mathbf{x}\| - \|\mathbf{x} - \mathbf{a}_i\|)^2 \quad (1.22)$$

Unfortunately, finding the global solution of (1.22) turns out to be a very hard problem. Reference [14] proposes a squared range-difference LS (SRD-LS) approach to address this problem, which is summarized below.

By writing (1.21) as $d_i + \|\mathbf{x}\| = \|\mathbf{x} - \mathbf{a}_i\|$ and squaring both sides, we obtain

$$(d_i + \|\mathbf{x}\|)^2 = \|\mathbf{x} - \mathbf{a}_i\|^2 \quad (1.23)$$

which can be simplified to

$$-2d_i\|\mathbf{x}\| - 2\mathbf{a}_i^T \mathbf{x} = g_i, i = 1, \dots, m \quad (1.24)$$

where $g_i = d_i^2 - \|\mathbf{a}_i\|^2$. In practice (1.24) does not hold exactly due to measurement noise that contaminates the data d_i 's. In other words, if d_i 's in (1.24) are taken to be real-world data, then we only have

$$-2d_i\|\mathbf{x}\| - 2\mathbf{a}_i^T \mathbf{x} - g_i \approx 0, i = 1, \dots, m \quad (1.25)$$

Reference [14] proposes a LS solution for the problem at hand by minimizing the sum of squared residues on the left side of (1.25), namely,

$$\underset{\mathbf{x} \in R^n}{\text{minimize}} \sum_{i=1}^m (-2\mathbf{a}_i^T \mathbf{x} - 2d_i\|\mathbf{x}\| - g_i)^2 \quad (1.26)$$

By introducing new variable $\mathbf{y} = [\mathbf{x}^T \|\mathbf{x}\|]^T$ and noticing nonnegativity of the compo-

nent y_{n+1} problem (1.26) is converted to

$$\underset{\mathbf{y} \in \mathbb{R}^{n+1}}{\text{minimize}} \|\mathbf{B}\mathbf{y} - \mathbf{g}\|^2 \quad (1.27a)$$

$$\text{subject to: } \mathbf{y}^T \mathbf{C} \mathbf{y} = 0 \quad (1.28b)$$

$$y_{n+1} \geq 0 \quad (1.28c)$$

where $\mathbf{g} = [g_1 \dots g_m]^T$ and

$$\mathbf{B} = \begin{pmatrix} -2\mathbf{a}_1^T & -2d_1 \\ \vdots & \vdots \\ -2\mathbf{a}_m^T & -2d_m \end{pmatrix}, \mathbf{C} = \begin{pmatrix} \mathbf{I}_n & \mathbf{0}_{n \times 1} \\ \mathbf{0}_{1 \times n} & -1 \end{pmatrix} \quad (1.29)$$

Because of the presence of the nonnegativity constraint in (1.27c), (1.27) is no longer a GTRS problem hence the technique used for the case of range measurements does not apply. Nevertheless reference [14] presents a rigorous argument which shows that the optimal solution of (1.27) either assumes the form of

$$\tilde{\mathbf{y}}(\lambda) = (\mathbf{B}^T \mathbf{B} + \lambda \mathbf{C})^{-1} \mathbf{B}^T \mathbf{g}$$

where λ solves

$$\tilde{\mathbf{y}}(\lambda)^T \mathbf{C} \tilde{\mathbf{y}}(\lambda) = 0 \quad (1.30)$$

and makes $\mathbf{B}^T \mathbf{B} + \lambda \mathbf{C}$ positive, or is the vector among $\{\mathbf{0}, \tilde{\mathbf{y}}(\lambda_1), \dots, \tilde{\mathbf{y}}(\lambda_p)\}$ that gives the smallest objective function in (1.27a), where $\{\lambda_i, i = 1, \dots, p\}$ are all roots of (1.30) such that the $(n+1)$ 'th component of $\tilde{\mathbf{y}}(\lambda_i)$ is nonnegative and $\mathbf{B}^T \mathbf{B} + \lambda \mathbf{C}$ has exactly one negative and n positive eigenvalues. We shall refer the global solution of (1.27) to as the SRD-LS solution.

