USING VERTICALLY POINTING BROAD BEAM TO MEASURE ATMOSPHERIC ASPECT SENSITIVITY OF VHF RADAR ECHOES

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ABSTRACT

Conventionally, atmospheric aspect sensitivity of VHF radar echoes is measured using a narrow beam radar in order to avoid the complications due to broad beam effects. However, in this study, a new technique using beam broadening effects has been developed. It used the relatively broad antenna beam (half power beam width is 7.4 deg) of the vertically pointing antenna of the new Chung-Li VHF radar. The aspect sensitivity measurement using this method is straightforward and free from the convolution effects introduced by the finite width of the antenna beam pattern. The observed value at heights from 2 to 8 km is about 0.5 dB/deg to 1 dB/deg which agrees very well with other measurements.

INTRODUCTION

Since WOODMAN and GUILLEN (1974) successfully measured the stratospheric and mesospheric wind field and turbulence with the Jicamarca VHF radar by using the modern MST radar technique, the fields of VHF radar probing the lower and middle atmosphere have been established. It is well known that, using powerful VHF radars, many important atmospheric parameters and dynamic phenomena, such as 3-dimensional wind fields, tropopause height, atmospheric refractive index structure constant (C_n^2), turbulent energy dissipation rate, atmospheric stability, gravity wave characteristics, turbulent structure, etc., can be measured or observed (GAGE and GREEN, 1978, 1979; RÖTTGER, 1980; VANZANDT et al., 1978; HOCKING, 1983a,b, 1985, 1987).

There are many kinds of echo mechanisms proposed by different scientific workers to explain the properties of MST radar returns. The so-called "isotropic turbulent scattering" proposed by BOOKER and GORDON (1950) explained the results of troposcattering; GAGE and BALSLEY (1980) and DOVIAK and ZRNIC (1984) took "anisotropic turbulent scattering" for illustrating the phenomenon of atmospheric aspect sensitivity (GAGE and GREEN, 1978; RÖTTGER et al., 1981; TSUDA et al., 1986). The concept of "Fresnel scattering" was introduced by GAGE et al. (1981) to account for the echoes from volume filling of specular layers observed by VHF radar. "Fresnel reflection" (or partial reflection) is also an important echo mechanism of MST radar and has been confirmed by many experimenters (RÖTTGER and LIU, 1978; RÖTTGER, 1980) and the echo mechanism of "diffuse reflection" has been discussed by RÖTTGER (1980).

Atmospheric aspect sensitivity (or angular spectrum) has been measured with MST radars for many years (RÖTTGER and VINCENT, 1978; VINCENT and RÖTTGER, 1980; RÖTTGER et al., 1981; WATERMAN et al., 1985; SATO et al., 1985; TSUDA et al., 1986; HOCKING et al., 1986). The width of the angular spectrum is closely related to atmospheric stability: the more stable the atmosphere, the more narrow the angular spectral width, and vice versa. The physical mechanisms that cause the angular dependence of VHF radar echo power are not yet fully understood. However, there are two possible echo mechanisms responsible for the aspect sensitivity which have been discussed extensively by many scientific workers. One is diffusive reflection from the corrugated refractive index surface (RATCLIFFE, 1956; RÖTTGER, 1980), and the other is anisotropic turbulent scattering (DOVIAK and ZRNIC, 1984; WATERMAN et al., 1985; WOODMAN and CHU, 1988).

The existence of aspect sensitivity will influence the accuracy of the atmospheric parameters evaluated from the Doppler spectrum of vertical or close to zenith pointing radar returns, such as horizontal wind velocity, turbulent rms velocity, etc. (RÖTTGER, 1980; TSUDA et al., 1986; HOCKING et al., 1986; HOCKING, 1987). Therefore, it is very important to measure accurately the correct aspect sensitivity before making an evaluation of atmospheric parameters from a VHF radar Doppler spectrum. The current method of aspect sensitivity measurement used at most MST radars around the world is the so-called beam swinging method, that is, tilting the radar beam continuously toward different zenith angles, the aspect sensitivity will then be obtained after evaluating the echo power for each pointing direction. The aspect sensitivity measured with this method is different from the actual one, because of the convolution effect with the antenna beam pattern. In this paper, a new method of aspect sensitivity measurement by using the beam broadening effect from the Doppler spectrum of vertically pointing radar beams, developed at the Chung-Li VHF radar in Taiwan, ROC, (WOODMAN and CHU, 1988), will be introduced and the results of measurements are also presented and discussed.

