by Joshua Wurman

UP CLOSE AND PERSONAL

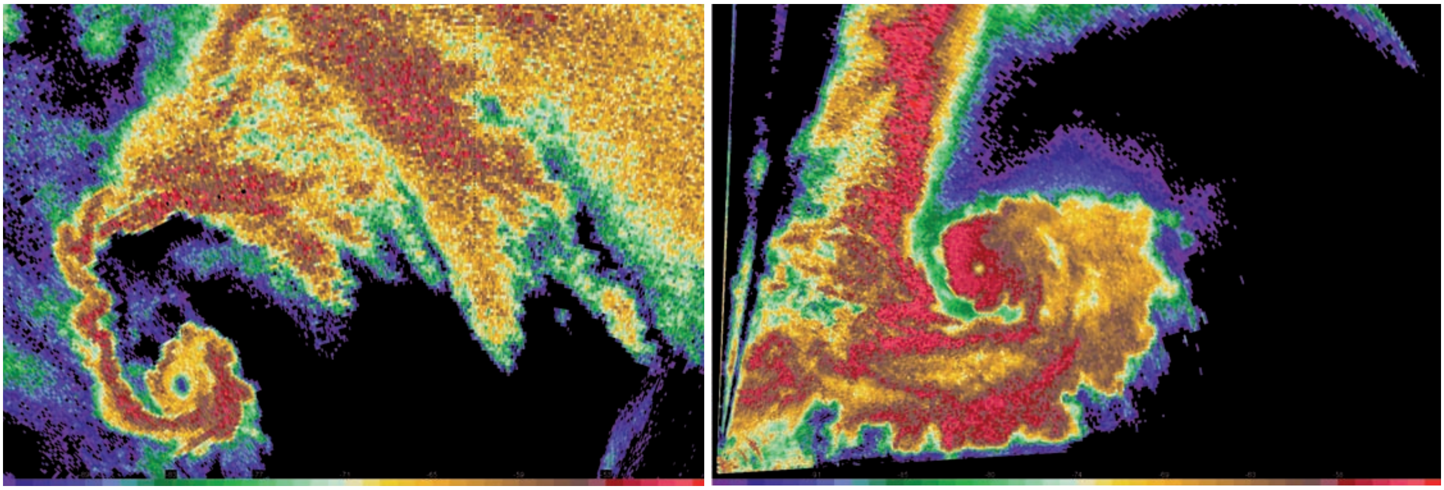
The challenge of observing small-scale phenomena

The mobile Doppler on Wheels (DOW) project produces radar results that are 10,000 times better than those of conventional radar systems. Inventor and legendary storm chaser Joshua Wurman highlights the advantages

Many important and interesting atmospheric phenomena are either small or short-lived and as such are challenging to observe. Some are also violent, precluding many types of observational techniques. For example, the average diameter of the core flow region of a tornado is only 250m, and their lifetime is typically just minutes. Small structures in the boundary layer of landfalling hurricanes are likely to be correlated with the highest surface winds and damage. These wind streaks and rolls have wavelengths of 100-300m. Mountain and valley circulations in the Alps contain very small and short-lived features. Shallow snow bands, boundary layer thermal plumes, and wildfire plumes are all difficult to observe because of their small scale.

Traditional national operational radar networks cannot hope to map these small-scale events. The USA's WSR-88D (Weather Surveillance Radar) network is typical. It is spaced at roughly 200km intervals over the lower 48 states to tile most of the nation with moderate resolution radar coverage. This results in a coverage area of approximately 50,000km^2 per radar (about 8 x 106km^2/150 radar), with individual radar surveying areas of about 120,000km^2. WSR-88Ds, like many operational radar, have beamwidths of approximately 1°. At a range of only 6km, their beamwidth exceeds 100m. Therefore only about one-thousandth of the surveillance area of any WSR-88D radar is within 6km of that radar. Only one-thousandth of the occurrences of any randomly spaced phenomenon, be it a severe thunderstorm or a microburst, would occur within a range where the radar's

The Doppler On Wheels (DOW) project has created mobile weather radars mounted on trucks that explore rare, short-lived and small-scale phenomena



A slice through a hook echo and tornado. The Doppler velocity field illustrates the intense rotational winds, which can exceed 480km/h. The reflectivity field shows the central eye and surrounding rings of centrifuged debris and rain

beamwidth is less than 100m. At a more typical range of 100km, the beamwidth of WSR-88Ds is more than 1,700m. As the area of the annulus between a range of 100km and 200km is 90,000km^2 – three times the 30,000km^2 area within 100km – 75% of all randomly spaced phenomena will occur outside this radius, and be observed by the WSR-88D (or any 1° beamwidth radar) with beamwidths ranging from 1,700-3,400m. To 'well resolve' a phenomenon (i.e. the observations are able to retrieve 80% of the magnitude of the feature), at least six to eight observations across a phenomenon are necessary.

