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## **Evaluation of multifrequency range imaging technique implemented on the Chung–Li VHF atmospheric radar**

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Abstract. The multifrequency range imaging technique (RIM) has been implemented on the Chung-Li VHF array radar since 2008 after its renovation. This study made a more complete examination and evaluation of the RIM technique to facilitate the performance of the radar for atmospheric studies. RIM experiments with various radar parameters such as pulse length, pulse shape, receiver bandwidth, transmitter frequency set, and so on were conducted. The radar data employed for the study were collected from 2008 to 2013. It has been shown that two factors, the range/time delay of the signal traveling in the media and the standard deviation of Gaussian-shaped range-weighting function, play crucial roles in ameliorating the RIM-produced brightness (or power distribution); the two factors are associated with some radar parameters and system characteristics. The range/time delay of the signal was found to increase with time; moreover, it was slightly different for the echoes from the atmosphere with and without the presence of significant precipitation. A procedure of point-by-point correction of range/time delay was thus executed for the presence of precipitation to minimize the bogus brightness discontinuity at range gate boundaries. With the RIM technique, the Chung-Li VHF radar demonstrates its first successful observation of double-layer structures as well as their temporal and spatial variations with time.

## 1 Introduction

The mesosphere-stratosphere-troposphere (MST) radar operated at very-high-frequency (VHF) band is a powerful instrument to study the atmosphere from near the ground up to the ionosphere. Among the capabilities of VHF-MST radar, continuous measurement of three-dimensional winds with a temporal resolution of several minutes and a vertical resolution of several hundred meters are praiseworthy (Lee et al., 2014). In addition to the air motion characterized by the wind field, small-scale structures of refractivity irregularities, such as thin layers with a thickness of tens of meters, exist commonly in the atmosphere and can reflect dynamic behavior of the atmosphere directly. However, a conventional atmosphere radar that operates at a specific frequency and a finite pulse length is unable to resolve the thin-layer structures embedded within the range gate. In view of this, a frequencyhopped technique was introduced to the pulsed radar to overcome this limitation (Franke, 1990). The frequency-hopped technique was initially implemented with two frequencies on the VHF-MST radar, which can only resolve a Gaussianshaped single layer in the range gate. Implementation of the frequency-hopped technique with more than two frequencies was not achieved until 2001 for an ultra-highfrequency (UHF) wind profiler (Platteville 915 MHz radar at 40.19° N, 104.73° W) (Chilson et al., 2003, 2004). Since then, the European Incoherent Scatter (EISCAT) VHF radar, the Middle and Upper Atmosphere Radar (MUR; 34.85° N, 136.10° E), the Ostsee Wind (OSWIN) VHF radar (54.1° N, 11.8° E), the Chung-Li VHF radar (24.9° N, 121.1° E), and so on have also implemented this technique to observe gravity waves, double-layer structures, Kelvin-Helmholtz instability (KHI) billows, convective structures, polar mesosphere summer echoes (PMSE), and so on, with high resolution in the range direction (e.g., Fernandez et al., 2005; Luce et al., 2006, 2008; Chen and Zecha, 2009; Chen et al., 2009). The terminologies of range imaging (RIM) (Palmer et al., 1999) and frequency interferometric imaging (FII) (Luce et al., 2001) were given to the frequency-hopped technique for the radar remote sensing of the atmosphere. Some advanced applications of RIM have also been proposed, e.g., a highresolution measurement of wind field in the sampling gate (Yu and Brown, 2004; Chilson et al., 2004; Yamamoto et al., 2014). Moreover, three-dimensional imaging of the scattering structure in the radar volume has been put into practice by combining RIM and coherent radar imaging (CRI) techniques (Hassenpflug et al., 2008; Chen et al., 2014a). Recently, some efforts on the calibration process of radar echoes were made to improve the performance of RIM (Chen et al., 2014b). In addition to the aforementioned works of RIM, a deconvolution procedure working with a swept-frequency pulse has been employed (Hocking et al., 2014), which also provided a range resolution higher than the pulse-defined value.

