Multiple-frequency range imaging on the mesosphere-stratosphere-troposphere radars

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1. Introduction

Using multiple frequencies for range imaging (RIM) of the atmosphere has become a standard technique of the mesosphere-stratosphere-troposphere (MST) radars. The main capability of the RIM technique is to resolve multiple irregularity layers in the radar volume, which improves the range resolution of backscattered power (or brightness distribution) greatly.

The OSWIN VHF radar (54.1°N, 11.8°E; Germany) has established the RIM technique recently. To validate the RIM technique in the radar is thus the main purpose of this study. We start with the essential work—phase calibration of the signals received with different frequencies, before applying the technique to various investigations of the atmosphere.

2. OSWIN VHF radar and range imaging technique

The OSWIN VHF radar, operated at a central frequency of 53.5 MHz, can transmit the frequencies from 53.25 MHz to 53.75 MHz without technical problems. The smallest frequency step is 1 kHz. Radar pulse shape can be Gaussian or rectangular, and a variety of receiver filter bandwidths ranging between 18.1 kHz and 404 kHz are available. Moreover, complementary codes are usually employed to improve the signal-to-noise ratio (SNR). For more descriptions of the radar configuration/characteristics, browse the website www.iap-kborn.de.

Range imaging is based on the inversion processing with the signals received by several carrier frequencies. Capon’s method [1], introduced to the MST community by Palmer et al. [6], is one of the inversion approaches. The Capon equations without Doppler frequency sorting are

\[
B(r) = \frac{1}{e^{H}R^{-1}e} \quad \text{and} \quad R = \begin{bmatrix}
R_{11} & R_{12} & \ldots & R_{1n} \\
R_{21} & R_{22} & \ldots & R_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
R_{n1} & R_{n2} & \ldots & R_{nn}
\end{bmatrix},
\]

where \(B(r)\) is known as the brightness in range \(r\). The superscripts \(H\), \(-1\), and \(T\) represent, respectively, the Hermitian, inverse, and transposition operators. \(R_{ij}\) is the zero-lag cross-correlation function of the signals calculated for a pair of carrier frequencies. \(k_n\) is the wavenumber of the \(n\)-th carrier frequency. After range-scanning processing, \(B(r)\) may possess several distinct brightness maxima, indicating multiple layers in the radar volume. The resolvable number of layers depends on the number of carrier frequencies used.

The phase imbalance between the signals with different carrier frequencies will lead to the
so-called phase bias problem that is introduced into the range imaging from the cross-correlation function of the signals (the $R_{ij}$ in (1)). Other factors such as the time delay of the signal in the media and/or radar system cannot be discarded either. The major causes of the error in range imaging are difficult to identify. But it is possible to correct the error by compensating proper phase angles in $R_{ij}$, making the brightness more continuous at gate boundaries.

### 3. Phase calibration

Several approaches have been employed for the phase calibration [4][5][7]; among them, reading the peak location of the distribution of FDI phases (defined as the phase of the $R_{ij}$ in (1)) [5] is much easier and so first employed. However, the shape of FDI phase distribution at each sampling gate is closely related to the weighted radar volume formed by range weighting function and radar beam both. Range weighting function results from the receiver filtering process and can be approximated by a Gaussian form [3]. On the other hand, the radar beam can be modeled by a two-dimensional Gaussian function on the plane perpendicular to the range direction. Consequently, the maximum weight will be at the center of the radar volume. This causes the measured FDI phase to deflect to the phase angle at the center of the radar volume. It is thus expected to obtain a quasi-Gaussian distribution of FDI phases having the peak at the phase angle predicted for the center of the radar volume, provided there is no phase bias in the FDI phase.

The peak location in the FDI phase distribution can be estimated in advance for each sampling gate when proper radar parameters are given (e.g., difference of a frequency pair, pulse width, lowest sampling height, sampling step, and so on.). To obtain a more reliable distribution of FDI phases, however, we usually stack the distributions of FDI phases of all range gates to form an integrated one.

#### 3.2.1. Mono pulses

The cases 1–4 listed in Table 1, which have different pulse shapes and receiver (Rx) filter bandwidths, were examined, as shown in Figure 1. According to the radar parameters employed, there are one, two, and four peaks for frequency differences $\Delta f=500$, 250, and 125 kHz, respectively, and the respective locations of the peaks should be around $180^\circ$, $(90^\circ, 270^\circ)$, $(45^\circ, 135^\circ, 225^\circ, 315^\circ)$, respectively. It is not hard to determine the phase biases in the case 1 for we can see clearly the biases of the peaks; on average, the phase biases for the three frequency pairs are about $60^\circ$, $30^\circ$, and $15^\circ$, respectively. It should be mentioned that, with the five equally spaced frequencies (denoted as $f_1$ to $f_5$), frequency separations between $f_1$ and $f_3$, $f_2$ and $f_4$, and $f_3$ and $f_5$ are the same, namely 250 kHz, and their FDI phase distributions are similar (not shown). Same feature also exists in the FDI phase distribution with the frequency separation of 125 kHz, irrespective of the frequency pair selected. Accordingly, there is a quasi-linear relationship between phase bias and frequency separation, which is similar to that examined by Chen [2] and could be attributed to the group delay of the signals in the media and the time delay from the data processing in the radar system. To compensate these phase biases, therefore, we can simply consider a time delay (or range error) in the RIM analysis. The time delay can be $\sim0.333 \mu s$ for the case here, corresponding to an error of 50 m in range.

