# A Low-Complexity Planar Antenna Array for Wireless Communication Applications: Robust Source Localization in Impulsive Noise

Moon-Sik Lee

**This paper proposes robust source localization methods for estimating the azimuth angle, elevation angle, velocity, and range using a low-complexity planar antenna array in impulsive non-Gaussian noise environments. The proposed robust source localization methods for wireless communication applications are based on nonlinear *M*-estimation provided from Huber and Hampel. Simulation results show the robustness performance of the proposed robust methods in impulsive non-Gaussian noise.**

**Keywords: Planar antenna array, low-complexity, antenna switching, source localization, impulsive noise.**

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## I. Introduction

Localization of moving sources are very important in a variety of wireless communication applications, such as mobile wireless sensor networks, intelligent transportation systems, wireless local area networks, radar sensor networks, and distributed sensor networks. Antenna arrays are used as an essential component for source localization [1]-[5]. Recently, an antenna array based on antenna switching has been an increasing interest as a promising substitute for the conventional multichannel array since it has various advantages, such as low cost and simple front-end circuitry [2]-[5]. Several methods for estimating the source parameters using such switching-type antenna arrays have been proposed in [2]-[5]. While schemes proposed in [2]-[4] consider linear antenna arrays, the method developed in [5] considers a planar antenna array which has a principal advantage that enables a two-dimensional (2D) direction finding of the azimuth angle and elevation angle of sources in Gaussian noise environments. In algorithms proposed in [2]-[5], the ambient noise is assumed to be Gaussian since the Gaussian assumption leads to mathematically tractable solutions. However, the ambient noise in many physical radio environments is known to be essentially non-Gaussian with essential impulsive phenomena through a variety of experimental measurements [6]-[9]. Therefore, the performance of the methods proposed in [2]-[5] can be degraded substantially in the presence of such impulsive non-Gaussian noise.

Huber and Hampel have proposed the *M*-estimators to decrease sensitivity of the estimates with respect to impulsive

  

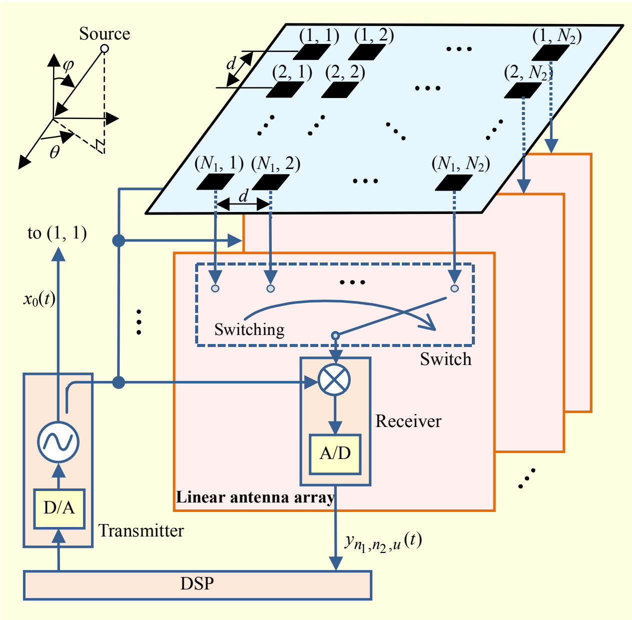


Fig. 1. Block diagram of the low-complexity planar antenna array with antenna switching.

noise [10]. The *M*-estimators are nonlinear in nature and use special nonquadratic loss functions [10]. Recently, these *M*-estimators have been studied in a variety of applications for parameter estimation in the presence of impulsive noise [11]-[15]. In particular, a robust method based on the Huber's loss function for estimating (azimuth) angle, velocity, and range using a one-dimensional linear antenna array is addressed in [13].

In this paper, we propose two robust source localization methods based on nonlinear *M*-estimation provided from Huber and Hampel for estimating the azimuth angle, elevation angle, velocity, and range using a low-complexity 2D planar antenna array in impulsive non-Gaussian noise. The low-complexity array considered in [5], which can be used as a sensor for source localization in wireless communication applications, consists of $N_1$ linear antenna arrays where each linear antenna array consists of $N_2$ receiving antennas, as shown in Fig. 1. Simulation results confirm that the proposed methods offer much more robust performance with respect to the intensity of the level of impulsive noise than the conventional least-squares (LS) method which degrades quickly when the noise is impulsive non-Gaussian. It demonstrates a valuable performance improvement of the proposed methods in impulsive non-Gaussian noise distributions. The comparison between two proposed methods is in favor of the proposed method based on Hampel's loss function.

