WIND SPEED ESTIMATION OF LOW-ALTITUDE WIND-SHEAR BASED ON MULTIPLE DOPPLER CHANNELS JOINT ADAPTIVE PROCESSING

Hai Li, Meng Zhou, Renbiao Wu, Yanfei Han

Tianjin Key Laboratory for Advanced Signal Processing, Civil Aviation University of China
Tianjin, China, 300300
elisha1976@163.com

ABSTRACT

When the airborne weather radar detects low-altitude wind-shear field, the echoes of wind-shear field are usually covered by strong clutter. In this paper, a novel method of wind speed estimation of low-altitude wind-shear based on multiple Doppler channels joint adaptive processing approach is proposed. The method constructs reduced-rank adaptive processors aimed to distributed meteorologic target to achieve clutter suppression and signal matching, and to obtain the wind speed of the wind-shear field. The experimental results show the proposed method can achieve clutter suppression and get accurate wind speed estimation with low computational burden.

***Index Terms*—** Wind-shear,Wind Speed Estimation,STAP, Reduced Rank,Airborne Weather Radar

1. INTRODUCTION

Among all the weather phenomenon, low altitude wind-shear has been list as one of the most serious threats to the transportation safety of civil aviation[1]. The detection of low-attitude wind-shear is the vital research subject to the research field of the modern civil aviation[2]. The wind speed estimation of the wind field is a vital and basic issue in low-attitude wind-shear detection process.

The airborne weather radar is an important facility to the aircraft [3]. It is designed to monitor the hazardous weather such as wind-shear, rainstorm and generate alerts to the pilots along the airways in real-time. When the radar detects the wind-shear in the look-down mode, the echoes of the wind-shear are often masked by the strong clutter background[4]. The basic ideal of the clutter suppression is to construct an appropriate filter to suppress the clutter while reserving the wind-shear signal as much as possible. The conventional methods of clutter suppressing include Clutter-map method[5], Multiple-sweep method[6], Null filter method[7], extend Prony based method[8], est. When the background clutter is strong, it is hard to suppress the clutter completely. The residuary of the clutter may lead performance degradation of the estimation of the wind speed.

Compared to the single antenna radar, the receive signals of the phased array radar (PAR) contain spatial information, thus have more advantage when it is applied to form space-time filter to achieve clutter suppression in strong clutter background. Space Time Adaptive Processing(STAP) is the key technique applied to clutter suppression and target detection in the phased array system[9]. By now, STAP method has been applied in detection of point target. The conventional STAP methods can generally be divided into two steps[4]: clutter whitening and signal matching. The process of signal matching needs steering vectors which describe the space and time properties of the interested target. To radar, wind-shear field is distributed target[10], as meteorological particles distributed in a vast space ranges from few kilometers to more than ten kilometers. This spatial distribution property leads the wind-shear field have range extension both in azimuth and pitch[11]. Meanwhile, as a mass of meteorological particles move independently both in direction and instantaneous velocity, the power spectrum of the wind-shear field echo is usually modeled as a Gaussian Process[12], which is different from that of maneuvering target. Hence, it may result in performance degradation to apply the conventional point target's space-time steering vector directly to describe the properties of the wind-shear filed.

Literatures [13][14] proposed methods of wind speed estimation based on the STAP. These methods introduce phased array radar to detect wind-shear field, can achieve accurate wind speed estimation result. However, the computation complexity of the estimation and inverse of covariance matrix is extremely heavy, due to the high dimension of the clutter-noise covariance matrix used in the optimum STAP method. The huge computational expense makes it hard to apply these methods to real-time processing. The main idea to reduce the computation complexity of STAP method is to design reduced-rank space-time adaptive filter. Much work has been done to look for realisable suboptimum approaches, such as the auxiliary channel receiver (ACR)[4], the joint domain local (JDL)[9] processing approach, multiple Doppler channels joint adaptive processing (M-CAP)[15] approach, est. Among the approaches, the M-CAP method can achieve near-optimum performances with lower computational expense and sampling requirements. It has more adaptive degrees of freedom (DOFs) than other methods and it is insensitive to element errors[15]. Therefore it may be available for the practical real-time processing of weather phased array radar.

