

THE PENTAGON SHIELD FIELD PROGRAM

Toward Critical Infrastructure Protection

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A recent study of meteorological conditions around the Pentagon will support development of a system to protect its 25,000+ occupants from chemical, biological, and radiological attack.

In the future, facilities that are probable terrorist targets may be protected by weather analysis and forecasting systems that are part of automated capabilities that warn of the approach of hazardous chemical, biological, or radiological (CBR) material in the atmosphere. Based on information provided by coupled meteorological and transport and dispersion (T&D) models and networked sensors, building ventilation systems can be adjusted in real time to minimize air infiltration, and potential evacuation

routes can be identified. Such atmospheric modeling systems must represent multiple scales of motion, from the mesoscale to the building scale. In addition to meteorological data that represent this range of scales, in situ and remotely sensed information on CBR contaminants must also be ingested. Not only is this effort scientifically challenging, the computational requirements are so formidable that building-scale, physics-based atmospheric models are not typically run operationally. Because the Pentagon is one

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of the most likely targets for a future terrorist attack with CBR weapons, the first building CBR protection system, called Pentagon Shield, is being developed to protect the Pentagon's 25,000+ occupants. This article describes the Pentagon Shield field program, during which meteorological and chemical-tracer data were collected, where these data are now being used to verify the atmospheric and T&D models employed in this system. These data are also being used to better understand the atmospheric properties and processes in this heterogeneous urban setting, which will enable the development of a more accurate operational system for the protection of the Pentagon.

During the Pentagon Shield field program, conducted from 9 April to 16 May 2004 by the organizations listed in Table 1, boundary layer (BL) measurements and tracer-transport studies were performed in this especially challenging urban environment. This field program complements other recent urban dispersion experiments in Salt Lake City and Oklahoma City, which had the aim of improving our understanding of BL properties and the T&D of contaminants in the urban environment (Allwine et al. 2002, 2004; Doran et al. 2002). However, the Pentagon Shield field program is distinct from these other urban studies in that 1) its focus is on the effects of a single building on the flow field and the T&D, and 2) the data are to be used for development and verification of an operational analysis and forecasting system.

Even though the objective of this paper is to describe the Pentagon Shield field program, it will provide a useful context to mention the general characteristics of the automated operational system that motivated it. The complete system will consist of coupled outdoor and indoor components, wherein the outdoor part is essentially a sensor-data-fusion

system that uses meteorological and contaminant observations as input to various models (see Fig. 1) to estimate 1) the properties of the contaminant source (e.g., location), 2) the current characteristics of the contaminant plume, and 3) the future path of the plume. A particular emphasis is on mapping contaminant concentrations and dynamic pressure on the Pentagon's exterior, and tracking the plume within the surrounding area of the Capitol. The indoor component of the system includes automatic controls of the heating, ventilation, and air-conditioning (HVAC) system, and methods for indoor tracking of the contaminant.

Outdoor gridded meteorological data are produced by a nested system of four data-assimilation and forecast models. Some of the specifications (e.g., grid increments) of the system described below may change slightly as development continues. Figure 1 shows a schematic of the nested system of models, as well as their specifications.

- On the largest (regional) scale, a version of the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) mesoscale model (MM5; Dudhia 1993; Grell et al. 1994) that has been adapted for the U.S. Army Test and Evaluation Command [The Real Time Four-Dimensional Data Assimilation (RTFDDA) system] has an outer grid that spans the eastern United States. There are three computational grids nested within this regional domain, with the finest one spanning the National Capitol Region (NCR) with a 1.5-km grid increment. The forecast length is 30 h for the three coarser grids, and 15 h for the finest grid. A new forecast is initiated every 3 h. Various types of data are assimilated, such as from

TABLE 1. Pentagon Shield field program participating organizations.
National Center for Atmospheric Research (NCAR)
University of Colorado
Defense Advanced Research Projects Agency (DARPA)
U.S. Army Dugway Proving Ground
U.S. Army Research Laboratory (ARL)
U.S. Army Corps of Engineers
Field Research Division, National Oceanic and Atmospheric Administration, Air Resources Laboratory (NOAA)
Washington Headquarters Services, Department of Defense
Naval Surface Warfare Center, Dahlgren Division
Pentagon Force Protection Agency (PFPA)
Coherent Technologies, Inc. (CTI)
Northrop Grumman Corp.

surface mesonets, radiosondes, ships and buoys, satellites [upper-air winds, and Quick Scatterometer (QuikSCAT) sea surface winds], wind profilers, and aircraft.

