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OBSERVATIONS OF THE HORIZONTAL STRUCTURE OF THE BOUNDARY LAYER WITH THE TURBULENT EDDY PROFILER

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Abstract—**In recent years the University of Massachusetts has developed a UHF imaging radar (TEP) and a FMCW radar for boundary layer research. TEP allows the study of the three-dimensional structure of the BL. Examples of convective boundary layer observations obtained during a recent field campaign are presented. Time-height reflectivity profiles are compared to spatial images. Vertical and horizontal slices of TEP's volume show features with scales comparable to the field of view and with radar-reflectivity variations of 10-20 dB at 100 m horizontal scales. These structures are advected by the mean horizontal wind. However, a considerable degree of temporal evolution of these features is also observed.**

I. INTRODUCTION

In recent years, the Microwave Remote Sensing Laboratory (MIRSL) at the University of Massachusetts has developed two unique radar sensors for Boundary Layer and Turbulence research: the Turbulent Eddy Profiler (TEP)(Mead et al., 1998; Pollard et al., 2000), a UHF volumetric radar-profiler; and a S-band fm-cw radar (FMCW)(Ince et al., 2000). During Summer and Fall 2001 both instruments were deployed at Amherst, Massachusetts, observing the convective boundary layer.

TEP is a 915 MHz volume-imaging Doppler radar designed to image local refractive index fluctuations and their radial velocity structure within a 30 degree cone centered about zenith. A single horn-antenna illuminates the field of view, while the backscattered signal is received by an array of up to 90 elements in an hexagonal grid.

Digital beamforming techniques are used in post-processing to produce up to 90 independent simultaneous beams. This results in high-resolution three-dimensional profiles of Doppler spectral moments.

TEP allows the study of the three-dimensional structure of the BL. It also provides vertical wind-profiles, providing a context in which to interpret the observations.

Umass' FMCW is a S-band radar designed to complement TEP measurements providing 2.5 m height-resolution vertical profiles of the BL. Its 3.5° beamwidth approximately matches that of a focused TEP-beam.

Table I summarizes the main characteristics of both radars.

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TABLE I

TEP characteristics	
Center frequency	915 MHz
Range coverage	200 m to 2 km
Range resolution	30 m
Receive array	61-element hexagonal lattice
Array diameter	5 m
Array beamwidth	4°
Transmit peak power	4 kW
Average power	40 W
Pulse repetition frequency	40 kHz
Transmit antenna beamwidth	25°
FMCW characteristics	
Center frequency	2.9 GHz
Range coverage	100 m to 2.5 km
Range resolution	2.5 m
Beamwidth	3.5°
Average power	200 W

In this paper time-height cross sections from both TEP and the FMCW radar are compared to spatial images obtained from slices through the TEP volume in the stream-wise, cross-stream, and horizontal planes.

II. EXPERIMENT DESCRIPTION

During Summer and Fall 2001 TEP and FMCW where deployed at a local site in Amherst, Massachusetts, together with a X-band radar (also developed at the University of Massachusetts), a SODAR, and a sonic-anemometer. The instruments were operated continuously during two periods in mid-August, capturing several full diurnal cycles, and a few days during early October, concentrating on the diurnal BL. This small field-campaign had the dual objective of testing recent upgrades to TEP and FMCW, while providing boundary layer data to the collaborating scientists.

III. OBSERVATIONS

Since the primary focus of this research is the local horizontal structure of the BL, it is useful to concentrate on

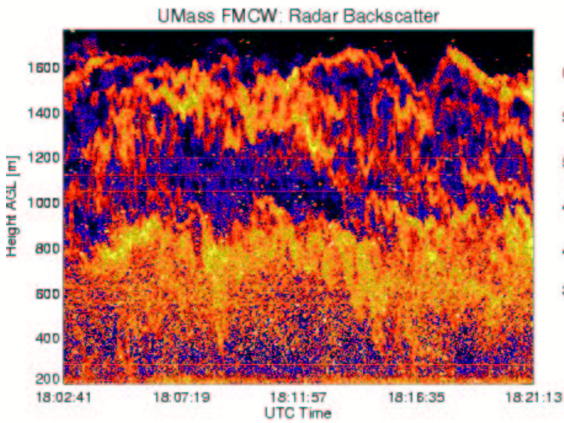

Fig. 1. Time-height reflectivity image produced by the fmcw profiler. This 20-minute segment was obtained during Oct 3, around 2pm local-time. Bright dots in the image are produced by biological targets (insects). Multiple thin layers are resolved.