In this paper, an architecture of reduced-rank processor that can be applied to detection and parameter estimation of the distributed target such as wind-shear field is introduced. The simulation results show that the method can suppress ground clutter adaptively and accumulate low-altitude wind-shear signal, thus get accurate estimation of wind speed.

2. PROBLEM STATEMENT

Figure 1 illustrates the geometry of the radar. The system under consideration is a forward-looking pulsed Doppler radar on the airborne

This work was supported by National Nature Science Foundation of China (NSFC) under grant 61471365, 61571442, 61231017, National University's Basic Research Foundation of China under grant No.3122015B002. The work is also supported by the Foundation for Sky Young Scholars of Civil Aviation University of China.

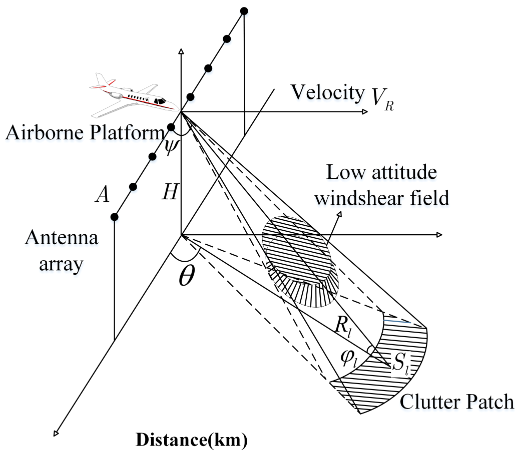


Fig. 1. The geometry of the forward-looking radar

platform.The platform is at altitude H and moving with constant velocity V_R. The antenna system of the radar is a uniform linear array (ULAs) consist of N elements. The element spacing is $d = 0.5\lambda$, where λ is the wavelength of the radar transmitted pulse. Forward-looking means the angle between platform's speed direction and the antenna array is 90°. The radar transmits a K pluse coherent waveform with pulse repetition frequency (PRF) f_r. The signal received by the radar on its coverage can be written as a $NK \times L$ dimension matrix[9], given by

$$\mathbf{x} = \begin{bmatrix} \mathbf{x}_1 & \mathbf{x}_2 & \cdots & \mathbf{x}_L \end{bmatrix}^T_{NK\times L} \tag{1}$$

where, L denotes the amount of the range bin within the coverage range of the radar. $\mathbf{x}_l$ represents the space-time snapshot of the $lth(l = 1, 2, \cdots, L)$ range bin, given by:

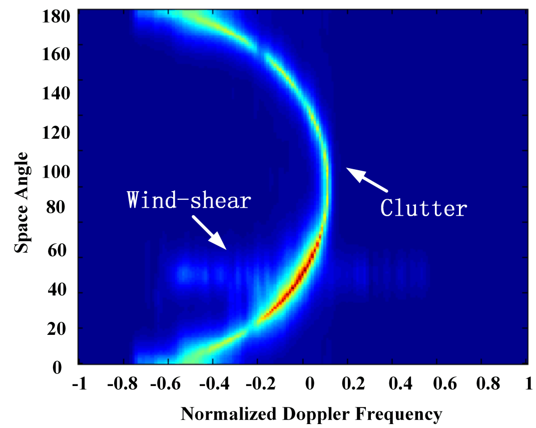
$$\mathbf{x}_l = \mathbf{s}_l + \mathbf{c}_l + \mathbf{n}_l \tag{2}$$

where, $\mathbf{s}_l$ represents the samples of the wind-shear field echo of the lth range bin. $\mathbf{c}_l$ denotes the clutter, in this paper, we assume the clutter is non-fluctuating. $\mathbf{n}_l$ is the additive white gaussian noise[9].