- A four-dimensional Variational Doppler Radar Assimilation and nowcasting System (VDRAS; Sun and Crook 2001) covers the NCR. This model assimilates the radial-wind data from the National Weather Service's Sterling, Virginia, Weather Surveillance Radar-1988 Doppler (WSR-88D). Other standard meteorological observations in the area are assimilated to produce analyses and 1-h forecasts of winds and other variables every 10 min on a 60 km × 60 km grid with a 1-km horizontal grid increment. The finest grid of MM5 provides lateral boundary conditions.
- A higher-resolution version of the above VDRAS system has been adapted for use with Doppler lidar data (Chai and Lin 2004), obtained here from a permanently installed scanning Coherent Technologies, Inc. (CTI), *Windtracer* lidar, located on the roof of a building approximately 800 m from the Pentagon. This Variational Lidar Assimilation System's (VLAS's) 6 km × 6 km computational grid spans a significant fraction of the downtown area of Washington, D.C., and has a horizontal grid increment of 100 m. Both analyses of current conditions and 30-min forecasts are produced every 10 min. This model also assimilates Doppler radar and other standard data that are within its domain, and uses the VDRAS analyses and forecasts for lateral boundary conditions.
- The highest-resolution models have a grid increment of 2–10 m that can represent the detailed structure of the Pentagon building and the airflow around it. One is a computational fluid dynamics (CFD) model (CFDUrban) developed by the CFD Research Corporation (CFDRC; Coirier et al. 2005), and the other is a much faster rule-based model (QUICUrb) from the Los Alamos National Laboratory (LANL; Pardyjak et al. 2004) which computes the Pentagon's effects on the wind field, based on training using CFD model solutions and wind tunnel data. The ambient flow field for both

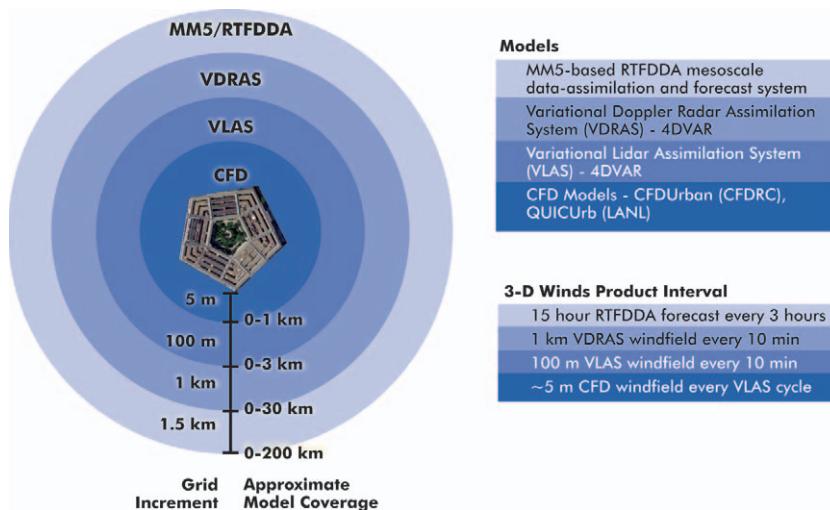


FIG. 1. Schematic of the nested system of models, and the model specifications. The numbers identifying the model coverage are approximate, and indicate the distance from the Pentagon that the model grid extends.

Models
MM5-based RTFDDA mesoscale data-assimilation and forecast system
Variational Doppler Radar Assimilation System (VDRAS) - 4DVAR
Variational Lidar Assimilation System (VLAS) - 4DVAR
CFD Models - CFDUrban (CFDRC), QUICUrb (LANL)

3-D Winds Product Interval
15 hour RTFDDA forecast every 3 hours
1 km VDRAS windfield every 10 min
100 m VLAS windfield every 10 min
~5 m CFD windfield every VLAS cycle

models is obtained from the VLAS output, and from wind profiles derived from raw data from the *Windtracer*.

