5.10 HIGH-RESOLUTION OBSERVATIONS OF THE BOUNDARY LAYER USING MULTIPLE-FREQUENCY RANGE IMAGING

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1 Introduction

The range resolution of pulsed radars is limited by the bandwidth of the system. Although resolution can be increased by transmitting shorter pulses, it requires not only larger system bandwidth, but also more transmitted power in order to keep the sensitivity constant. Neither requirement can be achieved easily and economically. Therefore, many efforts have been made to mitigate the range limitation such as pulse coding (Schmidt et al. 1979), and the frequency domain interferometry (FDI) technique (Kudeki and Stitt, 1987). The FDI technique was developed to detect a single thin layer structure embedded within the radar volume using a pair of shifted transmit frequencies. However, with the increased need for higher resolution, the inherent assumption of a single Gaussian-shaped layer in the dual-frequency FDI analysis limits its applications. The idea of using more than two frequencies to improve range resolution was proposed by Stitt and Bowhill (1987). A generalization of multiple frequency techniques, termed range imaging (RIM), was proposed by Palmer et al. (1999), which is free of the assumption made in FDI. As a result, fine details of atmospheric structure in range can be revealed within the radar volume using RIM. It should be noted that similar idea was proposed independently by Luce et al. (2001) and was termed frequency domain radar interferometric imaging (FII).

Although RIM is a relatively new technique, its potential for resolving small-scale structures has already been demonstrated using VHF radars such as the sounding system (SOUSY) radar in Germany (Palmer et al. 2001) and the middle and upper atmosphere (MU) radar in Japan (Luce et al. 2001). Recently, RIM has been implemented on the Platteville 915 MHz tropospheric profiler for studies of the boundary layer and the lower free troposphere (Chilson et al., 2001; Muschinski et al. 2001; Yu et al. 2001). In this work, preliminary results of implementing RIM on the multiple antenna profiler radar (MAPR) of the National Center for Atmospheric Research (NCAR) are presented. The MAPR system was modified from the conventional 915 MHz boundary layer profiler (BLR) (Eckund et al. 1988) and can provide boundary layer measurements on high temporal and range resolution of 30 sec and 50 m, respectively (Cohn et al. 2001). Moreover, RIM can improve upon the existing range resolution while using relatively long transmitted pulses.

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2 An Overview of Range Imaging

Mathematically, RIM can be posed as an inversion problem given measurement of the visibility function $V(\Delta k)$, which can be represented by the normalized correlation function at zero temporal lag as a function of the wavenumber difference Δk of signals from shifted frequencies (e.g., Yu and Palmer 2001).

$$V(\Delta k) = \int b_r(R)\, W_r^2(R)\, e^{-j2\Delta k\, R}\, dR \qquad (1)$$

where $W_r(R)$ is the range weighting function of the radar system at range R, at which the range brightness $b_r(R)$ is to be estimated. The range brightness is the angular averaged power density normalized by the total received power. The Doppler information of the range brightness can be obtained when the visibility function is represented by the normalized cross spectrum and the inversion is solved independently at each frequency.

From (1), it is evident that $V(\Delta k)$ and the product of $b_r(R)$ and $W_r^2(R)$ are a Fourier trans-form pair. Therefore, $b_r(R)$ and $V(\Delta k)$ are analogous to the power spectrum density and auto correlation function in the classical spectrum estimation, respectively. A straightforward method of estimating the range brightness is to take a discrete inverse Fourier transformation of (1) and remove the effect of $W_r^2(R)$. This is the so-called Fourier RIM and its resolution is limited by the selection of transmit frequencies (e.g., Palmer et al. 1999). Two high-resolution methods have been used with RIM, which are the Capon method (Palmer et al. 1999) and the multiple signal classification (MUSIC) method (Luce et al. 2001). Both methods have been widely used in other applications such as spectrum analysis, and array signal processing (e.g., Haykin et al. 1985). Capon RIM was derived by solving a constrained optimization and can be represented in the following matrix form (Palmer et al. 1999 and the references therein).