1.2.2 Improved Solution Using Iterative Re-weighting

The Algorithm

We now present a method for improved solutions over SRD-LS solutions. The method incorporates an iterative re-weighting procedure into the SRD-LS approach, hence it is in spirit similar to the IRWRS-LS approach described in Sec. 2.3.2. We begin by

considering the weighted SRD-LS problem

$$\underset{\mathbf{x} \in R^n}{\text{minimize}} \sum_{i=1}^m w_i \left(-2\mathbf{a}_i^T \mathbf{x} - 2d_i \|\mathbf{x}\| - g_i \right)^2 \quad (1.31)$$

where weights w_i for $i = 1, \dots, m$ are fixed nonnegative constants. The counterpart of (1.27) for the problem (1.31) is given by

$$\underset{\mathbf{y} \in R^{n+1}}{\text{minimize}} \|\mathbf{B}_w \mathbf{y} - \mathbf{g}_w\| \quad (1.32a)$$

$$\text{subject to: } \mathbf{y}^T \mathbf{C} \mathbf{y} = 0 \quad (1.32b)$$

$$y_{n+1} \geq 0 \quad (1.32c)$$

where $\mathbf{B}_w = \mathbf{\Gamma} \mathbf{B}$, $\mathbf{g}_w = \mathbf{\Gamma} \mathbf{g}$ and $\mathbf{\Gamma} = \text{diag}\{\sqrt{w_1}, \dots, \sqrt{w_m}\}$, which will be referred to as the weighted SRD-LS (WSRD-LS) problem. On comparing (1.32) with (1.27), it follows immediately that the global solver for problem (1.27) characterized by data set $\{\mathbf{B}, \mathbf{g}, \mathbf{C}\}$ can also be used for solving problem (1.32) by applying it to data set $\{\mathbf{B}_w, \mathbf{g}_w, \mathbf{C}\}$.

Concerning the assignment of weights $\{w_i, i = 1, \dots, m\}$, we recall (1.23), (1.24) and observe that the i th term of the objective function in (1.31) can be written as

$$\begin{aligned} & w_i \left(-2d_i \|\mathbf{x}\| - 2\mathbf{a}_i^T \mathbf{x} - g_i \right)^2 \\ &= w_i \left((d_i + \|\mathbf{x}\|)^2 - \|\mathbf{x} - \mathbf{a}_i\|^2 \right)^2 \\ &= w_i (d_i + \|\mathbf{x}\| + \|\mathbf{x} - \mathbf{a}_i\|) (d_i + \|\mathbf{x}\| - \|\mathbf{x} - \mathbf{a}_i\|) \end{aligned}$$

Clearly, the last expression above would become the i th term of the objective function in the RD-LS problem (1.22) if weights w_i were set to $1/(d_i + \|\mathbf{x}\| + \|\mathbf{x} - \mathbf{a}_i\|)^2$ so that the first two factors are cancelled out. This suggests that a realizable weight assignment for performing practically the same cancellation can be made by means of iterative re-weighting for problems (1.31) and (1.32) where the weights in the k th iteration are assigned to

$$w_i^{(k)} = \frac{1}{(d_i + \|\mathbf{x}_{k-1}\| + \|\mathbf{x}_{k-1} - \mathbf{a}_i\|)^2}, i = 1, \dots, m \quad (1.33)$$

Based on the analysis above, a localization algorithm for range-difference measurements can be outlined as follows.

Algorithm 2

1) Input data: Sensor locations $\{\mathbf{a}_i, i = 0, 1, \dots, m\}$ with $\mathbf{a}_0 = \mathbf{0}$, range-difference measurements $\{d_i, i = 1, \dots, m\}$, maximum number of iterations k_{max} and convergence tolerance ξ .

2) Generate data set $\{\mathbf{B}, \mathbf{g}, \mathbf{C}\}$

$$\mathbf{g} = \begin{pmatrix} d_1^2 - \|\mathbf{a}_1\|^2 \\ \vdots \\ d_m^2 - \|\mathbf{a}_m\|^2 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} -2\mathbf{a}_1^T & -2d_1 \\ \vdots & \vdots \\ -2\mathbf{a}_m^T & -2d_m \end{pmatrix}, \mathbf{C} = \begin{pmatrix} \mathbf{I}_n & \mathbf{0}_{n \times 1} \\ \mathbf{0}_{1 \times n} & -1 \end{pmatrix}.$$

Set $k = 1$, $w_i^{(1)} = 1$ for $i = 1, \dots, m$.

3) Set $\mathbf{\Gamma}_k = \text{diag}\left(\sqrt{w_1^{(k)}}, \dots, \sqrt{w_m^{(k)}}\right)$, $\mathbf{B}_w = \mathbf{\Gamma}_k \mathbf{B}$ and $\mathbf{g}_w = \mathbf{\Gamma}_k \mathbf{g}$.

