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13. ABSTRACT (Maximum 200 words)

This report summarizes MIRSL's activities under the Department of Defense University Research Initiative (URI) to develop a radar remote sensing system that is able to measure atmospheric turbulence for ABL studies, including the verification of LES results. This radar, called the Turbulent Eddy Profiler (TEP) is capable of imaging the structure of trubulence 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 verified TEP's ability to resolve the three-dimensional Cn2 and velocity fields at spatial and temporal scales comparable to LES communications. We observed agreement in qualitative and quantitative comparisons of the morphology and intermittency of small-scale ABL structures.

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FINAL REPORT:
Remote Sensing Turbulence in the Atmospheric Boundary Layer

ARO Grant: DAAL03-92-G-0110

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1 Statement of the Problem Studied

In the recent history of the study of the ABL, supercomputers and computational fluid dynamics have replaced the traditional tools of Reynolds-decomposition [1]. In particular the development of the successful direct-numerical simulation (DNS) and large-eddy simulation (LES) methods has made the field of turbulence simulation particularly accessible. Each of those two methods can be used to simulate ABL turbulence. While DNS is an exact solution to the governing equations, it is limited by current computational abilities to low Reynolds number turbulence studies; a "Reynolds number similarity" hypothesis is used in order to extend it to the high Reynolds number flows of practical importance [2]. Unlike DNS, LES is not exact. It uses a hybrid of simulation and modelling that filters the governing equations into "subgrid" and "resolvable" scales, and models the effects of the subgrid scales on the resolvable scale quantities [3].

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 [1]. Wind profilers [4, 5, 6], sodars [7, 8], FM-CW radars [9, 10] radio sondes [11], and in situ sensors [12, 13] 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.

This report summarizes MIRSL's activities under the Department of Defense University Research Initiative (URI) to develop a radar remote sensing system that is able to measure atmospheric turbulence for ABL studies, including the verification of LES results. This radar, called the Turbulent Eddy Profiler (TEP) 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 indicate that TEP is able to resolve the three-dimensional C_n^2 and velocity fields at spatial and temporal scales comparable to LES computations.

The ability of TEP to measure C_n^2 fields is an important feature of the instrument. Volume-imaging lidars [14, 15] can measure three-dimensional velocity fields on time scales on the order of minutes. The lidar senses the backscattered return from aerosols, however, and thus cannot measure C_n^2 directly. TEP is currently the only instrument to provide volume-images of C_n^2 on the time-scales necessary for the study of the evolution of turbulent structures. Recent results from our colleagues at PSU [16, 17] suggest that LES could be used to predict acoustic and electromagnetic scattering properties by generating statistics of "local," or pixel-sized C_n^2 values. Experimental verification of those LES predictions was a focus of this program.
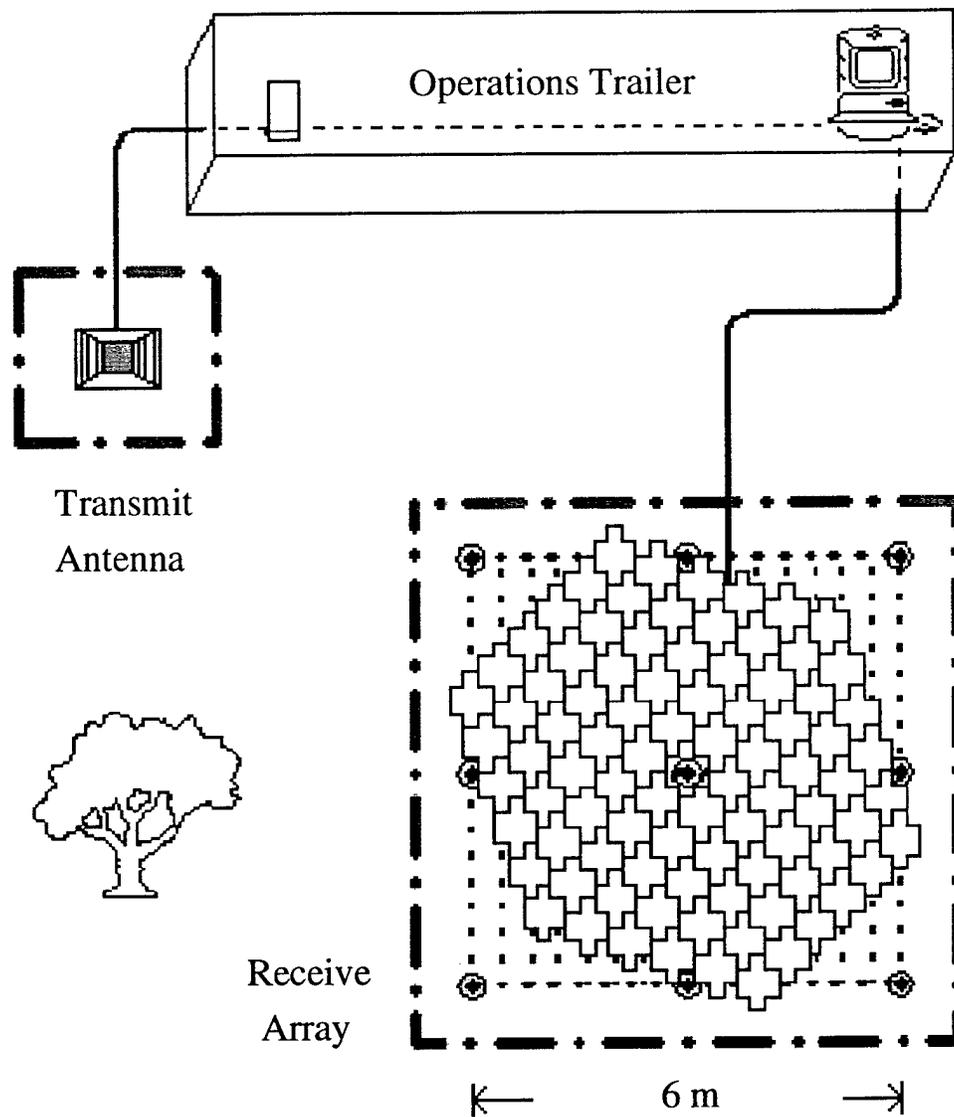
Figure 1: TEP field deployment site plan.

