NOAA TR ERL 351-WPL 44

NOAA Technical Report ERL 351-WPL 44

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Environmental Research Laboratories

Meteorological Applications of the FM Doppler Radar

R.G. STRAUCH
W.C. CAMPBELL
R.B. CHADWICK
K.P. MORAN

BOULDER, COLO.
DECEMBER 1975

U.S. DEPARTMENT OF COMMERCE
Rogers C. B. Morton, Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Robert M. White, Administrator
ENVIRONMENTAL RESEARCH LABORATORIES
Wilmot N. Hess, Director

NOAA TECHNICAL REPORT ERL 351-WPL 44

Meteorological Applications of the FM Doppler Radar

R.G. STRAUCH
W.C. CAMPBELL
R.B. CHADWICK
K.P. MORAN

BOULDER, COLO.
December 1975

For sale by the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20402

CONTENTS

METEOROLOGICAL APPLICATIONS OF THE FM DOPPLER RADAR

R. G. Strauch, W. C. Campbell, R. B. Chadwick, and K. P. Moran

NOAA/ERL/Wave Propagation Laboratory
Boulder, Colorado 80302

Microwave FM-CW radars have been used for about 5 years to monitor the structure of atmospheric regions with large refractive-index fluctuations. We have recently devised a scheme that retrieves the Doppler velocity spectrum for each range resolution cell measured by an FM radar. In this paper we report initial results of meteorological measurements with this new capability and discuss its potential in remote sensing of the boundary layer.

1. INTRODUCTION

High resolution probing of the atmosphere with a microwave FM-CW radar was first demonstrated by Richter (1969). The FM-CW radar, normally operated in a zenith-pointing mode, has been used as a boundary layer probe to detect clear air refractive-index fluctuations with a range (height) resolution of less than 2 m (Richter, 1969; Gossard and Richter, 1970a; Bean _et al._, 1971; Richter _et al._, 1973). Clear air radar echoes in the boundary layer are usually found in layers, often with wave-like structure (Gossard and Richter, 1970b; Gossard _et al._, 1971, 1972). Radar reflectivity for scattering from turbulent fluctuations in refractive index is given by $\eta = 0.38\, C_n^2\, \lambda^{-1/3}$ (Ottersten, 1969) for homogeneous isotropic turbulence where C_n^2 is the radio refractive-index structure constant and λ is the radar wavelength. Within the limitations of the assumptions used in the scattering theory, a calibrated radar can therefore remotely measure C_n^2 in the scattering layers. However, the most useful results from FM-CW radar data have been the display of the spatial and temporal configuration of the scattering layers as they are influenced by driving forces such as gravity waves. The Wave Propagation Laboratory of the National Oceanic and Atmospheric Administration has operated an FM-CW radar for about 18 months, and Doppler capability has recently been added to this radar (Strauch _et al._, 1975). The complete Doppler velocity spectrum of discrete or distributed targets can be measured for each range resolution cell. The addition of Doppler capability to the FM-CW radar will permit measurement of the mean wind distribution within the scattering layer and thereby reveal the role that wind shear may play in the production of turbulence associated with scattering layers.

Although the frequency of the scattered signal depends on both range and velocity for an FM radar, the complete Doppler velocity spectrum can be measured in each range resolution cell by measuring the change in phase of the signal from sweep-to-sweep. We obtain range from the backscattered signal frequency with the usual FM signal processing techniques. The Doppler processing can be accomplished in a variety of ways that offer flexibility in range and velocity resolution. The particular implementation used to process data presented in this report provides 33 range resolution elements, from 0 to a selectable maximum range. Thirty-one of the range cells have 33 velocity resolution increments, from 0 to plus or minus a selectable maximum velocity. The first and last range increments have 17 velocity resolution elements, and the sign of the velocity is not resolved in these range cells; i.e., the negative velocity portion of the spectrum is folded onto the positive portion. An arbitrary number of velocity spectra can be averaged, thereby reducing the variance of the estimate of each spectral density value.

In this paper we present initial results obtained with a zenith-pointing FM Doppler radar, and we discuss the potential application of the FM radar as an all-weather boundary layer wind profiler. The data were obtained in Boulder, Colorado, in the summer of 1975. The radar transmitter and receiver are similar to those used by Richter (1969). Radar returns from both precipitation and refractive index fluctuations were observed. The fall speed of precipitation scatterers separates the velocity spectrum of the desired signal from ground clutter, but since the vertical air motion was usually small, the mean radial velocity of refractive index fluctuations was near zero so these signal spectra were not shifted from the ground clutter. Nevertheless, it is possible to discern weak atmospheric signals from strong ground clutter because the velocity spectra of refractive index fluctuations appear in several velocity locations whereas ground clutter appears as a distinctive sharp peak.

