N87-10468

7 P.

4.0 INTERCOMPARISON AND CALIBRATION OF WIND AND WAVE MEASUREMENTS AT VARIOUS FREQUENCIES

R. A. Vincent

Physics Department, University of Adelaide
Adelaide, Australia 5001

18933

AB 830877

INTRODUCTION

Radars are increasingly being used for determinations of the small-scale wave and turbulence fields of the atmosphere. It is important to understand as fully as possible the likely sources of error or bias in radar velocity determinations. This is especially true for the determination of wave and turbulence parameters which often rely on the measurement of first or 'second order' deviations from the prevailing wind and therefore require better precision and time resolution than is usually required for measurements of the mean winds alone. The intercomparison of velocity measurements made with different techniques (e.g., radar and balloon) can be expected to help determine not only the relative effectiveness of the different methods, but also the degree of reliability.

SYSTEMATIC AND RANDOM ERRORS IN RADAR WIND MEASUREMENTS

Systematic errors. In most respects, the more serious velocity errors are systematic in origin for the commonly used Doppler technique whereby the horizontal wind components are inferred by tilting the radar beam away from the zenith, systematic errors are most probably caused by the aspect sensitivity of the scattering irregularities. The effective pointing angle of the radar beam from the zenith is a product of the actual beam pattern and the angular dependence of the scattering, so if there is enhanced scattering from the zenith then the effective pointing angle of the radar beam will be less than the physical angle (e.g., ROTTGER and LARSEN, 1984). If such effects occur and are left uncorrected, then the net effect is to bias the wind speeds to low values. Recent multi-angle Doppler measurements made with the Kyoto MU radar show that aspect sensitivity problems are especially severe in the stratosphere (T. Tsuda, private communication) and that horizontal wind measurements are biased for pointing angles of less than 8-10°; these observations support the recommendations of the Second MST Workshop (VINCENT, 1984) that the optimum pointing angles are between 10° and 15°. However, when using large off-vertical angles care must be taken that any signal leakage through vertically pointing sidelobes are also accounted for (STRAUCH et al., 1984).

Radars provide a particularly powerful means of measuring vertical velocities (w) by observing the Doppler shifts of echoes received in vertically pointing beams. Because of the small magnitudes of w, however, care must be taken to remove any contamination due to the horizontal wind components. Contamination can arise in a number of ways (ROTTGER, 1984) and may be significant at VHF where specular reflections from tilted irregularities can be important. Special care must be taken in inferring vertical velocities when the transmitting and receiving antennas are separated, as would be the case in the SA experiment. Because of the geometry, the signals will be scattered at small angles to the vertical and the contamination will be significant, especially at low heights where the effect is most severe (May, private communication). ROTTGER (1984) has shown how interferometer measurements can be used, in principle, to correct observations of w.

The major source of systematic errors in the spaced antenna technique is likely to be the 'triangle-size effect'. If the receiving antenna size is too small compared with the average pattern size of the diffraction pattern, then the velocities will tend to be underestimated. The factors which control the pattern size are discussed in VINCENT (1984) where recommendations are made for minimizing this effect, but more work needs to be done to understand its causes.

Random errors. DOVIAK et al. (1979) have discussed the factors which influence errors in Doppler measurements. The mean square error (σ_v^2) of a radial velocity (v_r) is given by

$$\sigma_v^2 = V_N^2 e^{(\pi\sigma_n)2} [(N/S)^2 + (\frac{2N}{S})(1-e^{-2(\pi\sigma_n)^2}) + \pi^{3/2}\sigma_n]/(2\pi^2 M) \qquad (1)$$

where S/N is the signal-to-noise ratio, σ_n is the spectral width normalized to the Nyquist velocity, V_n, and M is the number of samples. For S/N > 10 dB the rms error is approximately

$$\sigma_v^2 \sim V_n^2 \sigma_n e^{(\pi\sigma_n)^2} /(2M\pi^{1/2}) \qquad (2)$$

while at low S/N (<0 dB) the error is approximately

$$\sigma_v^2 \sim (N/S)^2 v_n^2/(2\pi^2 M) \qquad (3)$$

For example, based on data taken with the MU radat, typical fractional errors in 90 s estimates of the horizontal wind component are about 0.07 in the lower troposphere (S/N ∿ 30 dB), about 0.13 in the upper troposphere (S/N -6 dB) and up to 0.25 in the lower stratosphere with S/N ∿ 6 dB.