2 Summary of Results

MIRSL and PSU were awarded URIs in 1992 to further understanding of the atmospheric boundary layer. The UMass URI supported the creation of a digital beamforming, 915 MHz radar that could remotely sense the index of refraction structure-function parameter C_n^2 through the measurement of the volume backscatter [18]:

$$\eta \approx 0.38 \ C_n^2 \ \lambda^{-1/3},$$

where $\lambda = 0.328\text{m}$ is the radar wavelength. In addition to obtaining C_n^2 fields, this coherent radar is also capable of measuring fields of velocity vectors and spectral widths.

Construction of the TEP radar system began in 1992 and was completed in 1996. A site plan for TEP is shown in Figure 1. A 48' trailer houses the transmitter, radar electron-
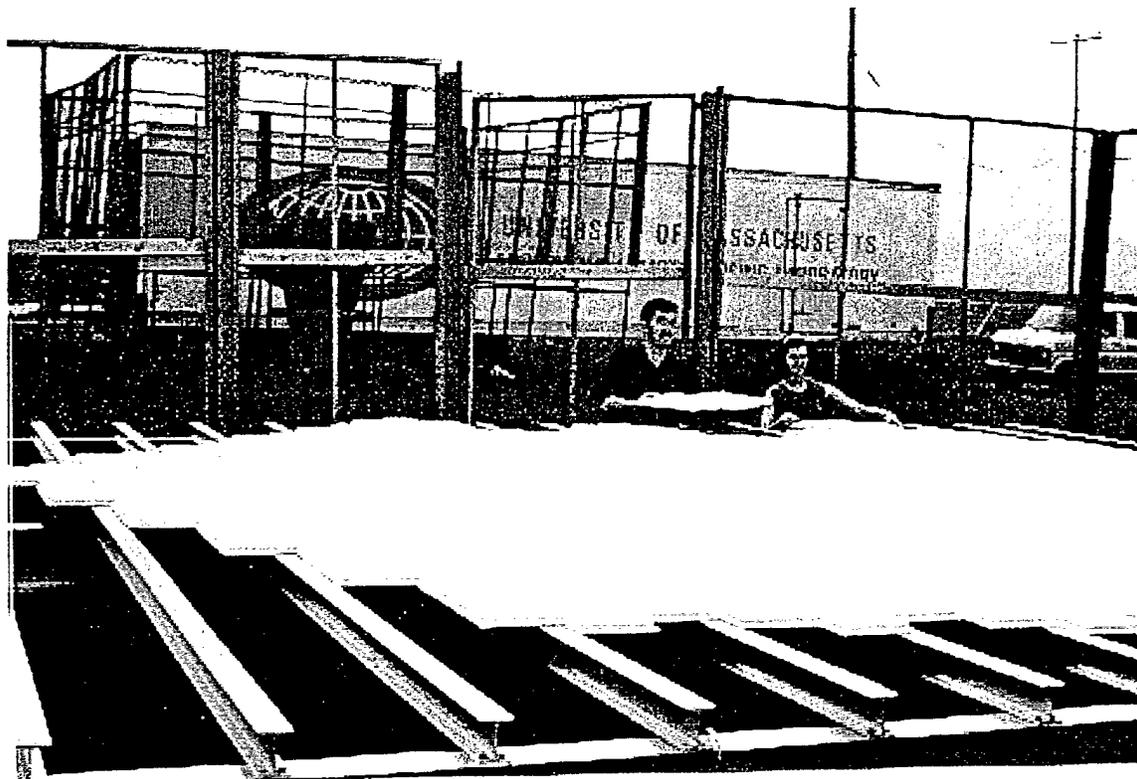
Figure 2: TEP array assembly at Rock Springs, PA. The TEP transmitter antenna and trailer are visible in hte background.

