Moving Source Localization in Near-field by a Stationary Passive Synthetic Aperture Array

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***Abstract*— A new method for localizing a near-field moving source using stationary underwater acoustic array is proposed in this paper. Using a phase correction factor calculated from two specific snapshots, the effective array aperture is extended, and the 2-D range-bearing spectrum can be obtained by the extended array aperture. According to the 2-D range-bearing spectrum, we can compute the source's location in near-field at any specified time instance. More snapshots around the specific snapshot are used to obtain a set of additional spectrums and average processing is carried out for these spectrums to suppress the effects of measurement error. Simulation results are presented to demonstrate the feasibility of the proposed method.**

I. Introduction

Source localization using a passive sensor array is an important issue in radar, sonar, radio astronomy and geophysics areas. In the far-field situation, the wavefront emanating from sources can be considered as plane waves at a uniform linear array (ULA) of sensors, hence source location can be characterized by its bearing. In addition, the moving source location could be regarded as a constant value in a longer time. However, when a source is in the near-field of an array, the plane wave assumption is no longer valid. Hence, near-field source localization requires estimation of both the range and the bearing. On the other hand, the source location relative to the array is changed rapidly by the moving of source. Therefore, the assumption of constant location is only valid within a small time interval in near-field situation. For near-field stationary source localization, many methods have been already proposed, including the modified MUSIC [1], weighted linear prediction (LP) [2], and second-order statistics (SOS) [3].

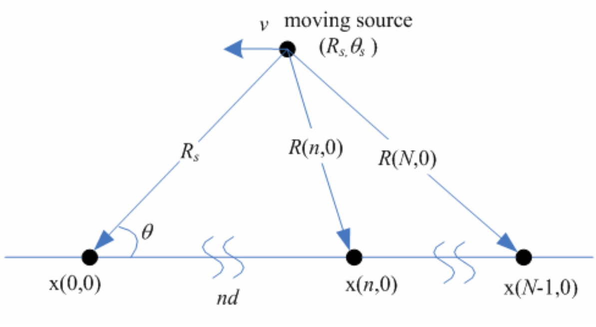
Our primary interest in this work is the near-field localization for moving source with a stationary array. Using the relative motion between the physical receiving array and the source, the synthetic aperture processing, a technique for increasing the effective aperture of a receiving sensor array, has attracted much attention. Recently, several passive acoustic synthetic aperture techniques have been proposed, such as Yen and Carey's method [4], which extended towed array measurements (ETAM) [5][6], the fast Fourier transform synthetic aperture (FFTSA) [7] and the maximum likelihood (ML) method [8]. These methods are all developed for source localization in far-field. For near-field situation, the focused passive synthetic aperture techniques [9] [10] are proposed for stationary source with a moving array.

In this paper, we proposed a method for localizing a near-field moving source using a stationary array. The effective array aperture could be extended by phase correction factors between two specific snapshots. The location of moving source can be estimated by the extended array aperture. For the influences caused by the error of measurement, we use more snapshots nearby the specific snapshots to obtain corresponding phase correction factors, and a set of spectrums computed by these factors can be acquired. After an average processing for these spectrums, the estimate error caused by error of measurement could be compensated and spurious peaks can also be avoided.

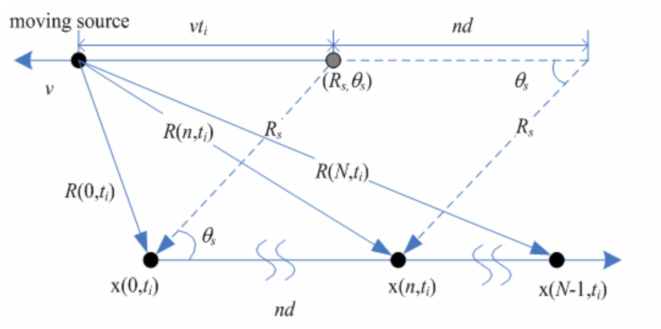
This paper is organized as follows. The problem and data model are formulated in Section II. In Section III, we then describe the data transform with phase correction factors and the details of the localization of a moving source in near-filed. In Section IV, we analyzed the influences produced by error phase factors and proposed the method of average processing to correct estimation result. The numerical results are presented in Section V. Finally, some conclusions are drawed in Section VI.

