FINAL REPORT: Use of Turbulent Eddy Profiler in Making Atmospheric Boundary Layer Measurements

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13. ABSTRACT (Maximum 200 words)

Following the purchase of a new TEP data acquisition system, TEP was deployed, along with UMass' FMCW profiler, during the CASES'99 Nocturnal Boundary Layer experiment near Leon, KS. During and following the experiment, several problems were identified in the new data acquisition system, and transmitter. During 2000, data acquisition problems were debugged, and a replacement transmitter was obtained in Spring 2001. TEP and the FMCW were deployed at a local field site in Amherst, MA. Coordinated operations confirmed successful operation of TEP, and collaborations with researchers at NOAA/ETL and U Nebraska are underway. Preliminary results are posted at http://abyss.ecs.umass.edu/tep/.

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1 Statement of the Problem Studied

An understanding of the dynamics of the atmosphere is crucial to the Army's mission. In addition to phenomina such as weather, climate, and global change, those dynamics effect the propagation of communication and radar signals, the fluctuations and dispersions of aerosols, and the ballistics of objects. Perhaps most crucial in understanding the dynamics of the atmosphere is an understanding of the Atmospheric Boundary Layer (ABL), the continuously turbulent atmospheric layer in contact with the surface of the earth.

While traditional turbulence methods are well grounded in experimental results, current simulation techniques are not; an outstanding question in using DNS and LES is how well they compare with experimental atmospheric data. Wind profilers, sodars, FM-CW radars, radio sondes, and in situ sensors have all been used with some success in measuring the structure of the ABL. Each of those methods, however, only produces a one-dimensional vertical profile of the atmosphere; both DNS and LES produce three dimensional, time-varying fields of temperature, velocity, and other quantities of interest. Experimental verification of those models would be optimally accomplished by measuring three-dimensional, time-varying fields on scales comparable to those used by DNS and LES.

Under a Department of Defense University Research Initiative (URI), the Microwave Remote Sensing Laboratory (MIRSL) at the University of Massachusetts developed a prototype radar remote sensing system able to measure atmospheric turbulence for ABL studies, including the verification of LES results. This digital beam-forming UHF radar system is capable of imaging the structure of turbulence throughout a conical volume that extends from the ground to the top of the ABL. Preliminary field measurements made at Duck, NC and Rock Springs, PA indicated that TEP was able to resolve the three-dimensional C_n^2 and velocity fields at spatial and temporal scales comparable to LES computations.

During the final year of the URI we were able to make some preliminary comparisons of TEP data with PSU LES computations. We used a 40 minute record of TEP data from a highly-convective, afternoon boundary layer (the inversion layer height $z_i = 1140$ m, the geostrophic wind $U_g = 0.9$ m/s). Our PSU colleagues provided us with C_n^2 and velocity data from a highly convective boundary layer ($z_i/L = -540$, $U_g = 1.0$ m/s). These data were subsequently analyzed and published [Pollard et al., 2000]. Following the measurements reported in [Pollard et al., 2000] the TEP receiver and data acquisition system underwent a significant rebuild, converting from a highly-distributed custom-built system which was difficult to manage, to a more centralized system based on VXI (VMEbus eXtensions for Instrumentation).

The objectives of the current research program were to complete and test engineering improvements to the TEP system, to obtain coordinated observations of the ABL by TEP and other sensors including the S-Band FMCW, NOAA Lidars, and higher frequency radar systems, and finally, to analyze the observations through 3-D and 4-D techniques.