$$\hat{b}_r(R_i) = \frac{1}{\mathbf{e}_r^{\dagger}\mathbf{V}^{-1}\mathbf{e}_r} \tag{2}$$

where the $\dagger$ is the Hermitian operator and $\mathbf{V}$ is the visibility matrix containing correlation function at zero temporal lag from all the frequency pairs (Palmer el at. 1999). The steering vector $\mathbf{e}_r$ is defined by the following equation.

$$\mathbf{e}_r = \left[\begin{array}{cccc} e^{-j2k_1R_i} & e^{-j2k_2R_i} & \dots & e^{-j2k_mR_i} \end{array}\right]^T \tag{3}$$

Estimation of the range brightness is improved by suppressing interference, which are signals at ranges other than the range where the range brightness is estimated. For MUSIC RIM, the resolution is improved by considering only signals from signal sub-space which are extracted using the singular value decomposition (SVD) algorithm. Note that MUSIC RIM is ideal for determining the location of infinitely thin layer, but the absolute magnitude of the range brightness cannot be obtained (Luce et al. 2001).

3 Experimental Results

The MAPR system has been recently modified to transmit multiple frequencies generated by independent frequency synthesizers. The field experiment of implementing RIM on MAPR has been conducted from 21 August to 10 September, 2001 at Marshall, Colorado. Other instruments, including the Miniature Elastic Backscatter Lidar (MEBL) of the Johns Hopkins University with vertical resolution of 1.5 m, the tethered atmospheric observation system (TAOS) of NCAR, and radiosondes, were also operated during some periods of the experiment.

During most of the experiment, four transmit frequencies were selected to have non-redundant frequency spacing at 914.667, 915.0, 916.0, and 916.667 MHz in order to improve the estimation of the range brightness (e.g., Palmer et al. 2001). These four frequencies were transmitted vertically on a pulse-by-pulse basis and four receivers were used. As a result, sixteen data streams were generated. However, RIM analysis requires multiple-frequency signals from only a single receiver. Therefore, the visibility matrix in (2) was calculated independently for each receiver and then was added coherently in order to increase the signal-to-noise ratio (SNR). The atmosphere was sampled every 100 m with a range resolution of 200 m. In other words, 50% oversampling in range was employed in an attempt to test the range consistency of RIM analysis. For each gate, the range brightness was estimated at 40 subgates by properly setting R_i in (2). An example of the range brightness estimated using Capon RIM is given in Figure 1(a). The data shown here were taken from 1716-1959 UT on 9 September, 2001. The lower plot gives the conventional range-time-intensity (RTI) plot of the SNR (in dB) from MAPR. Note that the region with more returned power is presented in darker tones. It is evident that the distinct layer at approximately 1.4 km can be clearly identified using the Capon RIM, especially during the period from 1830 UT to 1900 UT. The white strips are periods when the radio acoustic sounding system (RASS) was operated and only a single frequency was used. Note that Fourier and Capon RIM produced similar results while Fourier RIM provided broader structures due to the resolution limitation and therefore, results of Fourier RIM are not shown.

It is planned to compare the RIM results with the lidar measurements which has a fine range resolution of 1.5 m, but unfortunately, the lidar data from that period were very noisy for altitude above approximately 1 km. A possible explanation is that the top of the boundary layer was shallow at approximately 1 km and was lack of aerosols in the free troposphere. Moreover, neither TAOS or radiosondes were operated during that period. However, the 50% oversampling in range still provides an opportunity to examine the range consistency of RIM on MAPR. The Capon RIM from three adjacent gates, which are centered at 1.3, 1.4 and 1.5 km, are shown in Figure 2. Due to the oversampling in range, it is expected that when the layer at gate 13 moved to the lower half portion of the gate, it shall be observed in the upper half portion of gate