ics, and data acquisition system and is used to transport the entire system. A pyramidal horn transmit antenna is fed by a 25 kW peak-power transmitter and illuminates a 25 degree conical volume above the receiver array. The receiver array consists of 60 microstrip patch antennas, each with a low-noise receiver, digital accumulator, and control and storage electronics. Radar echoes are coherently integrated over short intervals ($<$ 10 ms) in the accumulator and then stored on disk or tape. Figure 2 shows a photo of the array being assembled at Penn State University's meteorological field site at Rock Springs, PA.

Beamforming is performed off-line. Software produces focused imagery from the collected data following the experiment. The output of the beamforming algorithm is a complex value representing the magnitude and phase of the backscattered field at each resolution cell. The remainder of the signal processing follows closely techniques used in conventional wind profilers in which the Doppler spectrum of the echo is estimated using Fourier transform or pulse-pair techniques. Ground clutter and any spurious signals are extracted from the spectra prior to computing the first three moments: total power, mean velocity, and spectral width. Volumetric images of any of these data products can be generated as often as ten times per minute.

Figure 3 shows a subset of the basic TEP data products. Figure 3a shows a TEP image of the backscatter intensity (C_n^2) taken at Rock Springs in August of 1996. The turbulence data shown is resolved into 30-m range gates between the altitudes of 900
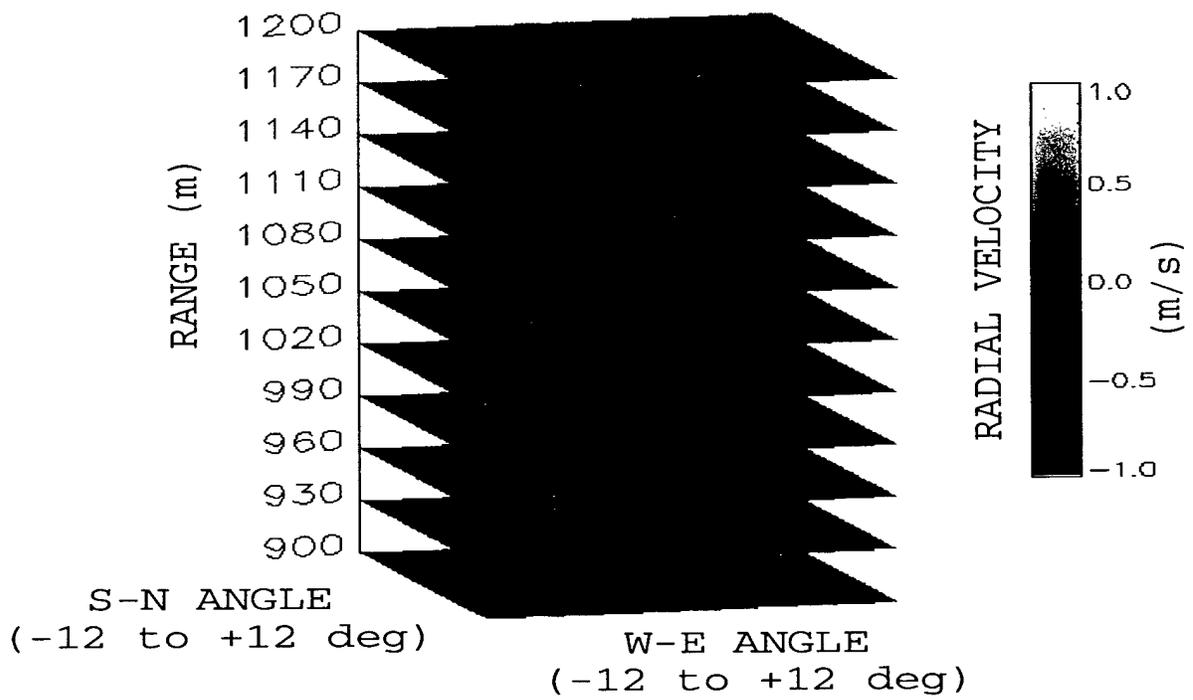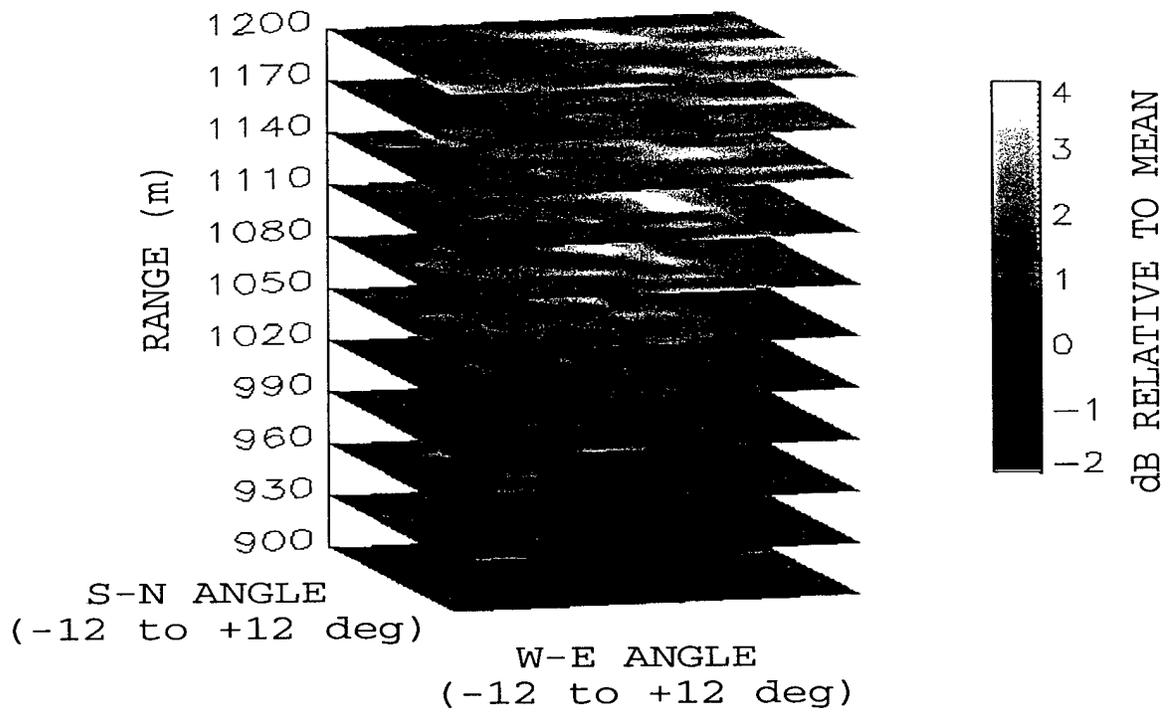
Figure 3: TEP backscattered intensity image