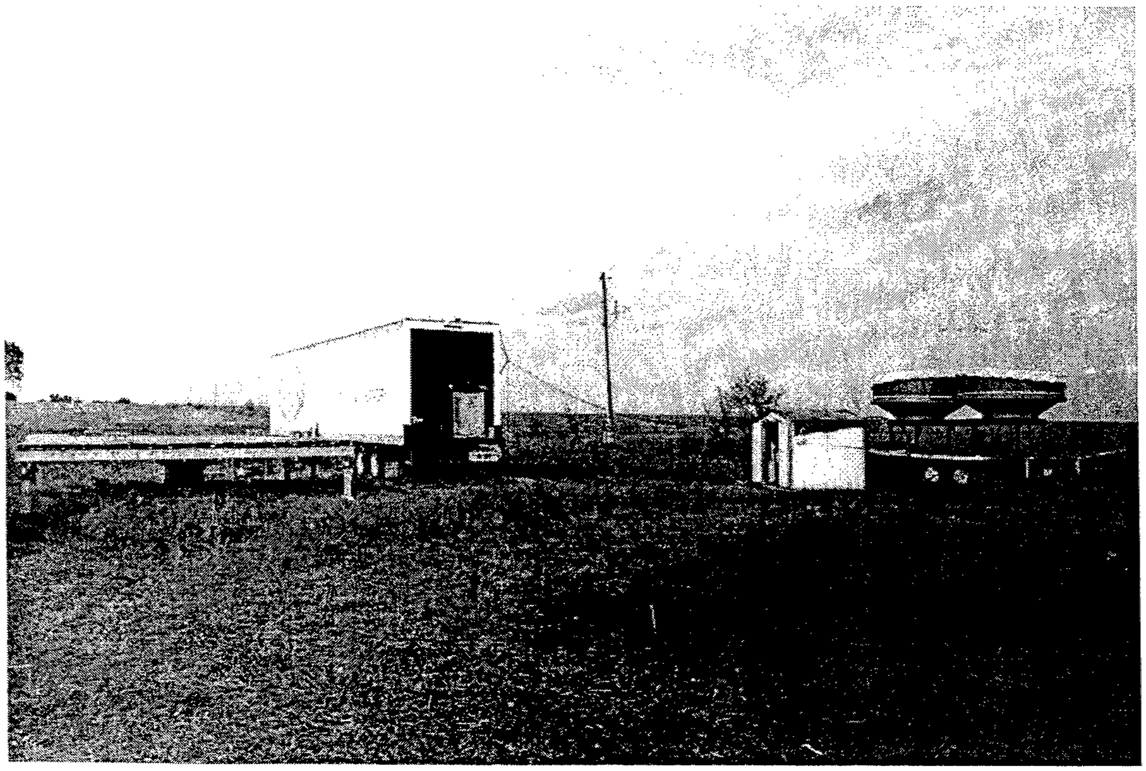

Figure 1: TEP receiving array (left), operations trailer (center), and FM-CW radar (right) deployed during the CASES'99 Nocturnal Boundary Layer Experiment

2 Summary of Results

2.1 CASES'99 Observations

MIRSL took delivery of the new VXI-based TEP receiver and data acquisition system from Quadrant Engineering, Inc. during summer 1999. At the same time, MIRSL was also developing an S-Band FMCW radar to provide high-resolution vertical profiles of ABL structure similar in design to earlier systems described in [Eaton et al., 1995, Strauch et al., 1976, Richter, 1969]. In October 1999, both TEP and the FMCW profiler were deployed during the CASES'99 Nocturnal Boundary Layer experiment near Leon, KS (Figure 1). This was the first field deployment for both new systems. During CASES, the S-band radar was used along with other remote sensors to provide real-time guidance for research aircraft probing elevated layers of turbulence. FMCW data was processed and submitted to the NCAR/JOSS data archive in the form of GIF and CDF images. We are currently working with other CASES investigators looking at particular nocturnal boundary layer events [Sun et al., 2001], and on a manuscript describing the FMCW radar and observations during the final intensive observation period.

Samples of observations are shown in Figures 2 and 3 that show two 3-hour segments from Oct 26-27, 1999. Echo intensities are reported in terms of C_n^2, (which is only meaningful for the