In this study, a large amount of RIM data that were collected by the Chung-Li VHF radar with various pulse lengths and shapes, phase codes, receiver bandwidths, frequency sets, and so on for the period from 2008 to 2013 were analyzed to evaluate the capability of the RIM technique implemented on the radar. It has been shown that the performance of RIM for the thin-layer measurement relies on a proper calibration of the radar data, including time delay of radar signal, signal-to-noise ratio (SNR), and the rangeweighting function effect (Chen and Zecha, 2009). The time delay of the radar signal traveling in the media - such as the cable lines, free space, and processing time in the radar system - leads to a range delay and thereby gives a range error in the RIM processing. Furthermore, the removal of the range-weighting function effect on the spatial distribution of the RIM-produced brightness is required to restore the finer structures in the radar volume (Chen et al., 2014b). To this end, the calibration approach proposed by Chen and Zecha (2009), which is more convenient for our analysis, was employed in this study.

This article is organized as follow. In Sect. 2, the RIM capability of the Chung–Li VHF radar is introduced briefly. Section 3 gives an example of RIM as well as its calibration results for different radar parameters such as receiver system and frequency set. Section 4 presents the observations of precipitation and some layer structures. It is found that the time delay measured for precipitation echoes was different slightly from that of clear-air turbulences. A deeper examination was made to improve the RIM-produced brightness for precipitation echoes. In addition, double-layer structures and finer parts within the structures were resolved success-

fully to demonstrate the capability of RIM implemented on the radar system. Conclusions are drawn in Sect. 5.

# 2 Range imaging technique of the Chung–Li VHF radar

The Chung-Li VHF radar system, operated at a central frequency of 52 MHz, has been upgraded for several years and carried out some valuable studies for the atmosphere (Chu et al., 2013; Su et al., 2014). In addition to a great improvement in radar signal processing, various pulse shapes such as rectangular, Gaussian, and trapezoid are available, and typical pulse widths are 1, 2, and 4 µs, yielding range gate resolutions of 150, 300, and 600 m, respectively. In addition, the range step can be as small as 50 m for oversampling (Chen et al., 2014b). Corresponding filter bandwidths can be chosen to match the transmitted pulse widths and pulse shapes. Barker and complementary codes are available to raise the signal-to-noise ratio of the received echoes, and more than five frequencies with a frequency step as small as 1 Hz can be set. These renovations and improvements in the radar characteristics enable the newly upgraded Chung-Li VHF radar to use the RIM technique to observe finer structures in the atmosphere. The first RIM experiment made with the Chung-Li radar was conducted successfully in 2008 (Chen et al., 2009), and since then plenty of experiments with the RIM mode have been carried out by the radar. Table 1 lists many of the observations and their calibration results that will be discussed later. As listed, 1 and 2 µs pulse lengths, three types of pulse shapes, and different bandwidths and frequency sets were tested. Moreover, three receiving channels (subarrays) were operated for reception of radar echoes. The analysis of various kinds of radar data can help us to realize the capability of the RIM technique implemented on the radar system for atmospheric measurements. A possible drawback of RIM may arise from the relatively broad radar beamwidth  $(\sim 7.4^{\circ})$ , which smears the measured structure imaging due to a noticeable curvature of the radar beam.

In the RIM processing, the Capon method (Palmer et al., 1999), one of the optimization methods, was employed to estimate the range-dependent brightness. Although other optimization methods such as maximum entropy (Yu and Palmer, 2001) and multiple signal classification (Luce et al., 2001) are usable for RIM, the Capon method is simple, less time consuming, and robust for the processing of radar data (Yu and Palmer, 2001). Nevertheless, some deficiencies of the Capon method in spectral analysis were also reported. When the number of carrier frequencies used for RIM was not larger than the number of distinct spectral lines in the signal (e.g., distinct moving layers or targets with different velocities), the Capon method could not resolve the distinct spectral lines effectively and might miss the weaker ones. Moreover, the Capon method was not superior to the fast Fourier transform for a continuous spectrum (Li and Stoica, 1996; Garbanzo-Salas and Hocking, 2015). In practical operation

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for the atmosphere, however, the number of carrier frequencies is limited, which will be discussed in Sect. 3.3. In addition, it is supposed that the principal layers or targets in the range gate interval (commonly from 150 to 600 m) are less than two or three. Therefore, the requirement of a large number of carrier frequencies can be discarded, and the Capon method is still sufficient for use with a smaller number of carrier frequencies, say, four or five.