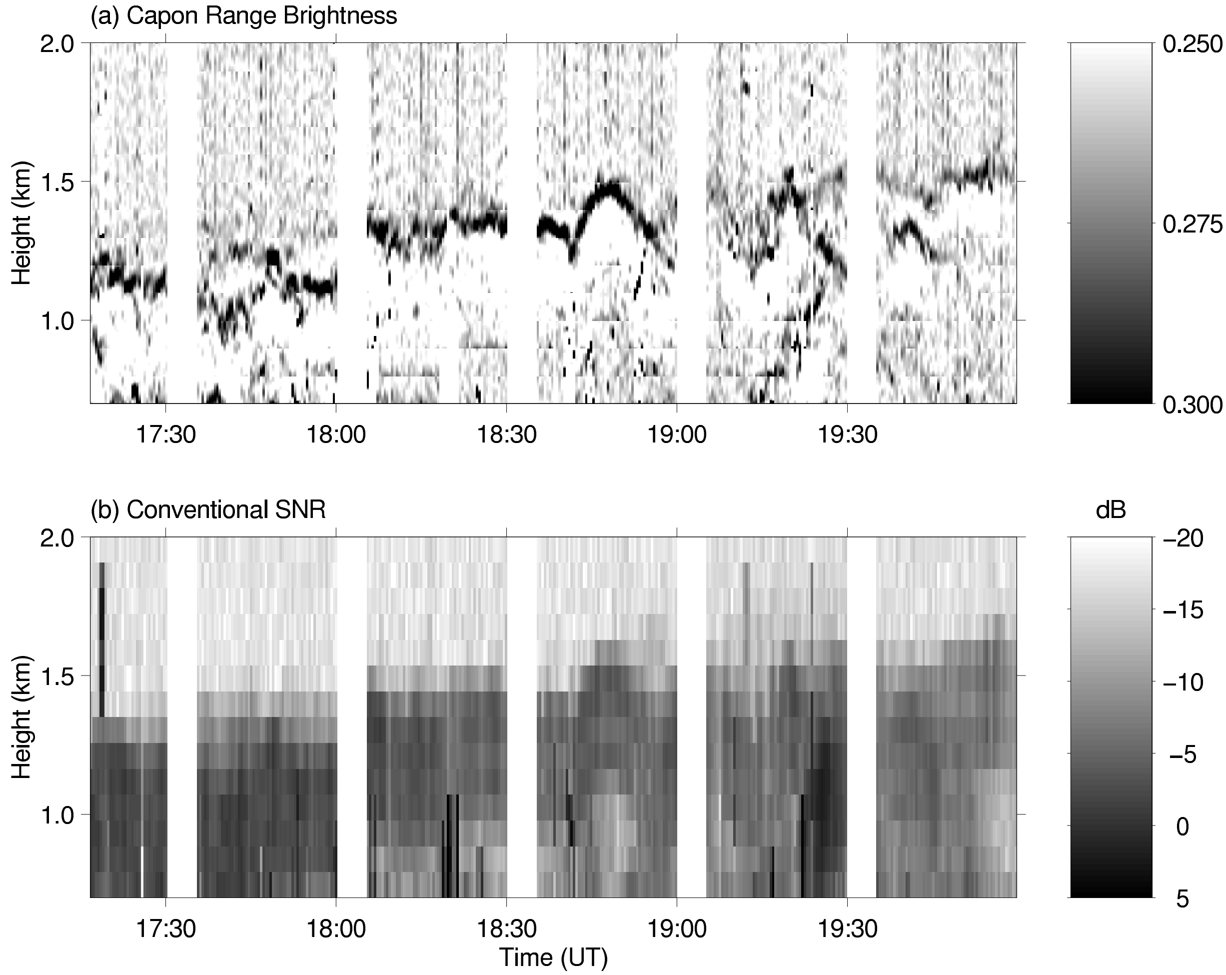

Figure 1: Comparisons of (a) SNR, (b) Capon range brightness. Similar structures are observed in both plots but more detailed structures are revealed using Capon RIM.