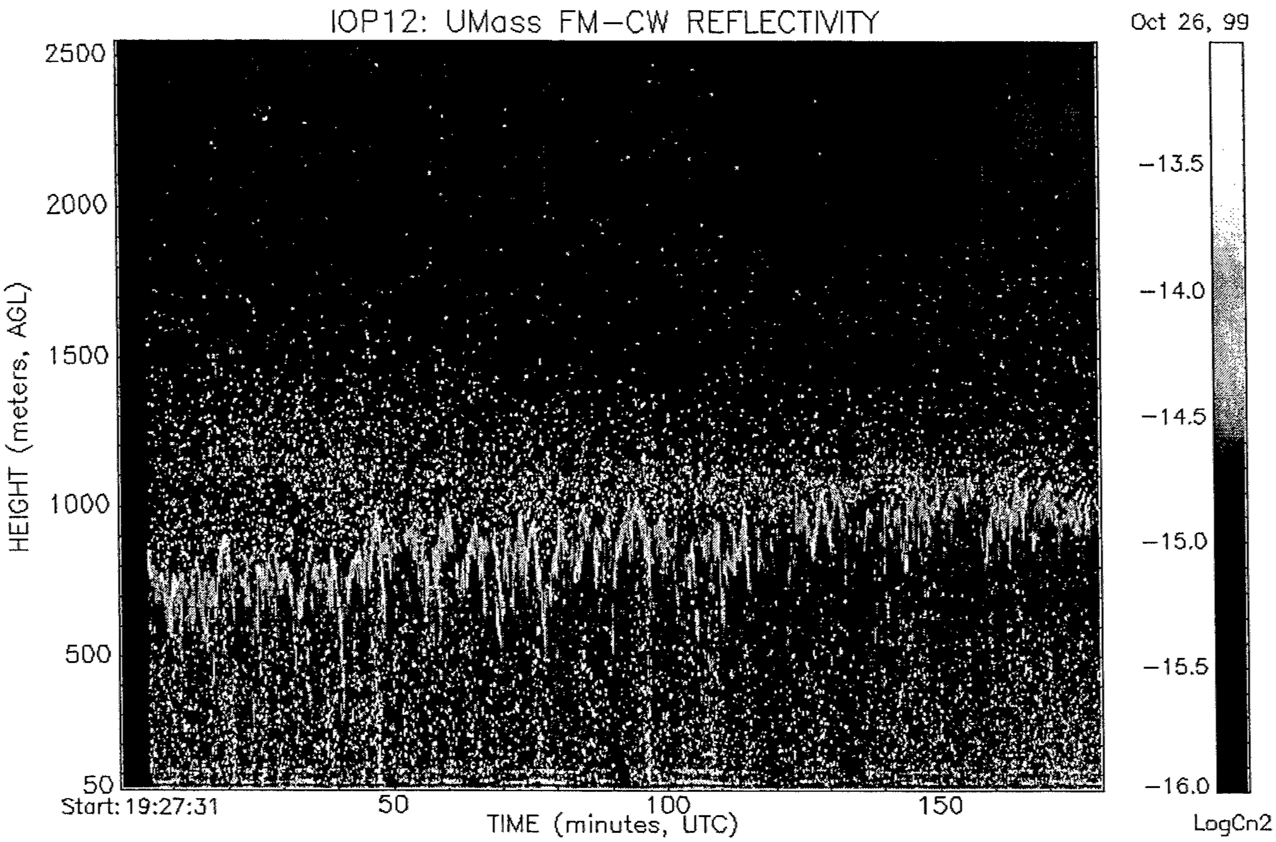

Figure 2: Afternoon convection observed on Oct 26, 1999 at CASES'99 field site

clear-air echo). System calibration was based on system parameters and pre-experiment laboratory measurements. Figure 2 shows afternoon convection with a maximum boundary layer height of approximately 1 km. The point scatterers are returns from insects which can serve as (imperfect) tracers of convection. Figure 3 shows radar observations of a nocturnal low-level jet roughly between 200 m and 500 m where a population of insects appear to be confined. A sounding obtained at 0657 UTC indicated a wind speed maximum in excess of 16 m/s at 150 m AGL. Below the jet, strong shear produces turbulence from the surface up to approximately 100 m AGL which is evident in the radar echo.

TEP's operation during CASES'99 was, unfortunately, less successful. Several problems were identified in the new data acquisition system, most of which were addressed during Winter 2000. More troubling, however, were persistent transmitter failures, one of which occured during the 6th IOP. As a result, no science quality data was produced by TEP. These failures plagued both the UMass transmitter and a spare loaned to us by Quadrant Engineering throughout the Summer and Fall of 2000. We determined that the supplier of the transmitter was no longer able to service the units. In August 2000, we proposed a replacement transmitter to the FY01 DURIP program, which was awarded and delivered in Spring 2001.