2. PRECIPITATION RESULTS

Velocity spectra of falling raindrops and profiles of fall speeds measured with a zenith-pointing FM Doppler radar are shown in Figs. 1 and 2. The data were acquired with a coherent integration time, T_C, of 0.035 sec (data window for a single spectrum) and an averaging time, T_A, of 1.75 sec (averaging 50 spectra); the entire data sample was acquired in 10 sec (T_O). The velocity profiles (Figs. 1a and 2a) are profiles of the mode of the averaged velocity spectrum. Fig. 1a shows the fall speed profile with a height resolution of 32 m. The heights shown are AGL, with the radar located at 1500 m MSL. The melting layer (Battan, 1973, p. 194) is indicated by the change in fall speed between 740 and 930 m AGL. Fig. 1b is a plot of the 33 power spectral density values measured for the height interval 224 to 256 m. Ground clutter appears at the zero velocity spectral point (in the middle of the spectrum) and, because of the width of the spectral window, also appears at the two adjacent velocity points. For the sweep parameters used in this data sample, the maximum unambiguous velocity interval is ±8 m/sec. Note that the velocity distribution is not completely encompassed by the ± 8 m/sec interval. The velocity spectrum is therefore partly folded, and for the data processing scheme used here, the spectrum folds into adjacent range cells. That is, the spectral power density at + 8 m/sec at the right hand edge of Fig. 1b is actually the spectral density at -8 m/sec for the height interval 256 to 288 m. Likewise, the portion of the velocity spectrum that corresponds to downward velocities in excess of 8 m/sec for the height interval 224 to 256 m appears as positive velocity in the range interval 192 to 224 m. Velocity folding with the FM Doppler radar is therefore different from that with pulsed Doppler radar in which the spectrum associated with a range interval folds but remains in the same range interval. The velocity spectrum in Fig. 1b also differs from usual pulsed Doppler spectra because the FM spectra are averaged. The variance of the estimate of spectral density at any given spectral point is 1/N times the variance for a single spectrum where N is the number of spectra that are averaged. One technique used to estimate the moments of the spectrum in the presence of noise is to discard all spectral values below a threshold level and compute the moments based on the remaining spectral points (Campbell, et al., 1971). Fig. 1c shows the spectral density at three height intervals after a threshold level has been subtracted.

Fig. 2 shows the velocity profile and some individual spectra measured with a height resolution of 100 m. These data were obtained approximately 1 min later than the data in Fig. 1. One hundred meter height resolution is similar to that of the pulsed Doppler radars used at the Wave Propagation Laboratory, but the FM Doppler radar can measure the velocity spectrum in the lowest 100 m whereas the minimum height that can be measured by a pulsed Dopper radar must exceed its height resolution. The measured velocity spectrum in the height interval 2800 to 2900 m, shown in Fig. 2b, illustrates range folding that occurs when signal frequencies greater than one-half the sampling frequency are not completely filtered prior to sampling. (The data are processed digitally, and the rate at which the signal is digitized establishes an upper limit on the signal frequency or range.) For the data processing scheme used here, signal frequencies greater than one-half the sampling frequency are aliased or folded about the maximum range interval in such a way that a negative velocity in a folded range interval appears as a positive velocity. Thus the peak in the spectrum at positive velocities in Fig. 2b actually results from the power spectrum in the folded range interval 3600 to 3700 m, and the velocity in the folded range interval is really negative (falling raindrops) as in the unfolded ranges.

An FM Doppler radar may be more useful than a pulsed Doppler radar for precipitation studies in applications that require low minimum range, excellent range resolution, or readily selectable range resolution. The low minimum range capability would be useful in measuring drop size distributions. A vertical velocity distribution of rainfall speeds can be converted to a drop size distribution (Atlas et al., 1973) provided the vertical air motion is known. A single pulsed Doppler radar cannot obtain unambiguous drop size distributions because the vertical air motion is unknown, but an FM radar could obtain the velocity spectrum near the surface where the vertical air motion is negligible or easily measured. The high resolution capability of the FM Doppler radar may be useful in the study of microphysics and particle growth processes.

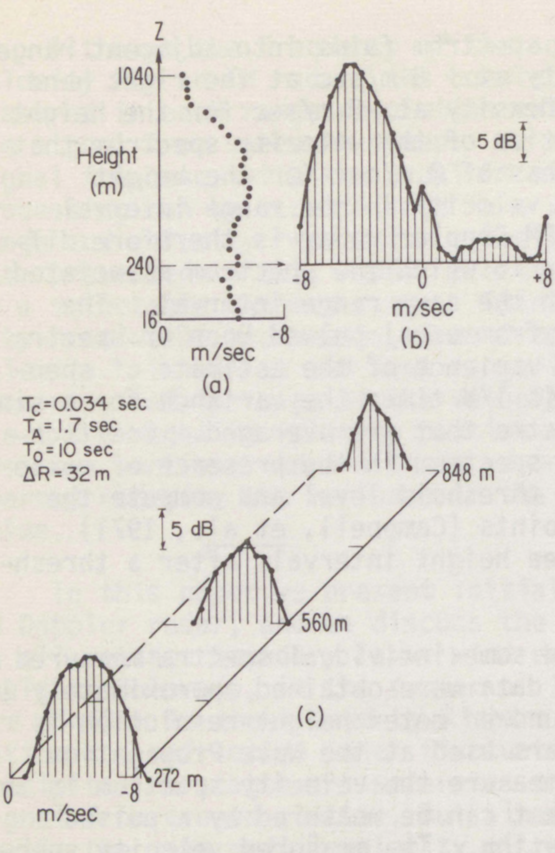

Figure 1. (a) Modal fall speeds of raindrops measured with FM Doppler radar. (b) Averaged velocity spectrum in height interval 224-256 m. (c) Sample Doppler spectra after applying threshold.