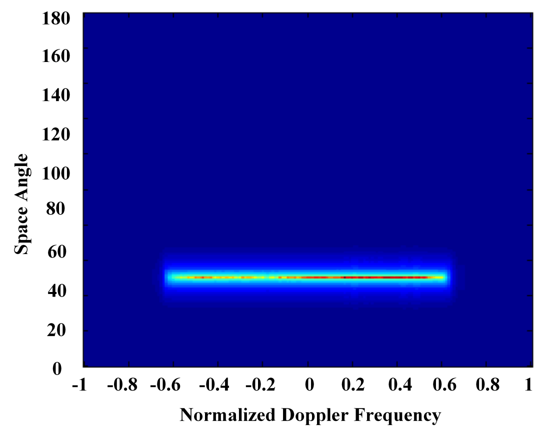
Figure 2(a) illustrates the space-time spectrum of the signal received by the radar on its coverage after aircraft speed compensation(in the condition of $CNR = 40dB$,$SNR = 5dB$). Figure 2(b) illustrates corresponding the space-time spectrum of the ideal wind-shear echo. From the space-time spectrum we know, the distribution of the wind-shear spectrum along the Doppler axis show as straight line. The distribution of the clutter spectrum along the Doppler axis show as ellipse, which indicates the coupling of the distance and the Doppler frequency of the clutter[4] (also called the range dependence). The echoes of the wind-shear field are almost masked by the strong clutter background, due to the power of the clutter is much larger than the wind-shear echo, which makes it difficult to detect the wind-shear field.

3. WIND SPEED ESTIMATION BASED ON MULTIPLE DOPPLER CHANNELS JOINT ADAPTIVE PROCESSING

The clutter-and-noise environment of the airborne forward-looking phased array radar is heterogeneous due to the geometry property of the array, which manifests as the snapshot statistics are range dependent[4]. Due to the range dependence, it is hard to estimate



(a) Space-Time Spectrum of the Actual Receive Signal



(b) Space-Time Spectrum of the Ideal wind-shear Echo

Fig. 2. Space-Time Spectrum of the Radar Receive Signal

the clutter-andnoise covariance matrix accurately, as the Independent and Identical Distributed (IID) samples can be used are quite limited. To obtain the enough IID samples, Space-Time Interpolation Principle [16] is applied to mitigate the range dependence.

Although the optimum STAP method can achieve clutter suppression and the signal matching optically, the computational expense to construct the optimum filter is huge, which make it hard to achieve real-time processing. In this section, M-CAP method is applied to the wind speed estimation. A reduced-rank processor architecture aimed to distributed target such as wind-shear field is built as it is shown in figure 3. Without loss of generality, this section take 3-CAP as an example to discuss the proposed method.

3.1. Reduced-Rank processing

3-CAP processor firstly adopts a set of Doppler filters to process the receive signal. It transfers the full space-time clutter into directional narrow-band active jamming of a fixed Doppler channel, thus achieves the rank reduction from space-time 2D to spatial 1D[15]. Let f_{dm} denotes the central Doppler frequency of the mth Doppler channel. The spatial receive data of the mth Doppler channel after rank reduction can be written as:

$$\mathbf{Y}_m = \left(\mathbf{I}_N \otimes \left(\mathbf{W}_{tm} \odot \mathbf{g}_t(\sigma_f)\right)\right)^T \mathbf{x}_l \tag{3}$$