4) Solve WSRD-LS problem

$$\begin{aligned} & \underset{\mathbf{y} \in \mathbb{R}^{n+1}}{\text{minimize}} \quad \|\mathbf{B}_w \mathbf{y} - \mathbf{g}_w\| \\ & \text{subject to: } \mathbf{y}^T \mathbf{C} \mathbf{y} = 0 \\ & \quad \quad \quad y_{n+1} \geq 0 \end{aligned}$$

to obtain its global solution \mathbf{x}_k .

5) If $k = k_{max}$ or $\|\mathbf{x}_k - \mathbf{x}_{k-1}\| < \xi$, terminate and output \mathbf{x}_k as the solution; otherwise, set $k = k + 1$, update weights $\{w_i^{(k)}, i = 1, \dots, m\}$ as

$$w_i^{(k)} = \frac{1}{(d_i + \|\mathbf{x}_{k-1}\| + \|\mathbf{x}_{k-1} - \mathbf{a}_i\|)^2}$$

and repeat from Step 3).

It is evident that the complexity of the algorithm is practically equal to the complexity of the WSRD-LS solver involved in Step 4 times the number of iterations, k , which is typically in the range of 3 to 6. We shall call the solutions obtained from Algorithm 2 IRWSRD-LS solutions. Technical details on how to solve (1.32) can be found in Appendix 1.

A variant of Algorithm 2

Like in the case of range measurements, once the IRWSRD-LS solution is obtained by applying Algorithm 2, which is expected to be within a small vicinity of the true global solution of the RD-LS problem (1.22), the gap can be closed by running a good local method that takes the IRWSRD-LS solution as an initial point. Again, the Newton method is chosen for its fast convergence, low complexity due to the extremely low dimension n , and the availability of closed-form formulas to compute the gradient and Hessian of $F(\mathbf{x})$ in (1.22).

Assuming $\mathbf{x} \neq \mathbf{a}_i$ for $i = 0, 1, \dots, m$, the gradient and Hessian of $F(\mathbf{x})$ is found to be

$$\mathbf{g}(\mathbf{x}) = \sum_{i=1}^m c_i (\mathbf{q}_i - \tilde{\mathbf{x}})$$

and

$$\mathbf{H}(\mathbf{x}) = \sum_{i=1}^m \left[(\mathbf{q}_i - \tilde{\mathbf{x}})(\mathbf{q}_i - \tilde{\mathbf{x}})^T + c_i (\mathbf{Q}_{1i} + \mathbf{Q}_2) \right]$$

respectively, where

$$c_i = \|\mathbf{x} - \mathbf{a}_i\| - \|\mathbf{x}\|, \mathbf{q}_i = \frac{\mathbf{x} - \mathbf{a}_i}{\|\mathbf{x} - \mathbf{a}_i\|}, \tilde{\mathbf{x}} = \frac{\mathbf{x}}{\|\mathbf{x}\|}$$

and

$$\mathbf{Q}_{1i} = \frac{1}{\|\mathbf{x} - \mathbf{a}_i\|} (\mathbf{I} - \mathbf{q}_i \mathbf{q}_i^T), \mathbf{Q}_2 = \frac{1}{\|\mathbf{x}\|} (\mathbf{I} - \tilde{\mathbf{x}} \tilde{\mathbf{x}}^T)$$

To ensure the positive definiteness of Hessian, eigendecomposition of $\mathbf{H}(\mathbf{x})$, namely,

$$\mathbf{H}(\mathbf{x}) = \mathbf{U} \mathbf{\Lambda} \mathbf{U}^T$$

may be performed, where \mathbf{U} is orthogonal and $\mathbf{\Lambda} = \text{diag}(\lambda_1, \dots, \lambda_n)$ with $\{\lambda_i, i = 1, \dots, n\}$ being the eigenvalues of $\mathbf{H}(\mathbf{x})$. Let λ_{min} be the smallest eigenvalue of $\mathbf{H}(\mathbf{x})$. If $\lambda_{min} > 0$, then $\mathbf{H}(\mathbf{x})$ is positive definite and the Newton algorithm is carried out without modification; if $\lambda_{min} \leq 0$, then the algorithm uses a slightly modified Hessian given by

$$\tilde{\mathbf{H}}(\mathbf{x}) = \mathbf{U} \tilde{\mathbf{\Lambda}} \mathbf{U}^T$$