SCIENTIFIC OBJECTIVES. The scientific objectives addressed by the field program involve the analysis of atmospheric structure and the T&D process near the building, the verification of the models, and the comparison of wind data obtained from the different measurements systems. The specific questions are as follows:

- What are the characteristics of the wind field perturbations produced by the building, including circulations in the light wells between the building rings and in the center courtyard?
- What are the vertical structures of the wind, temperature, and turbulence fields within the BL throughout the diurnal cycle?
- How quickly does the atmosphere surrounding the Pentagon, within the light wells between the rings, and in the central courtyard, purge itself of contaminant after the passage of a plume?
- How similar are the winds observed by hot-wire anemometers on a tethered lifting system (TLS), anemometers on a tower, sodar, Doppler lidars, and anemometers near the surface and on the roof of the Pentagon?
- How well do T&D models that employ winds from both VLAS and the CFD models simulate observed concentrations of tracer gas near the building?
- How well do winds observed in the vicinity of the Pentagon compare with solutions from building-

aware models, including CFDRC's model, which is based on Reynolds-averaged Navier–Stokes equations; LANL's rule-based model; and the NCAR EuLag large-eddy simulation model (Prusa and Smolarkiewicz 2003)?

- To what degree do winds observed in the vicinity of the Pentagon compare with the flow around a physical model of the building, simulated in the wind tunnel of the Environmental Protection Agency's Fluid Modeling Facility?

FIELD PROGRAM DESIGN. The field program period from mid-April to mid-May 2004 was chosen based on the necessity for having timely measurements to guide the development of the operational hazard assessment and prediction system in 2004 and 2005, the availability of the participants, and the time required to organize the field program after the project started in early 2004. These constraints meant that all of the preparation was concentrated within the 7–8-week period before the start on 9 April, an extraordinarily short period of time. Most meteorological observations were made for the entire period, but additional measurements were taken during several intensive observation periods (IOPs) when desired wind conditions prevailed for the release and measurement of a tracer gas. Critical to the field program's success was compliance with the many

security requirements associated with working within an environment such as the Pentagon.

Meteorological sensing systems. Meteorological measurements were obtained from the sensors listed in Table 2, where most of the locations are shown in Fig. 2. Instrumentation was selected and positioned in order to characterize the state of the BL in the vicinity of the Pentagon, even though there were many constraints and compromises that resulted from operating in an urban area, on sensitive military property, and in the airspace of nearby civilian and military aviation facilities (Reagan National Airport and Pentagon aviation).

One of the unique aspects of this field program was the simultaneous use of two scanning Doppler lidars (CTI *Windtracer*) with overlapping and synchronized scan patterns. One was permanently installed by the Defense Advanced Research Projects Agency (DARPA) on the roof of a wing of the Pentagon Annex, which is on a hill about 800 m to the west-southwest of the Pentagon itself ("W" in Fig. 2), and the other was deployed at Bolling Air Force Base by the Army Research Laboratory (ARL) for the period of the field program (located to the southeast of the Pentagon, not shown in Fig. 2). These pulsed lasers are eye safe, with a wavelength of 2 μm . The permanent lidar on the Pentagon Annex completed

TABLE 2. Meteorological sensor platforms.

Sensor platform	Variables measured or derivable	Number	Data frequency	Remarks
PWIDS	Horizontal wind speed and direction, temperature, relative humidity	15	1 s	2 m AGL, 10-s average
Super PWIDS	Three wind components, temperature, humidity, turbulence statistics, heat and momentum fluxes	10	0.1 s	Same as PWIDS, but with 3D sonic anemometer
32-m tower with four Super PWIDS, and five additional temperature probes	Three wind components, temperature, humidity, turbulence statistics, heat, and momentum fluxes	1	0.1 s	
Doppler lidar (CTI <i>Windtracer</i>)	Radial wind speed, turbulence statistics	2	~ 4 min for data volume from 90 deg scan	6 km \times 6 km area, 0–3 km AGL
TLS	Two wind components, turbulence intensity, temperature	1	1 s	Column from surface to 1 km, depending on time of day
Mini-sodar (AeroVironment)	Three wind components, turbulence intensity	1	1 s	Column from 10 m to 200 m AGL at 5-m increments
Net radiometer	Solar and terrestrial radiation	1		
REAL aerosol lidar	Aerosol backscatter	1	~ 25 s for single level of data from 90 deg scan	

a volume scan about every 4.5 min, and was typically programmed to scan 90° in azimuth, centered on the Pentagon, and 24° in the vertical. This resulting volume of radial winds covered roughly a 6 km × 6 km area, to a depth of about 3 km AGL, with a data-point spacing in the radial direction (range-gate size) of 72 m and a 0.5° angular resolution in the azimuth, which corresponds to an 8.73-m range-gate transverse width at 1 km.