## II. Signal Model

Consider a low-complexity planar antenna array with a rectangular configuration of $N_1 \times N_2$ receiving antennas where all antennas share a single transmitter radiating a linear frequency modulated (FM) signal, as shown in Fig. 1. Each antenna element is denoted by ($n_1$, $n_2$), where $1 \le n_1 \le N_1$ and $1 \le n_2 \le N_2$. We assume that the transmitted linear FM signal is given by

$$x_0(t) = \exp(j2\pi(f_0 t + f_1 t^2/2)), \quad 0 \le t < T, \tag{1}$$

where $T$ is the pulse period, $f_0$ is the initial frequency, and $f_1$ is the chirp rate and is given by $f_1 = F/T$, where $F$ is the bandwidth. The pulses are transmitted starting at the time instants $((u-1)N_2 + n_2 - 1)T$, $u = 1, 2, \ldots, U$, $n_2 = 1, 2, \ldots, N_2$, where $U$ is the number of cycles. The receiving antennas on each linear antenna array are switched to the single receiving channel from the 1st antenna to the $N_2$-th antenna periodically once every cycle.

An echo signal from a source received by the antenna element denoted by ($n_1$, $n_2$) at the $u$-th cycle, $x_{n_1,n_2,u}(t)$, is mixed with the complex conjugate transmitted signal $x_0^*(t)$, and then we obtain a frequency down converted received signal:

$$\mathbf{y}(t) = \mathbf{a}(\theta, \varphi, v, \rho, t) s(t) + \mathbf{m}(t), \tag{2}$$

where $s(t)$ and $\mathbf{a}(\theta, \varphi, v, \rho, t)$ respectively denote the desired signal and its corresponding steering vector, $\mathbf{a}(\theta, \varphi, v, \rho, t) = (a_{n_1,n_2,u}(\theta, \varphi, v, \rho, t))_{N_1 N_2 U \times 1}$, $\theta$ is the azimuth angle, $\varphi$ is the elevation angle, $v$ is the velocity, $\rho$ is the range, and $\mathbf{m}(t)$ refers to "other-signals-plus-noise" vector.

In (2), the signal $s(t)$ and the steering vector $a_{n_1,n_2,u}(\theta, \varphi, v, \rho, t)$ are given by

$$s(t) = g_{1,1,1}(t) \exp\left( j2\pi \left( -f_0 t_{1,1,1} + \frac{1}{2} f_1 t_{1,1,1}^2 \right) \right) \times \exp(j2\pi(-f_1 t_{1,1,1} t)), \tag{3}$$

$$a_{n_1,n_2,u}(\theta, \varphi, v, \rho, t) = \exp\left( j2\pi \left( f_0 (t_{1,1,1} - t_{n_1,n_2,u}) + \frac{f_1}{2} (2t - t_{1,1,1} - t_{n_1,n_2,u})(t_{1,1,1} - t_{n_1,n_2,u}) \right) \right), \tag{4}$$

where $g_{1,1,1}(t)$ is the attenuated amplitude, and

$$t_{n_1,n_2,u} = \frac{2}{c}(\rho + v((u-1)N_2 + n_2 - 1)T + vt) + \tau_{n_1,n_2}, \tag{5}$$

$$\tau_{n_1,n_2} = \frac{1}{c}((d(n_1 - 1)\cos\theta + d(n_2 - 1)\sin\theta)\sin\varphi), \tag{6}$$

where $\tau_{n_1,n_2}$ is the time-delay of the wave propagation from the reference antenna located at (1, 1) to the ($n_1$, $n_2$)th antenna, $c$ is the velocity of propagation, and $d$ is the interelement spacing of the antennas.