where $\tilde{\mathbf{\Lambda}} = \text{diag}(\tilde{\lambda}_1, \dots, \tilde{\lambda}_n)$ with

$$\tilde{\lambda}_i = \begin{cases} \lambda_i & \text{if } \lambda_i > 0 \\ \delta & \text{if } \lambda_i \leq 0 \end{cases} \quad i = 1, \dots, m$$

and δ a small positive constant. Obviously, $\tilde{\mathbf{H}}(\mathbf{x})$ is guaranteed to be positive definite. In what follows, solutions obtained by the proposed two-step method are called *hybrid* IRWSRD-LS solutions.

1.2.3 Numerical Results

Performance of the proposed algorithms was evaluated and compared with existing state-of-the-art methods by Monte Carlo simulations with a set-up similar to that of [?]. SR-LS and SRD-LS solutions were used as performance benchmarks for Algorithm 1 and 2, respectively. In both cases the system consisted of m sensors $\{\mathbf{a}_i, i = 1, 2, \dots, m\}$ randomly placed in the planar region in R^2 , and a radiating source \mathbf{x}_s , located randomly in the region $\{\mathbf{x} = [x_1; x_2], -10 \leq x_1, x_2 \leq 10\}$. The coordinates of the source and sensors were generated for each dimension following a uniform distribution. Measurement noise $\{\varepsilon_i, i = 1, \dots, m\}$ was modelled as independent and identically distributed (i.i.d) random variables with zero mean and variance σ^2 . Accuracy of source location estimation was evaluated in terms of mean squared error in the form $\text{MSE} = E\{\|\mathbf{x}^* - \mathbf{x}_s\|^2\}$ where \mathbf{x}_s denotes the exact source location and \mathbf{x}^* is its estimation obtained by SR-LS(SRD-LS) and IRWSR-LS(IRWSRD-LS) methods, respectively. Table 1.1 and 1.2 provide comparisons of these methods with SR-LS(SRD-LS), where each entry was averaged MSE over 10,000 Monte Carlo runs of the method. The last column in each table represents relative improvement of the proposed methods over SR-LS(SRD-LS) solutions in percentage.

The simulation studies of Algorithm 2 considered $m = 11$ sensors $\{\mathbf{a}_i, i = 1, 2, \dots, 10\}$ with $\mathbf{a}_0 = \mathbf{0}$ and other ten sensors placed in the region $[-15; 15] \times [-15; 15]$, with σ being one of five possible levels $\{10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}, 1\}$. The range-difference measurements used in matrix \mathbf{B} in (20) were calculated as a noise-contaminated version of d_i in (??) plus ε_i , and Step 4 of Algorithm 2 was carried out using the SRD-LS algorithm in [?]. Again, the IRWSRD-LS solutions offer considerable improvement over SRD-LS solutions.

Table 1.2: Averaged MSE for SRD-LS and IRWSRD-LS methods

σ	SRD - LS	IRWSRD-LS	Improvement, %
1e-04	8.4918e-09	4.1050e-09	51.7
1e-03	5.8553e-06	3.5105e-06	40.0
1e-02	6.3508e-05	5.0378e-05	20.7
1e-01	1.6057e-02	1.0055e-02	37.3
1e+0	1.2773e+00	6.2221e-01	51.2

1.3 Extensions

As noted in [13], methods developed in this chapter for localization based on range measurements can be adopted to solve the problem of source localization from energy measurements.

The theory supporting this statement can be found in [7, 8, 9, 10, 19].

The energy, acoustic or RF, of the signal received by the sensor is inversely proportional to the distance between sensor and the radiating source ([7, 8, 9, 10, 19]).

”The localization based on the received signal strength uses the property that sound energy attenuates with the square of the distance from the source.”

This section provides an example of ...

In this section, a reformulation of the maximum likelihood source localization using acoustic energy measurements is offered.

(from [13]) ”The source localization problem from range measurements is related to the problem of source localization from energy measurements [7, 8, 9, 10, 19]. The energy measurement based source localization approach, advocated in [7], [9] is based on the fact that the energy of the signal received by the i th sensor over a (relatively small) time interval is inversely proportional to $\|\mathbf{x} - \mathbf{a}_i\|$, for $i = 1, 2, \dots, m$.

Using this fact and some simple manipulations (see, e.g., [7] for details), it is possible to obtain an equation in the unknown vector \mathbf{x} that is somewhat similar to (2), namely:.....”