Weather conditions near the surface and near the Pentagon roof were obtained from a network of 15 Portable Weather Information Display Systems (PWIDS; “P” in Fig. 2) and 10 Super PWIDS (“S” in Fig. 2). Wind speed and direction, temperature, and relative humidity were measured with the PWIDS using mechanical wind sensors and the Super PWIDS using three-dimensional sonic anemometers. The systems were mounted on tripods, light poles, and other available structures. Additionally, Super PWIDS were mounted at four levels on a 32-m tower (“T” in Fig. 2).

Vertical profiles of winds and other standard variables were obtained from radiosondes, an AeroVironment Model 4000 mini-sodar (“M” in Fig. 2) located about 400 m to the west of the Pentagon, and the TLS (“B” in Fig. 2) located in the parking lot to the southwest of the building. The TLS consisted of a 21-m³ blimp with meteorological and turbulence packages suspended below the blimp platform (Balsley et al. 1998, 2003; Frehlich et al. 2003). The turbulence package measured the temperature and velocity fluctuations at a sampling rate of 200 Hz with a fast-response fine-wire, cold-wire, and hot-wire turbulence sensor. The blimp with sensors was raised and lowered with a winch, with civilian and military aviation activities limiting the altitude of the deployment to 1 km between 0200 and 0500 EDT, and to 76 m at all other times. During IOPs, radiosondes were launched hourly from the southern end of Arlington National Cemetery to the west of the Pentagon. Last, a net

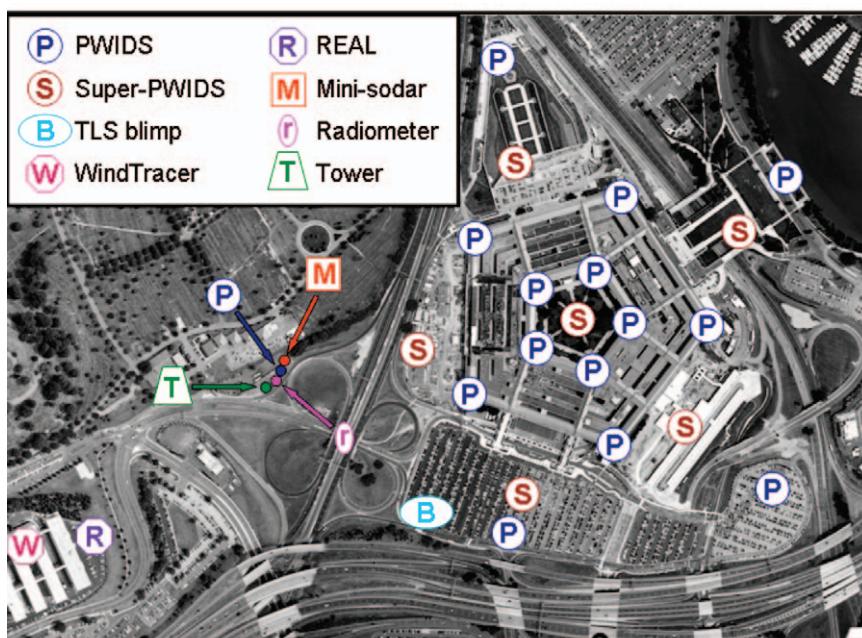


FIG. 2. Instrument siting for the field program. The PWIDS shown at the outer corners of the Pentagon, and at the corners of the interior courtyard, are located on the roof. The Army Research Laboratory’s lidar was located to the southeast of this image (not shown).

radiometer measured solar and terrestrial radiation (“r” in Fig. 2).

Raman-shifted Eye-safe Aerosol Lidar (REAL). Because potential airborne hazards include particulate matter (such as bacteria related to anthrax, tularemia, and other infectious diseases) whose detection would be important to a building protection system, the Pentagon Shield field program was used as an opportunity to test a new aerosol lidar developed at NCAR (Mayor and Spuler 2004; Spuler and Mayor 2005). This 1.54- μm elastic backscatter lidar was located just to the east of the CTI *Windtracer* system on the hill of the Pentagon Annex (“R” in Fig. 2). During the period of the field program, the REAL continuously mapped the aerosol distribution with horizontal and vertical scans. Horizontal scans often revealed complex dispersion paths from a variety of sources, some of which could be identified as mineral dust from nearby excavations, exhaust from jet aircraft in the region, and aerosols elevated over a wide area by high winds from mesoscale phenomenon (e.g., see the gust front in Fig. 4, described later). Vertical scans routinely showed the depth of the planetary boundary layer—a quantity important to assessing diffusion.