Errors for the SA method are not so easy to evaluate, but MAY and BRIGGS (1985) have derived an expression for the random errors which is a particularly important development for this technique. The velocities are found using the time shifts to the maxima in the cross correlation functions (τ_{max}) and the times for the autocorrelation to fall to the value of the cross correlation at zero lag (τ_x) (BRIGGS, 1984). The respective errors are:

$$\sigma_{max} \sim 0.5\, \tau_{1/2}^{3/2}\, T^{-1}(1 - \rho_m^2)/\rho_m \qquad (4)$$

$$\sigma \sim 0.5\, \tau_{1/2}^{5/2}\, T^{-1/2}\tau_x^{-1}(1 - \rho_x^2)/\rho_x \qquad (5)$$

where $\tau_{1/2}$ is the mean fading time (proportional to the spectral width), T is the record length (proportional to M) and the correlation values (ρ_m, ρ_x) are evaluated before the effects of the noise are removed. In the mesosphere, for SA measurements made at MF with S/N ∿ 10 dB and fading times 2-5 s, May finds fractional errors in velocity of up to about 10%.

In the lower atmosphere, comparisons made with the Adelaide VHF radar operating in the spaced antenna mode with radiosonde winds made from a site 35 km away show rms differences of about 3 ms^{-1}.

ERRORS IN WAVE AND TURBULENCE MEASUREMENTS

Wave Fluxes. The random errors cited above give some idea about the averaging times which are required to achieve a desired level of accuracy in measuring gravity-wave parameters. Estimates of gravity-wave amplitudes vary, but balloon measurements suggest rms amplitudes of about 1-2 ms^{-1} for stratospheric inertio-gravity waves (e.g., BARAT, 1983). High resolution rocket smoke trail measurements also give rms amplitudes of about 1 to 2 ms^{-1}

in the lower to mid-stratosphere (DEWAN et al., 1984) with little or no geographic or seasonal variation. VHF radar measurements in the upper troposphere reported by BALSLEY and CARTER (1982) give similar amplitudes to those quoted above.

There are relatively few measurements of vertical wave amplitudes in the lower atmosphere, but unique constant-pressure balloon observations reported by MASSMAN (1981) for the Southern Hemisphere show differences between the upper tropical troposphere and the lower midlatitude stratosphere. Amplitudes were larger in the troposphere ($w' \sim 0.2$ ms^{-1}) than in the stratosphere ($w' \sim 0.1$ ms^{-1}). The intrinsic periods of the wave events observed by Massman ranged between 30 and 180 min, so using the gravity-wave dispersion relation, the corresponding rms horizontal amplitudes were also between 1 and 2 ms^{-1}. Overall, there appears to be relatively good agreement about wave amplitudes as observed by a variety of different techniques.

An important wave parameter is the vertical flux of horizontal momentum and particularly the zonal component, $\overline{u'w'}$. Radar estimates can be made by correlating u' and w' (e.g., SMITH and FRITTS, 1983) or by observing the mean square radial velocities along two radar beams offset at an angle θ to the zenith (VINCENT and REID, 1982) viz:

$$\overline{u'w'} \quad (\overline{v_1^{\,2}} - \overline{v_2^{\,2}})/(2 \sin 2\theta) \tag{6}$$

Because the difference of two quantities $\overline{v_1^{\,2}}$, $\overline{v_2^{\,2}}$ which are similar in magnitude is involved, the effects of random errors can be large. Approximately, the error is