and 1290 meters. Sequential images for a nine-minute interval appear at the Web site: http://acadia.ecs.umass.edu/html/tep-psu96.html. Figure 3b shows the radial velocity sampled concurrently with the intensity image shown in figure 3a Each image represents a five-second average of the atmospheric return.

The three-dimensional fields obtained by TEP are unique compared to other clear air radars because the beam forming process allows the simultaneous measurements of backscatter and velocity at every pixel [19]. Thus, TEP affords a synoptic view of the ABL that is not currently possible with other remote sensing instruments. However, additional research is needed before TEP can fulfill its promise for contributing to the understanding of ABL turbulence. Measurements from this system must be compared to C_n^2 and velocity measurements obtained by other remote sensing systems such as lidars and FM-CW radars.

During the last 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) that should compare well with the TEP data.

Qualitatively, similar features can be seen in the local structure of the TEP and LES data sets. Figure 4 shows TEP measured horizontal wind vectors overlayed on backscattered intensity (C_n^2) and vertical velocity images, respectively, from a height of 990 m ($z = 0.87z_i$). There is a convergence of the horizontal winds on to the area of high relative C_n^2, corresponding to a downdraft feature in vertical velocity. Such features appear frequently in the TEP data set, and always correspond to a small, coherent downdraft feature surrounded by a larger updraft feature. LES shows similar correspondance between converging horizontal winds, coherent downdrafts in vertical velocity, and locally high C_n^2 values. Figure 5a shows the local C_n^2 predictions from LES at $z = 0.95z_i$ plotted on a dB scale with horizontal velocity vectors overlayed; figure 5b shows the corresponding LES vertical velocity image. The qualitative similarity of the LES predictions and the TEP measured data suggests that LES may be correctly predicting local C_n^2 behavior.

We have also compared TEP and LES C_n^2 values quantitatively. By taking cross-wind slices through the data shown in Figure 3a and plotting them as a function of time, larger volumes are created. Such volumes assume that the turbulence is frozen in space and time and advected through the radar beam by the mean wind [20]. Such a volume is shown in figure 6, and provides a better statistical approximation of the LES domain.