CHARACTERISTICS OF THE CHUNG-LI VHF RADAR

The Chung-Li VHF radar is located on the campus of the National Central University in Taiwan, ROC, (25°N, 121°E). The operation of this radar began on June 1,1985. It consists of three identical and independent modules, the antenna area and peak transmitted power of each module are 1600 m^2 and 60 kW, respectively. The antenna module is composed of 64 (8x8) Yagi antennas arranged in a square of sides 40 m. The antenna configuration is shown in Figure 1. The radar frequency is 52.2 MHz (radar wavelength is 5.77m), and the pulse width can be set as 1, 2, 4, 8, and 16 μs arbitrarily. The maximum duty cycle is 2%. The phase code is a complementary code with 2, 4, 8, or 16 elements. The direction of the radar beam for each antenna module or for full antenna aperture can be pointed independently from zenith toward northeast, southeast, southwest, northwest with fixed zenith angle 17° and the beams can also be pointed vertically. The azimuth angle for the off-vertically pointing beams are shown in Figure 1. The half power beam width (HPBW) for each module and full aperture is 7.4° and 5°, respectively. The maximum probing range is about 1 to 25 km. However, occasionally, the echoes of mesospheric irregularities can be observed (CHU et al., 1988a). The characteristics are summarized in Table 1.

THE METHOD OF ASPECT SENSITIVITY MEASUREMENT WITH VERTICALLY POINTING RADAR BEAMS

The Doppler spectral width is an extremely important VHF radar echo parameter. Much atmospheric information, such as turbulent rms velocity and energy dissipation rates, can be evaluated from this radar parameter. However, there are quite a few physical mechanisms which can contaminate the width of the Doppler spectrum. For example, the beam broadening effect, wind shear effect, and gravity wave oscillation effect will broaden the Doppler spectral width (ATLAS et al., 1964; GAGE and BALSLEY, 1978; BRIGGS, 1980; HOCKING, 1983a,b, 1985, 1986), whereas the Doppler spectral width will also be narrowed by the aspect sensitivity for vertical or close to vertical pointing radar beams (RÖTTGER, 1981; WOODMAN and CHU, 1988). Therefore, because of the broadening and the narrowing effects coexisting in the observed Doppler spectrum, the estimation of true atmospheric information from spectral width will be impossible if the contaminating factors are not thoroughly removed from the spectrum.

For a sufficiently broad antenna beam, if the echoing mechanism is isotropic turbulent scattering, the observed echo power at a specified Doppler frequency, f, will then be the integration result of the echo power scattered from the refractive index fluctuations which are located linearly within the radar volume with the corresponding angular positions and arranged perpendicularly to the horizontal wind direction. From Figure 2 it is easy to show that the signals returned from the irregularities located on the line AB will have the same Doppler frequency, f, and the mathematical relation between f and zenith angle Θ measured along the horizontal wind direction will be

$$f = -2\,U\,\Theta/\lambda \qquad (1)$$

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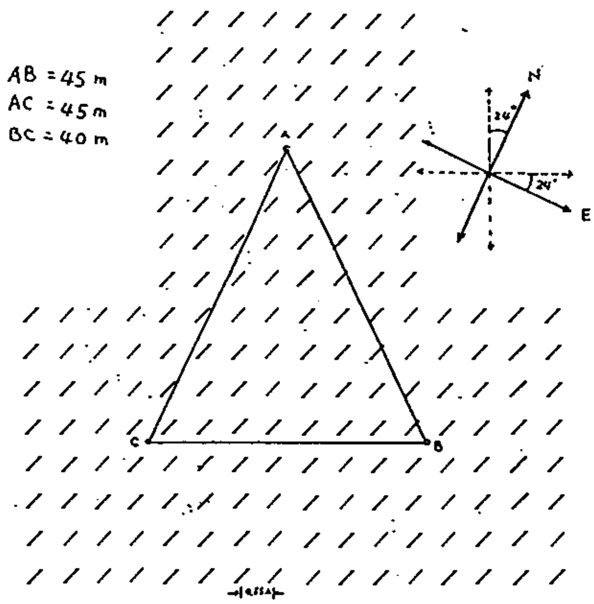

Figure 1. The configuration of the Chung-Li VHF radar antenna. The arrows with dashed tails are the pointing directions of the radar beam and the arrows with solid tails are the geographic direction.