$$\delta(\overline{u'w'}) \sim \overline{2u'\delta u'}/(\sin 2\theta) \tag{7}$$

In the mesosphere, for observations at an angle of, say, 10°, $u' \sim 3.5$ ms^{-1} (corresponding to a 20 ms^{-1} horizontal rms amplitude) and $\delta u' \sim 0.5$ ms^{-1} for a 4-min observation at 2 MHz so that to achieve an accuracy of ~ 1 m^2 s^{-2} requires about a 6-hr average. The only observations of $\overline{u'w'}$ so far for the mesosphere are radar measurements; typically, $\overline{u'w'} \sim 1$-5 ms^{-1} in magnitude. For the lower atmosphere, MASSMAN (1981) found from balloon measurements mean values of $\rho_o \overline{u'w'}$ of about 0.04 Nm^{-2} in the upper troposphere and 0.02 Nm^{-2} in the stratosphere for freely propagating gravity waves. The respective values of $|\overline{u'w'}|$ are 0.18 and 0.06 m^{2}s^{-2}. To achieve accuracies of 0.01 m^{2}s^{-1} would require about 2 days of radar observations if an rms radial velocity of $u' \sim 0.25$ ms^{-1} and a comparable value for $\delta u'$ are assumed. These estimates are crude and may be overestimates of the averaging times required. REID (1981) found that mean square difference between Doppler velocities measured in the mesosphere over 3 days by two radar beams connected to independent receiving and digitizing systems was only 0.1 m^2 s^{-2}.

It should be noted that the radar technique of VINCENT and REID (1982) is not suitable for measuring the fluxes associated with topographic waves ($c = 0$). However, aircraft and balloon observations show the fluxes for stationary waves can be large in the troposphere and as PALMER et al. (1985) have noted, breaking mountain waves may be an important source of drag in the lower atmosphere. The momentum fluxes associated with these waves are found to be in the range 0.1 to 1 Nm^{-2}.

Turbulence Parameters. Radars can be used to estimate turbulence parameters such as eddy dissipation rates (ε) and diffusion coefficients (D), in a number of ways. However, the best way appears to be via measurements of the spectral width of the received signals, after the effects of shear and beam broadening, as well as "spikes" due to specular reflections, are taken into account. These effects are relatively more important for wider beam radars and as the mean velocity of the background flow increases. HOCKING (1985) has recently summarized the various techniques and limitations of radar estimates of turbulence.

For example, the spectral width broadening due to turbulence, σ_t, is given by

$$\sigma_t^2 = \sigma_e^2 - \sigma_s^2$$

where σ_e and σ_s are the experimental (measured) and shear broadened width, respectively. Hocking points out that in many experimental situations σ_e and σ_s are similar in magnitude so that statistical fluctuations can cause negative values for σ_t^2; these should be taken into consideration along with the positive values, otherwise the estimates of ε will be biased too high. Often it may not be possible to obtain reliable estimates of σ_t^2 at all.

Indirect comparisons of radar measurements of ε in the lower atmosphere (~ 0.2 m^{2}s^{-1}) suggest they may be an order of magnitude greater than aircraft estimates (e.g., SATO and WOODMAN, 1982; Lilly et al., 1974). These discrepancies do not yet appear to have been resolved and it would be very desirable if simultaneous intercomparisons of balloon, radar and aircraft techniques were arranged.

TECHNIQUES FOR MEASURING HORIZONTAL WAVELENGTHS AND PHASE VELOCITIES

If the role played by gravity waves in the middle atmosphere is to be fully understood, then more measurements are required of horizontal scales (λ_x) and phase velocity (c) since these are amongst the least well-known gravity-wave parameters. A number of radar techniques have been devised but not yet widely applied. All methods measure the time for waves to pass between horizontally separated observing locations. The main differences between techniques depends on whether a single radar is used or a network. VINCENT and REID (1982) used a single radar to compare the wave motions observed in one beam with the motions measured in another, widely separated beam. Some assumptions have to be made in analyzing the results and there is the possibility of ambiguities for waves with λ_x less than the separation of the observed regions. ROTTGER (1984) has used an interferometric technique to compare the wave motions observed in a radar beam pointed in two directions close to the zenith. A network of spaced antenna stations (GRAVNET) has been used by MEEK et al. (1985) to study scales and velocities in the mesosphere and the results are similar to those found by VINCENT and REID (1982), while CARTER et al. (1984) used a network of three ST radars with vertically directed beams to investigate waves in the troposphere. An important finding of all these measurements is that monochromatic waves occur relatively infrequently and some way must be found of describing the rather random wave field which appears to be the norm in all regions of the atmosphere.

