Special experiments using VHF Radar for observing the tropical mesoscale convective systems
6.1 Introduction

All the observations presented in the previous chapters were carried out by employing the standard DBS techniques. One of the limitations of this technique is its inability to measure the horizontal winds during the convective system passages due to inhomogeneity in the velocity fields. The Space Domain Interferometry (SDI) is a very good technique to obtain wind information during the disturbed atmospheric conditions like convective systems, when DBS technique gives erroneous values in those conditions. It is also possible to localize the scatterers in the radar observational volume from the angle of arrival measurements from the SDI observations. Keeping this in view, the SDI experiments have been carried out during 1999 convection campaign. Using the regular six beam experiment (E, W, Zx, Zy, N, S), which makes use of DBS technique, it is not possible to obtain the three dimensional reflectivity and radial velocity field in the spatial domain. To overcome this limitation a multi beam experiment is designed to scan the convective system in the spatial domain using radar beams with various zenith angles.

In this chapter, a scanning-beam experiment using the electronic beam steering facility of the VHF radar is discussed. This experiment was carried out to scan the convective system during one of the campaigns. The results from these observations are also discussed. Apart from this, the implementation of the SDI technique using the VHF radar at Gadanki is demonstrated. The potential of the SDI technique for studying the lower atmosphere is presented here. These are the preliminary results from the SDI observations in the lower atmosphere at this latitude. The SDI measurements in the present study are limited to the cross-spectral analysis and vertical velocity estimations.
6.2 Multi beam experiment

A scanning-beam experiment is designed using VHF radar to scan the convective system over the observational site. As mentioned in Chapter 2, the VHF radar phased antenna array can be used to tilt the radar beam up to 20° in both East-West and North-South planes. This beam steering facility is used to sequentially scan the convective system in the horizontal direction in both the planes. The beam sequence used in the experiment along with other specification is given in table 6.1. Using these beam combinations, the convective system has been scanned in spatial domain in both East-West and North-South planes.

On 14 September 2001, VHF radar observations were carried out continuously from 1430 to 1730 Hrs. The convective system was scanned in both East-West and North-South planes using the radar beams with various zenith angles as given in table 6.1. Figure 6.1 (a) shows a conical section of reflectivity (in terms of SNR) corresponding to the first scan cycle in the East-West plane. The x-axis represents the distance from the radar antenna array in East and West directions. Figure 6.1(b) shows the conical section of radial velocity corresponding to the first scan cycle. From these two figures an exciting feature can be seen at the height region ~10 ~14 Km. The reflectivity section shows a weak echo region (WER) in these height regions. Already, these WERs are discussed in chapter 4. However, the present observations using the multi beam configuration have shed some more light on the interpretation of this feature. In the above mentioned height region, the radial velocity plot shows an interesting feature. Both the eastward and westward radial velocity in this
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<td>Highest range bin (km)</td>
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**Beam sequence:** (N1, Zx, E1, W1, Zy, S1; N2, Zx, E2, W2, Zy, S2, N3, Zx, E3, W3, Zy, S3, N4, Zx, E4, W4, Zy, S4, N5, Zx, E5, W5, Zy, S5, N6, Zx, E6, W6, Zy, S6, N7, Zx, E7, W7, Zy, S7, N8, Zx, E8, W8, Zy, S8, N9, Zx, E9, W9, Zy, S9)
Figure 6.1: Conical section of VHF radar (a) signal to noise ratio (dB) and (b) radial velocity (m/s) in the East-West plane taken at 1450 hrs.