II. Signal Model

We consider a near-field scenario shown in Fig.1, where signal from a source moving at a constant velocity *v*, with a path parallel to the array baseline. The receiving array is assumed to be a stationary ULA consisting of N sensors. The 2-D range/bearing coordinates of the source's initial location is (R_s, θ_s) relative to the first sensor of the receiving array.



(a) At the initial time t=0



(b) At a given time t_i

Fig. 1 Geometry for a near-field source when it is moving with velocity v and a path parallel to the receiving ULA's baseline. The near-field source's initial location is characterized by range Rs and bearing θs

We can assume that a hypothetical stationary source exists at the moving source's initial location, with the same parameters as the moving source except velocity v. Its signal received by the first sensors of the ULA can be regarded as the reference signal

$$s(t) = Ae^{j(2\pi ft+\phi_o)} \tag{1}$$

here A and ϕ_o are the amplitude and initial phase of the moving source. Then the n-th hydrophone received signal of the moving source at a given time t_i can be formulated as

$$x(n,t_i) = s(t_i)e^{j\phi(n,t_i)} + w(n,t_i) \tag{2}$$

where $n = 0,1,\dots N-1$ is spatial index of array elements, $w(n,t_i)$ is additive Gaussian noise, $\phi(n,t_i)$ is the relative phase due to the time delay between the reference signal $s(t_i)$ and the n-th sensor received moving source's signal at time t_i. By geometric relationships, the relative phase can be modeled as

$$\phi(n,t_i) = 2\pi f\frac{R(n,t_i)-R_s}{c} \tag{3}$$

with

$$R(n,t_i) = \sqrt{R_s^{\,2} + (vt_i + nd)^2 - 2(vt_i + nd)R_s\cos\theta_s} \tag{4}$$

where c is the propagation velocity of a source signal in medium, f is the frequency of source, d is the spatial distance of adjacent sensors. Using the second-order Taylor series expansion, the range $R(n,t_i)$ is parameterized by the initial range R_s and bearing θ_s of source, i.e.,

$$R(n,t_i) \approx R_s - (vt_i + nd)\cos\theta_s + \frac{(vt_i+nd)^2}{2R_s}\sin^2\theta_s \tag{5}$$

Thereby, after an elapse lasting τ seconds, the received signal $x(n,t_i+\tau)$ is expressed by

$$x(n,t_i+\tau) = s(t_i+\tau)e^{j\phi(n,t_i+\tau)} + w(n,t_i+\tau) \tag{6}$$

where

$$s(t_i+\tau) = s(t_i)e^{j2\pi\tau} \tag{7}$$

$$\phi(n,t_i+\tau) = 2\pi f\frac{R(n,t_i+\tau)-R_s}{c} \tag{8}$$

and

$$\begin{aligned} R(n,t_i+\tau) &= \sqrt{R_s^{\,2} + (vt_i + v\tau + nd)^2 - 2(vt_i + v\tau + nd)R_s\cos\theta_s} \\ &\approx R_s - (vt_i + v\tau + nd)\cos\theta + \frac{(vt_i+v\tau+nd)^2}{2R_s}\sin^2\theta \end{aligned} \tag{9}$$