To acquire proper imaging of refractivity structures, corrections of range error and range-weighting function effect are essential. In this study, we employed the calibration approach given by Chen and Zecha (2009) to make necessary corrections, which has been successfully tested for the Chung-Li radar and the MUR (Chen et al., 2009). The estimator of mean square error that is used to determine the optimal parameters for correcting the RIM-produced brightness is given by

$$\Delta B = \sum_{i=1}^{N} \frac{(B_{1i} - B_{2i})^2}{B_{1i}B_{2i}},\tag{1}$$

where  $B_{1i}$  and  $B_{2i}$  are two sets of RIM-produced brightness values in the overlapped sampling range intervals of two adjacent range gates. N is the number of brightness values. Although the echoing structures in the overlapped sampling range intervals are the same and are supposed to have similar  $B_1$  and  $B_2$  values, the estimated  $B_1$  and  $B_2$  values may not be close to each other owing to two factors: sampling range error and range-weighting effect. Therefore,  $B_1$  and  $B_2$  values are expected to approximate to each other after the two factors are mitigated. In the calibration process, the optimal mitigation of the two factors gives the smallest value of  $\Delta B$ , which is achieved by changing iteratively the sampling range error and the standard deviation of the Gaussian-shaped rangeweighting function in computing.

#### **3** Observations and calibrations

Table 1 lists 16 cases of RIM experiments that were carried out between 2008 and 2013 by using the Chung–Li VHF radar. With the plentiful radar data, the long-term variation in some of the characteristics of radar system will be addressed and discussed. In addition, the RIM experiments conducted on 9 November 2009 (cases 9 and 10) are presented as typical cases for specific demonstration in the following.

#### 3.1 Different receiver systems

Figure 1 shows the statistical results of the calibrationestimated phase bias (left panels) and standard deviation  $\sigma_z$  (right panels) of the Gaussian range-weighting function  $\exp(-r^2/\sigma_z^2)$ , where *r* is the range relative to the gate center, for the radar data of case 10. Only the atmospheric echoes with the SNR larger than  $-9 \,\text{dB}$  were analyzed and are presented in Fig. 1. Note that the phase bias is a



**Figure 1. (a)** Histograms of the calibrated parameters for three independent receiving channels. Phase bin is 20°, and  $\sigma_z$  bin is 10 m. The shapes and sizes of the three receiving arrays are the same. (b) Scatterplot of the calibrated parameters vs. SNR for the second receiving channel (Rx\_2). The curve describing the relationship between  $\sigma_z$  and SNR is a fitting curve for correcting the RIM-produced brightness. Data time: 06:49:27–08:49:47 UT, 9 November 2009.

value transformed from the following equation: range delay  $\times 360^{\circ}$  / range gate interval. Therefore, in this case the phase bias of 360° corresponds to a range delay of 150 m or a time delay of 0.5 µs for the signal propagation.

As shown in Fig. 1, the phase bias histograms of the three receiving channels were consistent with each other. The mean phase biases were centered at around  $1230^{\circ}$  (peak location), corresponding to a range delay of 512.5 m or a time delay of  $\sim 1.708 \,\mu$ s. Note that some data with low SNR caused randomly distributed phase biases with numbers much less than those at peak location. In general, the distributions of phase biases for all of the RIM experiments listed in Table 1 were centered at their respective mean values, and the mean values of the three receiving channels were nearly the same.

In view of this, the three receiver systems are thought to be approximately identical in conducting the RIM experiment. This, however, does not mean that the system phase difference between receiving channels, which is a crucial parameter for spatial radar interferometry, is close to zero. Similarity of phase bias distributions between different receiving channels suggests that the range/time delay is not the main cause of the system phase difference, if one exists, between receiving channels of the Chung–Li radar. This issue needs to be clarified by other means and will not be discussed further in this study.