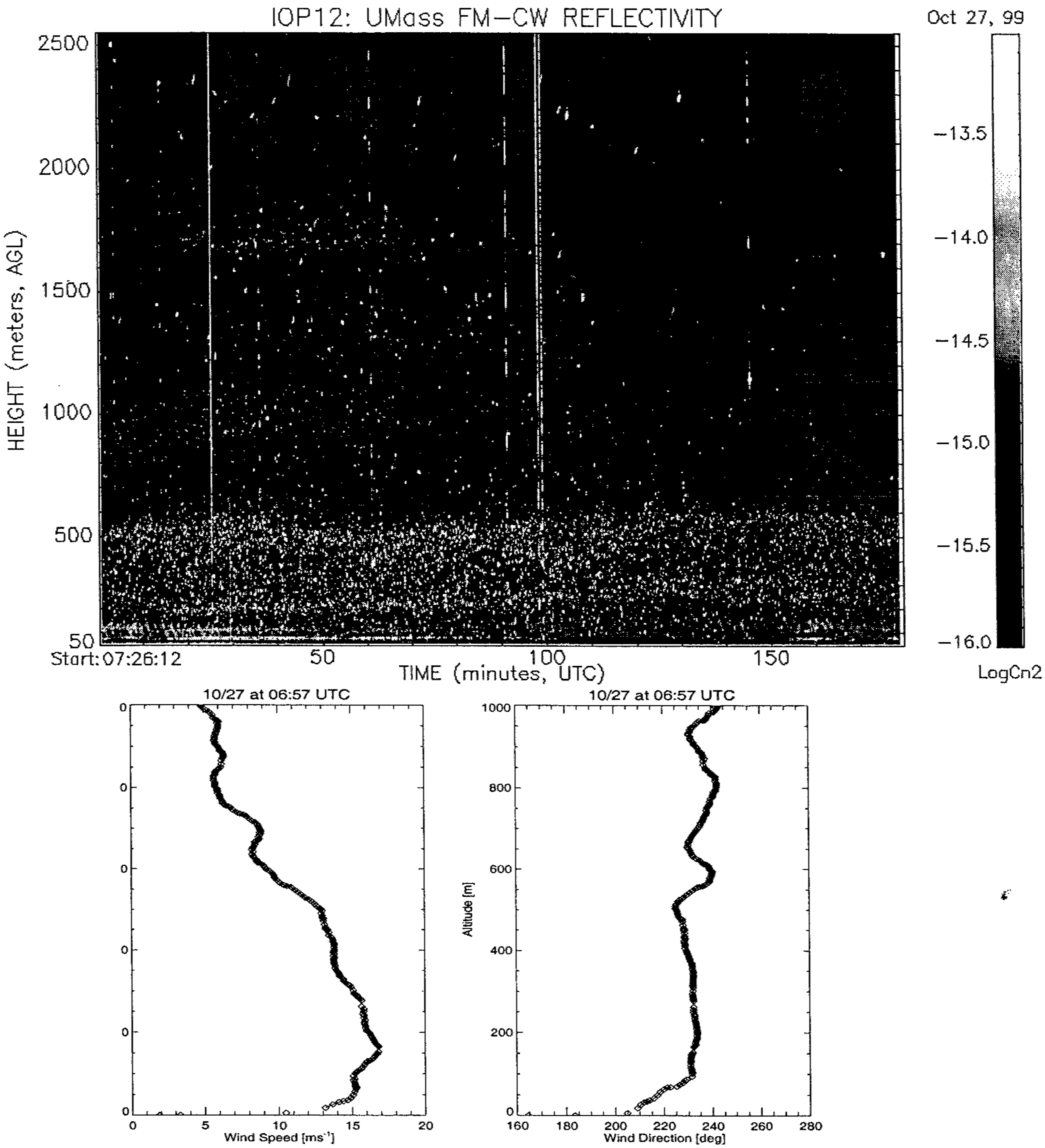

Figure 3: Top: Late evening observation of a low-level jet confining a population of insects and shear-driven surface level turbulence. Bottom: Sounding data obtained at 0657 UTC indicating jet maximum near 150 m and shear below 100 m.

Prior to receiving the new transmitter, both TEP and the FMCW participated in DOE's Vertical Transport and Mixing (VTMX) experiment in the Salt Lake valley during October 2000. Figure 4 shows sample timeseries and a streamwise slice of the TEP volume from a decaying convective boundary layer. There, the systems operated throughout six IOPs. Overall, radar echoes were sparse due to dry and cold conditions.

2.2 Results from Local Deployment

During Summer and Fall 2001, TEP and the FMCW were deployed at a local field site in Amherst, MA (Figure 5). With a new transmitter and with earlier hardware problems addressed, we are now in a position to collect high-quality observations with TEP. Similar to Figure 4, Figure 6 shows time-height cross sections of FMCW and TEP data collected in Amherst, MA on Oct 4, 2001. Besides the difference in range resolutions (2.5 m for FMCW, 30 m for TEP), the notable difference between the two radar images is the sensitvity to Rayleigh scatter from insects. The radars differ in frequency by a factor of 3.2, yielding a 20 dB difference in sensitivity to small particles. It is clear, however, that they observe common clear-air signals.

Figure 7 shows a detailed segment of the time-series. The left panel shows a two minute segment of time-height imagery. Based on horizontal wind retrievals (to be discussed), this time period corresponds roughly to the advection time of features through the TEP volume. A streamwise slice through the volume obtained at the midpoint of the time sequence is shown in the right panel. Here, the structures are advecting from left to right. Thus, the time-height image and the spatial image appear as nearly mirror images.

Figure 8 shows retreived horizontal winds from the TEP volume obtained at two-minute intervals over the same twenty minute period. Several sophisticated wind retrieval techniques algorithms exist, including algorithms for Doppler Beam Swinging (DBS) systems [Weber et al., 1993, Cornman et al., 1998] and spaced antenna systems [Cohn et al., 1997], all are targeted to a small number of channels: either a small number of beams (e.g. 3-5 for DBS), or a small number of spaced antennas. These profiles were obtained by exploiting all available beams of the radar finding the best fit mean wind (in a least-squares sense) to all observed radial velocities for each height. The two minute averaging time is consistent with advection through the TEP volume given the wind speed. Individual heights and were processed independently. The smoothness of the observed profiles in height and time suggests that retrieved profiles are realistic, though they have not been validated.