## III. LS Method

In this section, we briefly introduce a well-known linear algorithm, the LS method. Consider the following quadratic criterion:

$$J(s(t),\theta,\varphi,v,\rho)=\sum_{n_1=1}^{N_1}\sum_{n_2=1}^{N_2}\sum_{u=1}^{U}\left\|\mathbf{y}(t)-\mathbf{a}(\theta,\varphi,v,\rho)s(t)\right\|^2. \quad (7)$$

We obtain the estimated signal $\hat{s}_{\mathrm{LS}}(t)$ from the minimization on the signal $s(t)$ of the criterion (7) as in [16]:

$$\hat{s}_{\mathrm{LS}}(t)=\frac{1}{N_1N_2U}\mathbf{a}^H(\theta,\varphi,v,\rho,t)\mathbf{y}(t), \quad (8)$$

where $(\cdot)^H$ is the Hermitian transpose. Then, the estimates of $(\theta, \varphi, v, \rho)$ for the LS method are defined as solutions of the problem:

$$(\hat{\theta},\hat{\varphi},\hat{v},\hat{\rho})=\arg\max_{\theta,\varphi,v,\rho} P_{\mathrm{LS}}(\theta,\varphi,v,\rho), \quad (9)$$

where

$$P_{\mathrm{LS}}(\theta,\varphi,v,\rho)=\frac{1}{W}\sum_t|\hat{s}_{\mathrm{LS}}(t)|^2. \quad (10)$$

In (10), $W$ is the total number of observations.

## IV. Proposed Robust Source Localization

In this section, we propose robust source localization methods for estimating the source parameters $(\theta, \varphi, v, \rho)$ from the array observations (2) using the considered planar antenna array in impulsive non-Gaussian noise.

Consider the following nonquadratic criterion:

$$J(s(t),\theta,\varphi,v,\rho)$$
$$=\sum_{n_1=1}^{N_1}\sum_{n_2=1}^{N_2}\sum_{u=1}^{U}[F(e_{I,n_1,n_2,u}(t))+F(e_{I,n_1,n_2,u}(t))], \quad (11)$$

$$\mathbf{e}(t)=\mathbf{y}(t)-\mathbf{a}(\theta,\varphi,v,\rho,t)s(t), \quad (12)$$

where $\mathbf{e}(t)$ is the vector of residuals, and the subindexes $I$ and $Q$ represent real and imaginary components of variables, respectively, that is, $\mathbf{e}_I(t)=\mathrm{Re}\{\mathbf{e}(t)\}$, $\mathbf{e}_Q(t)=\mathrm{Im}\{\mathbf{e}(t)\}$. In (11), the loss function $F(x)$ is convex, bounded, and even, $F(x)=F(-x)$.

The estimated signal $\hat{s}(t)$ is defined by

$$\hat{s}(t)=\arg\min_{s(t)} J(s(t),\theta,\varphi,v,\rho), \quad (13)$$

and then we obtain the estimates of $(\theta, \varphi, v, \rho)$ from

$$(\hat{\theta},\hat{\varphi},\hat{v},\hat{\rho})=\arg\min_{\theta,\varphi,v,\rho}\left(\frac{1}{W}\sum_t J(\hat{s}(t),\theta,\varphi,v,\rho)\right). \quad (14)$$

Usually, the term $M$-estimate is used for estimates obtained by minimizing a sum of nonquadratic loss functions, for example, (11). In this paper, $\hat{s}(t)$ and $(\hat{\theta},\hat{\varphi},\hat{v},\hat{\rho})$ are $M$-estimates of the signal $s(t)$, azimuth angle $\theta$, elevation angle $\varphi$, velocity $v$, and range $\rho$, respectively. A special choice of the loss function $F(x)$ results in the estimates robust with respect to unknown distributions of the noise components of the observations.

We would like to discuss briefly connections between the $M$-estimates and the minimax robust estimation [10], [13]. We assume that the real and imaginary components of the elements of the random vector $\mathbf{m}(t)$ in (2) are independent with the same symmetric distribution $P(x)=1-P(-x)$. Then, the $M$-estimates of $s(t)$ (13) and $(\theta, \varphi, v, \rho)$ (14) are asymptotically unbiased, and their variances have a common factor:

$$V(F,P)=\frac{E\{(F^{(1)}(x))^2\}}{(E\{F^{(2)}(x)\})^2}, \quad (15)$$

where $F^{(1)}(x)=dF(x)/dx$, $F^{(2)}(x)=d^2F(x)/dx^2$, and the expectation $E\{x\}$ is calculated with respect to the noise distribution $P$. $V(F, P)$ is the only term of the variance depending on the loss function $F$ and the noise distribution $P$. Therefore, the estimation accuracy depends on $F$ and $P$. The analysis and optimization of $V(F, P)$ can be used for a selection of the loss function $F$ with information available on the distribution of the noise. We assume that the unknown $P(x)$ belongs to the class of distributions $\Gamma$, and the optimal loss function is found as a solution of the minimax optimization problem:

$$F_0(x)=\arg\min_F\max_{P\subset\Gamma} V(F,P), \quad (16)$$

where the loss function $F_0(x)$ is selected as the best giving the minimal variance provided that the noise distribution is the worst from the class $\Gamma$.