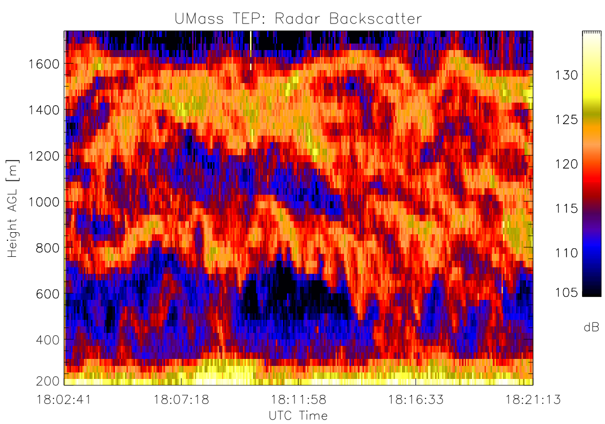

Fig. 2. Time-height reflectivity image produced by TEP. The image shows the same basic features seen by the fmcw, at coarser vertical resolution resolution. Due to the longer wavelength, TEP is far less sensitive to scattering from insects and other small point-targets.

rather short sequences, revealing the level of detail associated with these structures. Figures 1 and 2 shows an example of time-height profiles obtained with FMCW and TEP during October 3, around 2pm local time. Both images show approximately 20 minutes of data. The same features are seen in both images, with FMCW clearly showing a much higher vertical resolution which allows it to discriminate very thin layers of high reflectivity, which correspond to strong gradients in refractive index. Bright dots in the FMCW image are caused by biological targets, mainly insects, with a high density of those below 800 m AGL. Because of the longer radar-wavelength, TEP is much less sensitive (in the order of 20dB) to small point scatterers.

Wind-profiles are obtained by combining the Doppler information from all TEP beams. For each beam, the radial velocity is obtained by calculating the first moment of the Doppler spectrum. Assuming a uniform wind field

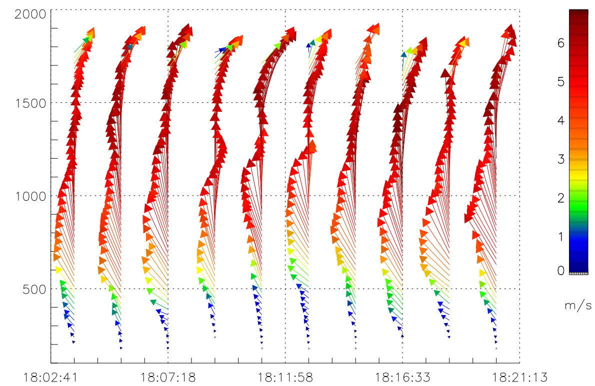

Fig. 3. Wind-profiles obtained by TEP, in system coordinates. Wind-profiles are obtained combining the Doppler information from all TEP beams. The radial velocities obtained for each beam are combined as in beam-swinging windprofilers to obtain a best fit of the mean wind vector. Winds are calculated independently for each range gate.

at each particular range, the wind-vector is calculated by minimizing, in a least mean square sense, the difference between the radial velocities for each beam and the radial component of a best fit horizontal wind.

Figure 3 shows 2-minute averaged wind profiles for the same time segment shown in Figures 1 and 2. Wind speed increases rapidly up to 900-1000 m, suggesting the the bright layer at this height is the top of the CBL. Turbulent layers at higher altitudes could be induced by wind-shear that appears in the wind-profiles as a change of wind-direction. These changes in wind direction with height preclude a uniquely defined down-stream direction for the imaged volume.