Table 1. The Characteristics of the Chung-Li VHF radar.

Location	Chung-Li, Taiwan (25°N, 121°E)
Frequency	52.2 MHz
Wavelength	5.77 m
Peak transmitter power (for each module)	60 kW
Pulse width	1 - 16 μs
Maximum duty cycle	2%
Antenna	
Type	3 square arrays of Yagi (8x8)
HPBW	7°
Steerability	Vertical and North, East, South, West with 17° zenith angle
Total geometrical area	3x1600 m^2

where U is the horizontal wind speed, λ is the radar wavelength. The Doppler spectrum thus obtained is called the beam broadening Doppler spectrum or nonturbulent Doppler spectrum (HOCKING, 1983a). However, if there is aspect sensitivity in existence, the shape of the observed Doppler spectrum for a vertically pointing broad antenna beam will be determined from the multiplication effect between the beam broadening Doppler spectrum and the aspect sensitivity if the wind shear, turbulent fluctuation and gravity wave oscillation effects are all neglected, as shown in Figure 3. The dashed curve in Figure 3 represents the aspect sensitivity, A(f), the dotted curve is the beam broadening Doppler spectrum, B(f), responsible for a given horizontal wind speed and the antenna beam pattern, and the solid curve represents the observed Doppler spectrum, S(f). Therefore, the mathematical relationship between S(f), B(f), and A(f) can be described as follows:

$$S(f) = A(f) \cdot B(f) \tag{2}$$

The beam broadening spectrum can be easily estimated if the Gaussian assumption of the antenna beam pattern is made and the horizontal wind speed is known. The width of this spectrum will be (HOCKING, 1985; CHU, 1986):

$$\sigma = U\,\Theta_{0.5}/(2\sqrt{2\ \ln 2}) \tag{3}$$

where σ is the beam broadening spectral width, $\Theta_{0.5}$ is the HPBW. Therefore, the aspect sensitivity, $A(\Theta)$, will be evaluated by the following equation:

$$\mathrm{LoG}\ A(\Theta) = \mathrm{Log}\ S(f) - \mathrm{Log}\ B(f) \tag{4}$$

where the relationship between f and Θ is shown in equation (1). The aspect sensitivity measured in this way results from the narrowing effect on the beam broadening Doppler spectrum of the vertically pointing radar beam. The beam broadening effect contributed to the observed Doppler spectrum will be remarkable if the antenna beam width is broad enough. This fact can be proven from the exercise taken as follows: for the Chung-Li VHF radar the HPBW is 7.4°, if the horizontal wind speed is assumed to be 10 m/s, the beam broadening Doppler spectral width will be 0.56 m/s calculated from equation (3), while the spectral width contributed from turbulent fluctuations and gravity wave oscillations is less than 0.3 and 0.1 m/s during quiet conditions, respectively (SATO and WOODMAN, 1982; CARTER et al., 1984). Therefore, because the beam broadening effect is much larger than the turbulent and gravity wave effect contributed to the observed Doppler spectral width, it is practicable for a broad antenna beam to measure the aspect sensitivity in terms of beam broadening Doppler spectrum for a vertically pointing radar beam. In the following section an experiment of aspect sensitivity measurement, made by the Chung-Li VHF radar, and the observed results are presented and discussed.

EXPERIMENT AND RESULTS

The data used here were observed at the Chung-Li VHF radar on April 23, 1986, 0723 - 0809 LT. The three antenna beams were tilted toward northeast, northwest, and zenith directions, respectively. The pulse width was selected as 2 μs (300 meters range resolution), interpulse period (IPP) was 500 μs and coherent integration time was 0.25 s. The altitude of observation started at 1.8 km and 40 range gates were set. The FFT of 64 points was performed and 170 resulting raw spectra were averaged incoherently for the radar returns of each channel and each range gate. The normalized averaged Doppler spectra are shown in Figure 4, plotted with the solid curve. From the two oblique Doppler spectra, the mean horizontal wind velocity can be estimated by use of the moment method for each range gate if the signal-to-noise ratio is high enough. The profile of the horizontal mean speed measured is shown in Figure 5, plotted with the solid curve. The dashed curve in Figure 5 is the rawinsonde wind observed at the Pan-Chiao station apart from the Chung-Li VHF radar about 25 km northeast. Once the horizontal wind speed is evaluated, the beam broadening spectrum will be determined exactly according to equation (3) if the antenna beam pattern is assumed to be Gaussian shaped. The normalized beam broadening spectra are shown in Figure 4, plotted with the dotted curve. The beam broadening spectra are not evaluated above