By wind profiler standards, these are quite fine resolution profiles in both height and time. It is of interest to determine over how short a time interval reliable winds can be computed. The spatial diversity of the multiple contiguous beams implies a certain equivalent temporal averaging (given the sampling volume) even when dwell time is just a few seconds. In principle, a mean wind can be fit to a nearly instantaneous realization of the radial winds. The deviations of individual pixels would then represent either turbulent motions on the pixel scale or random noise, depending upon the signal-to-noise ratio. The statistics of these deviations can be studied to determine consistence

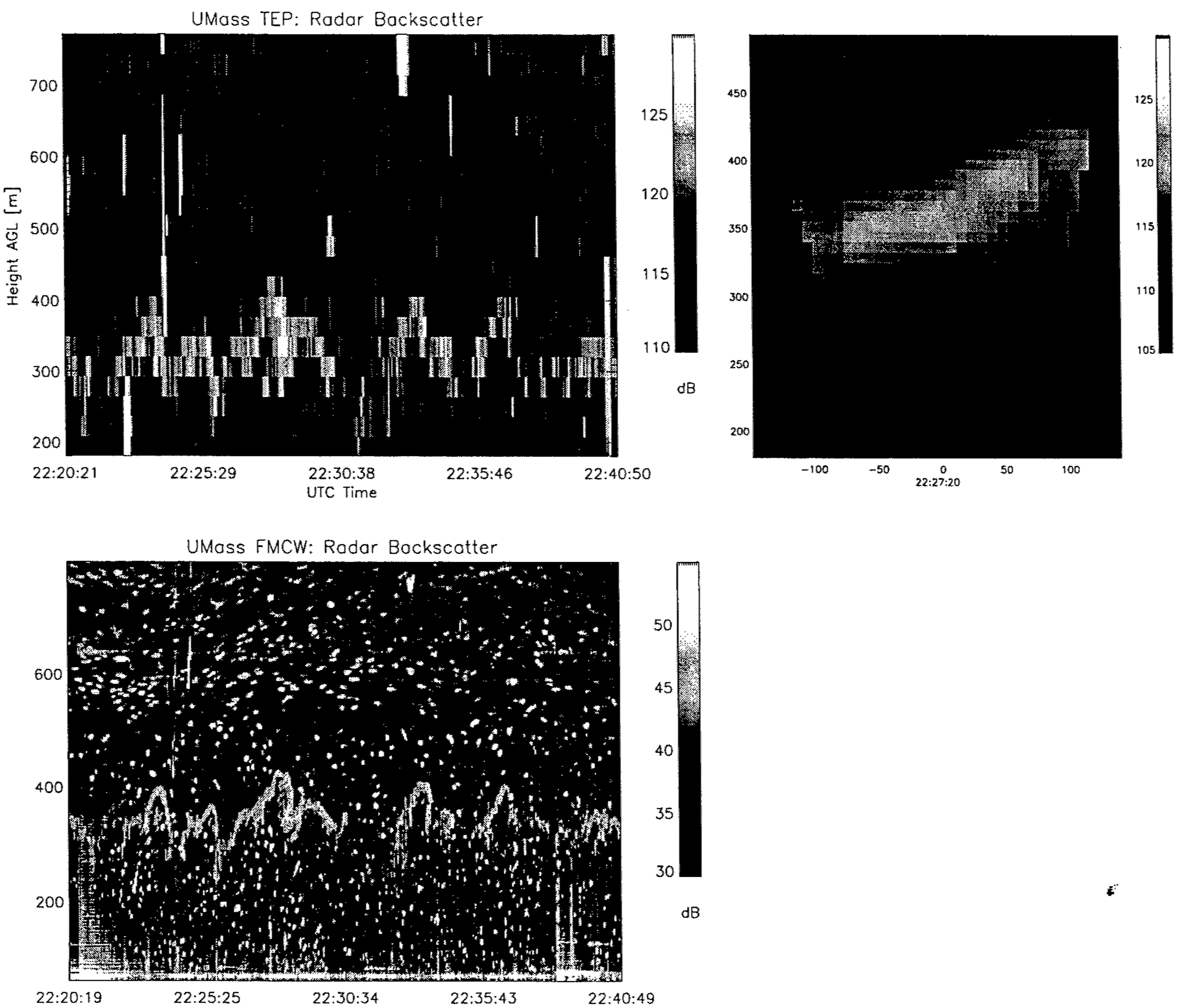

Figure 4: Top left: TEP vertical beam timeseries of a decaying CBL from VTMX Oct 17, 2000. Top Right: Streamwise slice through TEP volume at 22:27 UTC. Bottom: FMCW observation of same CBL structure. Note increased sensitivity to Rayleigh scatter from insects.