The REAL transmitted 10 laser pulses per second and scanned at 4° s⁻¹. Therefore, an 80° sector scan

could be completed in 20 s. Backscatter intensities were recorded at 3-m intervals along each laser beam. The useful maximum range of any lidar depends on local weather conditions, which control backscattering and extinction. During the field program, REAL collected useful data out to several kilometers range in weather conditions having visibilities from fair to excellent.

Tracer gas releases and measurements. In order to verify T&D calculations from the prototype Pentagon building protection system, and also to better understand the T&D of contaminants around this particular building, sulfur hexafluoride (SF_6) was released from various locations around the Pentagon during IOPs. The resulting T&D patterns were estimated through the use of three types of chemical detection devices. Programmable Integrating Gas Samplers [PIGS; operated by the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory]

each collected 12 samples of 5-min duration for an hour; the resulting ~5800 samples were analyzed after the completion of the field program. The PIGS measurements were supplemented by fast-response, real-time measurements using Tracer Gas Analyzers (TGA-4000, built by Scientech, Inc.). Depending on the IOP, 95–100 PIGs and 6–8 TGAs were employed, both outdoors and inside the Pentagon. Remotely sensed observations of gas distribution were available from three Fourier transform infrared spectrometers operated by Aerospace Corporation and Northrop-Grumman, Inc.

Intensive observation periods. Five IOPs were conducted, each with multiple releases of SF_6 . Because the optimal locations of the PIGS and TGAs were wind-direction sensitive, and because significant time was required to deploy them, the availability of accurate weather forecasts was crucial to the success of the mission. Dugway Proving Ground's forecasters made their