Figure 1b presents scatter diagrams of phase bias (left) and  $\sigma_z$ (right) vs. SNR. As shown, for the data with SNR > 0 dB, the phase biases are distributed mainly in a range of 1080–1440°, centered at around 1230°. By contrast, the  $\sigma_z$  values were SNR dependent, as seen in the right panel of Fig. 1b. A curve has been determined to represent the relationship between  $\sigma_z$  and SNR (Chen and Zecha, 2009), which is beneficial to produce the structure at gate boundaries with smoother imaging and is given below:

$$\sigma_z = \frac{1}{\frac{a}{(\mathrm{SNR} + 10)^C} + b} - d,\tag{2}$$

where the four constants a, b, c, and d are given in the plot (reading from top to bottom). The fitting curve reveals that the  $\sigma_z$  value tended to approach a constant value of about 100 m as the SNR increased. This curve-approached  $\sigma_z$  value at high SNR was close to the peak location of  $\sigma_z$ histogram ( $\sim 115 \text{ m}$ ) shown in the right panels of Fig. 1a. The  $\sigma_z$  value at large SNR or the peak location of the  $\sigma_z$ histogram can describe the theoretical shape of the Gaussian range-weighting function. As derived in the previous studies (e.g., Franke, 1990), the standard deviation of the Gaussian range-weighting function is given by  $0.35 c\tau/2$ , where c is the speed of the light and  $\tau$  is the pulse width. This value is obtained for a rectangular pulse shape used with its matched filter; for example, 52.5 m for 1 µs pulse width. According to our definition of Gaussian range-weighting function, however,  $\sigma_z$  equals  $\sqrt{2} \times 0.35c\tau/2$ , namely, about 74 m for 1 µs pulse width. This number is smaller than the calibrated value (100 or 115 m). This is because the case presented in Fig. 1 employed a Gaussian instead of rectangular pulse shape, resulting in a range-weighting function broader than that defined by the standard deviation of 74 m. By contrast, a trapezoid pulse shape that is close to a rectangular shape was employed in case 8, thereby resulting in a value of 80 m for the peak location of  $\sigma_z$ , which is not far from the value of 74 m. As for the dependence of the  $\sigma_z$  value on SNR, it is not unaccountable because the performance of the Capon method is also SNR-dependent (Palmer et al., 1999; Yu and Palmer, 2001). As the SNR decreases, the RIM brightness becomes less accurate. In addition, there should be less and less to image as the SNR gets lower. As a result, the range-weighting effect becomes unimportant and a larger value of  $\sigma_z$  is obtained from the calibration process for a lower SNR case. It



**Figure 2.** Time delays in different time periods. Refer to Table 1 for the observational time period of each case.

should be recalled that the relationship curve for  $\sigma_z$  and SNR could vary with the optimization method of range imaging; the calibration results exhibited in this paper are valid only for the Capon method.

## **3.2** Time- and radar-parameter-dependent characteristics

As revealed in Table 1, the peak location of phase bias varied with time. For 1 µs pulse length, the peak location was larger in 2013 than in 2009. For 2 µs pulse length the peak locations obtained in 2011 and 2012 were evidently larger than those obtained in 2008. The increase in phase bias with time is presumably due to the aging of cable lines or some components in the radar system that cause additional time delay of signal. As shown in Fig. 2, the time delay estimated from the phase bias of receiver 1 (Rx\_1) indeed has a tendency to increase with time. Nevertheless, those values of time delays for 1 µs pulse length in 2009 were obviously larger than the level indicated by the increasing tendency of time delay. It is thus worthy of additional investigation in the future to learn whether the radar system responds to different pulse lengths to result in various time delays; this can provide us a fully understanding of the characteristics of the radar system or other fundamental factors.

On the other hand, the peak location of the  $\sigma_z$  histogram,  $\sigma_{z, \text{peak}}$ , was not time dependent. Instead, it is a function of pulse shape and filter bandwidth, for example, the three radar experiments (cases 2–4) conducted on 11 April 2008 with different pulse shapes and filter bandwidths that were set alternately in the experiments (Chen et al., 2009). The experiment with Gaussian-shaped pulse and 250 kHz bandwidth (case 2) had a larger  $\sigma_{z, \text{peak}}$  than that with squared pulse shape but the same filter bandwidth (case 3), and also larger than that with the same pulse shape but 500 kHz bandwidth (case 4), indicating a dependence of  $\sigma_z$  value on radar pulse shape as well as receiver bandwidth.