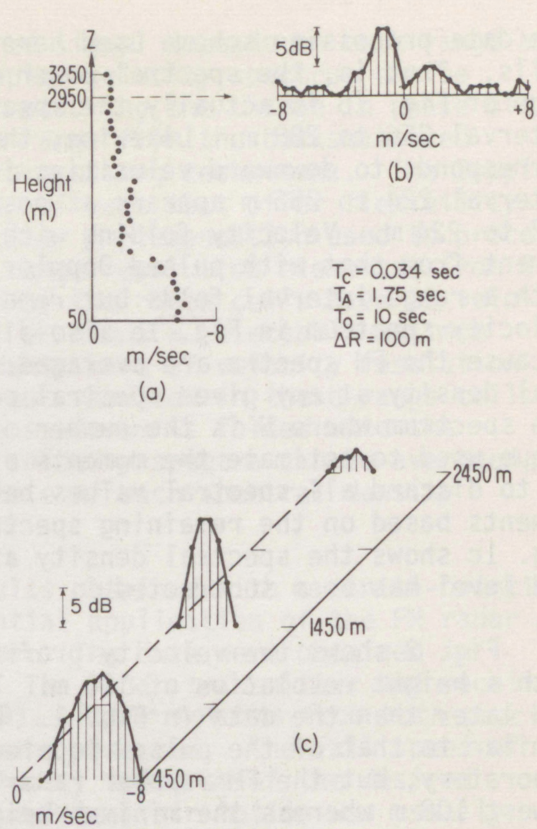

Figure 2. (a) Velocity profile of modal fall speeds of raindrops. (b) Doppler spectra illustrating range folding effects. (c) Sample Doppler spectra after applying threshold.

3. CLEAR AIR RESULTS

We have conducted several experiments to evaluate the potential of FM Doppler radars to measure wind in the clear air. Fig. 3 illustrates profiles of vertical velocity measured in the convective boundary layer at the same time an acoustic echo sounder acquired the record shown in Fig. 4. The FM Doppler radar obtained a continuous profile of vertical velocity to greater than 600 m altitude while the acoustic sounder intensity profiles were recorded to about 300 m. A velocity profile was measured with the FM Doppler radar every 2 min during the period of the acoustic record shown in Fig. 4 and every profile was vertically continuous. We cannot attribute the FM radar returns to scattering from atmospheric refractive-index fluctuations in this case because during the daytime in May and June 1975 there was a continuous supply of cottonwood seeds carried aloft by convection. A peak vertical velocity of + 2.8 m/sec was measured from 225 to 275 m altitude at 1122 MDT. Direct sunshine on an asphalt parking lot adjacent to the radar probably accounts for this strong updraft.

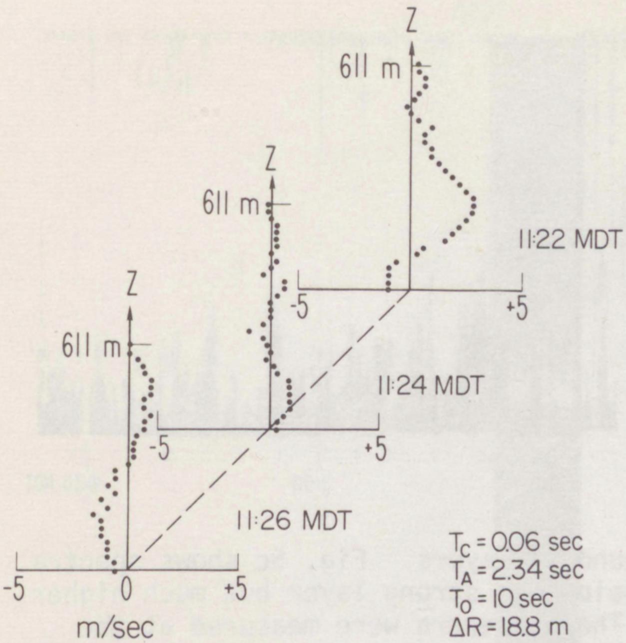

Figure 3. Vertical velocity profiles measured with FM Doppler radar in clear air. Signal returns are primarily from cottonwood seeds.