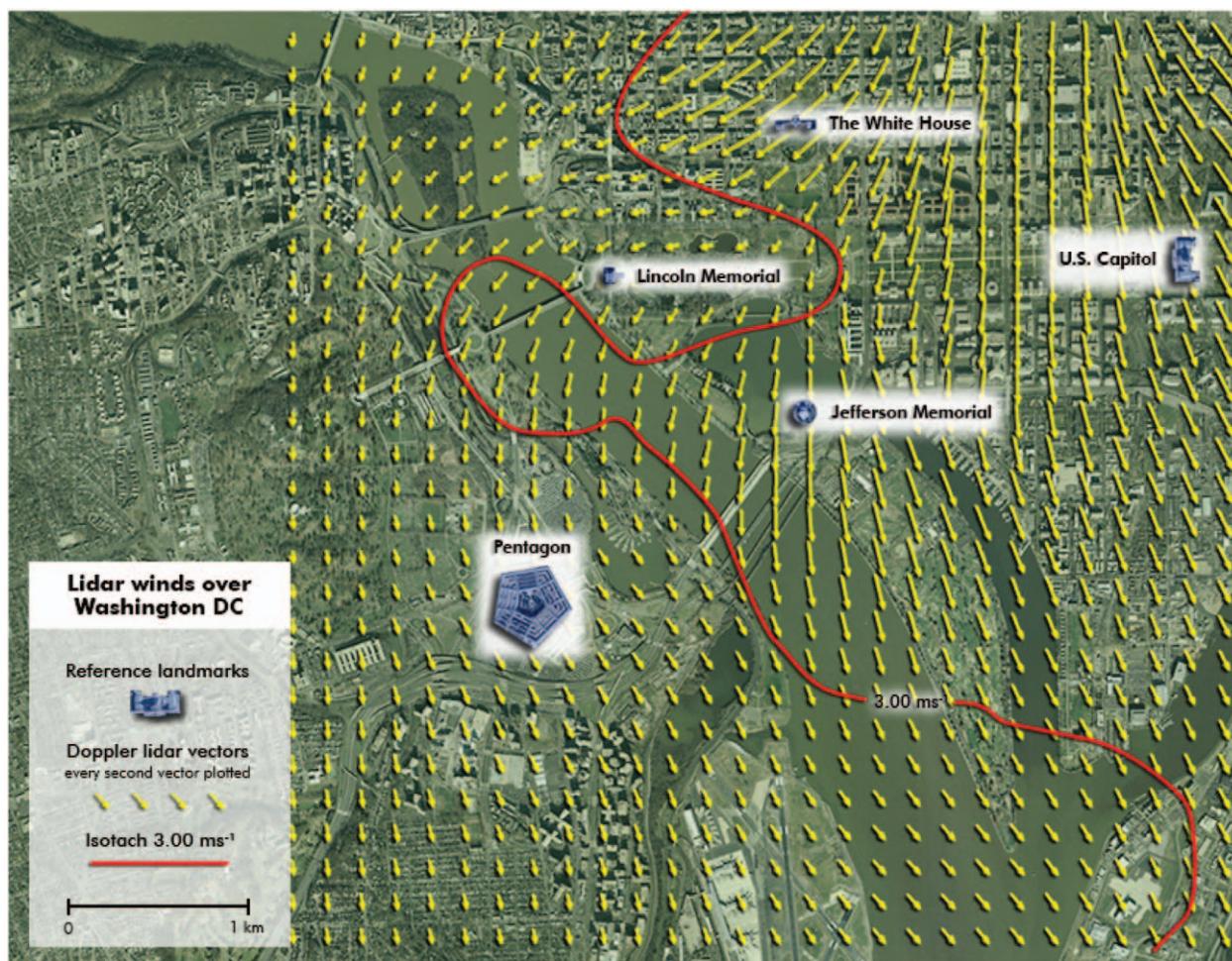


FIG. 3. Wind vectors for approximately 1424 EDT 7 May 2004, on a horizontal surface about 25 m AGL, based on the VLAS analysis of the CTI Doppler lidar radial winds and other meteorological data. Every second vector is shown in the image. The wind vectors coinciding with the plotted isotach have a length corresponding to 3 m s⁻¹.

forecasts using conventional numerical model products and observations; the field program's observations; and output from the RTFDDA and VDRAS modeling systems for the NCR, which will be part of the Pentagon's operational system. Operations for each IOP typically began in the late afternoon and ended very early the following morning. This schedule was dictated by the fact that indoor SF_6 measurements could be performed more easily after normal business hours, and the fact that the TLS could be used at higher altitudes only at night. In addition, an IOP objective was to manipulate the Pentagon's HVAC system in real time to minimize indoor penetration of the tracer gas, and this could be best accomplished at night when the building's population is lower.

PRELIMINARY ANALYSIS OF DATA.

As an example of the types of wind field structures that can be observed by a Doppler lidar, Fig. 3 shows a low-level VLAS wind analysis based on input from the lidar to the west of the Pentagon, for a time when a gust front generated by convective activity to the north was moving to the southwest across the NCR. This analysis, applicable at about 25 m AGL, illustrates a large spatial variability in the wind speed and direction. Ahead of the gust front, on the west side of the Potomac River, the speeds are about 1 m s^{-1} , whereas speeds behind the front to the northeast are $8\text{--}10 \text{ m s}^{-1}$. For comparison, Fig. 4 shows a backscatter image from the REAL for a horizontal surface about 25 m above the roof of the Pentagon, for the same time as the wind analysis in Fig. 3. The yellow and red colors in Fig. 4 indicate a strong backscatter signal from aerosols. The westward bulge in the aerosol cloud in Fig. 4 corresponds roughly with the shape of the 3 m s^{-1} isotach in Fig. 3, where the leading edge of both features is located at about the Potomac River. This suggests that the dust was locally elevated from the surface by the strong winds. The small areas of higher backscatter to the west of the gust front in