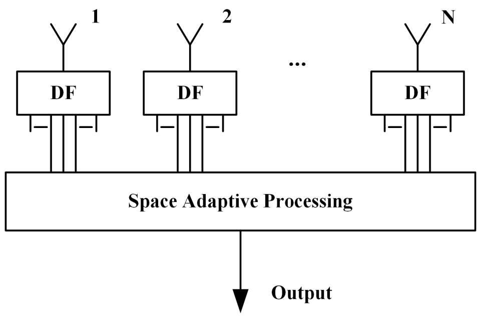


Fig. 3. The Architecture of the Proposed Method

in which, $\mathbf{I}_N$ denotes the $N \times N$ spatial unit matrix, $\mathbf{x}_l$ is the receive signal of the lth range bin. $\mathbf{W}_{tm}$ is the weight of the mth Doppler Channel, given by

$$\mathbf{W}_{tm} = \begin{bmatrix} 1 & e^{j\pi \frac{4v}{\lambda f r}} & \cdots & e^{j\pi(K-1)\frac{4v}{\lambda f r}} \end{bmatrix}_{K\times 1}^{T} \tag{4}$$

$\mathbf{g}_t(\sigma_f)$ is the denotes the Gaussian frequency extension function under the assumption[17] that the central Doppler frequency of the wind-shear field of a fixed range bin obeys Gaussian Distribution $f_d \sim N(f_0, \sigma_f^2)$[12].

$$\mathbf{g}_t(\sigma_f) = \begin{bmatrix} 1 & e^{-2\pi^2\sigma_f^2} & \cdots & e^{-2\pi^2(K-1)^2\sigma_f^2} \end{bmatrix}_{K\times 1}^{T} \tag{5}$$

where, σ_f^2 represents the spectral width of the wind-shear echo[11]. It means the wind-shear echo of single range bin can be viewed as a signal with a fixed center frequency and fixed spectral width. $(\mathbf{I}_N \otimes \mathbf{W}_{tm})^T$ constructs the actual dimension reduction matrix[15].

3.2. Spatial adaptive processing

The main idea of the spatial adaptive processing is to transfer the problem to be settled into an optimization problem, then calculate the optimum weights of the spatial filter. Firstly, take the $(m-1)th$ and $(m+1)th$ Doppler channel as the auxiliary channel. $\mathbf{Y}_{m-1}$ and $\mathbf{Y}_{m+1}$ denote the spatial receive data of these two Doppler channels.We define a new vector $\mathbf{Z}_m$ as follows:

$$\mathbf{Z}_m = \begin{bmatrix} \mathbf{Y}_m & \mathbf{Y}_{m-1} & \mathbf{Y}_{m+1} \end{bmatrix} \tag{6}$$

By utilizing the $\mathbf{Z}_m$, the spatial covariance matrix can be formed as:

$$\mathbf{R}_{Zm} = \mathrm{E}\left[\mathbf{Z}_m \mathbf{Z}_m^H\right] \tag{7}$$

According to the linearly constrained minimum variance criterion, we have the following optimisation problem

$$\begin{cases} \min \omega_{Zm}^H \mathbf{R}_{Zm} \omega_{Zm} \\ s.t. \;\; \omega_{Zm}^H \mathbf{S}_{Zm} = 1 \end{cases} \tag{8}$$

where $\mathbf{S}_{Zm}$ is a 2-dimensional space-time steering vector given by

$$\begin{aligned} \mathbf{S}_{Zm} = [&\mathbf{v}_s(\theta_i, \varphi_l) \odot \mathbf{g}_s(\theta_i, \sigma_\theta; \varphi_l, \sigma_\varphi)\,, \\ &g_{m-1}\, \mathbf{v}_s(\theta_i, \varphi_l) \odot \mathbf{g}_s(\theta_i, \sigma_\theta; \varphi_l, \sigma_\varphi), \\ &g_{m+1}\, \mathbf{v}_s(\theta_i, \varphi_l) \odot \mathbf{g}_s(\theta_i, \sigma_\theta; \varphi_l, \sigma_\varphi)]^T \end{aligned} \tag{9}$$

where,$\mathbf{v}_s(\theta_i, \varphi_l)$ is the space steering vector of the point target at the pitch φ_l and azimuth θ_i, given by:

$$\mathbf{v}_s(\theta_i, \varphi_l) = \begin{bmatrix} 1 & e^{j\frac{\pi d}{2\lambda}\cos\theta_i\cos\varphi_l} & \cdots & e^{j\frac{\pi d}{2\lambda}\cos\theta_i\cos\varphi_l} \end{bmatrix}_{N\times 1}^{T} \tag{10}$$