Figure 4 shows a comparison of time-height profiles with vertical slices through TEP's volume. The upper panels show a 3-minute segment of Figure 2. Assuming Taylor's frozen turbulence hypothesis, given a wind-speed around 6 m/s at 800 m AGL, this would correspond to a kilometer-long vertical slice along the downstream direction. The lower panels in Figure 4 show a sequence of stream-wise (at 800 m) slices through TEP's volume. Around 800 m, features found in the spatial images can be clearly identified in the time-sequence. Because of the change in wind direction at higher altitudes, horizontal features match less clearly.

Horizontal slices through TEP's volume provide a different look at the horizontal structure of the BL. As an example, Figure 5 shows a sequence of horizontal slices at different heights. Advection of features in agreement with the winds plotted in Figure 3 can be observed, but, simultaneously, the features appear to evolve considerably. An alternative look at the data is offered in Figure 6, showing a stack of horizontal slices between 600 m and 900 m

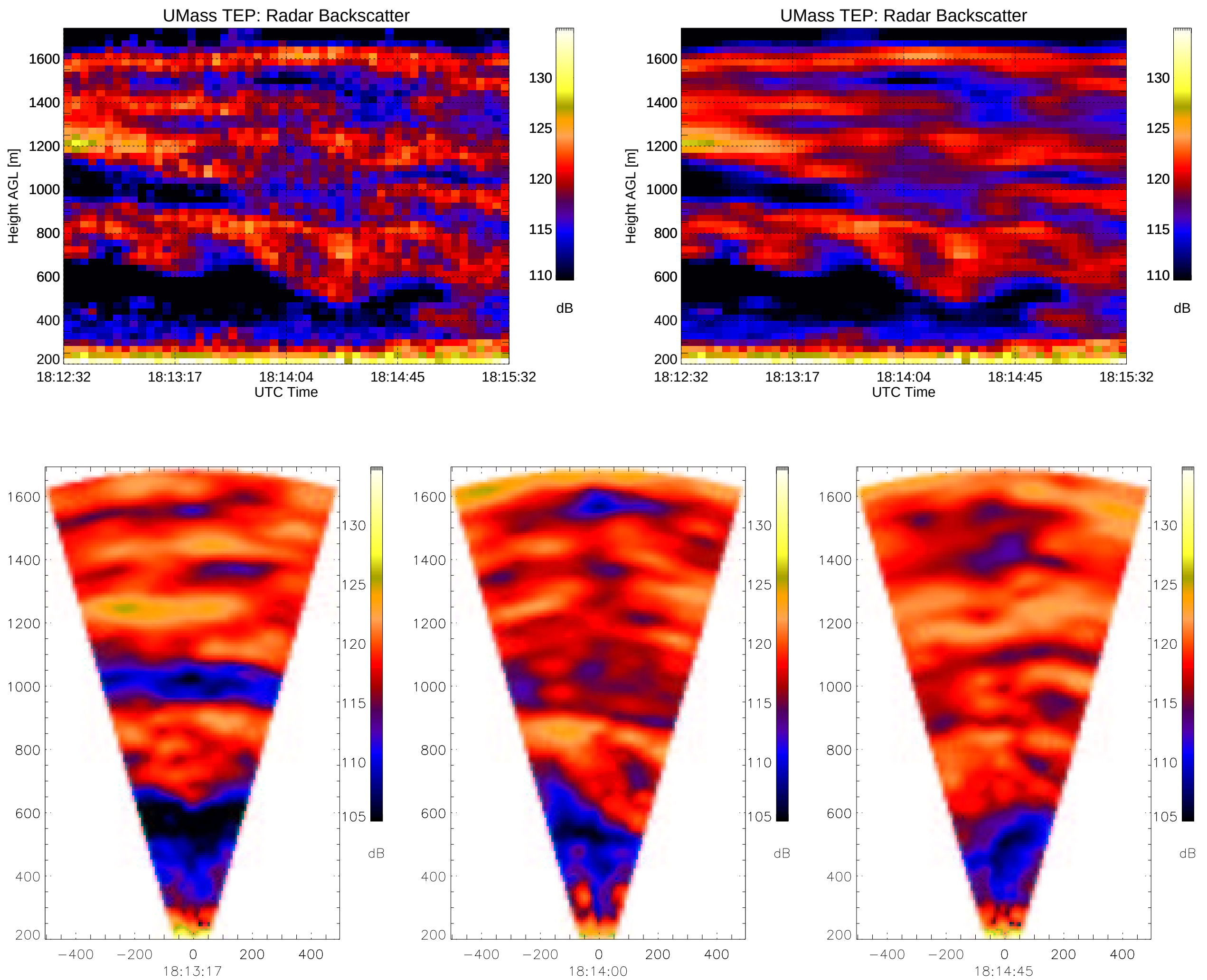

Fig. 4. Comparison of time-height profiles with slices through TEP's volume. The upper-left panel shows a 3 minute segment of Figure 2. Assuming Taylor's hypothesis, this time-height profile corresponds to a stream-wise vertical slice of the atmosphere. The upper-right panel shows the same image smoothed to approximate TEP's horizontal resolution. The lower three panels show vertical slices through TEP's volume spaced 45 seconds along the stream-wise direction at 800m AGL. At 800 m the same features can be recognized in the temporal and spatial images. This is less the case at higher altitudes because of the change in wind direction (Figure 3) resulting in the upper portion of the slices not being stream-wise cuts.

AGL. This image is a good example of features commonly observed in our data-sets:

- Radar-reflectivity shows variation of 10-20 dB at 100 m horizontal scales.
- Observed structures are often larger than the horizontal span of TEP's volume.
- Images suggest a degree of isotropy at the scales observed by TEP (i.e. scales of imaged structures are similar along-stream as cross-stream).

Computer animations of volumetric slices provide a unique view of the translation of scattering features. Although advection of turbulent features can be clearly seen, these sequences also suggest significant evolution of these structures as they are advected. Interpretation is complicated in some cases, when horizontal mean-winds vary in both magnitude and direction with height. Also, some apparent evolution of structures observed in vertical or horizontal slices may be the result of the instantaneous wind having a component perpendicular to the viewing plane, advecting structures through it. In short, interpretation of the data is hindered by the difficulty of displaying full three-dimensional data.

IV. Conclusions

In this paper we have presented some samples of boundary layer data recently collected with TEP and FMCW. The data show TEP's capabilities to study the local, three-dimensional structure of the boundary layer.