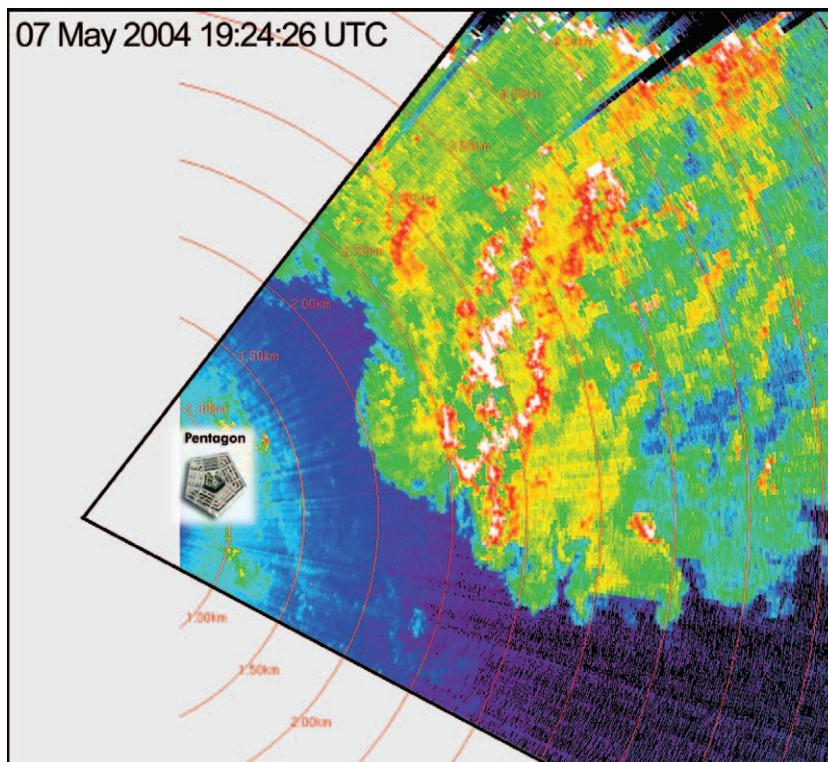


FIG. 4. Backscatter from the REAL, for approximately 1424 EDT 7 May 2004, on a horizontal surface that is approximately 25 m above the roof of the Pentagon. The lidar is located at the center of the range rings in this figure, and at the location designated “R” in Fig. 2. Backscatter signals close to the Pentagon are likely related to dust and vehicle exhaust from construction activities. The coverage area of this image is the same as that of the wind vectors in Fig. 3.

Fig. 4 are typical of those observed at construction sites in the area. Winds are being analyzed from the Pentagon Shield VLAS system to develop a wind-field climatology for that part of the Capitol area, and to determine the prevalence of variability on the neighborhood scale that could result from causes in addition to the gust front shown here.

Because one of the objectives of the field program was to reconcile wind estimates from different observing platforms, Fig. 5 shows examples of some preliminary comparisons of vertical profiles. The vertical scale is the ratio of the height above ground (z) to the BL mixing height (H), defined as the maximum gradient in the profile of energy dissipation rate, ϵ . The left two panels compare observations of wind speed and direction from the TLS (solid line), Doppler lidar (open blue circles), and sodar (open red circles) for the period 0227–0254 EDT 11 May 2004. The sodar and lidar data were averaged over the period of time required for the TLS to be raised through the layer. The lidar wind speed and direction were determined by best fits to the radial velocity over the

3D volume scan (Frehlich et al. 2006). Except for some discrepancy in the wind direction very near the surface, the wind profiles obtained from the different systems are quite similar. Clearly the vertical resolution of the TLS identifies many finescale features that are not resolved by the lidar and sodar. The eddy-dissipation rates (ϵ) derived from the TLS and lidar data are plotted in the right panel of Fig. 5. The large fluctuations of ϵ are atmospheric variability and not measurement error (Frehlich et al. 2004). The height at which there is a rapid decrease in ϵ (mixing height H) is chosen as the top of the BL. The estimates of ϵ (open blue circles) were derived from the lidar data using a new processing algorithm with higher vertical resolution (Frehlich et al. 2006). This algorithm is based on structure functions of the radial velocity perturbations in the azimuthal direction (see Figs. 3, 4, and 7 of Frehlich et al. 2006) instead of the structure function in the radial direction (Frehlich et al. 1998). The improved vertical resolution of the lidar data processing is able to represent the sharp drop in ϵ at the mixing height H . Because the lidar estimates represent a larger spatial average than the TLS estimates, there will be differences produced from effects of terrain and inhomogeneities in the turbulent field. The temperature profile measured by the TLS is approximately neutral below $z/H = 0.5$, is roughly isothermal from $z/H = 0.5$ to $z/H = 1.2$, and has a sharp inversion above that level. Note the curious very shallow sheet of cooler air at the top of the BL that would be difficult to observe with other instrumentation.

SUMMARY AND DISCUSSION. This Pentagon Shield field program was conducted from 9 April to 16 May 2004 to define the BL thermal structure, wind field, and T&D processes in the vicinity of the Pentagon. It was a component of a DARPA- and PFFA-sponsored project to develop and deploy an