More examples are the radar experiments carried out on 27 July and 9 November in 2009 (cases 8–10). The pulse length

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Case Exp. date Pulse length (µs)/ Filter band-Sampling Calibration results: Freq (hh:mm, UT) shape/code or width (kHz) set (MHz)/ time (s) peak location of phase bias/ $\sigma_{z, \text{ peak}}$ range delay/time delay oversampling freq. no.  $Rx_1$  $Rx_2$ Rx\_3 1 2008/03/30 2/s500 0.256 320°/160 m 320°/180 m 330°/170 m  $f_a/5$ (17:05-24:00)(267 m/0.889 µs) 2 2008/04/11a 2/g 250  $f_a/5$ 0.256 350°/260 m 340°/250 m 350°/260 m (02:50-04:20)(292 m/0.972µs) 3 2008/04/11b 2/s250  $f_a/5$ 0.256 325°/210 m 340°/200 m 330°/210 m (02:50-04:20)(271 m/0.903 µs) 4 2008/04/11c  $f_a/5$ 0.256 340°/210 m 350°/210 m 350°/220 m 2/g 500 (02:50-04:20)(283 m/0.944 µs) 5 345°/220 m 2008/09/12a 2/s250  $f_a/5$ 0.256 350°/220 m 350°/220 m (02:54-05:17)(288 m/0.958 µs)  $f_{\rm b}/5$ 6 2008/09/12b 250 0.256 340°/220 m 350°/225 m 350°/220 m 2/s(02:54-05:17)(283 m/0.944 µs) 7 315°/160 m 2008/09/12c 2/s/7 bit Barker 500  $f_a/5$ 0.32 320°/180 m 320°/170 m (06:12-07:15)(267 m/0.889 µs) 8 2009/07/27 1/T 1000 0.512 1180°/80 m 1180°/85 m 1200°/80 m  $f_{\rm d}/5$ (05:30-08:23) (492 m/1.639 µs) 9 2009/11/09a 1/g 1000  $f_e/7$ 0.1792 1230°/115 m 1230°/115 m 1250°/115 m (03:08-05:38)(513 m/1.708 µs) 10 2009/11/09b 1/g 1000  $f_{\rm f}/7$ 0.1792 1230°/115 m 1230°/115 m 1240°/120 m (06:49-08:49)(513 m/1.708 µs) 11 500°/210 m 505°/200 m 505°/200 m 2011/12/02 2/g/over 500  $f_a/5$ 0.128 (03:39-05:52)(417 m/1.389 µs) 500°/150 m 12 500°/150 m 500°/150 m 2012/01/05 2/s/over 500  $f_a/5$ 0.128 (417 m/1.389 µs) (02:22-04:56)13 2012/01/05 2/s/over 1000  $f_a/5$ 0.128 520°/135 m 520°/140 m 530°/140 m (04:59-07:38)(433 m/1.444 µs) 14 2012/08/08a 2/s/over 500  $f_c/7$ 0.1792 610°/160 m 620°/160 m 615°/160 m (05:32-07:02) (508 m/1.694 µs) 615°/150 m 15 2012/08/08b 2/s/over 500  $f_g/7$ 0.1792 610°/150 m 615°/160 m (508 m/1.694 µs) (07:07-08:37) $f_{\rm d}/5$ 16 2013/08/21 1000 0.128 1410°/110 m 1420°/110 m 1410°/110 m 1/g 586 m/1.958 µs) (00:00-07:00)

Table 1. RIM experiments of the Chung-Li VHF radar and calibration results.

 $f_{a}: 51.75, 51.875, 52.0, 52.125, 52.25; f_{b}: 51.75, 51.8, 52.0, 52.1, 52.25; f_{c}: 51.75, 51.8, 51.875, 52.0, 52.1, 52.125, 52.25; f_{d}: 51.5, 51.75, 52, 52.55, 52.5; f_{c}: 51.5, 51.6, 51.75, 51.8, 51.6, 51.75, 51.8, 51.25, 52.25, 52.5; f_{f}: 51.5, 51.75, 51.8, 52.0, 52.25, 52.5; f_{f}: 51.5, 51.75, 51.8, 52.0, 52.1, 52.15, 51.25, 52.5; f_{f}: 51.5, 51.75, 51.8, 52.15, 52.5, 52.5; f_{f}: 51.5, 51.75, 51.8, 52.15, 52.5, 52.5; f_{f}: 51.5, 51.75, 51.8, 52.15, 52.5, 52.5; f_{g}: 51.75, 51.8, 53.3334, 51.916667, 52.0, 52.083333, 52.166666, 52.25; pulse shape: g = Gaussian, s = square, T = trapezoid; over: oversampling with a range step of 50 m.$ 