(Only off-zenith beams are used in this plot).
height region shows the same sign, i.e. both showing that the winds are moving away from the radar site. In normal conditions, if the Eastward (Northward) radial velocity shows that the winds are coming towards the radar site then Westward (Southward) radial velocity shows that the winds are moving away from the radar site and vice versa. This is evident from the power spectra shown in the figure 2.5 (chapter 2). But in the present observations exactly the opposite is happening. To confirm the consistency of the observations, the reflectivity and radial velocities obtained in the North-South plane are also examined and are shown in figures 6.2 (a) and (b) respectively. From these plots also the weak echo region can be seen at the same height region as seen in the East-West plane. The North and Southward radial velocities again show the winds moving away from the radar site at the weak echo region heights. From these figures, it can be concluded that at the weak echo regions the winds in East-West and North-South planes are moving away from the radar site indicating wind divergence. This can happen when there exists a strong rotating updraft in the convective system. Figures 6.3 (a) and (b) show the height -time section of reflectivity and vertical velocity respectively. The reflectivity section readily showing the WER during 1430-1500 hrs in the height region of ~8-16 km. During this time interval, a well-defined updraft at the same height-region can be noticed from the figure 6.3 (b). It is interesting to note that the WER, the unusual radial velocity directions and the strong updraft all are seen at the same height regions and at the same time interval. From the figure 6.3 (b), it is evident that a strong updraft passed over the radar site, and if it is associated with anti-clockwise rotation then the air around it should move away from the radar site due to divergence. This is what exactly happening in the radial velocity directions as shown in figures 6.1 (b) and 6.2 (b). These features are observed only during the passage of strong updraft and are absent in other
Figure 6.2: Same as figure 6.1 but for the North-South plane.
6.3: Height-time sections of (a) signal to noise ratio (dB) and (b) vertical velocities (m/s). Arrows indicate the observations taken for plotting figures 6.1, 6.2, 6.4 and 6.5.
scans. Figures 6.4 (a) and (b) show the conical section of radar reflectivity and radial velocities in East-West plane respectively. Figures 6.5(a) and (b) are also same as figure 6.4 but for North-South plane. These scans were taken when there was no updraft core in the system. This plot does not show any special features like WER and unusual radial velocities. From these observations, it can be confidently stated that very strong updrafts associated with rotation produce the WERs in the VHF radar observations. Due to the rotation of the cell the drier air of the environment may entrain into the convective system. Due to the mixing of drier air and the humid air in the system, the refractive index fluctuations may be smoothed out, which results in reduced radar reflectivity as discussed in chapter 4.

6.3 The Space Domain Interferometer Technique

Interferometry using radio waves had been widely employed and developed in Radio Astronomy, lightning detection and positioning, and radio frequency direction finding. All these are passive interferometer methods, since the detected and analysed signals are not originated from or generated by the observer himself. Radar interferometry detects and analyses echoes, which result from targets illuminated by an active transmitter, which is usually controlled by the observer. The radar interferometer technique was first introduced for ionospheric applications by Woodman [1971] and later developed in more detail by Farley et al. [1981]. The first MST radar studies were published by Röttger and Ierkic [1985], while initial experiments, showing the applicability of basic interferometry with MST radars was performed as early as 1978 by Röttger and Vincent.
Figure 6.4: Same as figure 6.1 but taken at 1540 hrs.
Figure 6.5: Same as figure 6.4 but for the North-South plane.
Interferometry is applying measurement of phases of radio waves to increase the spatial resolution of radar targets, i.e. the atmospheric structure in the case of MST radar imaging. This technique can be implemented both in frequency and spatial domain. The space domain interferometry (SDI) applies the measurement of phases of radar echoes on one wavelength (frequency) at two or more antennas displaced in horizontal plane. An equivalent to the SDI is the frequency domain interferometry (FDI), where the spatial coordinates in the SDI are replaced by the wavelength (λ) (i.e. different frequencies). The FDI applies the measurements of phases of radar echoes on two or more wavelengths at one antenna. This improves the resolution in the vertical direction. Radar Interferometer technique in spatial domain basically provides information on the angular position of the discrete scatterers and their aspect sensitivity to the radar backscatter in the vertical plane containing the interferometer baseline. The method involves measuring the complex cross-spectrum of the signals received at two phase centres of the interferometer baseline. The cross-spectral phase and magnitude (coherence) provide the mean angle of arrival and root-mean-square (rms) deviation of the angular distribution of the returned signal respectively. The rms deviation from the mean angle of arrival of the backscattered signal is referred to as aspect angle. The technique is so remarkable that it could be effectively used to measure aspect angles of the order of 10²⁻³ degrees for the equatorial spread F irregularities. The angular distribution of the backscattered signal for a wave incident at normal to plane represents a measure of the aspect sensitivity of the medium. Using the phase measurements as a function of time, it is possible to derive the drift velocity along the base line as shown by Farley et al. [1981].
The radar interferometry in the lower atmosphere was first applied for correcting the vertical velocity observations [Palmer et al., 1991]. Typically, vertical velocities are estimated by pointing the beam of a Doppler radar in the vertical direction and processing the received signal to obtain the Doppler shift. But it has been proved that at VHF frequencies the received signal usually shows aspect sensitivity i.e. the reflectivity decreases as the beam is tilted off vertical [e.g. Tsuda et al., 1986]. If the refractivity surfaces are tilted away from the horizontal plane, the aspect sensitivity may cause errors in the estimate of the vertical velocity since the largest contribution to the received signals will come from an off-vertical direction. By finding the center of the aspect sensitivity function, tilt angles estimates with VHF radar were made by Vincent and Röttger [1980]. Röttger and Jerkic [1985] estimated tilt angles using SDI. Larsen and Röttger [1991] analysed the layer tilt angle measurements and provided the evidence that biases in the vertical velocity measurements resulted from the tilted refractive structures. Thus, SDI can be used for correcting the vertical velocities obtained in the DBS technique. It is also possible to obtain the horizontal velocity of the wind fields using this technique, which will be discussed later. As the present study deals with the SDI, FDI is not discussed in detail. In principle, SDI technique requires a minimum of three receivers to estimate the horizontal and vertical velocities unambiguously. However, due to the non-availability of the multiple receivers at the present observational site, a special experiment is designed to carry out the SDI technique using the existing facilities at this site.