In this paper, we consider two popular nonquadratic loss functions: Huber's loss function and Hampel's loss function [10]. Huber's loss function is given by

$$F(x)=\begin{cases}\frac{1}{2}x^2, & |x|\le\mu,\\ \mu|x|-\frac{1}{2}\mu^2, & |x|>\mu.\end{cases} \quad (17)$$

Hampel's loss function is given by

$$F(x)=\begin{cases}\frac{1}{2}x^2, & |x|\le\mu_1,\\ \mu_1|x|-\frac{1}{2}\mu_1^2, & \mu_1<|x|\le\mu_2,\\ \frac{\mu_1(\mu_2+\mu_3)-\mu_1^2+\mu_1\frac{(|x|-\mu_3)^2}{\mu_2-\mu_3}}{2}, & \mu_2<|x|\le\mu_3,\\ \frac{\mu_1(\mu_2+\mu_3)-\mu_1^2}{2}, & |x|>\mu_3.\end{cases} \quad (18)$$

The signal estimate $\hat{s}(t)$ (13) can be obtained by the following weighted LS algorithm. We represent (11) as the following weighted quadratic loss function:

$$J(s(t),\theta,\varphi,v,\rho)$$
$$=\sum_{n_1=1}^{N_1}\sum_{n_2=1}^{N_2}\sum_{u=1}^{U}[F(e_{I,n_1,n_2,u}(t))+F(e_{I,n_1,n_2,u}(t))]$$
$$=\sum_{n_1=1}^{N_1}\sum_{n_2=1}^{N_2}\sum_{u=1}^{U}\psi_{n_1,n_2,u}(t)(e^2_{I,n_1,n_2,u}(t)+e^2_{Q,n_1,n_2,u}(t)), \quad (19)$$

where

$$\psi_{n_1,n_2,u}(t)=\frac{F(e_{I,n_1,n_2,u}(t))+F(e_{I,n_1,n_2,u}(t))}{e^2_{I,n_1,n_2,u}(t)+e^2_{Q,n_1,n_2,u}(t)}. \quad (20)$$

**Step 0:** Initialization by the signal estimate of the LS method:

$$\hat{s}^{(0)}(t)=\frac{1}{N_1N_2U}\mathbf{a}^H(\theta,\varphi,v,\rho,t)\mathbf{y}(t), \quad (21)$$

$$\mathbf{\Psi}^{(0)}(t)=\mathrm{diag}\{\psi_{1,1,1}(t),\ldots,\psi_{N_1,N_2,U}(t)\}\,|_{s(t)=\hat{s}^{(0)}(t)}. \quad (22)$$

**Step *j*:** Iteration ($j=1,2,\ldots,J$):

$$\hat{s}^{(j)}(t)=\frac{\mathbf{a}^H(\theta,\varphi,v,\rho,t)\mathbf{\Psi}^{(j-1)}(t)\mathbf{y}(t)}{\mathbf{a}^H(\theta,\varphi,v,\rho,t)\mathbf{\Psi}^{(j-1)}(t)\mathbf{a}(\theta,\varphi,v,\rho,t)}, \quad (23)$$

$$\mathbf{\Psi}^{(j)}(t)=\mathrm{diag}\{\psi_{1,1,1}(t),\ldots,\psi_{N_1,N_2,U}(t)\}\,|_{s(t)=\hat{s}^{(j)}(t)}, \quad (24)$$

where $J$ is the maximum number of iterations, and the iteration is stopped if $|\hat{s}^{(j)}(t)-\hat{s}^{(j-1)}(t)|/|\hat{s}^{(j-1)}(t)|\le\gamma$ for some small number $\gamma$.