By comparison, it is more difficult to determine the phase biases in the cases 2–4. This is because the pulse shapes and Rx filter bandwidths employed in the cases 2–4 result in shallower range weighting functions, causing the difference between the peaks and the valleys in the FDI phase distribution smaller and less observable. This points out one possible defect of using FDI phase distribution for phase calibration when the used radar parameters produce a shallow range weighting.
function; in case of this, more data are usually needed to reveal the distributive shape associated with the range weighting function.

### 3.2.2. Coded pulses

Since coded pulses are commonly used in radar observations to raise the SNR, it is essential to validate the RIM experiment with coded pulses for practical applications. **Figure 2** shows two examples—the cases 5 and 6 listed in Table 1. As seen, the distributions of FDI phases are similar to the case 1, demonstrating that the coded operations do not affect the use of the RIM technique.

### 4. First results and conclusions

**Figure 3** shows the original height-time echo intensity and the height-time RIM brightness of the case 2, with the range resolutions of 300 m and 2 m, respectively. Apparently, the RIM brightness provides a more superior inspection of the atmospheric irregularity structures.

It should be mentioned that, in estimating the RIM brightness, the range-weighting effect is corrected with a Gaussian function having the standard deviation $\sigma_z=200$ m. Such correction is not very precise for we can see over-corrected brightness at gate boundaries sometimes, especially at low SNR. Although a theoretical range weighting function can be obtained from the radar pulse shape and receiver filter bandwidth, the correction of brightness seems better to vary with SNR to produce smoother brightness at gate boundaries. This issue is under pursuit.

In summary, the multiple-frequency technique is now available on the OSWIN VHF radar. Improvements of data processing and applications of this technique for the study of the atmosphere are proceeding.

### Acknowledgements

This work was supported by the National Science Council of ROC (Taiwan) through grants NSC95-2111-M-270-001-MY3. The OSWIN VHF radar is maintained by the Leibniz-Institut für Atmosphärenphysik (IAP) at Kühlungsborn, Germany.

<table>
<thead>
<tr>
<th>Case</th>
<th>Start time</th>
<th>End time</th>
<th>Pulse shape</th>
<th>Rx filter bandwidth (KHz)</th>
<th>Coded bits (c=complementary)</th>
<th>Range resolution (m)</th>
<th>Sampling step (m)</th>
<th>Sampling height interval (km)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>06/12/07 09:00</td>
<td>06/12/07 14:00</td>
<td>S</td>
<td>317</td>
<td>0</td>
<td>300</td>
<td>300</td>
<td>1.2 – 18.9</td>
</tr>
<tr>
<td>2</td>
<td>04/12/07 09:00</td>
<td>04/12/07 12:30</td>
<td>G</td>
<td>159</td>
<td>0</td>
<td>300</td>
<td>300</td>
<td>1.2 – 18.9</td>
</tr>
<tr>
<td>3</td>
<td>05/12/07 12:00</td>
<td>05/12/07 17:00</td>
<td>G</td>
<td>317</td>
<td>0</td>
<td>300</td>
<td>300</td>
<td>1.2 – 18.9</td>
</tr>
<tr>
<td>4</td>
<td>18/12/07 10:00</td>
<td>18/12/07 14:00</td>
<td>S</td>
<td>159</td>
<td>0</td>
<td>300</td>
<td>300</td>
<td>1.2 – 18.9</td>
</tr>
<tr>
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<td>31/08/07 16:00</td>
<td>01/09/07 09:00</td>
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<td>253</td>
<td>8c</td>
<td>300</td>
<td>300</td>
<td>2.4 – 20.1</td>
</tr>
<tr>
<td>6</td>
<td>01/09/07 12:20</td>
<td>02/09/07 13:30</td>
<td>G</td>
<td>317</td>
<td>4c</td>
<td>300</td>
<td>300</td>
<td>1.2 – 18.9</td>
</tr>
</tbody>
</table>

Remarks: Frequencies: [53.25, 53.375, 53.5, 53.625, 53.75] MHz  
G= Gaussian, S=square
\[ \Delta f = 500 \text{ kHz} \quad (f_1 \& f_5) \]
\[ \Delta f = 250 \text{ kHz} \quad (f_2 \& f_4) \]
\[ \Delta f = 125 \text{ kHz} \quad (f_3 \& f_4) \]

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\[ \Delta f = 125 \text{ kHz} \quad (f_3 \& f_4) \]

Figure 1: Distributions of FDI phases for mono pulses. (a) case 1, (b) case 2, (c) case 3, (d) case 4.

(a) \[ \Delta f = 500 \text{ kHz} \quad (f_1 \& f_5) \]
\[ \Delta f = 250 \text{ kHz} \quad (f_2 \& f_4) \]
\[ \Delta f = 125 \text{ kHz} \quad (f_3 \& f_4) \]

(b) \[ \Delta f = 500 \text{ kHz} \quad (f_1 \& f_5) \]
\[ \Delta f = 250 \text{ kHz} \quad (f_2 \& f_4) \]
\[ \Delta f = 125 \text{ kHz} \quad (f_3 \& f_4) \]

Figure 2: Distributions of FDI phases for coded pulses. (a) case 5, (b) case 6.

Figure 3: For case 2. Left: original height-time echo intensity. Right: RIM brightness, with \( \sigma_z = 200 \text{ m} \).
Range resolutions are 300 m and 2 m for left and right panels, respectively.

References