The standard technique involves transmitting the radar pulses with single high gain antenna and then cross correlating the backscattered signals received
on two (or more) physically separated antennas. If the distance between the phase centres is D, then the normalized cross correlation $S_{12}$ gives an indication of the distribution of signal arrival angles with respect to the vector D. The cross correlation function is given as

$$S_{12}(\omega) = \frac{<V_1(\omega) \cdot V_2(\omega)>}{<|V_1|^2>^{1/2}<|V_2|^2>^{1/2}}$$  \hspace{1cm} (6.1)$$

where $V_1$ and $V_2$ are the Fourier transform of the digitised signals from the phase centres. The angular brackets indicate ensembles averaging (time averaging in practice). The cross spectra are equivalent to the spatial autocorrelation on the ground at the separation of D, for the signal with a particular Doppler shift $\omega$. Following Farley et al. [1981], $S_{12}$ can be written as

$$S_{12}(\omega) = <\exp ikD \sin \gamma>$$  \hspace{1cm} (6.2)$$

where $k$ is the wave vector and $\gamma$ is the angle with respect to the normal to the baseline from which the echoes with Doppler shift $\omega$ are received. For each Doppler frequency $\omega$, $S_{12}$ can be described by its magnitude or coherence $|S_{12}|$ and its phase angle $\phi$. For scatterers small compared to the scattering volume, the coherence and phase angle are given as [Farley et al., 1981]

$$|S_{12}| = e^{-\frac{1}{2}k^2D^2\sigma^2}$$  \hspace{1cm} (6.3)$$

$$\phi = kD \sin \gamma$$  \hspace{1cm} (6.4)$$
where $\sigma_\alpha$ is the angular size of the scattering region. Thus, coherence values of the cross spectrum corresponding to each Doppler shift provides an estimate of how localized the particular scatterer within the radar volume and $\phi$ is the angular position of the scatterer with respect to the perpendicular bisector of the baseline. From equation 6.4, the position of the scatterer, $\delta x$ along the base line direction corresponding to a phase difference, $\delta \phi$ at an altitude $h$ can be written as

$$\delta x = h \delta \phi / k D$$

(6.5)

Hence, the rate of change of phase of particular scatterer with time will provide the drift along the direction of the base line.

### 6.3.1 Estimation of Horizontal and Vertical Velocities

The horizontal and vertical velocities can then be estimated using the following procedure.

The radial velocity equation is given as

$$V_r = V_H \sin \gamma^l + W \cos \gamma^l$$

(6.6)

where $V_H$ and $W$ are the horizontal and vertical wind components, respectively. Figure 6.6 shows the configuration used for the derivation. The angle $\gamma^l$ is the zenith angle in the direction of the wind vector, which will produce a radial velocity of $V_r$. This zenith angle $\gamma^l$ can be written in terms of zenith angle produced on the baseline i.e., $\gamma$. From the figure 6.1 it can be seen that
Figure 6.6: A schematic showing the configuration used for deriving the horizontal and vertical velocities using SDI technique.
\[ \cos (\alpha - \theta) = \tan \gamma / \tan \gamma' \]

where \( \theta \) and \( \alpha \) are the azimuth angles of the wind vector and the baseline, respectively. But, since for an interferometer experiment, the zenith angles are usually very small and hence the above equation becomes

\[ \cos (\alpha - \theta) = \sin \gamma / \sin \gamma' \]

Substituting for \( \sin \gamma' \) and using the fact that \( \cos \gamma' = 1 \), the radial velocity becomes (from equation 6.6)

\[ V_r = \frac{V_H \sin \gamma}{\cos(\alpha - \theta)} + W \]  

(6.7)

Substituting \( \sin \gamma \) in the equation 6.4,

\[ \phi = \left[ \frac{kD \cos(\alpha - \theta)}{V_H} \right] V_r - \left[ \frac{wkD \cos(\alpha - \theta)}{V_H} \right] \]  

(6.8)

This equation is easily seen to have the form of a line. First term in the right hand side represents the slope and the second term represents the intersection.