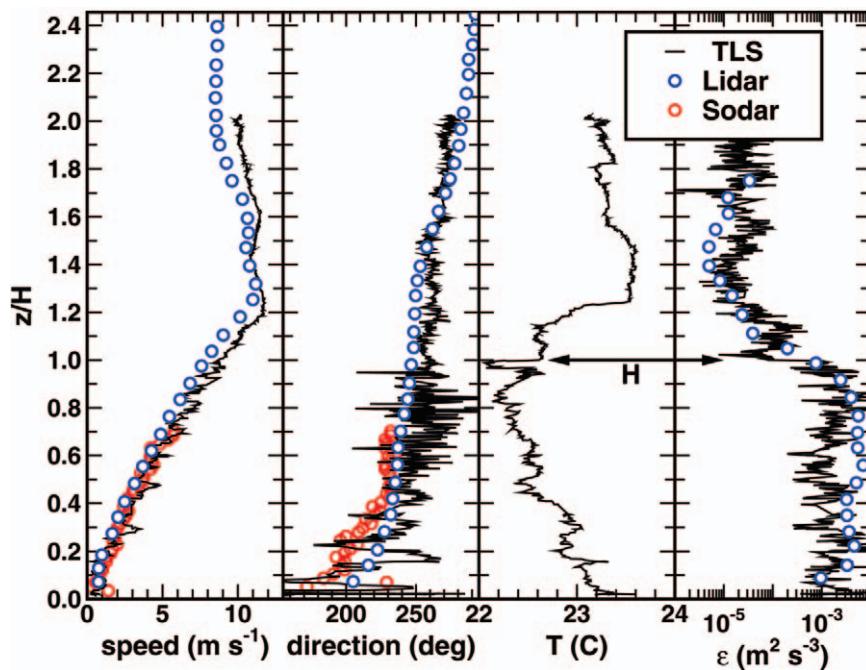


FIG. 5. Comparison of the vertical profiles of wind speed and direction from the TLS, Doppler lidar, and the mini-sodar for the period 0227–0254 EDT II May 2004. The vertical scale is the ratio of the height above ground (z) and the BL height or mixing height (H). Sodar and lidar data were averaged over the period of time required for the TLS to be raised through the layer. Also shown are the temperatures and eddy-dissipation rates obtained from the TLS and lidar. The estimated top of the BL is shown by the arrow with the “H” symbol.

atmospheric measurement and modeling system to protect the Pentagon’s approximately 25,000+ occupants, and our national defense infrastructure, against CBR attacks. The field program was unusual from a science perspective in that its objective was to characterize the meteorological conditions and T&D around a single (albeit large), relatively isolated, building. It was unusual from a logistical standpoint, as well, because of the constraints associated with operating in an urban area, very close to Reagan National Airport and Pentagon aviation activities, and in one of the most security-conscious military settings in the world. Current and future work that employs the data obtained during the field program, and the data that are routinely available from the operational system, includes the following.

- The winds from the Doppler lidar are being analyzed to define the energy on different scales, to determine, for example, the importance of neighborhood scales in the motion above rooftops. This will help answer the question about the amount of error in T&D calculations that would result if lidar-scale winds are not available.

- The building-perturbed wind field defined by the wind-tunnel data and the observations are being used to verify the solution from building-aware CFD models.
- Better techniques are being developed for dynamically integrating into a single seamless dataset the analyses and forecasts from different types of models.
- The T&D models are being verified against the tracer data.
- The benefits of dual-Doppler lidar versus single-Doppler lidar analyses of urban wind fields is being quantified.
- Algorithms are being developed that automatically identify plumes in the aerosol lidar's output data.
- The outdoor tracer-gas releases and measurements were coordinated with tests of the building's ventilation system.
- Experience was gained with the elevated siting of scanning aerosol lidars that can characterize aerosol distribution over a metropolitan area.

In summary, given the rapidly expanding interest and activity in urban meteorology, for a variety of applications including homeland security and air quality, the data and experience gained in this field program should be a good complement to those that have recently been obtained for other cities and climates. And, the building-protection system that these data are helping to verify should be readily adaptable for use in protecting other buildings and populations against the accidental or intentional release of CBR material into the atmosphere.

The field program also resulted in the following accomplishments in terms of urban field-program design and execution.

- It forced the development of safety protocols for the use of the TLS technology in urban settings. Given the utility of this system for urban field programs, this will contribute to an improved understanding of urban meteorological processes.
- Experience was gained with the rooftop siting and operational application of Doppler lidars, and with the use of multiple lidars to provide coverage of a large metropolitan area. Some of the problems addressed, and lessons learned, involve the following. A special challenge in urban areas is that the scanning lidar beam can reflect from hard targets (buildings), and damage the lidar's optics, if the instrument siting and scanning are not done properly. In addition, there are many tradeoffs related to the scan strategy that are critical for operational use, but are less relevant for more standard field program applications. For example, for operational use, the volume scans need to be completed quickly in order for the data set to be relatively current. Thus, instead of scanning over 360°, the approach here was to scan only a 90° sector by offsetting the lidar from the volume of atmosphere of interest.
- Because a focus was to study the dispersion of tracer plumes about a single building, forecasters learned to deal with special challenges. They had to predict wind directions within 5°–10° and speeds within a few knots, 12 h in advance, so that tracer samplers could be properly placed outside the building and point releases could be located so that the tracer gas would impact the building.

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