This means that even at a range of only 6km, WSR-88D radar can well resolve only objects with scales greater than 600m: larger than hurricane boundary layer rolls and above the level of the strongest winds in a microburst or tornado. And, at a range of 100km, phenomena need to be several kilometers in scale to be well resolved. As if this were not bad enough, at ranges beyond 30km, representing 98% of the full survey area, Earth's curvature creates a substantial blind area near the ground.

The beam spread problem

There are two rather obvious solutions to the problem of beam spreading. The first is to employ extremely narrow beamwidth radar. But beamwidths much less than 1° would be required. This is not practical at most microwave wavelengths because of unavoidable laws-of-physics diffraction limitations on antennas. WSR-88D radar uses 8m antennas to focus 1° beams. Achieving 100m beamwidths at 100km, in only one-quarter of the 200km survey area

A Doppler on Wheels unit observing a tornado near Attica, Kansas. DOW radars scan through tornadoes and other small phenomena, collecting fine-scale 3D wind and reflectivity data

of such a radar, would require an extremely narrow beamwidth of only one-sixteenth of a degree and an antenna diameter of about 128m. Use of very short wavelengths, i.e. less than 10mm, or even optical wavelengths, is not practical since short wavelength radiation does not penetrate intense precipitation very well, so the radar would not see into or through storms.

The second class of solutions involves placing radar closer to small, short-lived, intense weather phenomena. To achieve a 6km or greater range across the entire USA, a network of approximately 80,000 radars of 1° beamwidth would be required (about 8 x 106km^2/100km^2). This is unlikely to be practical even if radar costs are reduced drastically.

Moving closer

The only practical solution for resolving and mapping small atmospheric features is to get radar close. This is the core idea of the Doppler On Wheels (DOW) project. The DOWs are full-capability state-of-the-art weather radar, whose basic specifications equal or exceed those of most operational radar. The DOWs have beamwidths of 0.93°. Transmitted pulse lengths can be as short as 25m and they can oversample with range resolution of 12.5m. The DOWs use 250kW X-band (about 9.35GHz) magnetron transmitters. DOWs can scan at 50° per second, completing sector scans in four seconds, and full 360° scans in seven seconds. They have Doppler systems capable of fast pulsing at up to 5,000Hz, staggered pulse-repetition frequencies, clutter filtering, time series recording, and so on.

Getting closer with DOWs has dramatic effects on spatial resolution. A standard WSR-88D-type radar observing from a distance of 100km has a resolution volume of 1,750 x 1,750 x 200m, which equals 6 x 10^{8}m^3. A DOW radar at 3km range has a resolution volume of 50 x 50 x 25m, which equals 6 x 10^{4}m^3 – a striking 10,000 times smaller.

In addition to carrying out fine-scale observations, DOWs can be deployed to regions that are obscured to normal radar because of terrain and Earth's curvature.