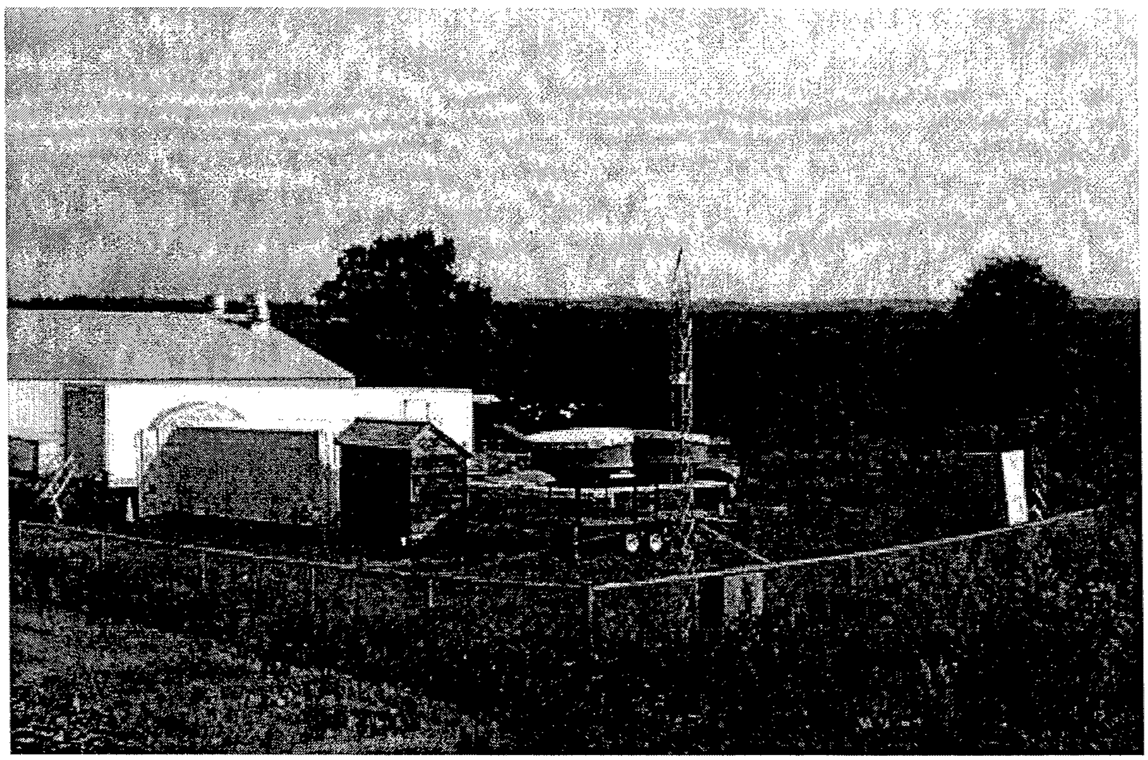

Figure 5: View of the Tilson Farm field site at UMass. Visible are a 20' tower with a 3D sonic anemometer, a Doppler sodar (on right), and the FMCW radar (behind tower). The TEP array is located behind the FMCW adjacent to the semi-trailer