Experiments were also conducted in the early morning hours, prior to the onset of convective mixing, to obtain FM Doppler data free of radar return from insects and seeds so that backscatter from only atmospheric refractive-index fluctuations would be observed. On June 29 and June 30, 1975, a layer of strong radar return was observed at 1300 m AGL at about 0630 MDT. Fig. 5a shows the radar reflectivity measured before and after the FM Doppler velocity measurements on 29 June. The background intensity setting of the display oscilloscope was reduced so that only the strongest returns were observed. Fig. 5b shows the Doppler spectra measured in the scattering layer. The averaging time was 3.6 sec, and the total observation time was 15 sec. The spectra are not symmetrical about the mean and are as broad as spectra we observe with chaff targets in the convective boundary layer using a pulsed Doppler radar. Prior to daytime heating, pulsed Doppler spectra are generally narrower.

The two major factors that contribute to the breadth of the Doppler spectrum for zenith-pointing observations of non-particulate scattering are wind shear and turbulence. Wind shear causes a spread in the Doppler spectrum because, when shear exists, backscatter from different parts of the pulse volume is observed with different radial velocities whereas turbulence broadens the spectrum by randomly moving the scatterers relative to the mean flow. Both of these effects will symmetrically broaden the spectrum. When spectra are averaged, as in these data samples, the averaged Doppler spectrum could be broadened by a time-varying mean velocity. This factor could also account for the lack of symmetry of the spectra about the mean. In Fig. 5a the radar reflectivity of the scattering layer is much stronger than that of other targets (probably insects), indicating a large C_n^2. Large C_n^2 values may often be associated with relatively strong mechanical turbulence so spectral widths of several m sec^{-1} may be characteristic of scattering from

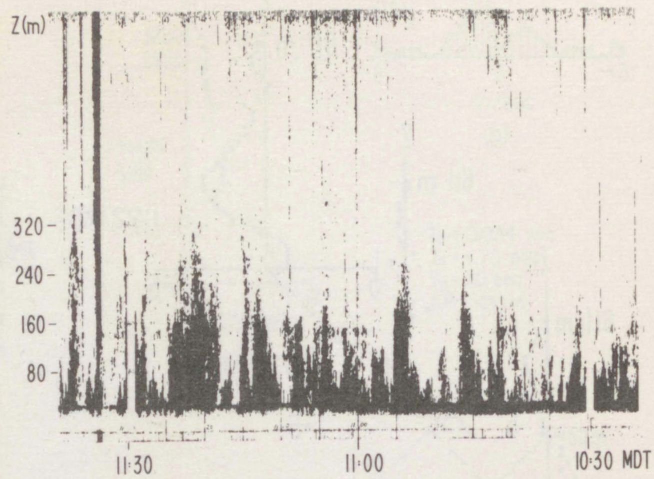

Figure 4. Acoustic sounder record taken at the same time data shown in Fig. 3 were acquired.

strong refractive-index fluctuations found in layers. Fig. 5c shows spectra measured from scattering at altitudes below the strong layer but much higher than the minimum observable altitude. These spectra were measured at the same time as those shown in Fig. 5b. In Fig. 5c ground clutter, detected in the antenna sidelobes, is the dominant feature. It appears at zero velocity and the two adjacent spectral points. The spectra measured at the height interval near 254 m are caused solely by ground clutter. The spectra at 367.5 and 424 m altitude result from ground clutter and clear air returns with near-zero velocity. Very little vertical air motion would be expected at these altitudes prior to surface heating.

Fig. 6a-c illustrate the results obtained from another early morning test on 30 June when a strong scattering layer was also observed. The layer is shown on a time-height display of reflectivity in Fig. 6a. Spectra of backscatter from this layer, shown in Fig. 6b, are similar to those measured the previous morning. However, spectra from altitudes below the layer, Fig. 6c, show refractive-index scattering either from a second layer that was much weaker than the layer at 1300 m, or from non-layered or background refractive-index fluctuations. The signal spectra from this second region are only partially masked by the strong ground clutter. If these returns were not associated with a layered structure whose height or radar reflectivity factor changes with time, it would have been very difficult to detect them with a data processing system that measured only the intensity of the radar signal because backscatter that does not change in time or height would not have been distinguishable from ground clutter. Doppler processing enables us to detect refractive-index scattering much weaker than the ground clutter if the signal spectra are displaced from zero velocity. If the antenna elevation angle is less than 90 deg, so that horizontal wind speed separates the signal and clutter spectra, the detection of weak signals will be further facilitated. Under such conditions, the FM Doppler radar can detect scattering regions with very weak C_n^2 at an altitude of a few tens of meters in the presence of strong ground clutter, even if the backscatter intensity is constant in height and time.