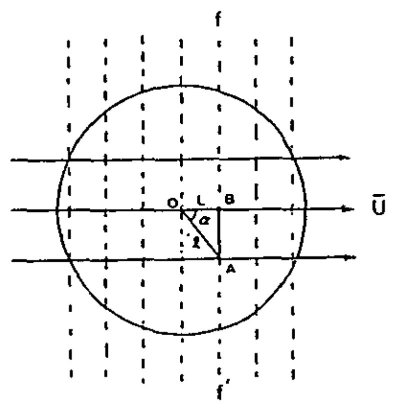

Figure 2. The solid circle represents the radar volume of vertical pointing at specified altitude z, U is the horizontal mean wind velocity, O is the zenith point, L is the distance between O and point B, which $L = \delta z$, δ is the zenith angle of point B. The Doppler frequency shifts at points B and A arising from the drifting effect are identical if U is constant.

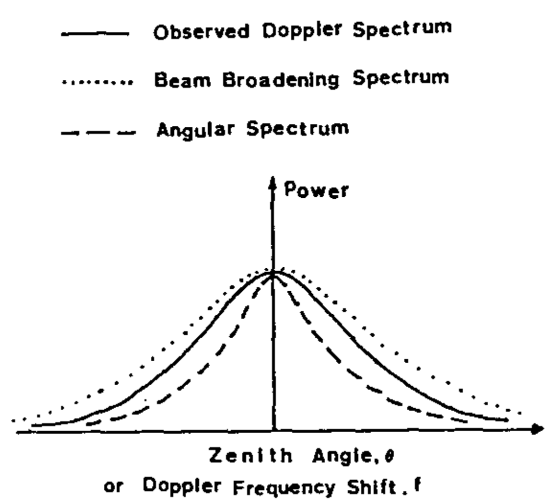

Figure 3. The schematic relationship between observed Doppler spectrum (solid curve), beam broadening spectrum (dotted curve) and angular spectrum (dashed curve), where the relationship between Doppler frequency shift, f, and zenith angle, Θ, is shown in equation (1).