Time-height profiles and down-stream slices through the

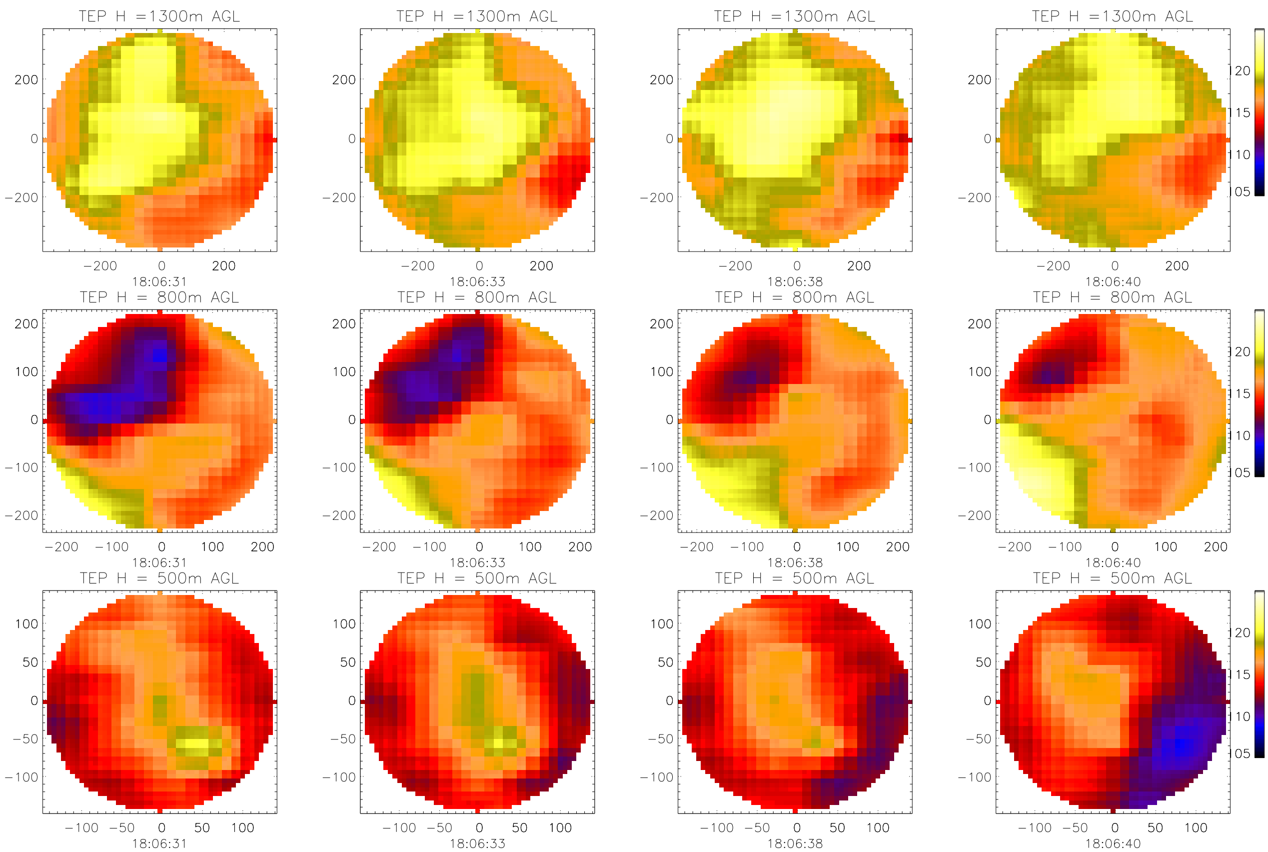

Fig. 5. 10-second sequence of horizontal slices through TEP volume. Slices at 500 show evolution and advection of features within the CBL; at 800 the slices cut through the top of the CBL; and at 1300 the slices cut through a layer of shear-induced turbulence.

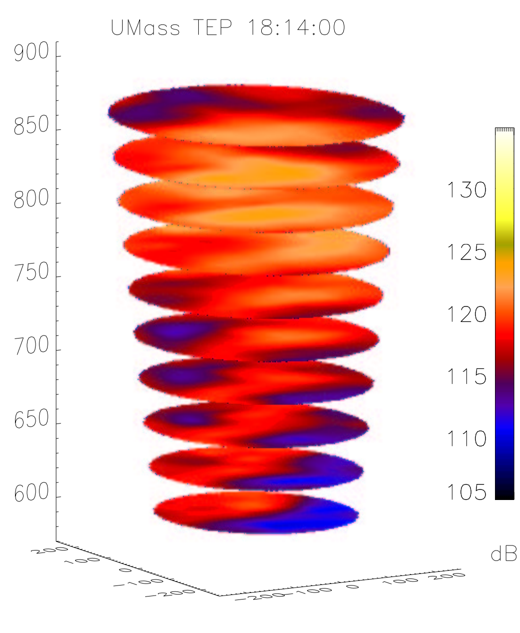

Fig. 6. Stack of horizontal slices of the TEP volume between 600 and 900 m AGL. This slices are separated 30 m, TEP's vertical resolution.

radar's volume are to some extent consistent with each other. However, the significant degree of temporal evolution of the structures captured by TEP observed indicates the limited applicability of Taylor's hypothesis to morphological studies of the BL, supporting the need for instrumentation that, like TEP, can capture its instantaneous, local structure.

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