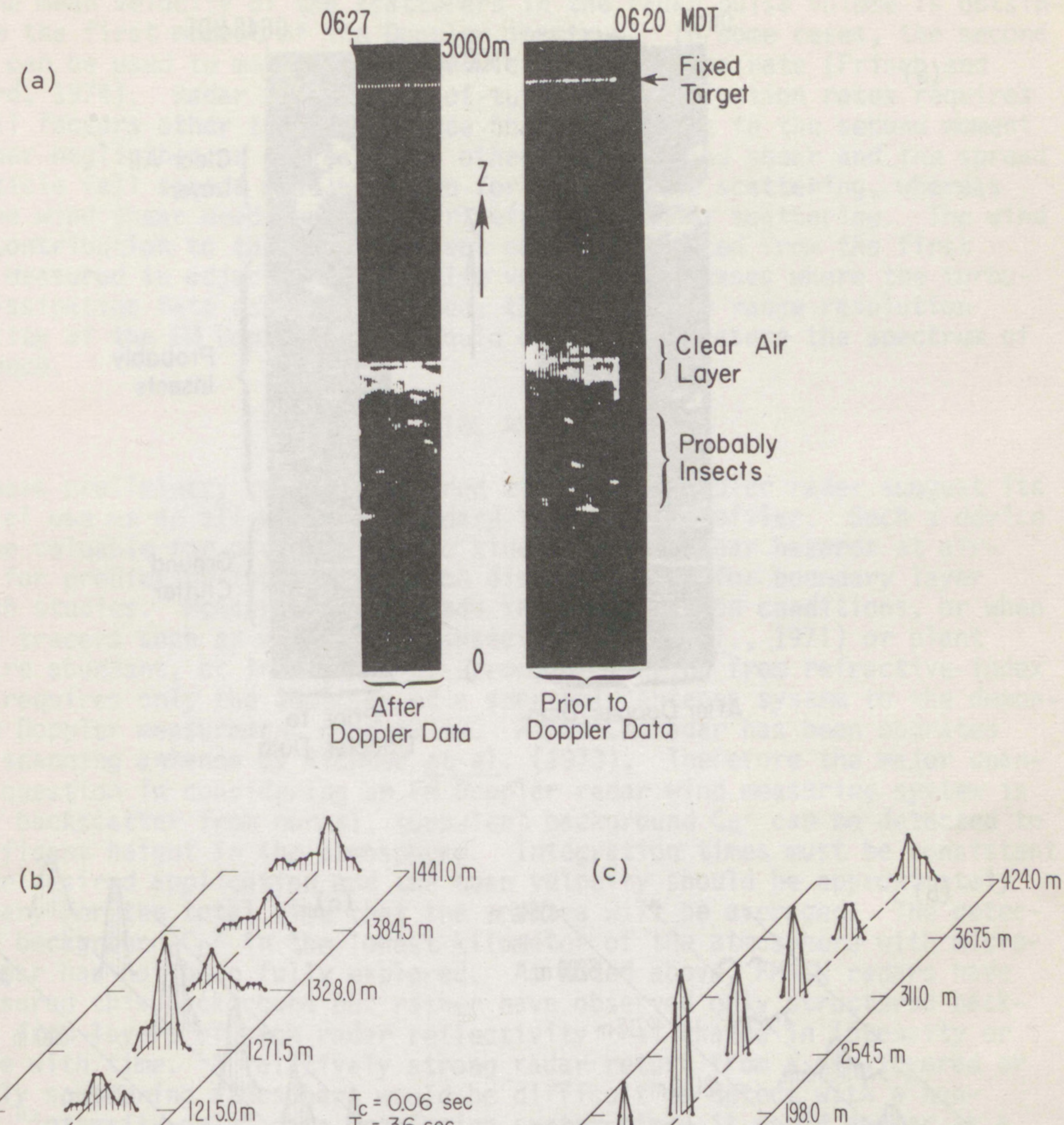

Fig. 5. (a) Radar scattering intensity from refractive index fluctuations in a strong scattering layer. (b) Doppler spectra of clear air return from a scattering layer (vertical velocity). (c) Sample Doppler spectra measured below the scattering layer. Spectra at 227 m and 283 m are caused solely by ground clutter.