III. ARRAY EXTENDED BY PHASE CORRECTION FACTORS

In this section, we describe the array extension with phase correction factors in detail. Form (9), we can assume that it is always possible to find a measure time τ that satisfy $qd = v\tau$ with q being an integer. Then $R(n,t_i+\tau)$ can be written as

$$R(n,t_i+\tau) \approx R_s - [vt_i + (n+q)d]\cos\theta + \frac{[vt_i+(n+q)d]^2}{2R_s}\sin^2\theta \tag{10}$$

and the signal received by the $(n+q)$th sensor at given time t_i can be expressed as

$$x(n+q,t_i) = s(t_i)e^{j\phi(n+q,t)} + w(n+q,t) \tag{11}$$

with

$$\phi(n+q,t_i) = 2\pi f\frac{R(n+q,t_i)-R_s}{c} \tag{12}$$

here

$$R(n+q,t_i) \approx R_s - [vt_i + (n+q)d]\cos\theta_s + \frac{[vt_i+(n+q)d]^2}{2R_s}\sin^2\theta_s \tag{13}$$

Use the (8) and (12), the following relation about the signal phase term can be established as,

$$\phi(n,t_i+\tau)=\phi(n+q,t_i) \quad (14)$$

Therefore, (6) and (11) are equivalent under the condition $qd=v\tau$, except for the term $e^{j2\pi\tau}$ and the noise. In other words, when ideal conditions are assumed, the relation between (6) and (11) is give by

$$x(n,t_i+\tau)=x(n+q,t_i)e^{j2\pi\tau} \quad (15)$$

It can be generalized as

$$x(n,t_i+m\tau)=x(n+mq,t_i)e^{j2\pi(m\tau)} \quad (16)$$

where $m=0,1\ldots M-1$ represents the m-th set of measurements in time. Now we can get phase correction factors

$$\psi_{(n,m)}=\arg\left\{x(n+mq,t_i)x(n,t_i+m\tau)^*\right\}, \quad n=1,2,\ldots,N-q \quad (17)$$

where $N-q$ is the number of overlapped hydrophones. As a result, the least-square estimate of the phase correction factors is given by

$$\hat{\psi}_m=\frac{1}{N-q}\sum_{n=1}^{N-q}\psi_{(n,m)} \quad (18)$$

Then the signal received by $(n+mq)$th sensor at t_i can be synthesized as

$$x(n+mq,t_i)=x(n,t_i+m\tau)e^{-j\psi_{(n,m)}}, \quad n=N-q+1,\ldots,N \quad (19)$$

As a result, the array aperture can be extended form Nd to $[N+(M-1)q]d$.

With the modified data, the sample correlation matrix of synthesis array can be estimated by

$$\mathbf{R}=\frac{1}{L}\mathbf{X}\mathbf{X}^H \quad (20)$$

where L is number of modified snapshots, $\mathbf{X}$ is the $[N+(M-1)q]\times L$ modified data. Then the estimates would be obtained by using any kind of bearing estimation algorithm. In this work, we determined the location of a moving source at a given time through searching the 2-D CBF spectrum as follow,

$$P(R,\theta)=\frac{1}{\mathbf{a}^H(R,\theta)\mathbf{R}\mathbf{a}(R,\theta)} \quad (21)$$

where the steering vector corresponds to the extended array consisting of $N+(M-1)q$ sensors as follows,

$$\mathbf{a}(R,\theta)=[1,\ldots,e^{j\phi(n,0)},\ldots,e^{j\phi(N+(M-1)q-1,0)}]^T \quad (22)$$

IV. Error phase factors analysis

Consider the case of $v\tau'\neq qd$, where $\tau'=\tau+\Delta\tau$ and $\Delta\tau$ is an arbitrary small time period produced by the measurement error of the parameters or other reasons. Let the source moving distance during $\Delta\tau$ be $v\Delta\tau=q\delta$. So $v\tau'=q(d+\delta)$, and the output of the n-th hydrophone at time $t_i+\tau'$ is expressed as