and filter bandwidth employed in the three experiments were the same, but the frequency sets and the pulse shapes were different. The trapezoid shape employed in case 8 is a modified square pulse with a suppression of the sharp slopes at rising and falling edges of the pulse. We shall show later that the number of frequencies was not the main cause of variation in  $\sigma_{z, \text{ peak}}$  when the number of frequencies was more than five. On the other hand, the pulse shape plays a role in determining the  $\sigma_{z, \text{ peak}}$  value, in which the trapezoid pulse shape resulted in a smaller value of  $\sigma_{z, \text{ peak}}$ . In addition, the peak location of phase bias on 27 July (case 8) was smaller than that on 9 November (cases 9 and 10) by about 50°; again, we attribute it to the aging of cable lines or some components in the radar system.

It is noteworthy that the experiment (case 7) carried out on 12 September 2008 used 7 bit Barker codes for pulse coding, with other radar parameters the same as the first RIM experiment conducted on 30 March 2008. There were no no-



Figure 3. Histograms of the calibrated parameters for different sets of transmitter frequencies, with the radar data collected from the second receiving channel ( $Rx_2$ ) in Fig. 1. The values quoted at the title locations are the transmitter frequencies; the unit is MHz.

ticeable differences in the calibration results between the two cases. Moreover, the radar system was stable in 2008 because the peak locations of phase biases were in general agreement with each other.

## 3.3 Different frequency sets

RIM exploits an advantage of frequency diversity. The number of carrier frequencies and the frequency step play crucial roles in determining the performance of RIM. Nevertheless, the number of carrier frequencies used in the experiment is subject to the radar parameters and target characteristics both. One of the assumptions of RIM is that the targets do not change their locations and characteristics during a cycle of carrier frequency set. When the target varies rapidly, the sampling time must be short enough, meaning the IPP should be short or the number of carrier frequencies cannot be too large. In all experiments listed in Table 1, the sampling times were sufficiently shorter than the variation timescale of the atmospheric targets ( $\sim 1$  s), satisfying the basic assumption of invariant targets for RIM.

Figure 3 compares the histograms of the calibrationestimated phase biases and  $\sigma_z$  values at different frequency sets and frequency steps with the radar data of case 10. As shown, except for the two-frequency mode with the frequency pair (51.5, 52.5) MHz, all of other histograms had distinct peaks with locations at around 1240°. This result



Figure 4. (a) (Left) Height-time-intensity with a range resolution of 150 m, and (right) range imaging with a range step of 1 m. (b) is similar to (a), but the radar data were collected later on the same day (9 November 2009).

clearly demonstrates that our calibration process is a robust approach to estimate the range/time delay of signal in the media and/or radar system. It can also be seen from Fig. 3 that the more the carrier frequency number is used, and the smaller the frequency separation is given, the more concentrated the distributions of phase biases and  $\sigma_z$  values will be. A closer examination shows that the peak locations of  $\sigma_z$  histograms approximate to a value of 120 m as the number of carrier frequencies increases.

In light of the fact that the performance of estimating the phase bias and the  $\sigma_z$  value is superior with more carrier frequencies and a smaller frequency step, we exhibit the RIM results of cases 9 and 10 to demonstrate finer atmospheric layer structures within the range gates, as shown in Fig. 4. The left panels of Fig. 4 shows the original height time-intensity (HTI) plots with a range resolution of 150 m, and the right panels displays the RIM-produced brightness distributions with an imaging step of 1 m. In Fig. 4, there were

some unknown interferences appeared periodically throughout range height but in short time intervals. There were also many echoes from airplanes, which were strong but limited within a short range and time interval. Ignoring these questionable echoes, a large number of thin-layer structures with thickness as small as 30 m or less can be observed from the RIM-produced brightness distributions. The temporal and spatial variations of the thin-layer structures were characterized by dynamic behavior, with the features of a prominent wavy structure (e.g., below the range height of 2.5 km in panel a), descending or ascending gradually with time, and sudden occurrence or disruption of the layers at specific heights (e.g., between the range heights of 5.0 and 6.0 km in the time interval of 4.0 and 5.0 h). In addition, double thinlayer structures with a separation as small as 100 m or less can also be resolved (e.g., between the range height of 3.5 and 4.0 km in panel b); we will discuss this type of layer structure in more detail in the next section.