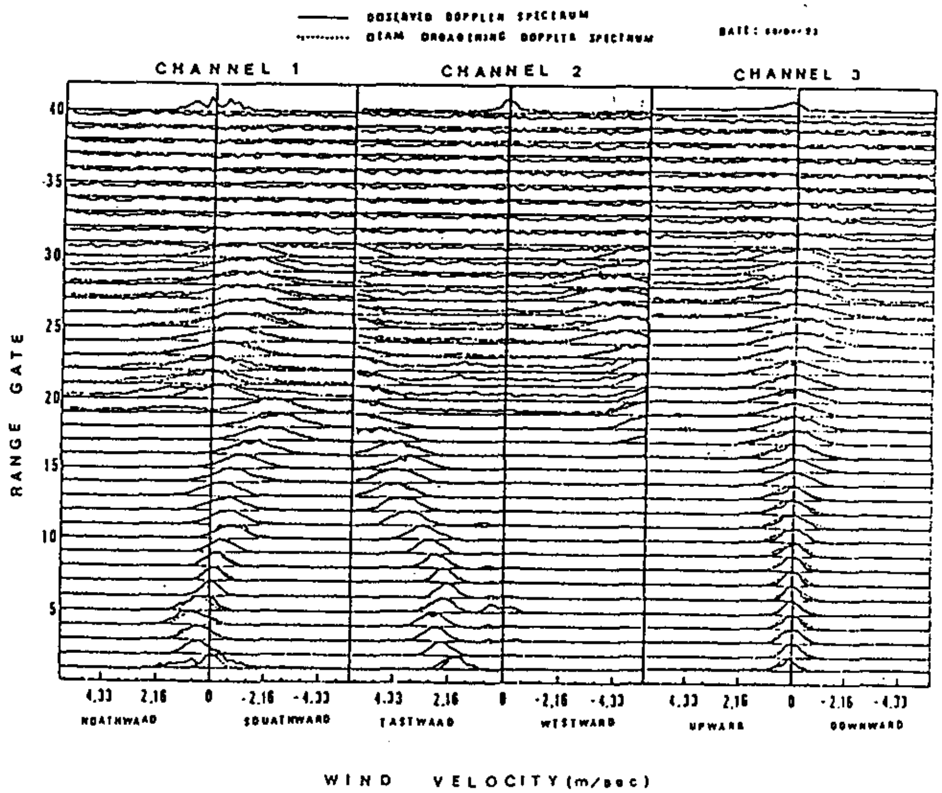

Figure 4. Comparison between normalized observed Doppler spectras (solid curve) and theoretical beam broadened Doppler spectra (dotted curve).

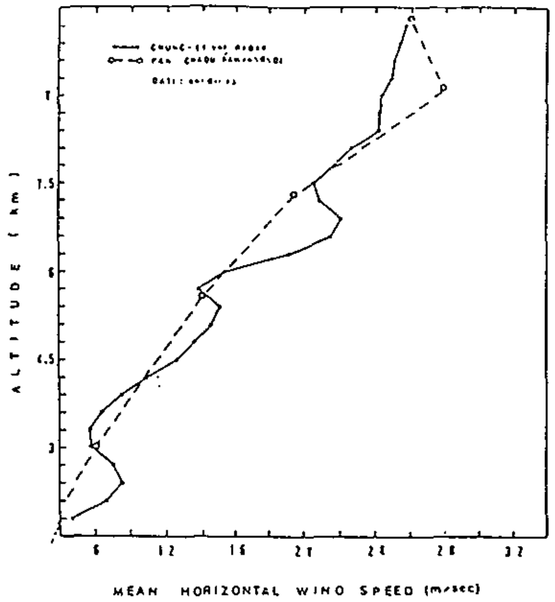

Figure 5. The comparison between radar-observed mean horizontal wind speed and rawinsonde wind speed.

range gate 30 because the signal-to-noise ratio is too low to calculate the accurate mean horizontal wind velocity. Comparing the observed and theoretical beam broadening Doppler spectra, it is obvious that the former are systematically narrower than the latter for vertical Doppler spectra, whereas, for oblique Doppler spectra, the former are broader than or equal to the latter. These phenomena can be seen more clearly from Figure 6 in which the abscissa is the beam broadening spectral width and the ordinate is the observed Doppler spectral width. It is noticed that some points distributed in panel (a) and panel (b) of Figure 6 (for oblique Doppler spectra) are deviated much from the line with slope 1. It is because the signal-to-noise ratio at these altitudes is not high enough so that the true Doppler spectral widths cannot be evaluated accurately from the observed Doppler spectra. However, the data quality for vertical Doppler spectra is quite good, as referred to Figure 4. Therefore, the aspect sensitivity can be estimated from the observed vertical Doppler spectra and the theoretical beam broadening spectra according to the previous illustration in equation (4). The measured aspect sensitivities at a specified altitude are shown in Figure 7 with the open circles. It is evident from Figure 7 that, in general, the echo powers decrease at the rate of 0.3 to 1 dB/deg, and the levelling of the aspect sensitivity can also be observed at a certain altitude. Specifically, there is no angular dependence of echo power at altitude 5.7 km. These features can be reconfirmed from Figure 8, in which the profiles of echo power for the three antenna beams and the generalized potential refractive index gradient, M, are presented. The aspect sensitivities at the altitude marked with the arrows in Figure 8 have been shown in Figure 7. The definition of M is (TATARSKII, 1961; VANZANDT et al., 1978)

$$M = -77.6 \times 10^{-6} \frac{P}{T} \left(\frac{\partial \ln \Theta}{\partial z}\right) \left[1 + \frac{15500\, q}{T} \left(1 - \frac{1}{2} \frac{\partial \ln q / \partial z}{\partial \ln \Theta / \partial z}\right)\right] \qquad (5)$$

