Steep Reflectivity Structures of Mesosphere Summer Echoes Detected by Multiple-Receiver Radar Interferometry

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ABSTRACT

With several receiving antennas at different locations, the incident angles of the echoes scattered/reflected from the atmospheric irregularities can be detected. One of the proper algorithms dealing with multiple-receiver signals is Capon's method. To improve the use of this technique, we developed a locating approach to finding the angular positions of the echoes, which enable us to examine numerous data quickly and correctly. The developed locating approach was applied to the mesosphere summer echoes (MSE) observed by the German-OSWIN VHF radar (11.8^{o}E and 54.1^{o}N, six receivers). In this case, multiple echo centers and large incident angles (close to 20°) of the echoes were seen in the upper portion of the MSE layer. Such large incident angles were not reported before and might indicate some specific characteristics such as very steep refractivity structures in the MSE layer.

1. INTRODUCTION

Multiple-receiver interferometry has been used with mesosphere-stratosphere-troposphere (MST) coherent radar for many years [14, 6, 15, 17, 10,13, 7, 5, 18]. More advanced version of this technique is termed as coherent radar imaging (CRI) [8, 19, 9, 12]. The main capability of the CRI technique is to identify the respective angular locations (incident angles) of multiple echo centers, provoking plenty of atmospheric researches such as irregularity structure, gravity wave activity, and so forth. Many algorithms can deal with the multiple-receiver echoes; among them Capon's method consumes less time and results in excellent products [20]. Since the CRI technique is to identify echo centers, a locating approach to finding the angular locations of the echo centers is greatly helpful for the related studies. In the literature, a two-dimensional Gaussian fitting is usually employed; unfortunately, the fitting is not suitable for the situation of multiple centers. *Chau and Woodman* [2] implemented a fitting technique using a number of anisotropic Gaussian blobs, which could be one way to locate multiple echo centers. Here we introduce a contour-base locating approach that can examine a large number of the CRI data quickly and correctly. The locating approach was applied to one case of the mesosphere summer echoes (MSE) observed by the German-OSWIN VHF radar (11.8^{o}E and 54.1^{o}N, six receivers). Some interesting features were found in this preliminary application.

2. CAPON'S METHOD

Capon's method estimates the average signal power density (or brightness) as a function of angle (namely, brightness distribution) for the signals received by spatially separated receivers. Mathematically, the Capon method is obtained from the optimally constrained approach [1, 12]. The equations for estimating the brightness in this study are

$$\mathbf{B(k)} = \frac{1}{\mathbf{e}^{+}\mathbf{R}^{-1}\mathbf{e}} \quad \text{and} \quad \mathbf{R} = \begin{bmatrix} R_{11} & R_{12} \dots R_{1n} \\ R_{21} & R_{22} \dots R_{2n} \\ \cdot & \cdot \quad \cdot \quad \cdot \\ R_{n1} & R_{n2} \dots R_{nn} \end{bmatrix}, \tag{1}$$

where **B** is the brightness function, **k** is the wavenumber vector in the direction where the brightness is to be estimated, $\mathbf{k} = (2\pi/\lambda)[\sin\theta\sin\varphi \ \sin\theta\cos\varphi \ \cos\theta]$, λ is the radar wavelength, θ and φ are, respectively, the zenith and azimuth angles. The symbols of $+$ and -1 represent Hermitian operator and inverse of matrix, respectively. $\mathbf{e} = [\ e^{j\mathbf{k}\cdot\mathbf{D}_1} \ \ e^{j\mathbf{k}\cdot\mathbf{D}_2} \ \ldots \ e^{j\mathbf{k}\cdot\mathbf{D}_n} \ ]^T$, where $\mathbf{D}_1, \mathbf{D}_2, \ldots, \mathbf{D}_n$ are the position vectors of receiving antennas and the index T is the transpose operator. **R** is a matrix composed of visibility function R_{ij}, where R_{ij} is the zero-lag cross-correlation function of the signals received by receivers i and j.