**Figure 5.** (upper) Height–time–intensity with a range resolution of 150 m, and (middle and bottom) RIM-produced brightness with, respectively, constant and adaptive values of range error in the correction process. Imaging range step is 1 m. Data time: 21 August 2013.

### 4 More observations and discussion

## 4.1 **RIM for precipitation echoes**

The calibration approach employed in the preceding section for RIM is based on the assumption that the atmospheric structures are continuous at the common edges of two ad-



Figure 6. (a) Rain rate measured by the disdrometer located near the radar site. (b) Three typical power spectra of radar echoes at the times indicated sequentially by the red arrows in (a).

jacent range gates. With this assumption, the RIM-produced brightness at the common edges should be nearly identical after the two factors of range/time delay and range-weighting function effect are compensated. This assumption is basically valid for random fluctuations of the atmospheric refractivity at the Bragg scale that serve as the scatterers to generate the radar returns. However, the continuity assumption may not be true for discrete targets such as precipitation particles. In such situation of discrete targets, the RIM-produced brightness did not vary smoothly through gate boundaries, even when the calibrated parameters were applied. One example observed on 21 August 2013 is shown in Fig. 5. In the plot, we should ignore the pulse-like echoes occurring quasi-periodically at range heights around 7 km, which were due to the airplanes landing at a nearby airport. On the other hand, the strong echoes in the time interval between 5.5 h (05:30 UT) and 5.75 h (05:45 UT), and at around 5.0 h, were not only from the continuous refractivity fluctuations but also from discrete precipitation particles. This feature can be verified from the power spectra of radar echoes as well as the rain rate measured by the disdrometer located near the radar site, as shown in Fig. 6. The rain rate in Fig. 6a shows two peak intensities that occurred during the periods between 04:54 UT (4.9 h) and 05:06 UT (5.1 h) and between 05:30 UT (5.5 h) and 05:42 UT (5.7 h). The rainfall rate was alleviated between the two periods and then almost vanished after  $\sim$  05:42 UT. In Fig. 6b, three typical power spectra of radar echoes with and without precipitation are shown; the corresponding times of these power spectra are indicated sequentially by the red arrows in Fig. 6a. In the rightmost panel of Fig. 6b, the Doppler velocities were around zero throughout the altitude range; it is clear that the echoes were generated by refractivity fluctuations without the contribution from precipitation particles. By contrast, Doppler velocities with large negative values were observed in the middle panel, which were associated with heavy rain. Note that the rainfall velocity was so large that Doppler aliasing happened. The leftmost panel shows the condition of moderate precipitation, in which the spectral power of precipitation was much lower than that of refractivity fluctuations.

After range imaging with the constant phase bias indicated in Table 1, the RIM-produced brightness in the middle panel of Fig. 5 exhibits evident discontinuities at the boundaries of range gates in the periods when intense precipitation occurred. This feature is presumably due to improper phase bias (range error) compensating in the RIM processing. When adaptable phase bias was adopted for each estimate of brightness, we obtained a better result as shown in the lowest panel of Fig. 5. As seen, discontinuity of the RIM-produced brightness through gate boundaries has been mitigated for precipitation echoes. In the following, we illustrate the necessity of using adaptable phase bias for precipitation echoes.

Figure 7a shows the histograms of phase biases and  $\sigma_{z}$  values for the data presented in Fig. 5. The overall features of the histograms of phase biases and  $\sigma_7$  values are similar to those shown in Fig. 1, except for the peak location of phase biases. Normalized distributions of phase biases and  $\sigma_7$  values varying with range gates are shown in panel b. In general, the phase biases are centered at around 1400°. However, some phase biases with values smaller than 1400° by as far as 90° can be observed in the range interval between the 11th and 25th range gates. An examination shows that these phase biases were associated with intense precipitation echoes. On the other hand, the distributions of  $\sigma_z$  values were quite consistent across all range gates. Accordingly, adaptable phase bias for correction of range/time error is required to produce a more continuous imaging structure; the result has been shown in the lowest panel of Fig. 5.