Then, we set the estimate of the signal as follows:

$$\hat{s}_{\text{Proposed}}(t)=\hat{s}^{(j)}(t). \quad (25)$$

Finally, we obtain the estimates of ($\theta$, $\varphi$, $v$, $\rho$) for the proposed method from

$$(\hat{\theta},\hat{\varphi},\hat{v},\hat{\rho})=\arg\max_{\theta,\varphi,v,\rho} P_{\text{Proposed}}(\theta,\varphi,v,\rho), \quad (26)$$

$$P_{\text{Proposed}}(\theta,\varphi,v,\rho)=\frac{1}{W}\sum_t|\hat{s}_{\text{Proposed}}(t)|^2. \quad (27)$$

## V. Simulation Results

We consider a planar antenna array of $N_1\times N_2$ receiving antennas with a half-wavelength interelement spacing, and a linear FM signal with $f_0$=24 GHz, the bandwidth $F$=150 MHz, and the pulse period $T$=100 μs. A single moving source with $\theta$=–30°, $\varphi$=30°, $v$=70 km/h, and $\rho$=50 m is considered. We assume that the attenuated amplitude $g_{1,1,1}(t)$ in (3) is replaced by $g_{1,1,1}+\eta(t)$, modeling the time-varying echo-signal attenuation effects by random $\eta(t)$. We use $g_{1,1,1}$=2, $N_1$=4 antennas, $N_2$=4 antennas, $U$=3 cycles, and $W$=100 observations.

We exploit the widely used two-term Gaussian mixture model for the additive noise. The probability density function of this noise model has the form $f(x)=(1-\alpha)N(0,\sigma_0^2)+\alpha N(0,\sigma_1^2)$, where $0\le\alpha\le1$ and $\sigma_1$=100$\sigma_0$. Here, $N(0,\sigma_0^2)$ and $N(0,\sigma_1^2)$ represent the nominal background noise and the impulsive noise components, respectively, with $\alpha$ representing the probability that impulses occur.

Three methods are considered: the LS method (7)-(10) and two proposed methods (19)-(27), namely, proposed method I and proposed method II. In addition, proposed method I uses Huber's loss function (17), and proposed method II uses

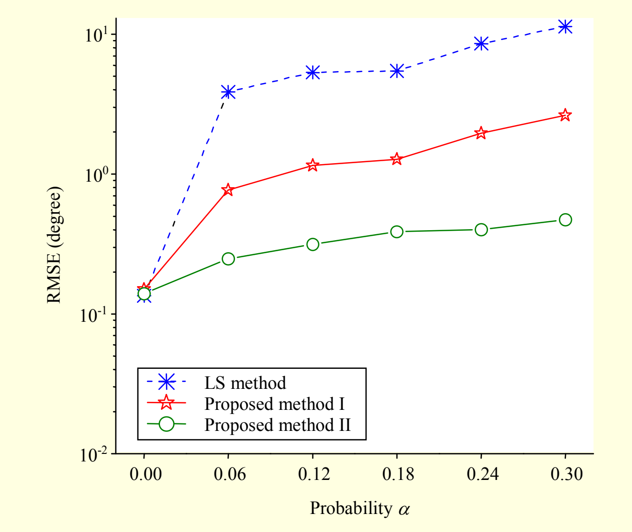


Fig. 2. Robustness performance on azimuth angle for the LS method, proposed method I, and proposed method II as a function of $\alpha$ for the probability that the impulses occur.

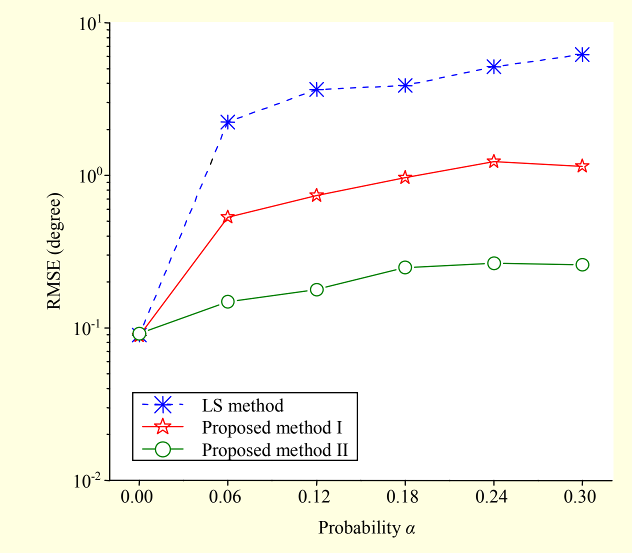


Fig. 3. Robustness performance on elevation angle for the LS method, proposed method I, and proposed method II as a function of $\alpha$ for the probability that the impulses occur.