$$x(n,t_i+\tau')=s(t_i+\tau')e^{j\phi(n,t_i+\tau')} \quad (23)$$

where

$$\phi(n,t_i+\tau')=2\pi f\,\frac{R(n,t_i+\tau')-R_s}{c} \quad (24)$$

with

$$\begin{aligned} &R(n,t_i+\tau')\\ &\quad\approx R_s-(vt_i+v\tau'+nd)\cos\theta+\frac{(vt_i+v\tau'+nd)^2}{2R_s}\sin^2\theta\\ &\quad=R(n+q,t_i)+R'(n)+R''(n) \end{aligned} \quad (25)$$

here

$$R(n+q,t_i)\approx R_s-[vt_i+(n+q)d]\cos\theta+\frac{[vt_i+(n+q)d]^2}{2R_s}\sin^2\theta \quad (26)$$

$$R'=\frac{2vt_iq\delta+(q\delta)^2+q^2\delta}{2R_s}\sin^2\theta-q\delta\cos\theta \quad (27)$$

$$R''(n)=n\frac{qd\delta}{2R_s}\sin^2\theta \quad (28)$$

Let $\phi'=2\pi fR'/c$, and $\phi''(n)=2\pi fR''(n)/c$, we can get

$$\begin{aligned} x(n,t_i+\tau')&=s(t_i)e^{j\phi(n+q,t_i)}e^{j2\pi\tau'}e^{j\phi'}e^{j\phi''(n)}\\ &=x(n+q,t_i)e^{j2\pi\tau'}e^{j\phi'}e^{j\phi''(n)} \end{aligned} \quad (29)$$

In this case, we should pay attention that the $e^{j2\pi\tau'}e^{j\phi'}$ in phase factor is a constant value defined by initial parameters, but $e^{j\phi''(n)}$ is a variable changed by n-th sensor. This situation is different from reference [6]. Therefore, if we still obtain the phase correction factors like (17) and (18) in any given situation, the result of estimation will be interfered by $e^{j\phi''(n)}$ at some special values of τ'. However, consider $2R_s \gg qd\delta$, the effect of $e^{j\phi''(n)}$ for the estimation of source's localization is tiny at most values of τ'. We can use some additional snapshots around $m\tau'$, such as $m\tau'+k\tau_s$, to get a set of phase correction factors $\hat{\psi}_{(m,k)}$, where τ_s is sample interval, $k=0,\pm1\ldots\pm K$ indicates additional snapshots before or after the given time $m\tau'$. For each value of *k*, we can obtain a corresponding spectrum as follows

$$P_k(R,\theta)=\frac{1}{\mathbf{a}^H(R,\theta)\mathbf{R}_k\mathbf{a}(R,\theta)},k=0,\pm1\ldots\pm K. \quad (30)$$

By average processing, the final spectrum can be written as

$$P(R,\theta)=\frac{1}{2K-1}\sum_{k=-K}^{K}P_k(R,\theta) \quad (31)$$

After this processing, the influences produced by each value of $m\tau'+k\tau_s$ are canceled by each other. Therefore the result of range/bearing estimation will be corrected, but the side-lobe level will be raised.

