

Calibration of Radar Beam Weighting Effect for 2-D Angular Imaging of VHF Atmospheric Radar Using Multiple Beam Directions

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Abstract

An approach using multiple beam directions is proposed for VHF atmospheric radar to yield an effective weighting pattern of radar beam for 2-D angular imaging. Such obtained beam pattern is found to be adaptive to signal-to-noise ratio of data. A practical radar experiment was conducted to demonstrate the proposed approach.

Keywords : Beam Weighting Effect, Radar Imaging, VHF Atmospheric Radar

1. Introduction

Radar technique using multiple receivers is capable of detecting the direction of arrival (DOA) of signal sources. It is termed coherent radar imaging (CRI) [1] when used with the VHF atmospheric radar. The CRI technique is expected to recover the angular turbulent structure in the atmosphere with some advanced algorithms of signal analysis such as Capon's method [2], and consequently, the DOAs of echo centers of the atmospheric structure can be estimated. However, the DOAs are usually biased owing to the weighting effect of radar beam pattern. Modification of DOAs with a simulated radar beam pattern usually leads to an unrealistic result. In view of this, a practical approach to mitigation of the radar beam weighting effect is pursued in this study.

2. Calibration Approach

The polar diagram of the backscatter power detected by VHF atmospheric radar can be written as $\exp(-\sin^2\theta/\sin^2\theta_s)$, where θ is zenithal angle and θ_s is an estimate of aspect sensitivity (termed aspect angle). The effective power distribution as a function of θ can be regarded as the product of $\exp(-\sin^2\theta/\sin^2\theta_s)$ and the radar beam weighting function, $\exp(-\sin^2\theta/\sin^2\theta_0)$, in which θ_0 is the half beam width of a vertical radar beam [3].

For an off-vertical radar beam and a tilted layer or non-homogeneous angular distribution of scatterers, the polar diagram of the backscatter power may not center on zenith. Therefore, the effective power distribution along the line of the tilted radar beam can be expressed

$$P(\theta) = \exp\left[-\frac{(\sin\theta - \sin\theta_T)^2}{\sin^2\theta_0}\right] \exp\left[-\frac{(\sin\theta - \sin\theta_{Ts})^2}{\sin^2\theta_s}\right] \quad (1)$$

where θ_T is the off-zenith angle of the radar beam direction and θ_{Ts} is the center of the scattering distribution. Eq. (1) is valid for θ_T and θ_0 less than $\sim 10^\circ$ [3]. Then it gives the polar diagram of the backscatter power:

$$A(\theta) = \exp\left[-\frac{(\sin\theta - \sin\theta_{Ts})^2}{\sin^2\theta_s}\right] = P(\theta) \exp\left[\frac{(\sin\theta - \sin\theta_T)^2}{\sin^2\theta_0}\right] \quad (2)$$

CRI-obtained power distribution (or termed brightness distribution) is supposed to indicate $P(\theta)$. Based on this, $A(\theta)$ can be retrieved theoretically after a proper correction of $P(\theta)$ with a suitable value of θ_0 . An estimate of θ_0 is thus needed, as addressed in the following.

Considering two symmetrically tilted radar beams that are transmitted almost simultaneously, the CRI brightness distributions of the two oblique radar beams originate basically from the same $A(\theta)$. Therefore, the backscattered power distributions, $A_1(\theta)$ and $A_2(\theta)$, retrieved from the two oblique radar beams are expected to be close. Such an expectation is valid especially around the zenith where the viewing regions of the two oblique radar beams overlap most greatly. Referring to [4], the following estimator can be used to calculate the difference between $A_1(\theta)$ and $A_2(\theta)$ around the zenith:

$$\Delta E = \sum_{i=1}^N \frac{[A_1(\theta_i) - A_2(\theta_i)]^2}{A_1(\theta_i)A_2(\theta_i)} = \sum_{i=1}^N \left[\frac{A_1(\theta_i)}{A_2(\theta_i)} - 2 + \frac{A_2(\theta_i)}{A_1(\theta_i)} \right] \quad (3)$$

where N is the number of the brightness values estimated around the zenith and along the line of the two oblique radar beams. Giving various values of θ_0 in (2) will result in different values of ΔE .

In (3), $\Delta E=0$ for $A_1(\theta)=A_2(\theta)$; if $A_1(\theta) \neq A_2(\theta)$, however, $\Delta E > 0$ and ΔE usually gets larger as the difference between $A_1(\theta)$ and $A_2(\theta)$ is larger. According to this, the value of θ_0 which makes ΔE smallest can be regarded as the optimal half beam width (termed effective beam width and denoted as θ_e hereafter). Such obtained θ_e varies with some parameters of echoes; especially the signal-to-noise ratio (SNR). The relationship between θ_e and SNR is expected to vary with the off-zenith angle of the two symmetrically tilted radar beams, which can be comprehended as follows. The traditionally used radar beam width, θ_0 , is given by assuming a Gaussian-shaped angular intensity distribution in the radar beam, which is only suitable for the angular region within $\sim \theta_0$. To give a more accurate description of angular intensity distribution in the radar beam, different values of θ_0 are needed for different off-beam-direction angles if the Gaussian form is employed. The zenithal direction, where the effective beam width θ_e is estimated to represent the value of θ_0 , corresponds to different off-beam-direction angles for various oblique radar beams; hence the value of θ_e varies with the off-zenith angle of the oblique radar beam. Consequently, the values of θ_e estimated from various oblique radar beams can be used to take shape the radar beam weighting pattern.