Peltier and Wyngaard [16] derived statistics of local structure-function parameters for humidity, C_Q^2, humidity-temperature correlation, C_{TQ}, and temperature, C_T^2 for a moderately convective boundary layer using LES. Through the relationship in [21],

$$C_n^2 = \alpha^2 C_Q^2 + 2\alpha\beta C_{TQ} + \beta^2 C_T^2$$

the statistics of local C_n^2 can be generated over the LES domain. A "variability index", or normalized variance, can be defined,

$$F_n = \frac{\text{variance of } C_n^2}{\text{squared mean of } C_n^2} , \tag{1}$$

which is computed over horizontal slices throughout the LES volume. Using equation 1, we
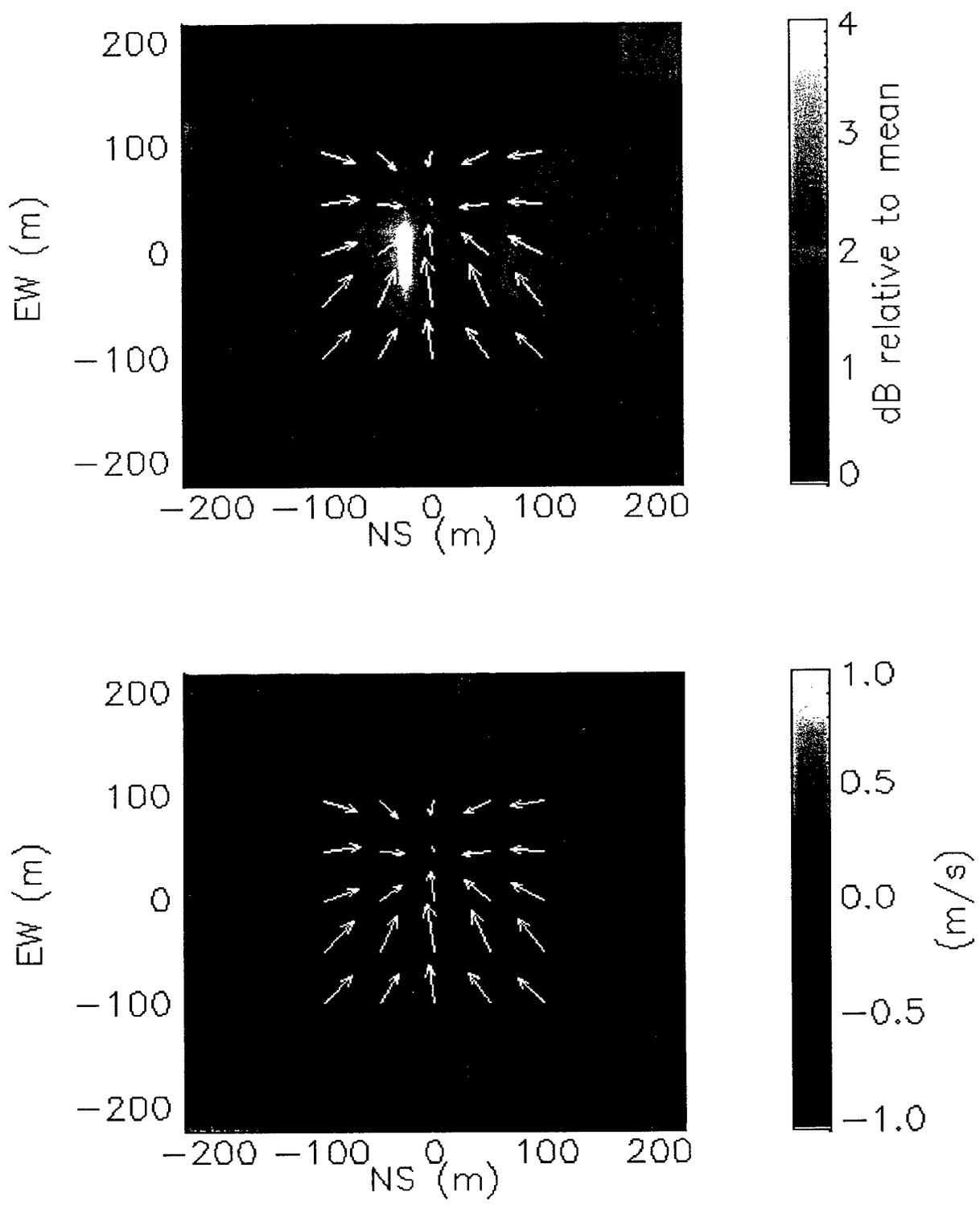
Figure 4: TEP convergence of horizontal winds on an area of high local C_n^2.