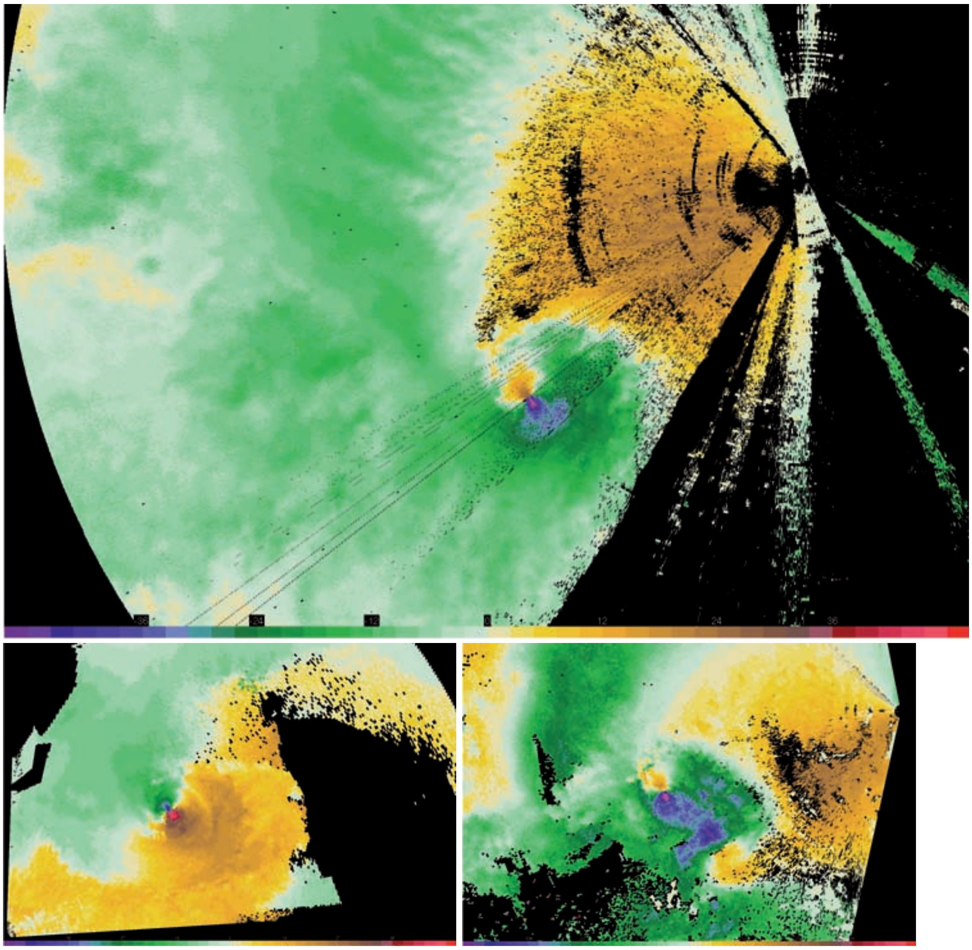
Pods weighing 50kg are dropped directly into the path of a tornado or along the coast for hurricanes at just 1m above ground level

The first prototype DOW radar was constructed in 1995 and immediately revolutionized the character of observations possible in tornadoes, hurricanes, wildfires, thunderstorms, convective initiation, mountain and valley weather, and others.

During its initial shake-out missions, a DOW conducted the first ever mapping of tornado winds. With the capability to resolve and map tornadic winds, a new era of observations began. For the first time, the core flow and surrounding regions of a tornado could be quantitatively visualized, the distribution of winds with radius and height could be mapped, the evolution of these winds could be observed, and central downdrafts were measured. The first ever mapping of multiple vortices within tornadoes documented the movement, size, intensity, and other behavior of these phenomena believed to be associated with the most severe damage caused by tornadoes. DOWs accomplished the first vertical profiles of tornadoes, documented the strongest winds ever measured in any terrestrial phenomena, and the largest measured tornadic circulations. The first mappings of anticyclonic tornadoes, comparisons with observed damage, and the first dual-Doppler wind field mappings of tornadoes and their surrounding conditions could be made. Since 1995, the DOWs have collected data in more than 140 different tornadoes throughout the Plains region of the USA.

Tropical cyclones

The prototype DOW was deployed to the coast of North Carolina, USA, near the point of landfall of the eye of Hurricane Fran in 1996. The goal was experimental: to see how well a DOW could perform in the hostile hurricane environment. The result was a discovery of unexpected but important phenomena: small-scale (about 300m wavelength) boundary layer rolls and wind streaks. These streaks, which have been observed in all 12 hurricane eyewalls observed by DOWs, are likely associated with the highest surface winds



Velocity depiction from a storm. The tornado is at the center of the velocity couplet (region with strong and contrasting winds side-by-side)

and most severe damage caused by landfalling hurricanes. Equally important, the transport of angular momentum and heat from the ocean and land surface aloft into the hurricane is modulated by these rolls. This likely plays a critical role in hurricane intensification.

The DOW radar have been used in more than two dozen different field programs in the USA and Europe. During the Mesoscale Alpine Programme (MAP), DOWs were deployed in the Tocino and other valleys in Switzerland and Italy, observing weather in these valleys that were invisible to non-mobile radar. During the Convective and Orographically-induced Precipitation Study (COPS), DOWs were deployed in Germany and France to study convective initiation in the Rhine Valley and Black Forest region. The DOWs are likely to return to Europe for the Hydrological cycle in the Mediterranean Experiment (HYMEX) project in 2011-2012.

DOWs have observed a wide variety of phenomena, both atmospheric and man-made, including turbulent flow structures in support of aviation, chemical plumes in support of homeland security, and water drops in support of firefighting.

Rapidly evolving phenomena

Small, intense phenomena tend to evolve very quickly. The advective timescale for a 200m scale object moving at 30m/s is just seconds. Microbursts and tornadoes form and intensify in less than one minute and multiple vortices spin around and evolve in even less. Hurricane boundary layer rolls change structure in less than a minute, as do intense convective plumes arising from fires.