The linear variation of the cross-spectra phase has \( \phi \) as a function of \( V_r \) was seen in a number of earlier experiments [e.g., Furley et al., 1981; Röttger et al., 1990] and is expected on physical grounds. Since the phase of the signal is related to the angular position from which the echoes are received, the radial velocity should change linearly for small zenith angles, as the angle changes from positive to negative.
One can estimate the three components of the wind vector by using the slope from equation 6.6.

\[
\text{Slope } m = kDV_H' \cos (\alpha - \theta) = kD(u^1 \sin \alpha + v^1 \cos \alpha)
\]

(6.9)

where \( V_H' = 1/ V_H \), \( u^1 \) and \( v^1 \) are the zonal and meridional components of \( V_H' \).

From the equation 6.9, it is evident that \( u^1 \) and \( v^1 \) can be calculated, if two independent estimates of the slope \( m \) are available from two pairs of receiving antennas. The relationship between \( u^1 \), \( v^1 \) and the slopes is given by the following equation for two independent slope measurements,

\[
\begin{pmatrix}
\sin \alpha_2 \cos \alpha_2 \\
\sin \alpha_3 \cos \alpha_3
\end{pmatrix}
\begin{pmatrix}
u^1 \\
u^1
\end{pmatrix} =
\begin{pmatrix}
m_{12} \\
m_{13}
\end{pmatrix}
\]

Solving the above matrix we can get the \( u^1 \) and \( v^1 \) and ultimately from these parameters the horizontal wind and direction can be estimated.

The vertical velocity can be estimated using the intersection term from the equation 6.8. However, another approach is to find the radial velocity when the beam is pointing exactly vertically, i.e. \( \phi = 0 \). When the phase difference between the signals in two adjacent receiving antennas is zero, the contribution must be from the true vertical direction within the accuracy of the mechanical layout of the system. This method has been used to estimate the vertical velocities in the present study. As already mentioned, because of non-availability of multi-receivers, at present, the horizontal wind measurements are
not attempted using the radar interferometry. However, the ongoing developments at this site are aimed at providing the full-fledged radar interferometry/imaging facilities.

6.3.2 Experiment description and preliminary results

A detailed description of various subsystems and operation of the radar are given in chapter 2. Hence, the description given here is limited to that relevant to the radar interferometer experiments. The antenna system occupying an area of 126 m × 126 m is a phased array of 32 × 32 three-element Yagi antennas consisting of two orthogonal sets, one set for each polarization (magnetic E-W and N-S). The array can be illuminated in either of the polarizations using 32 transmitters each feeding a linear sub array of 32 Yagi antennas. The outputs of the 32 transmitters are connected to 32 linear sub-arrays through equal number of transmit-receive (T/R) and polarization selection switches. The receiver part consists of 32 channels corresponding to the 32 linear sub arrays. The signal received through the 32 channels, after passing through the front-end amplifier and mixer units, are combined and fed to a phase coherent receiver at the IF level. This feature of the antenna and receiver network is made use of in the radar interferometer application. For signal reception, the whole array was divided into two equal parts along the north-south and east-west baseline with each part consisting of 16 linear sub-arrays with their phase centres separated by a distance of 32 m. However, by disconnecting the appropriate linear sub-arrays one can have the baselines of 32, 48, 64, 80 and 96 m. Since there is only one receiver for reception, it was switched between the two halves of the antenna array at every sampling interval. This was accomplished by introducing a Single Pole Double Throw (SPDT)
switch, operating in synchronism with the coherent integration pulses, between the two halves of the antenna array and the receiver. Figure 6.7 shows schematically the configuration of the antenna array, the control switch and the receiver, along with the transmitted and control signal (coherent integration pulse) waveforms. For the transmission purpose, the whole antenna array was used, thereby restricting the region probe to the main lobe of the interferometer pattern. Radar interferometry observations were made during the 1999 convection campaign using 2 μs (uncoded) pulse width and an inter pulse period of 500μs. The odd pulse returns were received by the North (East) antenna and the even pulse returns by the South (West) antenna. There was a time delay of 32 ms (because of coherent integrations) between the signals received by both the antennas. This, however, is not a serious limitation since the positions of the scatterers hardly change within 32 ms. The complex amplitudes of the backscattered signals were recorded in the form of inphase and quadrature components for the two phase centres. The alternate data samples of the complex time series as collected are separated off-line to form two separate series, one for the North (East) and the other for the South (West) phase centre.