$\mathbf{g}(\theta_i, \sigma_\theta, \varphi_l, \sigma_\varphi)$ denotes the angular signal distribution functions[10]. It reflects the extension of the wind-shear field both in pitch and azimuth. Commonly $\mathbf{g}(\theta_i, \sigma_\theta, \varphi_l, \sigma_\varphi)$ is assumed as a symmetric unimodal function whose symmetry axis is the DOA of the distributed source core[18], given by:

$$\begin{aligned} \mathbf{g}(\theta_i, \sigma_\theta, \varphi_l, \sigma_\varphi) = \big[\; &\mathrm{sinc}(\Delta_{1\theta})\mathrm{sinc}(\Delta_{1\varphi}) \quad \mathrm{sinc}(\Delta_{2\theta})\mathrm{sinc}(\Delta_{2\varphi}) \\ &\cdots \quad \mathrm{sinc}(\Delta_{N\theta})\mathrm{sinc}(\Delta_{N\varphi}) \;\big]_{N\times 1}^{T} \end{aligned} \tag{11}$$

where, $\Delta_{n\theta} = \frac{2d}{\lambda}(n-1)\sigma_\theta \cos\varphi_l \sin\theta_i, (n = 1, 2, \cdots, N)$, $\Delta_{n\varphi} = \frac{2d}{\lambda}(m-1)\sigma_\varphi \sin\varphi_l \cos\theta_i, (n = 1, 2, \cdots, N)$, σ_θ denotes the angle extension of θ_i, σ_φ denotes the angle extension of φ_l. $g_{m+i}(i = \pm 1)$ is the scale which can be expressed as follow:

$$g_{m+i} = \frac{\mathbf{W}_{tm}^H \mathbf{W}_{t(m+i)}}{\mathbf{W}_{tm}^H \mathbf{W}_{tm}} \tag{12}$$

Thus, we can obtain the dimension reduction optimum weights

$$\omega_{Zm} = \frac{\mathbf{R}_{Zm}^{-1}\mathbf{S}_{Zm}}{\mathbf{S}_{Zm}^H \mathbf{R}_{Zm}^{-1}\mathbf{S}_{Zm}} \tag{13}$$

This weights can suppress the directional narrow-band active jamming of the mth Doppler channel adaptively and accumulate the energy of the target's direction. The result of the jamming suppression and the signal matching is computed by:

$$y = \omega_{Zm}^H \mathbf{Z}_m \tag{14}$$

Weights of different main Doppler channel and the output of the corresponding filter can be obtained by changing the main Doppler channel and constructing the reduced-rank filter. Let $\hat{f}$ denotes the central frequency of the Doppler channel when the output reaches the maximum value. Thus the wind speed can be estimated by

$$\hat{v} = \frac{\lambda \hat{f} f_r}{4} \tag{15}$$

The central wind speed of each range bin can be obtained by repeating the all the procedures mentioned above to process the wind-shear echo data of every range bin respectively. Then the varying pattern of the wind speed along the distance can be obtained. The wind-shear field can be identified and the hazard level can be evaluated by further calculating the gradient of the wind speed.

4. NUMERICAL SIMULATIONS

In this section, we illustrate the performance of the proposed method and compare it with that of the conventional method. The airborne platform is moving at a velocity of $75m/s$, fight height is $600m$. The wind-shear echo is received by a ULA with half-wavelength inter-element spacing and $N = 8$, carrier wavelength of the radar is $0.05m$. The azimuth angle of the main lobe is 60° , pitch angle is 0°, main lobe width is 3.5°. Pulse repetition frequency is $7KHz$ and the minimum resolution distance is $150m$. Wind-shear filed is distributed $8.5 - 16.5km$ ahead of the airborne platform, signal-to-noise ratio(SNR) is $5dB$ and the clutter-to-noise ratio (CNR) is $40dB$. Assumed nomalized Doppler spectral width is $\sigma_f = 0.05$.