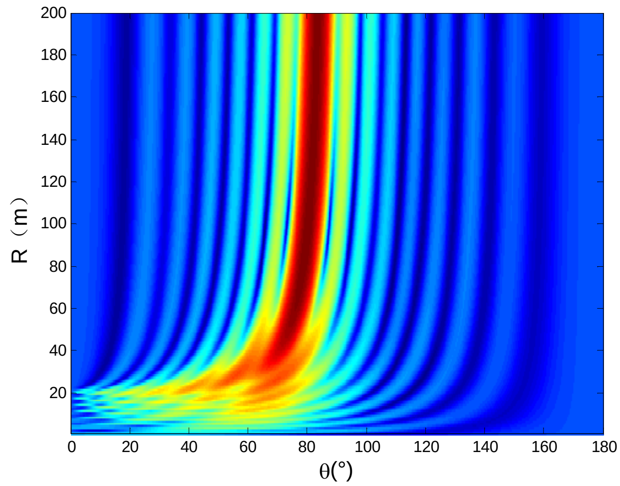
V. SIMULATION RESULTS

In computer simulation, a 16-element stationary physical array is considered, and the spatial distance of adjacent sensors is 1.5m. After aperture synthesis, the array is extended by 6 times and has 64 elements equivalently. The moving source was assumed to be a narrow-band point signal with initial localization at (100m, 80°). Its frequency, speed and SNR are 500Hz, 4m/s and 10dB. The sample rate was 2 kHz. The overlap size is half the length of the physical array, so q =8 and $\tau=qd/v$ is 4s.

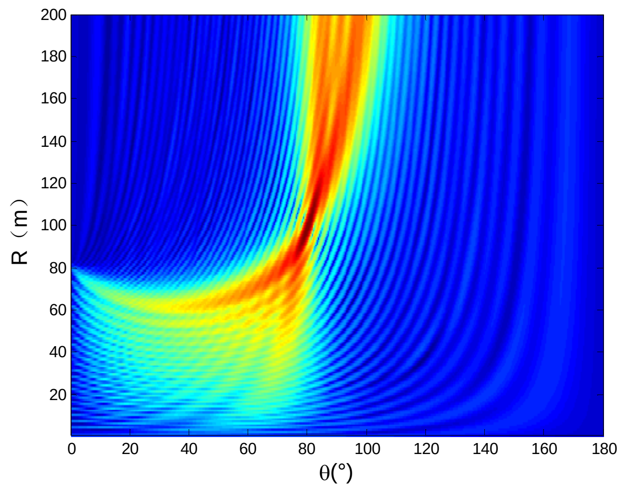
Fig.2 gives the 2-D range/bearing estimation of the physical array and synthetic array at near-filed situation. It is obviously that the resolution of both bearing and range are increased by synthetic array. The slices at the range R_s are shown in Fig.3, where Fig.3(a) shows the spectrum of $\tau=4$s, Fig.3(b) shows the spectrum of $\tau'=4.02$s, Fig.3(c) shows the spectrum of $\tau'=4.025$s, Fig.3(d) shows the spectrum of $\tau'=4.045$s. Fig.3(e),(f) describe the spectrum after average processing at $\tau'=4.02$s and $\tau'=4.025$s, the correction factor K is 10.

Obviously, the degree of influences for spectrum are defined by the value of τ'. Fig.3(b)~(d) are three typical estimated spectrums when $\tau'\neq\tau$, where Fig.3(b) shows that the spectrum is not influenced by $\tau'=4.02$s, Fig.3(c) shows that the peak of spectrum have deviation from the right place and the side-lobe level is raised when $\tau'=4.025$s. In Fig.3(d), the spectrum not only have a deviation for main-lobe ,but also have an additional spurious peak in spectrums when $\tau'=4.045$s.

From Fig.3(e),(f), we can see that the influences caused by various value of τ' can be canceled by average processing, but the side-lobe level raised form -13dB to -7dB. Fig.4 shows the bearing localization result caused by directly estimation and estimation after average processing, where dash line is the result of directly estimation at different τ', solid line is the corresponding result of average processing. Obviously, the estimate errors are corrected by the proposed method. Fig.5 shows the root mean square (RMS) errors according to K at $\tau'=4.045$s. It can be seen that *K*=10 is a proper value of trade off between accuracy and amount of calculation.