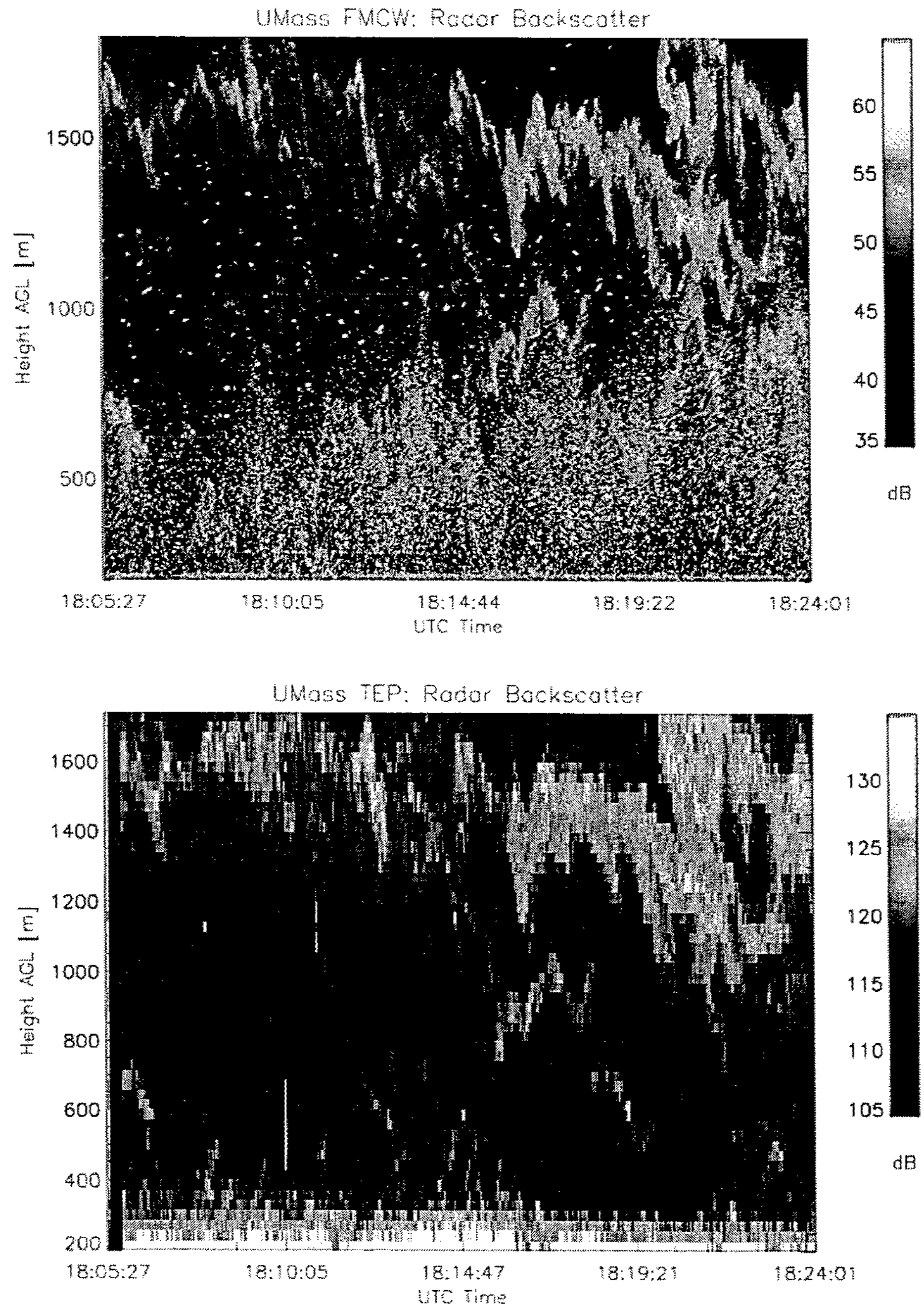

Figure 6: Top: FMCW time-height cross section of 20 minutes of early afternoon boundary layer on Oct 4, 2001. The lower portion of the images shows a heavily insect-laden mixed layer developing towards a capping inversion. Bottom: Corresponding TEP image shows same clear-air structure though with much less insect echo.

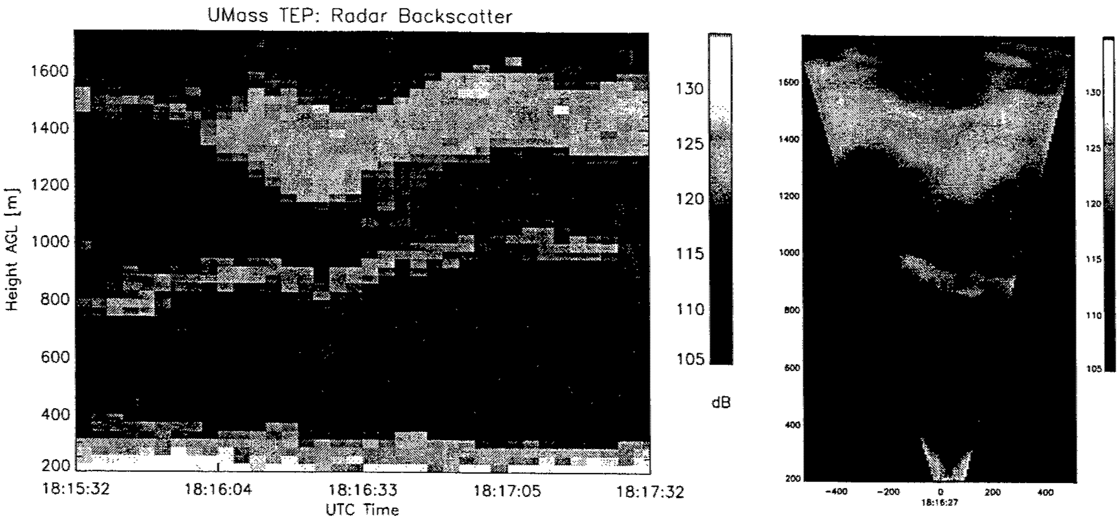

Figure 7: Left: Two minute time-height sequence of TEP radar backscatter. Right: Instantaneous streamwise slice of the TEP volume showing spatial morphology of advecting structures. Wind direction is from left to right in the image.

with expectations. Similarly computed horizontal wind fields and local C_n^2 values were compared to LES computed fields in [Pollard et al., 2000]. Though similarity between TEP and the LES was observed, a more detailed study of the power and velocity statistics with more complete characterization of the boundary layer is needed. This is indeed a planned activitiy in collaboration with researchers from NOAA/ETL, PSU, and UMass-Lowell.

2.3 Web Site

We have created a web site summarizing these and other boundary layer observations. The URL is **http://abyss.ecs.umass.edu/tep/**. A number of sample images from both TEP and the FMCW are browsable there. In addition, sample animations of TEP volumetric data are downloadable from this site. We are now using this site as a means of communications with our collaborators.