Figure 4 takes the $80th$ range bin as an example to illustrate the Improvement Factor of the proposed method. From the figure we can see, comparing with the optimum processor, the 3-CAP method can achieve near-optimum performances.

Figure 5 takes the $80th$ range bin as an example to illustrate the frequency response characteristics of the proposed method. Figure 5(a) is the frequency response characteristics of the whole Doppler domain. Figure 5(b) takes six Doppler channels whose central Doppler Frequency is -20,0,20,40,60,80 respectively, as examples to show space response characteristics of the proposed method. From the frequency responses chat we can see, spatial filters of each doppler channel can generate obvious gains at the target direction.

Fig. 6 compares the estimation results for various methods. In the same condition of SNR and CNR,the proposed method shares almost same performance with the optimum processor and is obviously better than the conventional methods, which proves the effectiveness of the method.

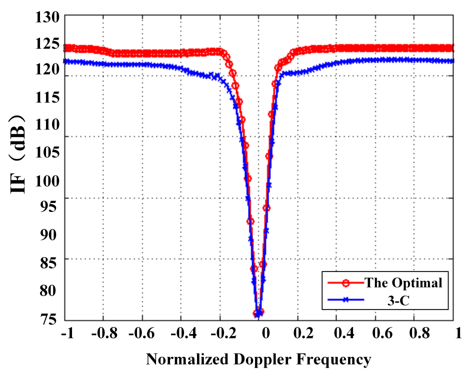
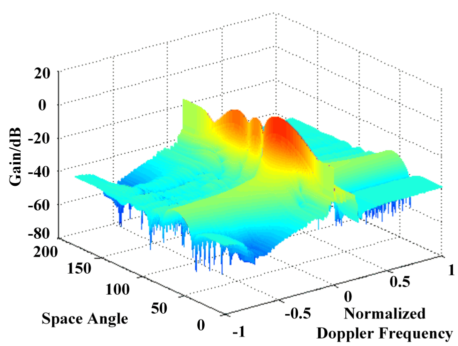


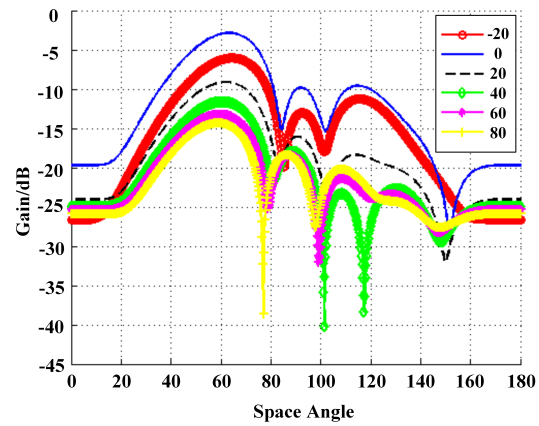
Fig. 4. Improvement Factor of the Proposed Method



(a) Frequency Response of the Whole Doppler Channel

5. CONCLUSION

In this paper, an architecture of reduced-rank processor that can be applied to detection and parameter estimation of the distributed target such as wind-shear is proposed. The method proposed constructs the reduced-rank processor to suppress clutter and match the wind-shear signal, has a strong ability of suppressing ground clutter which helps to get the accurate estimation of wind speed. Due to the reduced-rank architecture, the computational complexity of the proposed method is significantly reduced. The effectiveness of the method is verified via simulation results.