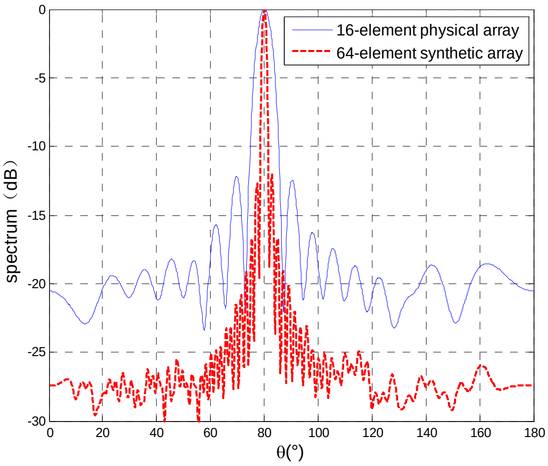


(a) 16 element stationary physical array

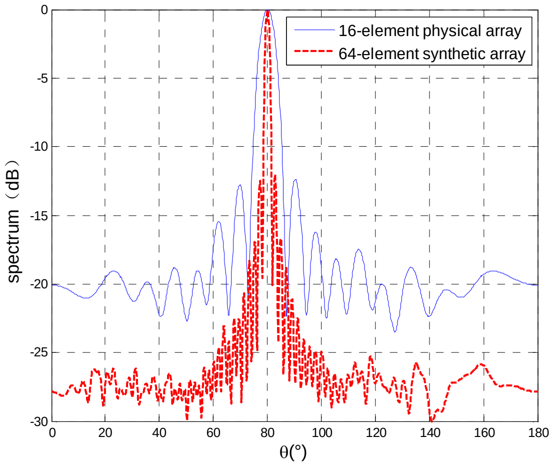


(b) 64 element synthetic array

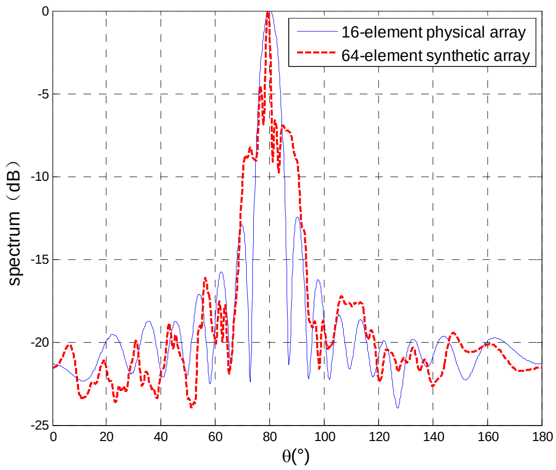
Fig. 2 The 2D CBF spectrum by stationary physical array and synthetic array