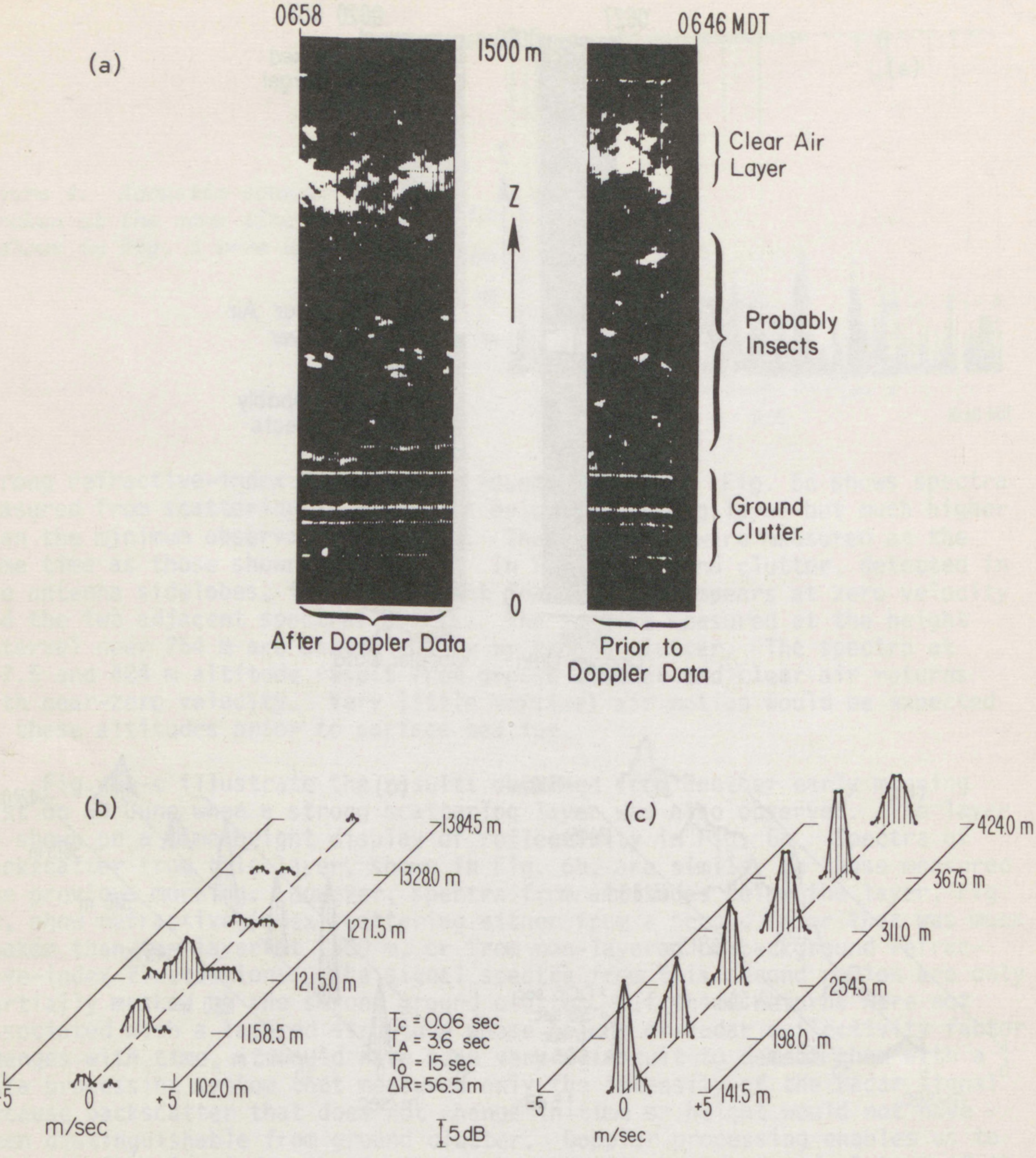

Fig. 6. (a) Radar reflectivity in clear air showing refractive index scattering layer at about 1250 m and discrete targets that are probably insects. (b) Doppler velocity spectra of clear air return from the scattering layer. (c) Sample Doppler spectra measured below the scattering layer. Ground clutter appears in only 3 spectral points so that clear air return is observed in the samples at each range location.

The mean velocity of the scatterers in the radar pulse volume is obtained from the first moment of the Doppler spectrum. In some cases, the second moment can be used to measure the turbulent dissipation rate (Frisch and Clifford, 1974). Radar measurement of turbulent dissipation rates requires that all factors other than turbulence that contribute to the second moment be either negligible or evaluated by other means. Wind shear and the spread of particle fall speeds must be known for particulate scattering, whereas only the wind shear need be known for refractive-index scattering. The wind shear contribution to the second moment can be evaluated from the first moment measured in adjacent radar pulse volumes. In cases where the turbulent dissipation rate can be estimated, the selectable range resolution capability of the FM Doppler radar could be used to measure the spectrum of turbulence.

4. A POTENTIAL APPLICATION

These preliminary results obtained with an FM Doppler radar suggest its potential use as an all-weather boundary layer wind profiler. Such a device would be valuable for predicting some kinds of wind-shear hazards at airports, for predicting fog or pollution dispersal, and for boundary layer research studies. Measurement of winds in precipitation conditions, or when natural tracers such as weak-flying insects (Bean et al., 1971) or plant seeds are abundant, or in regions of strong scattering from refractive-index layers requires only the addition of a scannable antenna system to the demonstrated Doppler measurement capability. An FM-CW radar has been operated with a scanning antenna by Richter et al. (1973). Therefore the major unanswered question in considering an FM Doppler radar wind measuring system is whether backscatter from normal, turbulent background C_n^2 can be detected to a significant height in the atmosphere. Integration times must be consistent with the desired application and the mean velocity should be approximately stationary for the total time that the spectra will be averaged. The detection of background C_n^2 in the lowest kilometer of the atmosphere with microwave radar has not been fully explored. As noted above, FM-CW radars have not measured this background but rather have observed only structured backscatter from layers of high radar reflectivity that change in intensity or altitude with time. A relatively strong radar return from a non-layered or uniformly scattering atmosphere would be difficult to detect with a non-Doppler "intensity-only" data processing system since it would appear as a uniform increase in the brightness of the display in a film recording system with range compensation as illustrated in Figs. 5a and 6a. Note also that increasing the integration time with a data system that processes intensity serves only to make this brightness increase more uniform and therefore does not assist in detecting scattering from background C_n^2. Doppler processing provides a method whereby background C_n^2 can be detected even in the presence of ground clutter that may be much stronger than the signal. In addition, FM-CW radars have usually operated with very high range resolution, but in searching for background C_n^2, a degraded range resolution would be used to increase the radar sensitivity because the backscatter would be spatially continuous. Therefore, it is likely that an FM Doppler radar system with coarse range resolution and long averaging times can observe atmospheric returns not previously detected with the FM-CW radar.