(b) Spatial Response of Different Doppler Channel

Fig. 5. Frequency Response Characteristics of the Processor

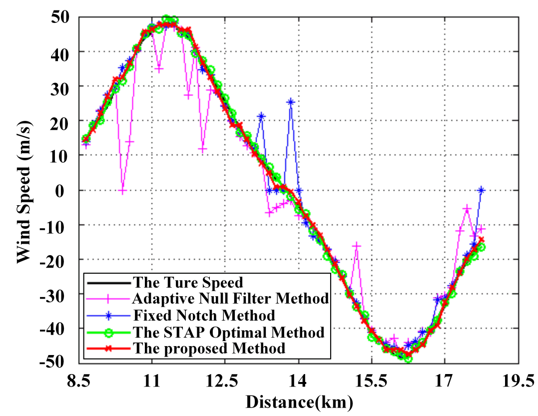


Fig. 6. Comparison of Estimation Results for Various Methods

References

[1] Yelun Xiao. *Principle of Fight in Amospheric Dsturbances*. National Defend Industy Press, 1993.

[2] Renbiao Wu, Xiaoguang Lu, Hai Li, and Yanfei Han. Overview on airborne forward-looking weather radar with windshear detection capability. *Journal of Data Acquisition and Processing*, 29(4):476–507, 2014.

[3] Steve Paramore, Daniel L Woodell, and Sarah Barber. Airborne weather radar system and radar display, September 19 2006. US Patent 7,109,913.

[4] Richard Klemm. *Principles of space-time adaptive processing*. IET, 2002.

[5] Xiuli Yan and Zengmiao Ruan. Application of the clutter-map technology to signal processing in radar terminals. *Modern Radar*, 26(5):34–36, 2004.

[6] Daniel L Woodell. Method and system for suppressing ground clutter returns on an airborne weather radar, August 5 2003. US Patent 6,603,425.

[7] Jianxin He, Xu Wang, and Yan Liu. Application of adaptive gaussuian frequency filter to weather radar. *Meteorological Monthly*, 26(6):117–121, 2010.

[8] Ernest G Baxa Jr, YC Lai, and Matthew W Kunkel. New signal processing developments in the detection of low-altitude windshear with airborne doppler radar. In *Radar Conference, 1993., Record of the 1993 IEEE National*, pages 269–274. IEEE, 1993.

[9] Yongliang Wang and Yingning Peng. *Space-Time Adaptive Processing*. Tsinghua University Press, 2000.

[10] Shahrokh Valaee, Benoit Champagne, and Peter Kabal. Parametric localization of distributed sources. *Signal Processing, IEEE Transactions on*, 43(9):2144–2153, 1995.

[11] VN Bringi and V Chandrasekar. *Polarimetric Doppler weather radar: principles and applications*. Cambridge University Press, 2001.

[12] Dusan S Zrnic and Richard J Doviak. Doppler radar and weather observations, 1992.

[13] Renbiao Wu, Zhang Biao, and Hai Li. Wind speed estimation for low-altitude windshear based on space-time adaptive processing. *Jounal of Electronics and Information Technology*, 37(3):631–336, 2015.

[14] Hai Li, Biao Zhang, Renbiao Wu, Xiaoguang Lu, and Yanfei Han. Wind speed estimation for low-altitude windshear based on space-time apes. In *Radar Conference (RadarCon), 2015 IEEE*, pages 0521–0526. IEEE, 2015.

[15] Y-L Wang, YN Peng, and Zheng Bao. Space-time adaptive processing for airborne radar with various array orientations. In *Radar, Sonar and Navigation, IEE Proceedings-*, volume 144, pages 330–340. IET, 1997.

[16] Vijay Varadarajan and Jeffrey L Krolik. Joint space-time interpolation for distorted linear and bistatic array geometries. *Signal Processing, IEEE Transactions on*, 54(3):848–860, 2006.

[17] Eric Boyer, Pascal Larzabal, Claude Adnet, and Monique Petitdidier. Parametric spectral moments estimation for wind profiling radar. *Geoscience and Remote Sensing, IEEE Transactions on*, 41(8):1859–1868, 2003.

[18] Hui Yao. Research on parameter estimation method for distributed sources. 2013.