Acoustic energy attenuation model presented here is based on assumptions of [7] and [9] (or please refer for details). Only single source localization is investigated in this section.

1.3.1 Acoustic Energy Attenuation Model and Parameter Estimator

Let m be a number of acoustic sensors. For consistency of notation, let \mathbf{a}_i denote the known location of the sensor i in space R^n , $n = 2$ or 3 . Each sensor measures the acoustic intensity radiated by a source $\mathbf{x} \in R^n$ over a time period $T = \frac{M}{f_s}$, where M is the number of sample points used for estimating the acoustic energy and f_s is the sampling frequency. (OR Received signal is an acoustic pulse M -samples wide.)

Acoustic energy received by sensor i over a time period T can be represented as:

$$r_i = g_i \frac{S}{\|\mathbf{x} - \mathbf{a}_i\|^\alpha} + \varepsilon_i \quad (1.34)$$

where $\|\mathbf{x} - \mathbf{a}_i\|$ is the Euclidean distance between the i th sensor and the source. g_i is a factor that takes into account i th sensor gain. It is assumed that the gain of individual sensors is either known, i.e. obtained at the sensor calibration stage, or is same for all sensors. S is the unknown acoustic energy measured 1 unit distance away from the source. α is the energy decay factor and is usually assumed to have a value 2 [7], [27]. ε_i denotes the square of the background noise affecting the measurement of sensor i . Based on the central limit theorem, it can be approximated well as a normal distribution/ It is assumed to be a wide-sense stationary Gaussian random process [20] / , namely, $\varepsilon_i \sim N(\mu_i, \sigma_i^2)$ with a positive mean value $\mu_i > \sigma_i$ that is no less than the standard deviation σ_i that can be estimated empirically from data samples. For justification and validity of this energy attenuation model, please see [8], [7], [9], [20] and its references.

References [8], [7] argues that the maximum likelihood estimation of the vector of unknown parameters $\boldsymbol{\theta} = [\mathbf{x}^T S]^T$ can be obtained by minimizing the quadratic form

$$\underset{\boldsymbol{\theta}}{\text{minimize}} \ell(\boldsymbol{\theta}) = \|\mathbf{Z} - S\mathbf{H}\| \quad (1.35)$$

where

$$\mathbf{H} = \begin{bmatrix} \frac{g_1}{\sigma_1 \|\mathbf{x} - \mathbf{a}_1\|^2} \\ \frac{g_2}{\sigma_2 \|\mathbf{x} - \mathbf{a}_2\|^2} \\ \vdots \\ \frac{g_m}{\sigma_m \|\mathbf{x} - \mathbf{a}_m\|^2} \end{bmatrix}, \mathbf{Z} = \begin{bmatrix} \frac{y_1 - \mu_1}{\sigma_1} \\ \frac{y_2 - \mu_2}{\sigma_2} \\ \vdots \\ \frac{y_m - \mu_m}{\sigma_m} \end{bmatrix},$$

and \mathbf{Z} are (estimated) normalized energy measurements for the case of the single radiating source. Important assumption about 1.35 is that μ_i and σ_i are considered known.

1.3.2 Reformulation

There are two things to note about (1.35). First, (1.35) is a *nonlinear* least square objective function because the vector \mathbf{H} is a nonlinear function of the n unknown source coordinates, where n is the dimension of the location coordinates. Second,

although there are m sensors reporting the acousting energy reading in fact there are $n + 1 \leq m$ unknowns, including the unknown acoustic energy S radiated from the source. To eliminate the unknown source energy S [8] propose first to compute the ratio k_{ij} of the calibrated energy readings from i th and j th sensor as

$$k_{ij} = \left[\frac{z_i/g_i}{z_j/g_j} \right]^{-1/\alpha} = \frac{\|\mathbf{x} - \mathbf{a}_i\|}{\|\mathbf{x} - \mathbf{a}_j\|} \quad (1.36)$$

for $i = 1, 2, \dots, m-1$, and $j = i+1, \dots, m$. For the case $0 < k_{ij} \neq 1$ all possible source coordinates \mathbf{x} that form a solution to (1.36) reside on a n -dimensional hyper-sphere described by the equation:

$$\|\mathbf{x} - \mathbf{c}_{ij}\|^2 = \rho_{ij}^2 \quad (1.37)$$

where the center \mathbf{c}_{ij} and the radius ρ_{ij} of the hyper-sphere associated with the sensors i and j are given by:

$$\mathbf{c}_{ij} = \frac{\mathbf{a}_i - k_{ij}^2 \cdot \mathbf{a}_j}{1 - k_{ij}^2}, \rho_{ij} = \frac{k_{ij} \|\mathbf{a}_i - \mathbf{a}_j\|}{1 - k_{ij}^2} \quad (1.38)$$