Ultra-sensitive pulsed radars have also been used to study clear air radar signals (Hardy and Katz, 1969). Only layered or cellular structure has been observed by these radars. However, the minimum range of the high-power sensitive radars is usually limited by receiver saturation caused by ground clutter so these radars are unable to search for weak atmospheric scattering at a range of less than about 1 km. In addition, most of the refractive-index scattering studies with pulsed radar have utilized only the signal intensity in processing and displaying the data so that atmospheric scattering cannot easily be detected in the presence of ground clutter even if the ground clutter level is below receiver saturation.

Van Zandt et al. (1975) have reported that profiles of radial velocity can be measured in the troposphere "at each height examined on almost every occasion" with a VHF pulsed Doppler radar at Sunset, Colorado described by Green et al., 1975. The minimum observable altitude was 4 km because of ground clutter. The VHF radar data are processed digitally. First a Fast Fourier Transform (FFT) algorithm is used to compute the power spectra and then the spectra are averaged. This type of signal processing, using integration times as long as 100 sec, does not reveal the presence of strong scattering layers and in fact treats scattering layers as anomalies of no particular interest. C_n^2 values in the upper troposphere are expected to be smaller than those in the boundary layer. Therefore, if the radar reflectivity relationship $\eta = 0.38\ C_n^2\ \lambda^{-1/3}$ is valid for radar wavelengths of 0.1 to 7.5 m, the VHF radar results suggest that similar data processing techniques may prove fruitful if applied to microwave radars probing the clear air. That is, an FM Doppler radar may have sufficient sensitivity to measure the wind continuously in the boundary layer. An FM radar designed for measuring wind profiles would have relatively poor range resolution so that the sensitivity to background C_n^2 would be increased. The sensitivity of the FM Doppler radar used to acquire the data for this paper was compared with that of the Sunset VHF radar with the comparison method developed by Chadwick and Little (1973). The FM Doppler radar should detect approximately the same minimum C_n^2 at a height of 1 km that the VHF radar detects at 10 km. However, aircraft measurements by Ochs and Lawrence (1972) show C_n^2 to be 10 to 20 dB greater in the first few hundred meters above the surface than at 3 km. They derived C_n^2 based on measurements of the temperature structure constant and found values of C_n^2 between 10^{-15} and 10^{-17} ($m^{-2/3}$) in the lowest kilometer of the atmosphere. The minimum detectable C_n^2 calculcated for our FM Doppler radar, assuming a range resolution of 32 m and a 20-sec integration time, is

$$C_{n\ \min}^2 = 1.5 \times 10^{-22}\ R^2\ m^{-2/3} ,$$

where R is the range in meters. Therefore, background C_n^2 should be generally detectable in the boundary layer with an FM Doppler radar.

5. CONCLUSIONS

The FM-CW radar, heretofore used primarily to qualitatively observe the structure of atmospheric layers with large C_n^2, should find additional meteorological applications because it can measure Doppler velocity spectra. A nearly all-weather boundary layer wind profiler appears feasible with this technique. The FM Dopper radar may also find applications in precipitation studies that require low minimum range or variable range resolution.

6. REFERENCES

Atlas, D. , R. C. Srivastava, and R. S. Sekhon, Doppler radar characteristics of precipitation at vertical incidence, *Rev. Geophys. Space Phys.*, 11, 1-35, 1973.

Battan, L. J., *Radar Observation of the Atmosphere*, Univ. of Chicago Press, Chicago 1973.

Bean, B. R., R. E. McGavin, R. B. Chadwick, and B. D. Warner, Preliminary results of utilizing the high resolution FM radar as a boundary-layer probe, *Boundary-Layer Meteorol.*, 1, 466-473, 1971.

Campbell, R. B., F. E. Compton, V. Friedman, and H. L. Groginsky, Doppler signal processing and instrumentation for modified "Porcupine" C-band pulse-Doppler radar, *AFCRL-71-0318*, May 1971.

Chadwick, R. B., and C. G. Little, The comparison of sensitivities of atmospheric echo-sounders, *Remote Sensing of Environment*, 2, 223-234, 1973.

Frisch, A. S. and S. F. Clifford, A study of convection capped by a stable layer using Doppler radar and acoustic echo sounders, *J. Atmos. Sci.*, 31, 1622-1628, 1974.

Gossard, E. E. and J. H. Richter, Internal waves in the atmosphere from high-resolution radar measurements, *J. Geophys. Res.*, 75, 3523-3536, 1970a.

___________ and ___________, The shape of internal waves of finite amplitude from high-resolution radar sounding of the lower atmosphere, *J. Atmos. Sci.*, 27, 971-973, 1970b.