The data presented here were collected on 02 and 04 June 1999. On these two days there was a mild convective activity over the radar site. Vertical velocities are very small compared to the earlier convection events presented in the previous chapters. A total number of 1024 FFT points are collected in each scan cycle, which are then separated as North (East) and South (West) phase centres each having 512 FFT points. These FFT points are further divided into small modules of 64 points for the ease of calculations. Figure 6.8 shows cross spectrum of the signals received at East and West antenna array in terms of coherence and phase. The linear portion of the phase can be readily noticed.
Figure 6.7: A schematic showing the Gadanki radar geometry along with the transmitter and control signal waveforms for SD measurements of the lower atmosphere.
Space Domain interferometer: Coherence and Phase

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Figure 6.8: Cross spectra of signals received at East and West antenna arrays in terms of coherence and phase at different times.
from these figures. These spectra are incoherently averaged as indicated in the figure. This linear portion of the phase is used to derive the vertical velocities. Figure 6.9 is also the same as figure 6.8 but for the signals received at North and South antenna arrays. These figures also show similar features as in figure 6.8. The coherence and phase shown in the figure corresponds to a single range bin (2.1 km), similarly these two parameters are estimated at all the range bins to get the vertical velocity height profiles. Figure 6.10 shows the vertical velocity height profiles estimated using Doppler method and SDI techniques on 02 June 1999. These profiles show very small vertical velocities and at the most of the levels they are comparing well. On this day, the baseline was fixed to 64 m. However, on 04 June 1999 by removing appropriate cables of the linear sub arrays, baselines were changed to 32, 64, 48, 80 and 96 m. Figure 6.11 shows the cross spectra obtained by using the different base line configurations in East-West plane. From these spectra, one can infer that as the base line length increases the linearity in the phase decreases drastically. The same can be seen from the figure 6.12, which is same as figure 6.11 but for the North–south base line. The linearity of the phase is checked for different combinations of incoherent integrations and no. of FFT points and is shown in the figure 6.13 and 6.14 for the 32 m and 48 m base line configurations respectively. The choice of the combination depends on the issues like velocity resolution and noise reduction. The reduction of no. of FFT points results in poor velocity resolution whereas reduction of incoherent integrations results in noisy spectrum.

As mentioned earlier, these are the preliminary results using radar interferometry at this latitude in the lower atmosphere. Much has to be done to completely explore this technique, particularly for convection studies. At this
Figure 6.9: Same as figure 6.8 but for the signals received at North and South antenna arrays.
Figure 6.10: Vertical velocity height profiles estimated using the Doppler method and SDI technique on 02 June 1999.
Figure 6.11: Cross spectra of signals received at East and West antenna arrays in terms of coherence and phase using the different base line configurations.
Figure 6.12: Same as figure 6.11 but for the signals received at North and South antenna arrays.
Figure 6.13: Cross spectra of signals received at East and West antenna arrays in terms of coherence and phase using the different combinations of FFT and incoherent integrations, base line is fixed at 32 m.
Space Domain Interferometer: Coherence and Phase

Baseline Distance: 48 m (E-W)
Interpulse Period: 500 nanosec
Pulse Width: 2 nanosec
Range: 2.1 km
Coherent Integration: 64

Date: 04 June 1994
Time (ST): 15:26:42

Figure 6.14: Same as figure 6.13 but for the baseline 48 m.
site, the task has been taken already to establish the full-fledged radar interferometer/imaging facility and the work is underway.

6.5 Summary

Multi beam experiments are carried out to scan the convective system in the spatial domain. Using the beam tilting facility of the VHF radar, a convective system is scanned in both East-West and North-South planes. The conical sections of signal to noise ratio and radial velocities are studied. These studies provided an opportunity to investigate the causative mechanism for the WERs.

Radar interferometry technique using the VHF radar has been carried out in the lower atmosphere. Analysis has been done on two mild convection days. Coherence is found to be more than 0.9 and the phase spectra are fairly linear. The technique is demonstrated to estimate the vertical velocities and the same is compared with the standard Doppler method. The comparison has shown the consistency of the analysis. As mentioned in the discussion these results are from preliminary observations and detailed study will be carried out in near future.