For the case when $k_{ij} \rightarrow 1$ the possible source locations \mathbf{x} reside on the hyperplane between sensors \mathbf{a}_i and \mathbf{a}_j :

$$\mathbf{x}^T \boldsymbol{\gamma}_{ij} = \tau_{ij}$$

where $\boldsymbol{\gamma}_{ij} = \mathbf{a}_i - \mathbf{a}_j$ and $\tau_{ij} = (\|\mathbf{a}_i\|^2 - \|\mathbf{a}_j\|^2)/2$.

Let I_1 and I_2 be two index sets such that $\forall \{i, j\} \in I_1 : 1 \leq i \leq m-1, i+1 \leq j \leq m$ it is true that $0 < k_{ij} \neq 1$ and $\forall \{i, j\} \in I_2 : 1 \leq i \leq m-1, i+1 \leq j \leq m, k_{ij} = 1$ and $I_1 \cap I_2 = \emptyset$. Let L_1 and L_2 denote the number of elements in sets I_1 and I_2 respectively (number of hyperspheres and hyperplanes) and $L_1 + L_2 = m(m-1)/2$. Then the unknown location of the source can be found via minimization of the criterion that is equivalent to (1.35):

$$\underset{\mathbf{x}}{\text{minimize}} \sum_{l_1=1}^{L_1} (\|\mathbf{x} - \mathbf{c}_{l_1}\|^2 - \rho_{l_1}^2)^2 + \sum_{l_2=1}^{L_2} (\mathbf{x}^T \boldsymbol{\gamma}_{l_2} - \tau_{l_2})^2 \quad (1.39)$$

For the brevity of notation the double indexes ij were replaced by single indexes l_1 and l_2 . The unconstrained problem in (1.39), due to mathematical analogy with (1.9), can be solved using Algorithm 1 developed in section 3.1. After some simple manipulations and necessary variable changes, can be converted to the constrained

problem that is similar to (1.10):

$$\underset{\mathbf{y} \in R^{n+1}}{\text{minimize}} \|\mathbf{A}\mathbf{y} - \mathbf{b}\|^2 \quad (1.40a)$$

$$\text{subject to: } \mathbf{y}^T \mathbf{D}\mathbf{y} + 2\mathbf{f}^T \mathbf{y} = 0 \quad (1.40b)$$

where

$$\mathbf{y} = \begin{bmatrix} \mathbf{x} \\ \|\mathbf{x}\|^2 \end{bmatrix}, \mathbf{A} = \begin{pmatrix} \mathbf{A}_1 \\ \mathbf{A}_2 \end{pmatrix}, \mathbf{b} = \begin{pmatrix} \mathbf{b}_1 \\ \mathbf{b}_2 \end{pmatrix} \quad (1.41)$$

$$\mathbf{D} = \begin{pmatrix} \mathbf{I}_{n \times n} & \mathbf{0}_{n \times 1} \\ \mathbf{0}_{1 \times n} & 0 \end{pmatrix}, \mathbf{f} = \begin{pmatrix} \mathbf{0} \\ -0.5 \end{pmatrix}$$

and submatrices of \mathbf{A} and elements of \mathbf{b} are formed as follows:

$$\mathbf{A}_1 = \begin{pmatrix} -2\mathbf{c}_1^T & 1 \\ \vdots & \vdots \\ -2\mathbf{a}_{L_1}^T & 1 \end{pmatrix}, \mathbf{b}_1 = \begin{pmatrix} \rho_1^2 - \|\mathbf{c}_1\|^2 \\ \vdots \\ \rho_{L_1}^2 - \|\mathbf{c}_{L_1}\|^2 \end{pmatrix} \quad (1.42)$$

$$\mathbf{A}_2 = \begin{pmatrix} \gamma_1^T & 0 \\ \vdots & \vdots \\ \gamma_{L_2}^T & 0 \end{pmatrix}, \mathbf{b}_2 = \begin{pmatrix} \tau_1 \\ \vdots \\ \tau_{L_2} \end{pmatrix}$$

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