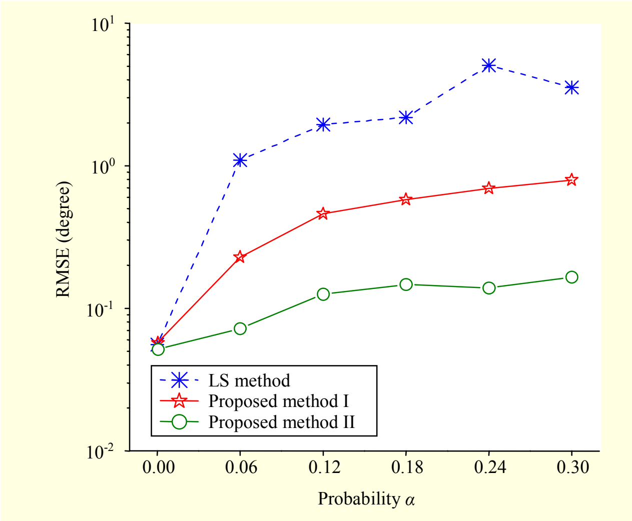


Fig. 4. Robustness performance on velocity for the LS method, proposed method I, and proposed method II as a function of $\alpha$ for the probability that the impulses occur.

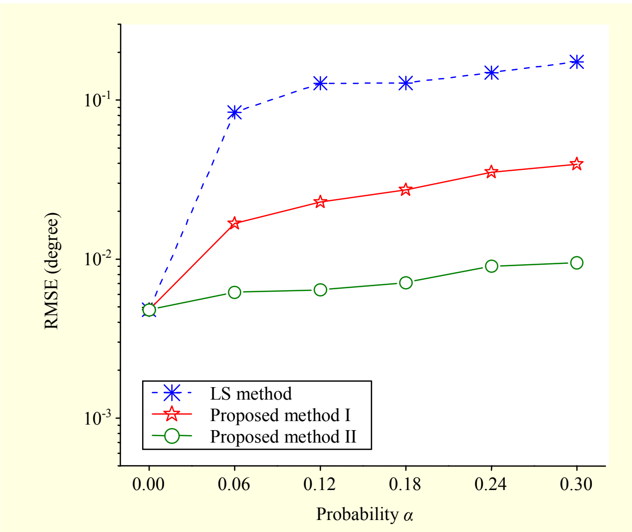


Fig. 5. Robustness performance on range for the LS method, proposed method I, and proposed method II as a function of $\alpha$ for the probability that the impulses occur.

Hampel's loss function (18).

In Figs. 2 to 5, we study the robustness performance of each method on the azimuth angle (Fig. 2), elevation angle (Fig. 3), velocity (Fig. 4), and range (Fig. 5) in Gaussian and non-Gaussian noise environments. The results in Figs. 2 to 5 are shown as a function of $\alpha$ for the probability that the impulses occur. $\alpha$=0 corresponds to the nominal Gaussian noise. The root-mean-square errors (RMSEs) of the azimuth angle, elevation angle, velocity, and range estimations are computed using 50 independent Monte Carlo simulation runs. It is seen from Figs. 2 to 5 that the considered methods give more or less equivalent accuracy performance when the noise is Gaussian, that is, $\alpha$=0. However, the LS method is sensitive to the impulsive non-Gaussian noise and suffers severe performance degradation as $\alpha$ increases, while the performance of the proposed methods remains robust with respect to the intensity of the level of impulsive noise. The comparison of the two proposed methods reveals the superiority of proposed method II based on Hampel's loss function.

## VI. Conclusion

In this paper, we have proposed robust source localization methods for estimating the moving source parameters in impulsive non-Gaussian noise environments using a low-complexity planar antenna array. The low-complexity array with antenna switching consists of $N_1$ linear antenna arrays where each linear antenna array consists of $N_2$ receiving antennas. In simulations, we have shown that the proposed robust methods offer significant performance gain over the LS method and have a decreased sensitivity of the estimates with respect to impulsive noise, with the best results given by proposed method II based on Hampel's loss function.

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