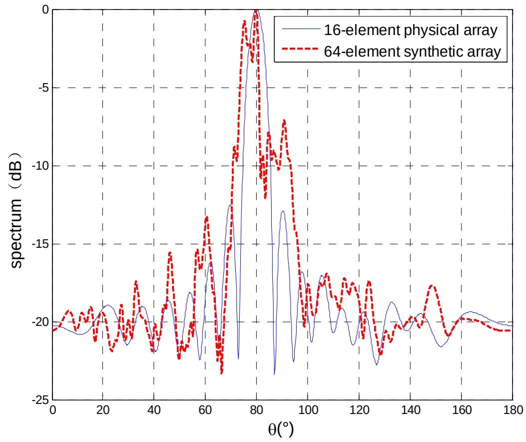
(a) the spectrum when $\tau'=\tau$



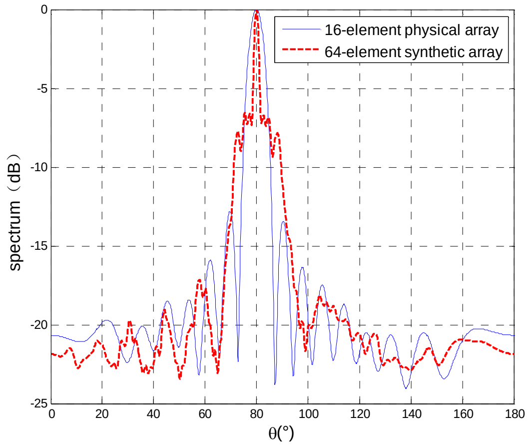
(b) the spectrum when τ'=4.02s



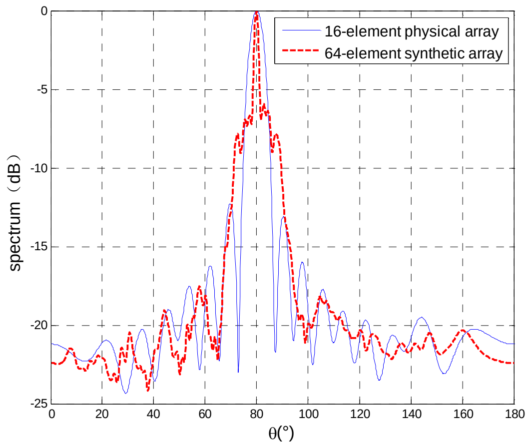
(c) the spectrum when τ'=4.025s



(d) the spectrum when τ'=4.045s



(e) average processing spectrum when τ'=4.025s



(f) average processing spectrum when τ'=4.045s

Fig. 3 The slices of 2D CBF spectrum at the range R_s with different values of τ',and the spectrum after average processing array

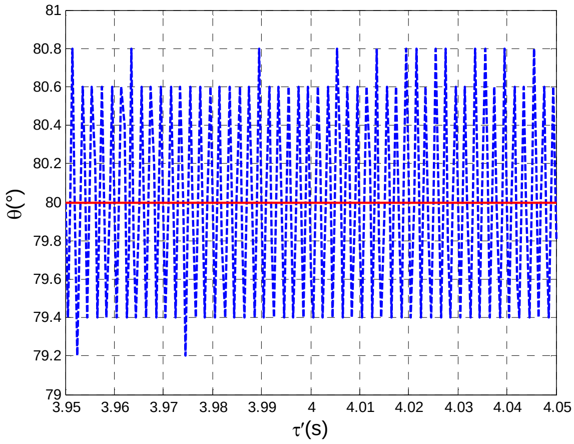


Fig. 4 Comparison of bearing localization at different τ', the dash line is the result of directly estimation, the solid line is the result after average processing

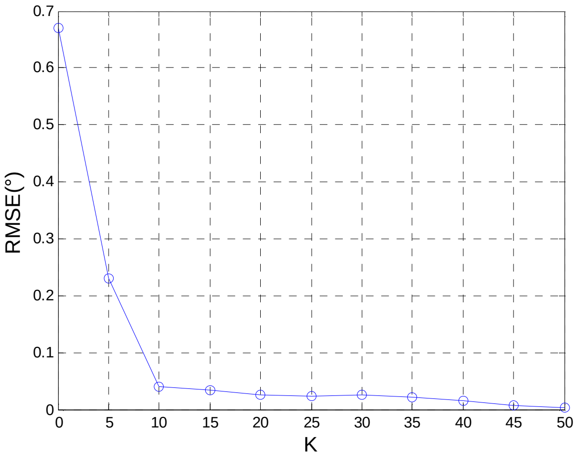


Fig.5 Bearing estimation RMS errors according to K at τ'=4.045s.

VI. Conclusions

A method for localizing a near-field moving source at any given time using a stationary array is proposed. We extend the array aperture by phase correction factors between two specific snapshots, and compute the bearing and range of the moving source use the extended array aperture. Our finding shows that the tiny error of measurement could influence the estimate result at different degrees, some times even a spurious peak can be caused. So we use more snapshots around the specific snapshots to obtain corresponding phase correction factor, and a set of spectrums computed by these factors can be acquired. After an average processing of these spectrums the estimate error caused by error of measurement could be corrected and the situation of spurious peak can also be avoided, yet the side-lobe level will be raised. Now the proposed method is only applied to the situation that the source's path is parallel to the array baseline. We will extend the method to be suitable for more complicated conditions in the future.

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