The cause of difference in phase bias between precipitation and refractivity fluctuations is still unknown. A plausible conjecture is spatially inhomogeneous distribution and temporally quick change of the discrete-natured precipitation particles in the radar volume, which may lead to a breakdown of the assumptions for calibration of RIM data. This issue may be investigated and clarified by using the technique of multi-receiver CRI (Palmer et al., 2005). Unfortunately, the Chung–Li radar does not have enough receiving channels for CRI technique, and we need other suitable radars with CRI capability to conduct the radar experiment to tackle the problem of difference in phase bias between precipitation and refractivity fluctuations.

#### 4.2 Double-layer structures

As shown in Fig. 4, various thin-layer structures can be disclosed by using the RIM technique. In this sub-section, two



**Figure 7. (a)** Histograms of the calibrated parameters for the radar data shown in Fig. 4. (b) Normalized distributions of the calibrated parameters at different range gates. The value attached on the right side of each gate is mean SNR in dB of that gate.

kinds of double thin-layer structures are inspected. In the lower panel of Fig. 8a, a stable double thin-layer structure separated by about 0.2 km was observed in the range interval between 3.2 and 3.6 km, which cannot be resolved by the original HTI shown in the upper panel of Fig. 8a. The physical processes involved in the generation of the double thinlayer structure are KHI or vertically propagating wave breaking, both of which are associated with strong wind shear occurring in a very narrow range extent. Strong turbulence mixing is expected to occur in the double-layer structure due to dynamic instability, which leads to an enhancement of perturbation of the atmospheric refractivity and causes intermittent occurrences of the relatively intense echoes between the two layers. The lower panel of Fig. 8b presents another type of double thin-layer structure that is characterized by temporal merging and separation of the upper and lower thin layers, and exhibits much finer height-time structures than the original HTI shown in the upper panel of Fig. 8b. Notice that, possibly being subject to a broad beam width ( $\sim 7.4^{\circ}$ ) of the Chung-Li VHF radar that may smear the RIM-produced brightness due to a limitation of poor horizontal resolution,



**Figure 8.** Two types of double-layer structures observed on 9 November 2009. In (**a**, **b**) both the upper and lower panels show, respectively, height–time–intensity and RIM-produced brightness.

the billow structures associated with the KHI were difficult to identify.

## 5 Conclusions

The Chung–Li VHF radar initiated multifrequency experiment in 2008, giving the capability of range imaging for detecting finer atmospheric structures in the radar volume. Plenty of radar data have been collected since then, using different radar parameters such as pulse length, pulse shape, receiver bandwidth, transmitter frequency set, and so on. With these radar data, the RIM technique has been evaluated widely. Various kinds of thin-layer structures with thickness of tens of meters were resolved even though the broad beamwidth of the radar beam may smear the echoing structures. For example, double thin-layer structures having occurrences of intense echoes within the two layers have been resolved for the first time for the Chung–Li VHF radar.

With the calibration process of RIM conducted in this study, it is found that the typical range/time delay of the signals can be obtained with only two-frequency data as long as the frequency separation of the two frequencies is small. For deriving the optimal range-weighting function, however, the use of seven carrier frequencies with 0.125 MHz frequency step resulted in much more accurate outcomes than the use of two carrier frequencies. A remarkable finding is that the longer the operating hours of the radar system is, the larger the range/time delay will be; this feature is presumably at-

tributed to the aging of cable lines or components in the radar system. One more important finding in this study is a visible shift of range delay when precipitation echoes are significant, which causes the problem of discontinuity in the RIMproduced brightness at range gate boundaries. We propose in this article a process of point-by-point correction of range error to mitigate the brightness discontinuity to improve the imaging quality of the RIM-produced structures for precipitation environment.

Based on the capability of the RIM technique in resolving finer atmospheric structures, it is expected that RIM can help us to reveal more detailed information on the topics of special atmospheric phenomena, such as a tremendously thin layer structure, minute turbulence configuration, and spatial precipitation distribution in the radar volume. It is also expected that in the future the RIM technique in combination with further modern methods can be applied to the ionosphere for observing plasma density fluctuations in the meteor trail as well as field-aligned plasma irregularities. High resolution at several meters may reveal the delicate structure of plasma irregularities in more detail, which can hopefully help us to understand the temporal evolution of plasma instability at the very beginning stage.

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