where P is the atmospheric pressure (mb), T is the temperature (K), q is the specific humidity and Θ is the potential temperature (°K). It is obvious that atmospheric stability is related to the value of M^2, the higher the stability, the larger the value of M^2. From Figure 8 it is clear that the profiles of echo power and M^2 are matched very well. This characteristic has been confirmed by many scientific workers (GAGE et al., 1981; TATARSKII, 1961; GAGE and BALSLEY, 1980). The correctness of the aspect sensitivity measured with the Chung-Li VHF radar by using the vertical Doppler spectrum and beam broadening effect can be further proven if the echo power of the oblique beam and vertical beam are compared. The echo power of the radar beam toward northwest is not available for comparison in this study because of the contamination by the intense cosmic noise from the Cygnus A radio star (PAN, 1987). After examining the echo power profiles of the vertical and oblique (toward northeast) radar beams in Figure 8, it is apparent that there are large aspect sensitivities existing in the atmosphere below 5.1 km and above 7.2 km with the echo power difference of 10 to 15 dB and 5 to 10 dB, respectively. However, there are little power differences (less than 2 dB) around the altitude 5.7 km. The aspect sensitivities measured at the specified altitude from the echo power profile of vertical and oblique beams are also plotted in Figure 7 with the crosses. Noting that the zenith angle of the oblique radar beam is 17°, it implies that the echo power of the oblique beam observed can be expected as the result of isotropic turbulent scattering, that is, no angular dependence. Therefore, the echo power of the oblique beam will be located at the levelling of the aspect sensitivity. From Figure 7 it is evident that the aspect sensitivity measured from these two independent methods are consistent. It is concluded that the method of aspect sensitivity measurement in terms of observed vertical Doppler spectrum and beam broadening effect developed at Chung-Li is practicable and correct.

DISCUSSION AND CONCLUSION

There are many assumptions in the method of aspect sensitivity measurement introduced in this study, such as the Gaussian antenna beam pattern, neglection of the wind shear, turbulent fluctuation and gravity wave oscillation broadening effect in the observed vertical Doppler spectrum. In general, the assumption of the Gaussian antenna pattern can be accepted if the angular range concerned in a broad antenna beam is limited within the range ± HPBW/2 measured from the main beam axis, that is, ± 4° for the Chung-Li radar. On the other hand, the wind shear effect will be very small and can be neglected if the antenna beam is pointed vertically and the range resolution is fine enough. The gravity wave effect can also be neglected if the time period for the averaged Doppler spectral estimation is shorter than 5 minutes (HOCKING, 1986) or the

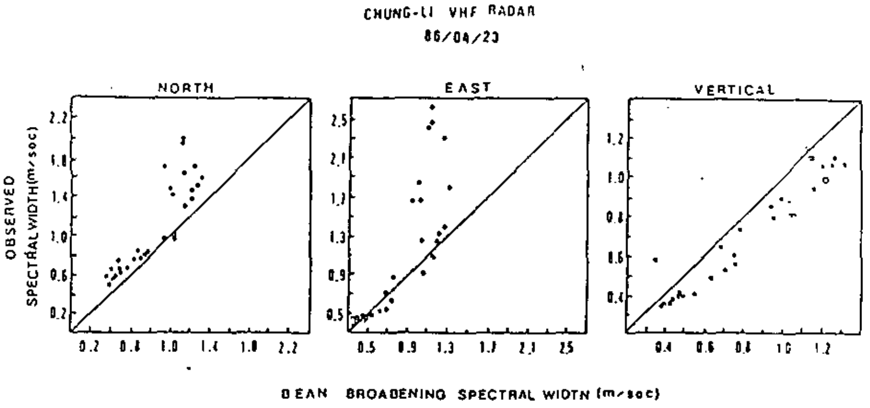

Figure 6. The scatter diagram of observed spectral width and beam broadening spectral width.