3. Instrument and Radar Imaging

The above calibration approach was demonstrated by using the Middle and Upper (MU) atmosphere radar in Japan (34.85°N, 136.11°E; central frequency: 46.5 MHz). Fig. 1a shows the antenna array configuration of the MU radar, in which A1~F5 indicate 25 antenna groups. These antenna groups can be combined arbitrarily for transmission and reception. In this study, full array was used for transmission, and nineteen antenna groups A2, A3, A4, B2, B3, B4, C2, C3, C4, D2, D3, D4, E2, E3, E4, F2, F3, F4, F5, were set for reception. Radar pulse length was 1 μ s and sampling time step was also 1 μ s, giving a range resolution of 150 m and a sampling height interval of 150 m, too. Radar beam was vertical. More characteristics and capabilities of the MU radar can refer to [5].

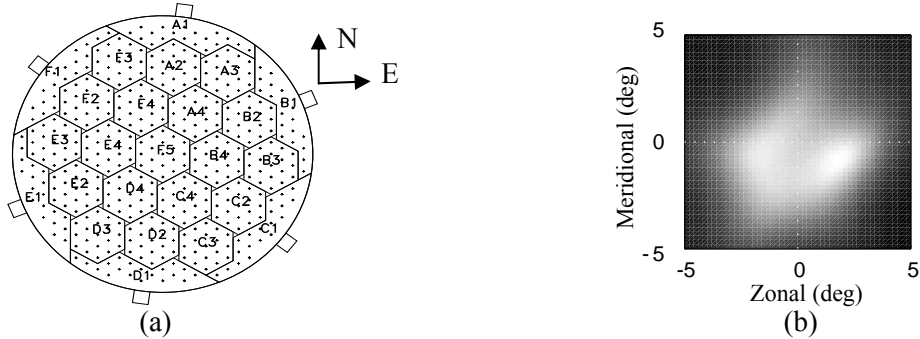


Figure 1: (a) MU VHF radar. The number of antennas (Yagi) is 475, and the radius of the array is ~ 55 m. A1 to F5 denote twenty five antenna groups. (b) Angular brightness distribution retrieved by Capon's method. The brightness values are normalized and displayed in linear scale.

A variety of inversion algorithms can be employed to deal with multiple-channel signals/echoes; in this study the Capon method was employed [2], [6]. The Capon method is time-

saving and suitable for distributed target like refractivity irregularities in the atmosphere, which can be used with the CRI data in both time and Doppler frequency domains. In this study, the time-domain calculation was executed to estimate the so-called angular brightness brightness– $P(\theta)$ in (2). One example is shown in Fig. 1b, where two scattering centers were observed.

4. Calibration Results

Fig. 2 shows the scatter diagram of θ_e versus SNR. As seen, θ_e approaches to some values as SNR is getting large. On the other hand, θ_e increases dramatically as SNR is close to ~ -10 dB. Based on the feature in Fig. 2, it is possible to find a set of equations for fitting the relationship between θ_e and SNR at different off-beam-direction angles, as follows:

- 1) Give a set of θ_0 for all beam pairs that can indicate the effective beam widths at infinite SNR. Such a value set, denoted as θ_{oe} hereafter, can be assigned approximately by extending the dependent relationship in Fig. 2 to very high SNR. For example, if the set of $\theta_{oe}=[2.80^\circ, 3.00^\circ, 3.50^\circ, 4.00^\circ, 5.50^\circ, 8.50^\circ, 12.50^\circ]$ are given for the beam pairs tilted to the zenith angles of $\theta_T=[1^\circ, 2^\circ, 3^\circ, 4^\circ, 6^\circ, 8^\circ, 10^\circ]$, then a cubic curve,

$$\theta_{oe} = c_1\theta_T^3 + c_2 \quad (4)$$

is capable of depicting the relationship between θ_{oe} and θ_T . Fig. 3 shows the fitting result, with the constants $c_1 \doteq 0.0096$ and $c_2 \doteq 3.1803$. Such obtained cubic equation can be employed to estimate effective beam widths at infinite SNR for various off-beam-direction angles, by regarding the off-zenith angle θ_T as the off-beam-direction angle of a radar beam.