SUMMARY

Considerable progress has been made in applying MST radars to studies of wave and turbulence motions in the middle atmosphere. Where comparisons can be made between measurements made by different techniques, the results are in reasonable accord, taking into account the temporal and spatial separations often involved. The usual comparisons have been between radiosonde balloons and radar determinations of the prevailing wind, but before MST radar techniques can be fully exploited for wave and turbulence observations, it is necessary to understand the errors and limitations likely to be encountered. While the use of relations like equation (1) can give some indication of the likely errors involved in a single observation, it is essential that they be checked by other means. For instance, one practical method would be to find the rms difference between velocities taken as closely spaced as possible in time or space. It is very important that further intercomparisons be made between as many different techniques as possible in order to test the basic assumptions which are inherent in any measurement of velocity. To this end, for example, the Kyoto and Adelaide atmospheric groups recently used the MU radar to make comparisons of velocities measured by the Doppler and SA methods. Multi-beam experiments were also made to test the assumption made in the "dual-beam" momentum flux techniques that the wave field is horizontally homogeneous. It is noted that most MST radar studies to date have been confined to observations of propagating waves. It would be an important development if these studies could be extended to investigations of orographic waves; joint experiments with balloons and aircraft are called for and the capability of radars to scan in azimuth and elevation needs to be exploited as well as the use of networks in order to measure such important properties as energy and momentum fluxes and wavelengths.

REFERENCES

Balsley, B. B., and D. A. Carter (1982), The spectrum of atmospheric velocity fluctuations at 8 km and 86 km, Geophys. Res. Lett., 9, 465-468.

Barat, J. (1983), The fine scale of stratospheric flow revealed by differential sounding, J. Geophys. Res., 88, 5219-5228.

Carter, D. A., B. B. Balsley, W. L. Ecklund, M. Crochet, A. C. Riddle, and R. Garello (1984), Tropospheric gravity waves observed by three closely spaced ST radars, Handbook for MAP vol 14, 219-228, SCOSTEP Secretariat, Dep. Elec. Computer Eng., Univ. IL, Urbana-Champaign.

Dewan, E. M. N. Grossbard, A. F. Quesada, and R. E. Good (1984), Correction, Geophys. Res. Lett., 11, 624.

Doviak, R. J., D. S. Zrnic', and D. S. Sirmans (1979), Doppler weather radar, Proc. IEEE, 67, 1522-1553.

Hocking, W. K. (1985), Measurements of turbulent energy dissipation rates in the middle atmosphere by radar techniques - A review, Radio Sci., 20, 1403-1422.

Lilly, D. K., D. E. Waco, and S. I. Adelfang (1974), Stratospheric mixing estimated from high-altitude turbulence measurements, J. Appl. Meteorol., 13, 488.

May, P., and B. H. Briggs (1985), Statistical errors in the spaced antenna technique, J. Atmos. Terr. Phys., submitted.

Massman, W. J. (1981), An investigation of gravity waves on a global scale using TWERLE data, J. Geophys. Res., 86, 4072-4082.

Meek, C., I. M. Reid, and A. H. Manson (1985), Observations of mesospheric wind velocities. I. Gravity wave horizontal scales and phase velocities determined from spaced wind observations, Radio Sci., 20, 1363-1382.

Palmer, T. N., G. J. Shutts, and R. Swinbank (1985), Alleviation of a systematic westerly bias in general circulation and numerical weather prediction models through an orographic gravity wave drag parameterization, to be submitted.

Reid, I. N. (1981), Radar studies of atmospheric gravity waves, Ph.D. thesis, University of Adelaide.

Rottger, J. (1984), Improvement of vertical velocity measurements, Handbook for MAP vol 14, 150-155, SCOSTEP Secretariat, Dep. Elec. Computer Eng., Univ. IL, Urbana-Champaign.

Rottger J., and M. F. Larsen (1984), Potential advantages of the spaced antenna method for operational wind profiling, Handbook for MAP vol 14, 134-138, SCOSTEP Secretariat, Dep. Elec. and Computer Eng., Univ. IL, Urbana-Champaign.

Sato, T., and R. F. Woodman (1982), Fine altitude resolution observations of stratospheric turbulent layers by the Arecibo 430 MHz radar, J. Atmos. Sci., 39, 2546.

Smith, S. A., and D. C. Fritts (1983), Estimation of gravity wave motions, momentum fluxes and induced mean flow accelerations in the winter mesosphere over Poker Flat, Alaska, Proc. 21st Conf. Radar Meteorol., Edmonton, Canada, 104-110.