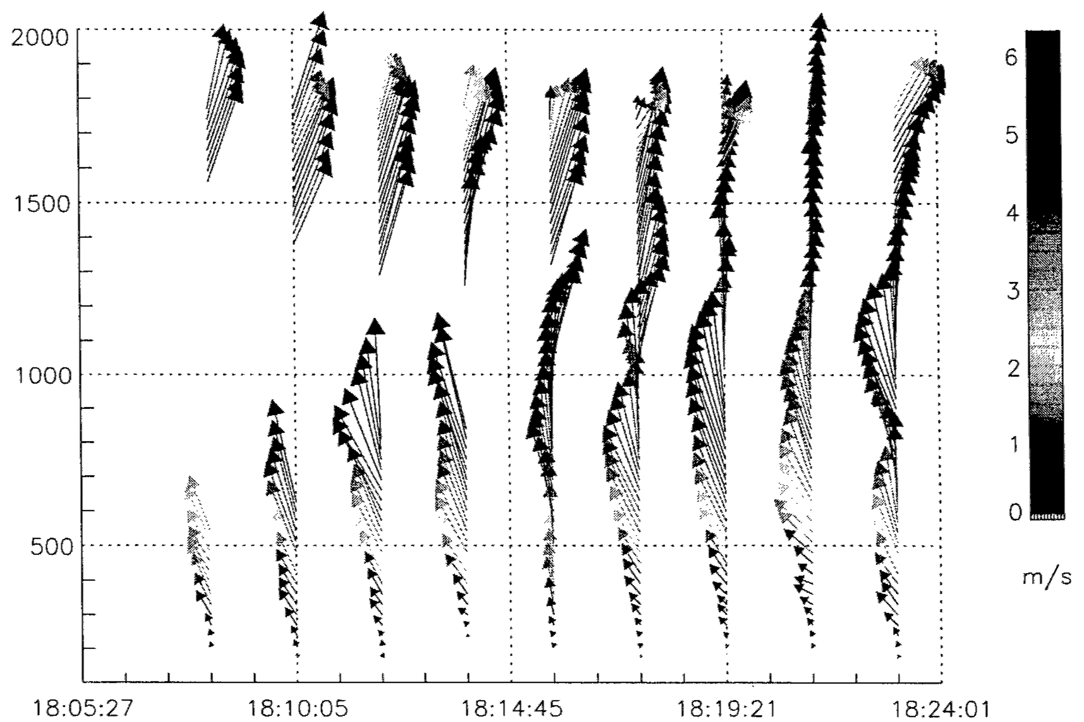

Figure 8: Two-minute averaged wind profiles obtained using all beams of the TEP array. The length and color of each arrow denotes wind speed, and arrow orientation denotes the wind direction in radar system coordinates.

3 Publication Summary

3.1 Refereed Journals

1. B.D. Pollard, S. Khanna, S.J. Frasier, J.C. Wyngaard, D.W. Thomson, R.E. McIntosh, 2000: "Local Structure of the Convective Boundary Layer from a Volume Imaging Radar", *J. Atmos. Sci.*, **15**, 2281–2296.

3.2 Conferences

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2. J. Li, F.J. Lopez-Dekker, T. Ince, S.J. Frasier, 2000: "Volume-Imaging UHF Radar Measurement of Atmospheric Turbulence", *Proceeding of 2000 International Geoscience and Remote Sensing Symposium (IGARSS'2000)*, Honolulu, HI, July, 2000, IEEE.

3. F.J. Lopez-Dekker, S.J. Frasier, 2000: "Radar Acoustic Measurement of Temperature using a Volume-Imaging UHF Wind Profiler", *Proceeding of 2000 International Geoscience and Remote Sensing Symposium (IGARSS'2000)*, Honolulu, HI, July, 2000, IEEE.

4. F.J. Lopez-Dekker, G. Farquharson, S.J. Frasier, 2001 (submitted): "Entropy-Based Phase Calibration of Antenna Arrays for Digital Beamforming Remote Sensing Radars", to appear in *Proceedings of the 2002 IEEE National Radar Conference*, Long Beach, CA, IEEE.

5. F.J. Lopez-Dekker, S.J. Frasier 2001 (submitted): "Observations of the horizontal structure of the Boundary Layer with the Turbulent Eddy Profiler" to appear in *Proceedings of 15th AMS Symposium on Boundary Layers and Turbulence*, Wageningen, NL.

4 Personnel

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1. Daniel H. Schaubert, PI

2. Stephen J. Frasier, Co-PI

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4. Eric J. Knapp, Research Engineer

4.2 Graduate Students

1. Jie Li (PhD, Sept 2001: "Volume-Imaging UHF Radar Measurements of Atmospheric Turbulence", University of Massachusetts, Amherst, 84 pages).
2. Fei Kong (MS, May 1999: "Development of a Data Acquisition System for a Digital Beamforming Atmospheric Radar").
3. Fransicso Lopez-Dekker (PhD Candidate).
4. Apoorva Bajaj (MS student).
5. Preyasee Kamath (MS student).

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