12 simultaneously. Similar argument is applied to the other half of gate 13 and 14. Such consistency can be clearly observed in Figure 2 especially when the layer is well-defined such as from 1830 UT to 1900 UT. In order to further verify RIM results quantitative, the layer position was estimated by calculating the first moment of the range brightness within one range gate at each time. The layer positions estimated using data shown in Figure 2 are shown in Figure 3. The correlation of the layer positions estimated from the three adjacent gates is extremely high from 1800 UT to 1900 UT. During this period, the layer width, defined as twice of the second moment of the brightness estimates, is approximately on the order of 60 m. Future work is to find cases where both the lidar and in-situ measurements (TAOS or radiosondes) are all available. Therefore, RIM can be further verified using these data.

4 Conclusions

RIM was developed recently to improve the range resolution of conventional pulsed radars using multiple transmit frequencies. By analyzing signals from shifted frequencies, the atmospheric structure can be revealed within the radar volume in the vertical extent. In this work, it has been shown that RIM on MAPR produced highly range-consistent results by using the distinct layer as a reference. Due to the high-resolution gained by RIM, the detail variation of the boundary layer top can be depicted as exemplified by Muschinski et al. (2001). Increased vertical resolution will also be beneficial in the stable boundary layer, where layering is likely. Moreover, other parameters such as the three-dimensional wind field and turbulence intensity can be obtained using spaced antenna method simultaneously with the high-resolution RIM measurements, which should provide more insight of the