Strauch, R. G., K. B. Earnshaw, D. A. Merritt, K. P. Moran, and D. W. van de Kamp (1984), Performance of the Colorado wind-profiling network, Handbook for MAP vol 14, 38-49, SCOSTEP Secretariat, Dep. Elec. Computer Eng., Univ. IL, Urbana-Champaign.

Vincent, R. A. (1984), Relationship of spaced antenna and Doppler techniques for velocity measurements, Handbook for MAP vol 14, 126-130, SCOSTEP Secretariat, Dep. Elec. Computer Eng., Univ. IL, Urbana-Champaign.

Vincent, R. A., and I. M. Reid (1982), HF Doppler measurements of mesospheric gravity wave momentum fluxes, J. Atmos. Sci., 40, 441.

SESSION SUMMARY AND RECOMMENDATIONS

The emphasis in this session was on velocity intercomparisons made not only between radars and radiosondes, but also between radars operating at different frequencies. There was general consensus that the agreement between radiosonde winds and the radar velocities whether measured by the Doppler or spaced antenna techniques was good. Typically, the rms differences were of the order of 3-5 ms^{-1}, which are generally within the limitations imposed by the spatial and temporal differences inherent in most of the comparisons made to date; even radiosonde packages flown on the same balloon give rms differences of about 3 ms^{-1}. Many comparisons have been of relatively short duration and it is desirable that more extensive series of evaluations be made so as to recognize and remove any sources of systematic bias which may be present in radar wind determinations. It was agreed that where feasible, special soundings be made in order to provide further intercomparisons that are as close in time and space as possible.

There was much discussion on the impact of random errors on radar measurements of wave turbulence parameters. In the lower atmosphere in particular, the random errors are likely to be of comparable magnitude to the wave amplitudes and there was general agreement that the errors in individual measurements needed to be assessed very carefully. Efforts should continue to find the optimum data reduction methods. Efforts should also continue to devise alternate techniques for measuring such important wave parameters as $\overline{u'w'}$. The dual-complementary-beam technique requires measurements from regions displaced horizontally in space but the best determinations will come from simultaneous measurements of u' and w' made in a common volume. Horizontally displaced receiving systems could be used to look at the same scattering volume from one or more angles other than backscatter. Such multistatic arrangements would not only allow more direct measurements of $\overline{u'w'}$ but also some of the assumptions of the dual-beam method to be tested.

Papers presented in this session gave further evidence of the ability of 50-MHz radars to make studies of precipitation during convective activity. There was much interest shown in this work which appears to provide opportunities for studies of cloud physics with low VHF radars.

Some of the most extensive discussions, both formal and informal, concerned the optimum frequency for clear-air wind profiling. To date, most ST radars have operated near 50 MHz, but now radars using frequencies near 400 MHz are being, or are about to be, evaluated. While a number of factors influence the choice of an operating frequency (including the availability of a suitable frequency band), concern was expressed that the effects of precipitation be taken into account when a choice is being made. Experience shows that the precipitation and turbulence echoes can be separated at 50 MHz but, near 400 MHz the observed signals will be from water droplets rather than turbulence-induced refractive index fluctuations in nearly all precipitating systems. Precipitation, no matter how light, will therefore preclude direct vertical-beam, vertical wind measurements at the higher frequency. It probably does not matter about measurements in strong convection. However, the direct vertical wind data will be missing also in stratiform rain, which can be extensive in horizontal extent. The measured vertical velocities are important in order to convert correctly the off-vertical radial velocities to horizontal motions. It is not possible to infer vertical air motion from horizontal measurements for 3 beam systems (1 zenith beam) when the scattered signal is from water droplets. Indirect vertical velocity measurements would require different or additional pointing angles; however obtaining the vertical velocity from integration of the continuity equations may not be accurate enough anyway. Thus, one cannot expect to obtain vertical air motion in precipitation with UHF radars. Note that this is a problem in the lowest 4-6 km in stratiform precipitation; above this altitude, the fall speed of the particles and the uncertainty of the vertical velocity are comparable. The determination of network-type vertical velocities by objective analysis techniques is still possible but will be valid for the scale of the network spacing.

Concern was expressed that, before large-scale networks of wind-profiling radars be established, the relative merits of operating in either the lower VHF or lower UHF bands be fully assessed. It may well be that an intermediate frequency near, say, 200 MHz is optimum.