___________, D. R. Jensen, and J. H. Richter, An analytical study of tropospheric structure as seen by high-resolution radar, *J. Atmos. Sci.*, 28, 794-807, 1971.

___________, J. H. Richter and D. R. Jensen, Effect of wind shear on atmospheric wave instabilities revealed by FM/CW radar observations, *Boundary-Layer Meteorology*, 4, 113-131, 1972.

Green, J. L., J. M. Warnock, R. H. Winkler, and T. E. VanZandt, A sensitive VHF radar for the study of winds, waves, and turbulence in the troposphere, stratosphere, and mesosphere, *Proceedings 16th Radar Meteorol. Conference*, April 22-24, 1975, Houston, Texas, 313-315, 1975.

Hardy, K. R. and I. Katz, Probing the clear atmosphere with high power, high resolution radars, *Proc. IEEE*, 57, 468-480, 1969.

Ochs, G. R. and R. S. Lawrence, Temperature and C_n^2 profiles measured over land and ocean to 3 km above the surface, *NOAA TR ERL 251-WPL-22*, U.S. Dept. of Commerce, Boulder, Colo., 1972.

Ottersten, H., Radar backscattering from the turbulent clear atmosphere, *Radio Sci.*, 4, 1251-1255, 1969.

Richter, J. H., High resolution tropospheric radar sounding, *Radio Sci.*, 4, 1260-1268, 1969.

__________, D. R. Jensen, R. A. Poppert, and V. R. Noonkester, New developments in FM-CW radar sounding, *Boundary-Layer Meteorol.*, 4, 179-200, 1973.

Strauch, R. G., W. C. Campbell, R. B. Chadwick, and K. P. Moran, FM-CW boundary layer radar with Doppler capability, *NOAA TR ERL 329-WPL 39*, U.S. Dept. of Commerce, Boulder, Colo., 1975.

VanZandt, T. E., J. L. Green, J. M. Warnock, and R. H. Winkler, Studies of winds in the upper troposphere with a sensitive VHF radar, *Proceedings 16th Radar Meteorol. Conference*, April 22-24, Houston, Texas, 316-319, 1975.

U.S. GOVERNMENT PRINTING OFFICE 1975 - 677-347/1235 Reg. 8

ENVIRONMENTAL RESEARCH LABORATORIES

The mission of the Environmental Reasearch Laboratories is to study the oceans, inland waters, the lower and upper atmosphere, the space environment, and the earth, in search of the understanding needed to provide more useful services in improving man's prospects for survival as influenced by the physical environment. Laboratories contributing to these studies are:

Atlantic Oceanographic and Meteorological Laboratories (AOML): Geology and geophysics of ocean basins and borders, oceanic processes, sea-air interactions and remote sensing of ocean processes and characteristics (Miami, Florida).

Pacific Marine Environmental Laboratory (PMEL): Environmental processes with emphasis on monitoring and predicting the effects of man's activities on estuarine, coastal, and near-shore marine processes (Seattle, Washington).

Great Lakes Environmental Research Laboratory (GLERL): Physical, chemical, and biological, limnology, lake-air interactions, lake hydrology, lake level forecasting, and lake ice studies (Ann Arbor, Michigan).

Atmospheric Physics and Chemistry Laboratory (APCL): Processes of cloud and preciptation physics; chemical composition and nucleating substances in the lower atmosphere; and laboratory and field experiments toward developing feasible methods of weather modification.

Air Resources Laboratories (ARL): Diffusion, transport, and dissipation of atmospheric contaminants; development of methods for prediction and control of atmospheric pollution; geophysical monitoring for climatic change (Silver Spring, Maryland).

Geophysical Fluid Dynamics Laboratory (GFDL): Dynamics and physics of geophysical fluid systems; development of a theoretical basis, through mathematical modeling and computer simulation, for the behavior and properties of the atmosphere and the oceans (Princeton, New Jersey).

National Severe Storms Laboratory (NSSL): Tornadoes, squall lines, thunderstorms, and other severe local convective phenomena directed toward improved methods of prediction and detection (Norman, Oklahoma).

Space Environment Laboratory (SEL): Solar-terrestrial physics, service and technique development in the areas of environmental monitoring and forecasting.

Aeronomy Laboratory (AL): Theoretical, laboratory, rocket, and satellite studies of the physical and chemical processes controlling the ionosphere and exosphere of the earth and other planets, and of the dynamics of their interactions with high-altitude meteorology.

Wave Propagation Laboratory (WPL): Development of new methods for remote sensing of the geophysical environment with special emphasis on optical, microwave and acoustic sensing systems.

Marine EcoSystem Analysis Program Office (MESA): Plans and directs interdisciplinary analyses of the physical, chemical, geological, and biological characteristics of selected coastal regions to assess the potential effects of ocean dumping, municipal and industrial waste discharges, oil pollution, or other activity which may have environmental impact.

Weather Modification Program Office (WMPO): Plans and directs ERL weather modification research activities in precipitation enhancement and severe storms mitigation and operates ERL's research aircraft.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
BOULDER, COLORADO 80302

USCOMM - ERL