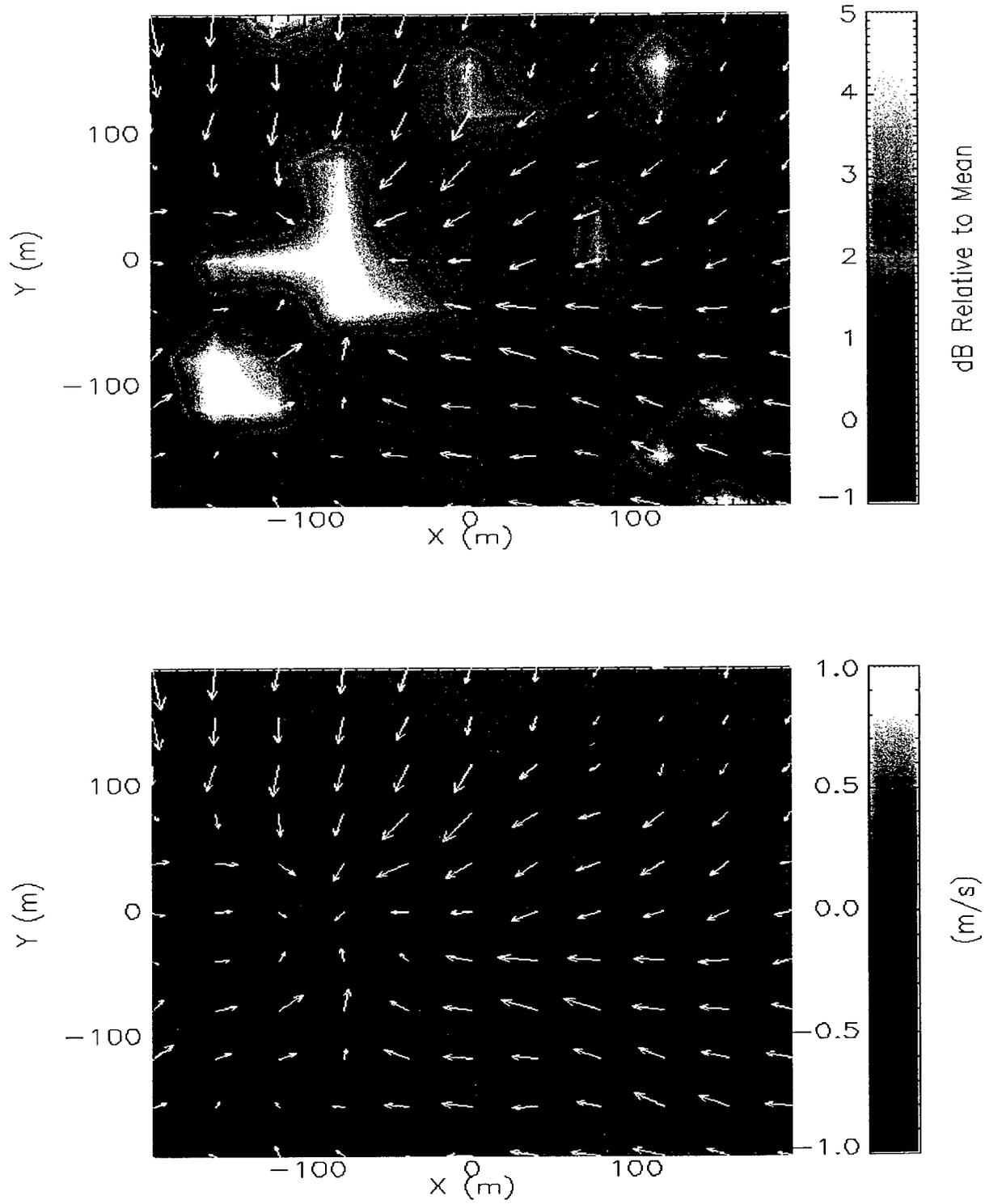
Figure 5: LES convergence of horizontal winds on an area of high local C_n^2.
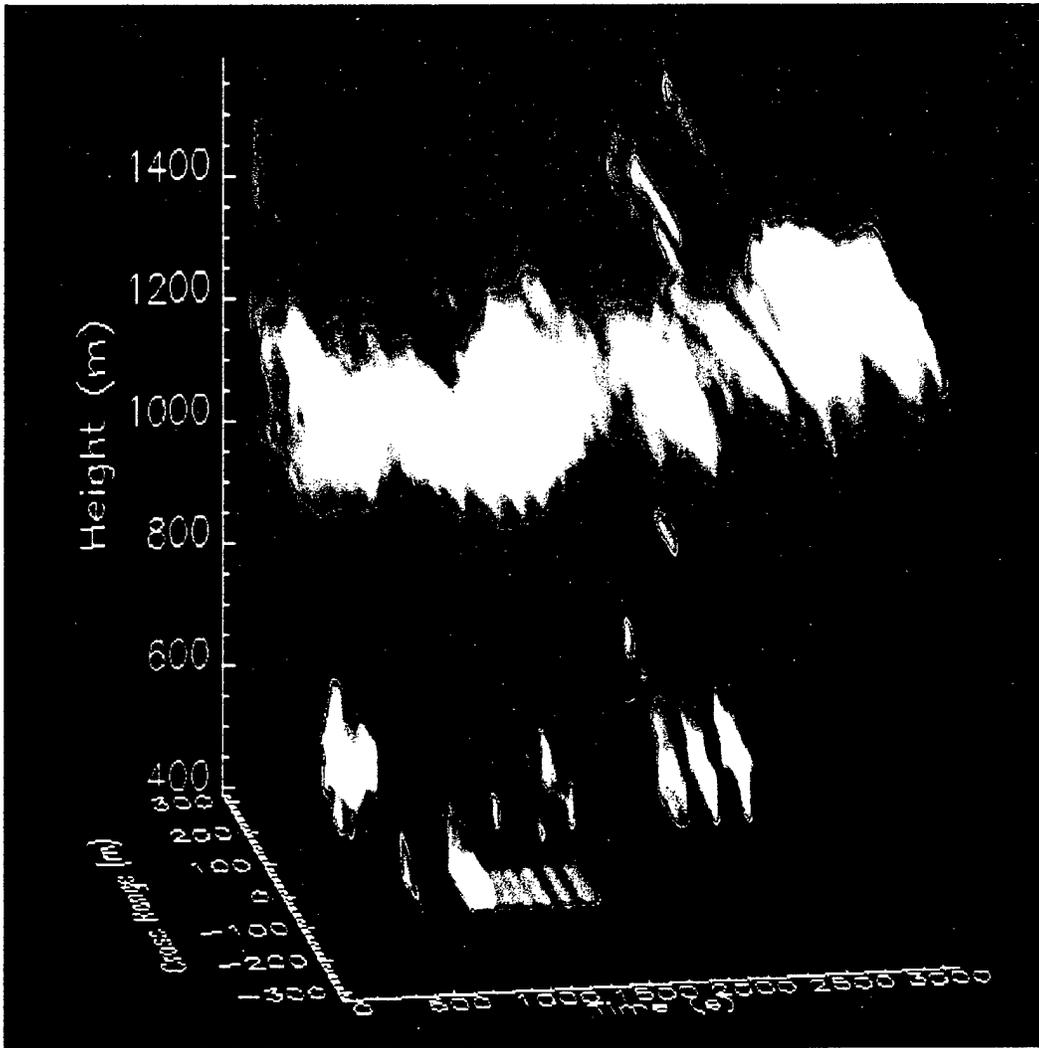
Figure 6: A crosswind slice versus time rendered as a three-dimensional volume
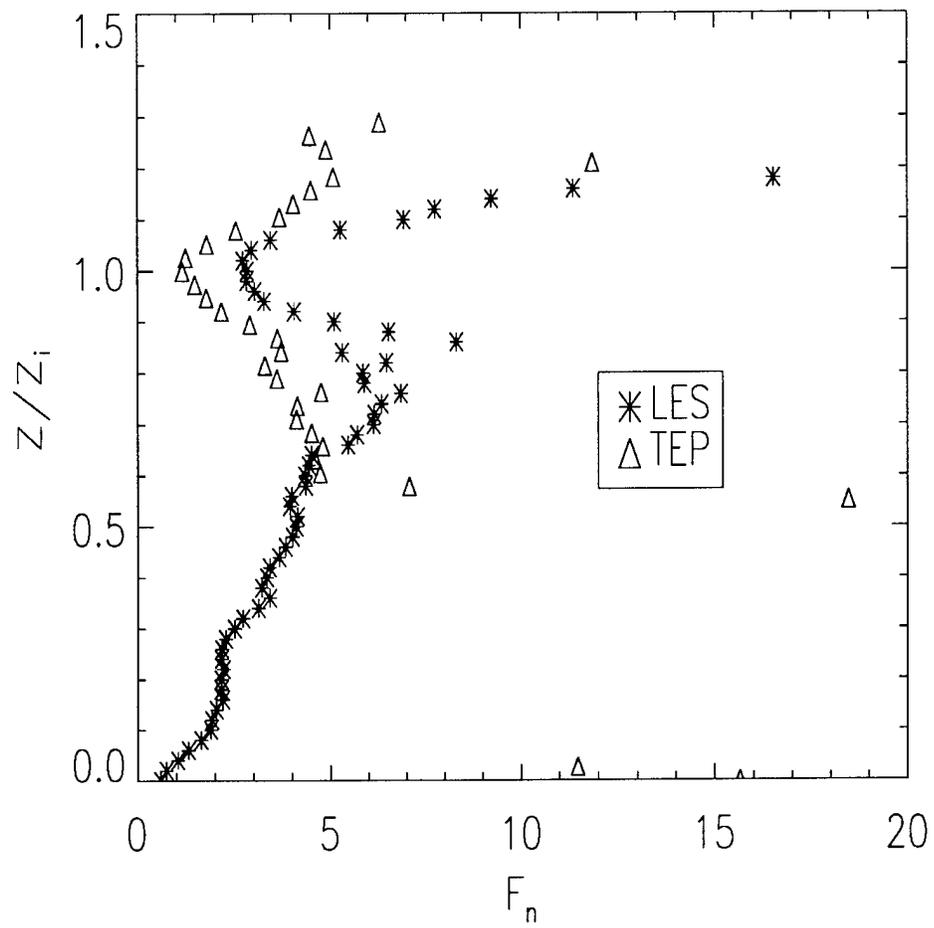
Figure 7: A comparison of TEP and LES variability.