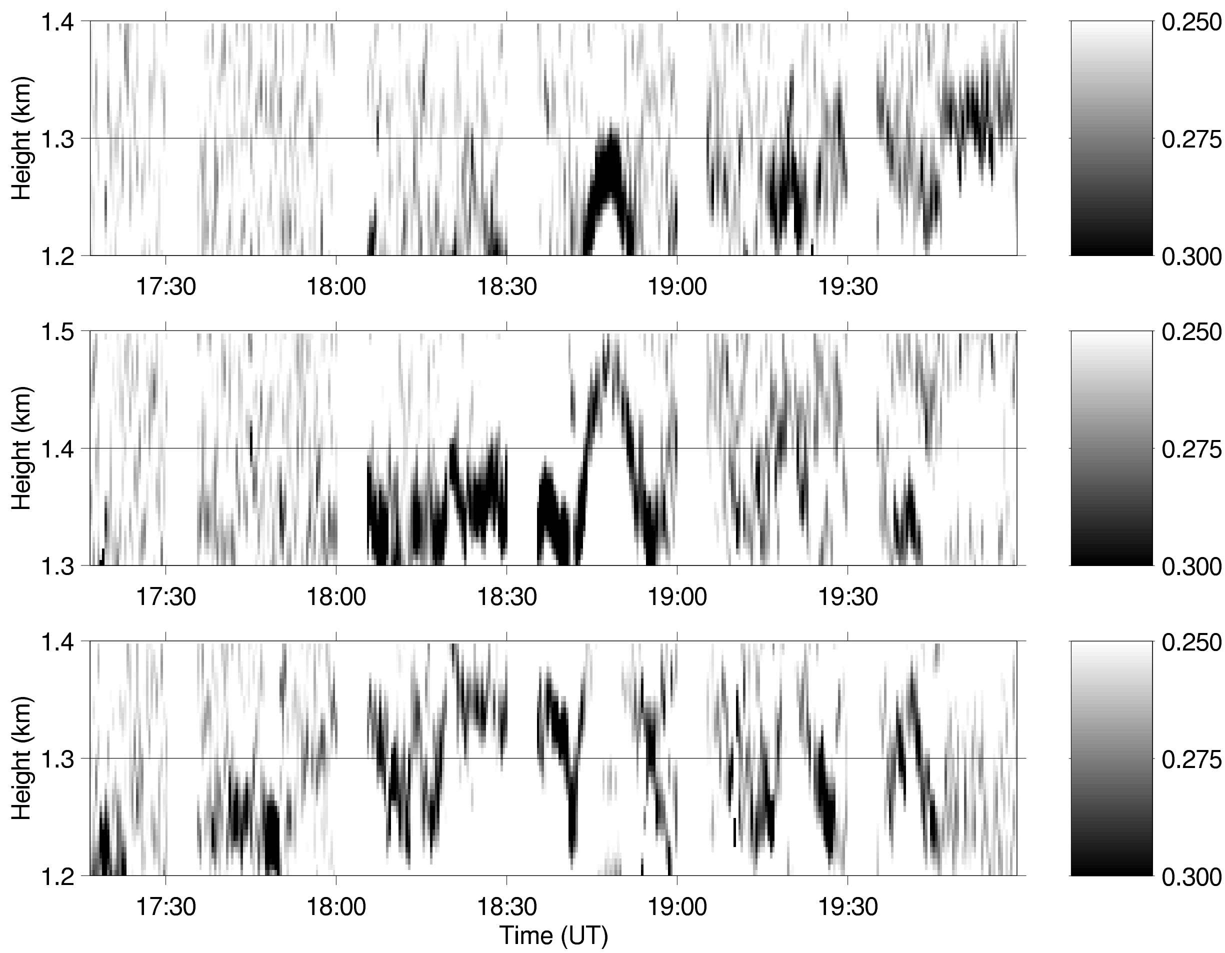

Figure 2: Capon range brightness from three adjacent gates, which are gate 12, 13 and 14 from the bottom to top plots, respectively. The center of each gate is indicated by a solid line. It is evident that the layer in the lower half part of gate 13 is consistent with the layer in the upper half part of gate 12. Similar correlation can be observed between gate 7 and 8 as well. The result demonstrates that RIM produces self-consistent estimates from gate to gate.

lower atmospheric dynamics.

Acknowledgments T.-Y. Yu was supported by the Advance Study Program of NCAR. Thanks are due to Mike Susedik, Gary Granger, and Charles Martin for modifying the MAPR system. Practical support for these efforts was obtained through the Department of Energy's Environment Meteorology Program.

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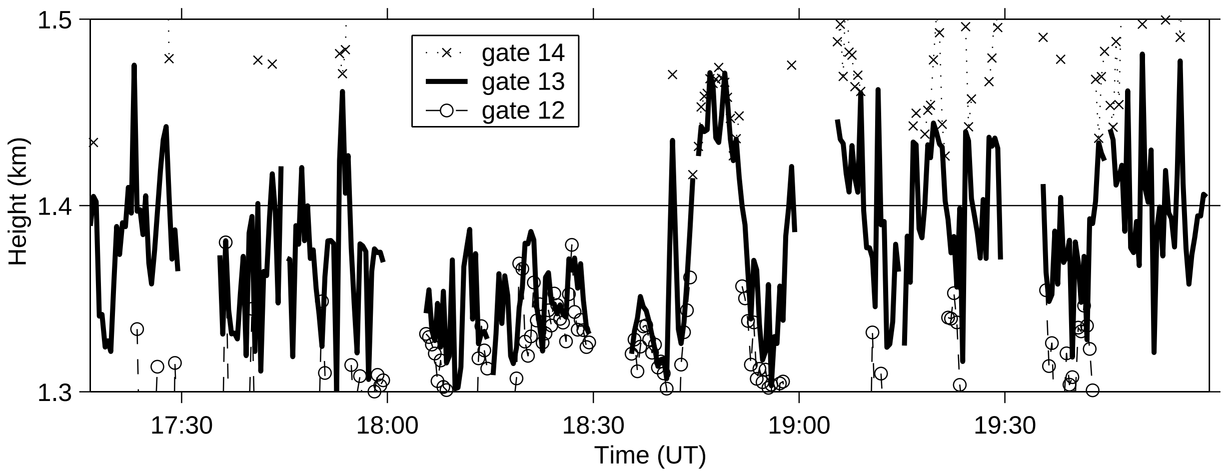

Figure 3: A comparison of layer position estimated using the Capon range brightness shown in Fig. 2. The layer positions estimated from the three adjacent gates are consistent.

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