3. LOCATING APPROACH AND PRELIMINARY APPLICATION

Once the brightness distribution as the function of angle is produced, we employ the built-in function [**C**, h]= contour(f, n) in the MATLAB software to contour the brightness distribution, in which f is the brightness distribution, n is contour level, **C** is a matrix depositing the coordinates of all contour lines. When the first and the last coordinates of a contour line are the same, the contour line must be a closed curve. Then the centroid of the closed curve is estimated, which can indicate one of the brightness centers. Multiple brightness centers can be identified in this way, but some steps are needed to avoid redundant centers. The detail steps are not described here due to the limit of page.

The above locating approach was applied to two experimental data sets. The first experiment is the aircraft echoes observed by the Chung_Li VHF radar, with three Yagi receiving antennas (for more details of the experiment, see [3]). Because the aircraft is a concrete and continuous moving object, it provides a good chance to validate the practice of the locating approach. The angular locations of the aircraft are expected to vary successively with time. Fig. 1 shows the results, as expected.

Another experiment is the mesosphere summer echo observed by the German-OSWIN VHF radar. This radar has six receiving antenna arrays, arranged by 3×2 (SA mode) or 6×1 (COL mode) or 1×6 (ROW mode). The SA mode transmits only vertical radar beam, but the COL and ROW modes can steer the radar beam in vertical and oblique directions (7°, 14°, 21°). For more descriptions of the radar, see the website *www.iap-kborn.de* or [11]. Two examples are shown in Fig. 2. The left panel of Fig. 2 shows the result of the SA mode. A duplicate two-blob pattern is seen, which reveals the grating pattern and the folding angle of $\sim15^{o}$. As expected, the brightness centers were determined explicitly and the 'valleys' were excluded successfully. The right panel of Fig. 2 is the consequence of the ROW mode with vertical radar beam, in which the grating pattern can also be seen but a three-blob pattern is replicate (folding angle $\sim45^{o}$). It should be mentioned that the ROW mode obtains only one-dimensional brightness distribution in the east-west line. We have extended the brightness to two dimensions so that the contour method can be applied. This was achieved by setting a Gaussian curve in the north-south direction for each brightness value, in which the brightness value in the east-west line is the peak magnitude of the north-south Gaussian curve. As for the standard deviation of the Gaussian curve, 7.5 deg was used (this can be changed but it results in the same central location). Similar approach can also be applied to the COL mode, but the Gaussian curve is in the east-west direction.
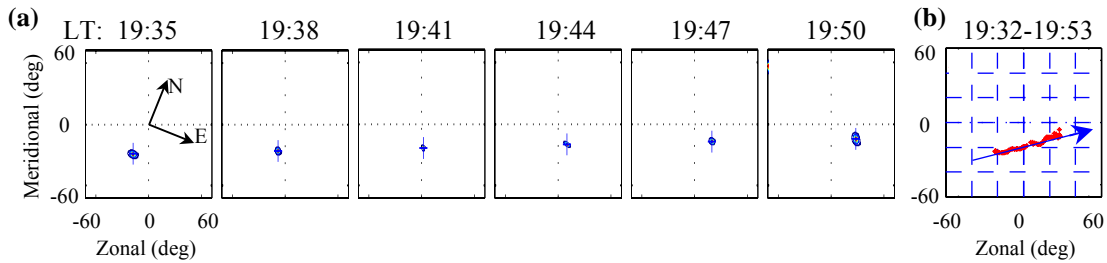