have compared TEP and LES statistics. Figure 7 shows that comparison, with each data set scaled to the boundary layer height z_i. The two curves exhibit a similar trend from 0.55 z_i upward, although it appears as though there is a small offset between the two curves. One hypothesis we have for that offset is that the beam efficiency of the TEP system is lower than we have anticipated. Future efforts to improve the reliability and calibration of TEP should improve the beam efficiency and test that hypothesis. Other sources of error could include the effects of the field site terrain and the length of the data set, and the experiments as part of this program will study those effects.

Below 0.55 z_i, the F_n for the TEP data is quite large. We believe that those effects are due to biological targets, such as bugs and birds, in the lower boundary layer. Such targets are very bright in radar backscatter and are quite intermittant, producing a large F_n. The deployment of a millimeter wave radar along with the TEP system would allow MIRSL researchers to identify and remove from the data non-atmospheric targets.

3 Publication Summary

3.1 Dissertations

1. Cherry, C.D., "Digital and Adaptive Beamforming Techniques for Environmental Remote Sensing Applications," University of Massachusetts Amherst, May 1996, 190 pages (D.H. Schaubert, Chair).

2. Hopcraft, G., "The Turbulent Eddy Profiler: A Digital Beamforming System for Clear-Air Turbulence Measurement," University of Massachusetts Amherst, Sep 1997, 99 pages.

3. Pollard, B.D., "Local Structure of the Convective Boundary Layer Measured by a Volume-Imaging Radar," University of Massachusetts Amherst, May 1998, 99 pages.

3.2 Refereed Journals

1. J. Mead, G. Hopcraft, B. Pollard, S. Frasier, C. Cherry, D. Schaubert, and R.E. McIntosh "A Volume Imaging Radar Wind Profiler for Atmospheric Boundary-Layer Turbulence Studies", *Journal of Atmospheric and Oceanic Technology*, 15(4), pp. 849–859, Aug. 1998.

2. B.D. Pollard, S. Khanna, S.J. Frasier, J.C. Wyngaard, D.W. Thomson, R.E. McIntosh, "Local Structure of the Convective Boundary Layer from a Volume Imaging Radar", manuscript in preparation, (for submision to *JAS*, 1998) .

3.3 Conferences

1. Pollard, B.D., S. Khanna, S.J. Frasier, J.C. Wyngaard, D.W. Thomson, R.E. McIntosh, "Convective Boundary Layer Features from a Volume Imaging Radar and Large Eddy Simulation," Proceedings of the 1997 Battlespace Atmospherics Conference, SPAWAR, San Diego, CA, Dec 2–4, 1997, pp. 349–357.

2. Pollard, B.D., S.J. Frasier, R.E. McIntosh, "Comparisons of Volume Imaging Radar Observations of Atmospheric Boundary Layer Turbulence with Large Eddy Simulations", Proceedings of the 1997 International Geoscience and Remote Sensing Symposium (IGARSS'97), Singapore, Aug 11-18, 1997.

3. Pollard, B.D., S.J. Frasier, J.B. Mead, G. Hopcraft, R.E. McIntosh, "Preliminary Comparisons of Volume Imaging Radar Observations of the Atmospheric Boundary Layer with Large-Eddy Simulations", Proceedings of the 12th AMS Symposium on Boundary Layers and Turbulence, Vancouver, BC, Jul 28–Aug 1, 1997, pp. 376-377.

4. Mead, J.B., G. Hopcraft, B. Pollard, R.E. McIntosh, "A Digital Beamforming Radar Profiler for Imaging Turbulence in the Atmospheric Boundary Layer," proceedings of the *1996 International Geoscience and Remote Sensing Symposium* (IGARSS'96), Lincoln, NE, May 27-31, 1996, pp. 1923–1925.

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1. Robert McIntosh, Distinguished University Professor, P.I.

2. James Mead, Research Associate Professor, Co-P.I.

3. Stephen Frasier, Research Fellow (now Assistant Professor).

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1. Christopher Cherry, Ph.D. 1996.

2. Geoffrey Hopcraft, Ph.D. 1997.

3. Brian Pollard, Ph.D. 1998.

4. Minfei Leng, M.S. 1998.

5. Kristen Tuttle (Pisarczyk), M.S. 1997.

6. Ray Bambha

7. William Donnelly

8. Fei Kong

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