- 2) Substitute the value of θ_{oe} , estimated with (4) for an off-beam-direction angle (i.e., the variable θ_T), into the following equation which describes the relationship between θ_e and SNR (in dB):

$$\theta_e = \frac{c_3\theta_{oe}^2 + c_4}{SNR + 10} + \theta_{oe} \quad (5)$$

where $c_3 \doteq 1.4751$ and $c_4 \doteq -9.7430$ for the fitting curves shown in Fig. 2. Notice that c_1 – c_4 are constants resulting from fitting processes.

Eqs. (4) and (5) are empirical and they are not unique. In addition, in the use of (5) SNR must be larger than -10 dB to avoid a negative θ_e . In view of this, other expressions which can describe the relationship between θ_e and SNR well can also be employed.

Fig. 4 exhibits two examples of original and modified CRI brightness distributions, presented with contour lines. As seen, the contour map corrected by a fixed beam width is unrealistic (Fig. 4(b)), which is of no use. By contrast, the contour map rectified with an adjustable beam width reveals some noticeable features (Fig. 4(c)): (1) in the left column, the raw contour map shows a double-center pattern, which also appears in the corrective map but with a larger separation between the two centers; (2) in the right column, the single echo center in the raw map changes to double echo centers. In view of this, correction of radar beam weighting effect on CRI brightness is indeed crucial sometimes; it may revise the number and locations of echo centers, the brightness width, and then reveal some concealed information in the radar echoes of the atmosphere. Extended works of the present study are: (1) validating the proposed approach for various radar parameters and atmospheric conditions; (2) applying the proposed approach to practical issues such as measurements of vertical wind and aspect sensitivity of the atmosphere.

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Acknowledgments

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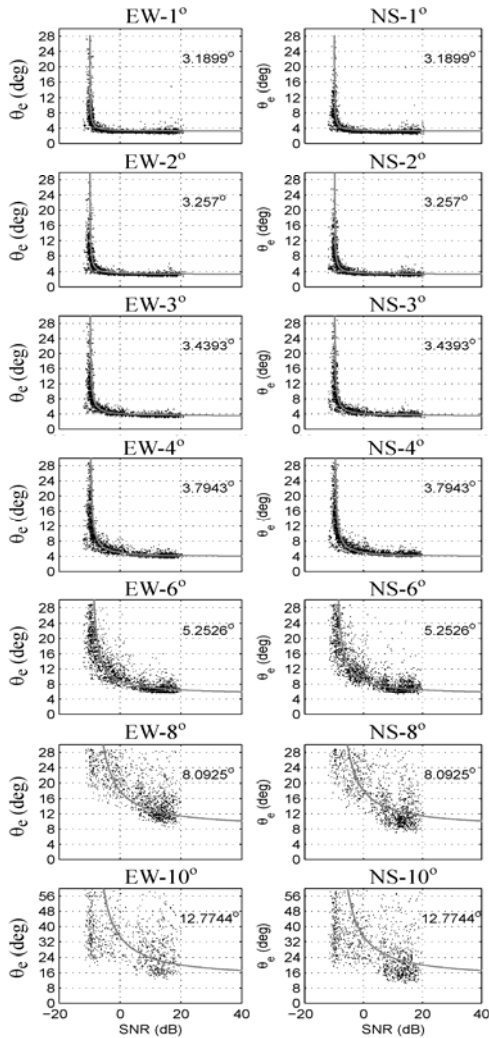


Figure 2: Scatter diagram of effective beam width (θ_e) versus signal-to-noise ratio (SNR). The curves result from (5). The value given in each panel is the effective beam width estimated with (4) for the condition of infinite SNR.

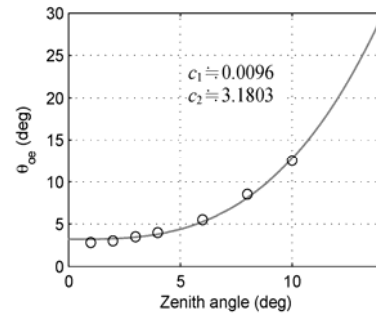


Figure 3: Relationship between effective beam width and off-zenith angle of the radar beam direction for the condition of infinite SNR. The fitting curve results from (4).

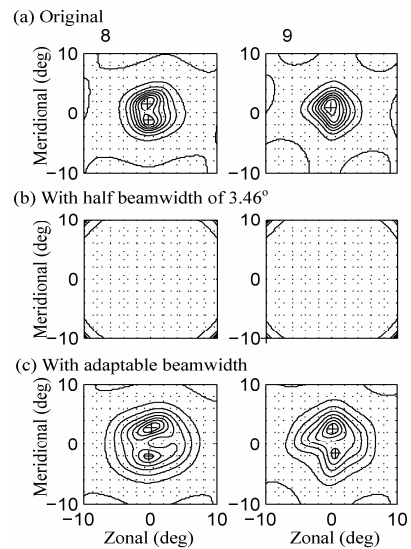


Figure 4: Contoured CRI brightness distribution (self-normalized): (a) original, (b) modified with the half beam width of 3.46° , and (c) modified with adaptable beam width. Plus sign indicates the mean location of echo center. Contour levels are ten.