Figure 1. (a) Contour plots of brightness distribution for the aircraft echoes at different times, The symbol '+' indicates the angular location of the aircraft. (b) Continuous angular locations of the aircraft, where the arrowheaded line is the trajectory of the aircraft recorded by a video camera. Note that zonal and meridional coordinates are based on the configuration of receiving antennas. The true geographic east and north directions are indicated in the first chart.
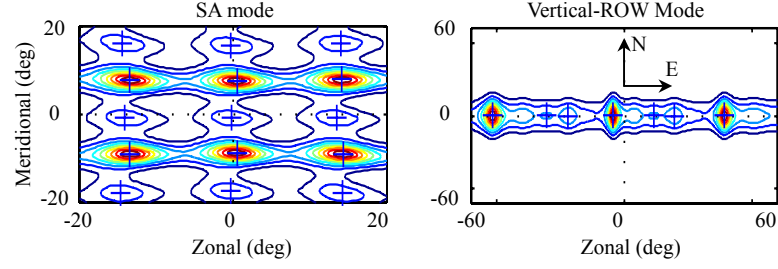
Figure 2. Contour plots of brightness distribution for the mesosphere summer echoes observed by the OSWIN VHF radar, with vertical-SA and vertical-ROW modes. The symbol '+' indicates the brightness center. The true geographic east and north directions are indicated in the right chart.

To demonstrate the practical application of the above locating approach, a case of the MSE, observed by the SOWIN VHF radar on 15 July 2000 during 0900-1600UTC, is presented here. Fig. 3 shows the histogram of angular locations of the brightness centers for the vertical-COL mode. As seen below the height of ~86 km, three resembling groups of angles indicate that the folding begins at ~45° zenith; that is, the two groups of angles on both sides are duplicate ones. Substantial features appeared in the upper portion of the MSE layer: (1) between –20° and 20° there were one group of angles around zenith and two groups of angles on both sides of the zenith that didn't intermix with the duplicate ones ($< -20^o$ and $> 20^o$), and (2) the two groups of angles on both sides of the zenith moved apart from the zenith gradually, in which the incident angles of echoes increased with the altitude and were close to 20° zenith in the very height. Similar feature was also observed by the oblique beam and the ROW mode (not shown). *Chen et al.* [4] have examined the SA data collected during the same period and found two groups of incident angles (around 1° and 8° respectively) by investigating the brightness maps directly. However, the large incident angles of echoes seen in Fig. 3 cannot be observed by the vertical SA mode because the folding angle of the SA mode is only ~15°. In addition, multiple centers more than two are difficult to be resolved by the SA mode because the mode has only three receiving antenna modules in the north-south direction and two in the east-west direction. As far as the author knows, such large incident angles were not reported before. One mechanism for the large incident angles of echoes could be steep refractivity structures in the MSE layer, as has been argued by *Röttger et al.* [16]. Further examination of this issue is worthy of executing in the future.

4. CONCLUSIONS

The coherent radar imaging using Capon's method is presented. An approach to locating the incident angles of the scattering/reflecting centers was developed and applied to the mesosphere summer echoes and
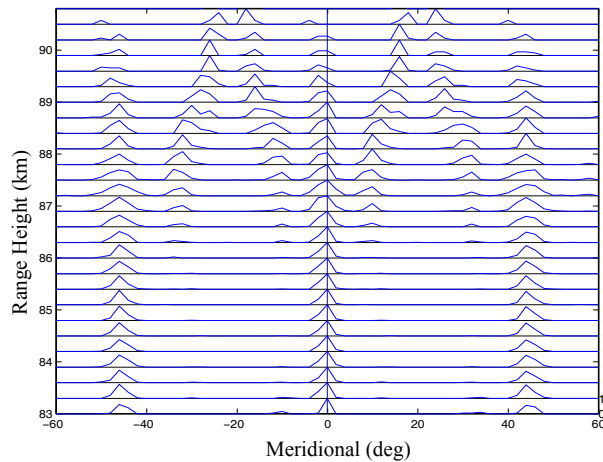

Figure 3. Histogram of angular locations of the brightness centers for the MSE, observed by the OSWIN VHF radar with vertical-COL mode (north-south line).

the aircraft echoes observed, respectively, by the OSWIN VHF radar (Germany) and the Chung-Li VHF radar (Taiwan). The locating approach was demonstrated practicable. It is thus very helpful in the future to investigate a large number of the CRI data for examining the physical characteristics of the atmosphere. Preliminary application to a MSE layer shows that multiple echo centers and large incident angles (close to 20°) of the echoes occurred in the upper portion of the layer. Steep refractivity structures in the layer could be one mechanism responsible for the large incident angles of echoes. More investigations are needed to clarify it.

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