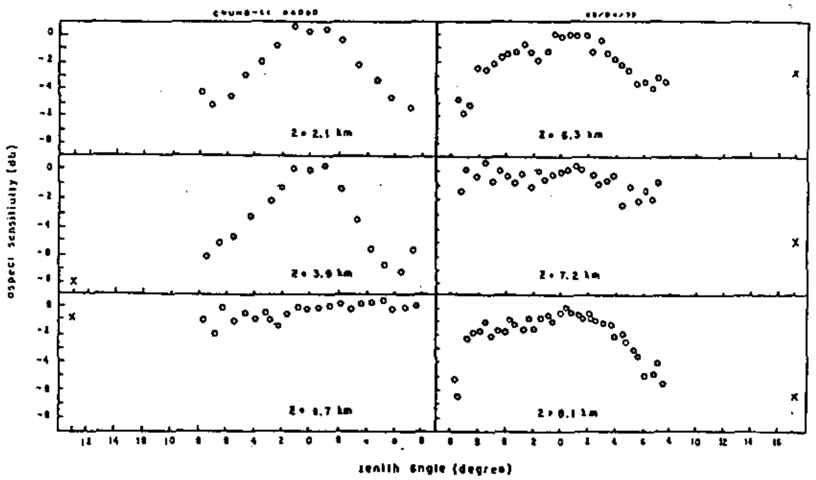

Figure 7. The aspect sensitivity measured with the Chung-Li VHF radar. The open circle curve represents the measurement results from the observed Doppler spectrum for vertically pointing beams and the cross is the echo power difference between vertical and oblique beams.

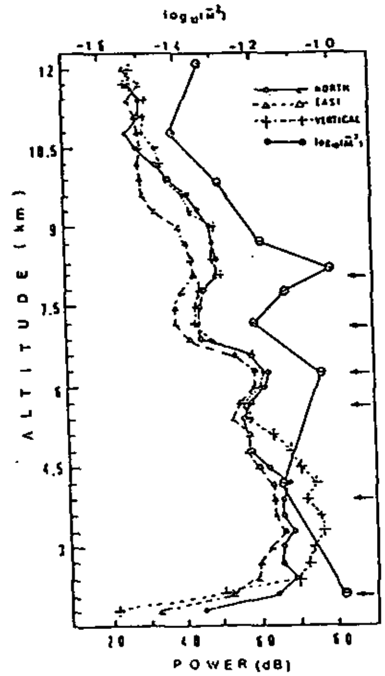

Figure 8. The profiles of echo power for beams toward north, east, and vertically pointing and M^2 calculated from meteorological data observed at the Pan Chaio rawinsonde station.

atmospheric condition is very quiet (CARTER et al., 1984). As for the turbulent broadening effect, the degree of its contribution to the vertical Doppler spectral width can be estimated from the comparison between the width of the observed oblique Doppler spectrum and the beam broadening spectrum. If the former is larger than the latter, it implies that the turbulent broadening effect will be very important and cannot be neglected. Under this situation, although the detailed structure of the aspect sensitivity cannot be evaluated from the observed vertical Doppler spectrum, the characteristic width of aspect sensitivity will be calculated from the information of beam broadening spectral width, vertical and oblique observed Doppler spectral width (CHU, 1988). However, if the observed oblique Doppler spectral width is equal or approximate to the vertical one, it implies that the turbulent fluctuation will be so weak that the turbulent effect can be neglected. From Figure 4 it is clear that the observed oblique spectral widths are approximate to the beam broadening spectral width, that is, the turbulent effect can be neglected during this observation. The gravity wave effect can be neglected also because there are no gravity waves existing in this observation after examining the time series of radial wind fluctuation. Therefore, because of no contamination from wind shear, turbulent and gravity wave effect, the result of aspect sensitivity measurement shown in Figure 7 is the true one.

In general, the disadvantages of the traditional beam swinging method for aspect sensitivity measurements are (1) the spatial fine structure of aspect sensitivity cannot be measured because of the convolution effect with the antenna beam pattern; (2) the temporal resolution of aspect sensitivity cannot be high enough because of the time consumed for the radar beam swing; (3) the actual angular distribution of echo power cannot be measured because the zenith angle from which the most echo power is returned is not the angle the radar beam pointed. Of course, these disadvantages can be eliminated if the pencil-like narrow radar beam is used for observation. Because of no beam swinging and convolution of the antenna beam pattern, the disadvantages mentioned above will not exist in the measurement results of aspect sensitivity introduced in this study. Therefore, the quality of aspect sensitivity measured from the broad radar beam pointed vertically is better than the beam swinging method.

From the previous discussion, it is concluded that for a VHF radar with which the aspect sensitivity cannot be measured by using the beam swinging method, the measurement methods in terms of beam broadening effect on the vertically pointing radar beam will be applied if the antenna beam is broad enough and the horizontal wind speed can be evaluated precisely.

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