Although deployment of DOWs close to interesting phenomena has provided about 10,000 times better 3D spatial resolution, the improvement of temporal resolution has been considerably more modest. Fast scanning, at rates up to 50°/s, permits multi-tilt 3D volumes to be obtained in one or two minutes. This is considerably faster than the five-minute intervals typical for WSR-88D operational radar. However, it is not nearly fast enough to resolve evolution occurring on the one-minute timescale. Several observations are required during the time period of a structural change to well resolve that change, exactly analogously to the spatial resolution issue. To observe a phenomenon that lasts one minute, observations are required approximately every 10 seconds.

Phased-array radar capable of very rapid scanning has existed for decades, used primarily for military applications. But this technology is extremely expensive: phased-array radar suitable for meteorology cost in excess of US$10 million. In addition, their expense, size and robustness mean that major phased-array testbeds are stationary. Stationary phased-array radar, while fast-scanning, suffer all the spatial resolution limitations of stationary conventional radar.

The Rapid-Scan DOW

Until recently, the choice was between fast and blurry imagery from phased arrays, and slow and sharp imagery from traditional DOW-like radar.

The Rapid-Scan DOW was developed to obtain fast and sharp 3D imaging of various phenomena. A traveling wave tube (TWT) transmitter transmits a series of short (0.17 microsecond) contiguous pulses each at a different frequency, through a dispersive 86 x 86 element slotted waveguide array antenna, which steers by 1° in elevation per 76MHz. In plain terms, the Rapid-Scan DOW transmits six nearly simultaneous narrow pulses, each aimed at a different elevation angle. Then a multichannel receiver listens simultaneously at the multiple frequencies for returns that originate from the different beams. In effect, several simultaneous beams are transmitted and received, each at a different elevation angle. Three-dimensional volumetric scans are obtained within 4-14 seconds. The Rapid-Scan DOW antenna focuses a narrow 0.8° beam for very fine spatial resolution so that spatial and temporal observing scales are matched. The antenna is mechanically scanned rapidly in azimuth, at 50°/second. Deeper volumetric scans can be obtained by coarse manual elevation steps. Critically, the cost to construct a Rapid-Scan DOW is less than US$1 million.

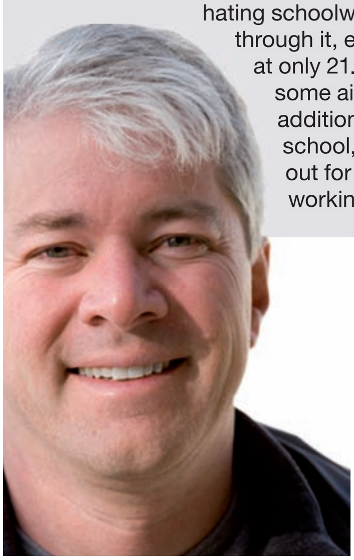
The Rapid-Scan DOW prototype has obtained high-quality 3D volumetric data in several tornadoes, a 200 volume series in a

HOW I BECAME A STORM CHASER...

I grew up in Pennsylvania, bereft of any really meaningful opportunities to experience severe weather, hurricanes, even really deep snow. As a youth, I tried to impress friends and girls with my home weather station and insect collection.

Naturally I moved on to a party school – the Massachusetts Institute of Technology (MIT) – to search for a better social life. But hating schoolwork, I rushed through it, earning my MS at only 21. Then after some aimless additional years in school, I dropped out for three years, working for the US Air Force on nuclear winter computer simulations and other cheery subjects.

Returning to MIT, I earned my doctorate and moved to Colorado to work at the National Center for Atmospheric Research (NCAR) on bistatic radar networks, a new type of weather radar system that I had invented. However, after seeing real High Plains thunderstorms close up, and tornadoes, I got distracted and conceived of building a network of big, fast-scanning radar that could drive right up to tornadoes and fires, inside hurricanes, and into other nice weather. The DOW program was born, and I moved down to Oklahoma to be a professor for a few years, chase tornadoes and hurricanes, file patents, teach and write papers. In the middle of this, I traveled to Asia on a research project and met my wife, who was operating a weather radar on an island off the coast of Hong Kong, and conned her into believing that Oklahoma was just like Hong Kong. After receiving tenure and the implied lifetime sentence at the university, I did the sensible thing: I quit and moved back to Boulder and founded my own non-profit research institution: the Center for Severe Weather Research (CSWR). My wife and I run CSWR, manage the DOWs as National Science Foundation (NSF) Facilities, and conduct research programs such as the VORTEX2 study and hurricane studies.



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long-lived tornado during the Verification of the Origin of Rotation in Tornadoes Experiment 2 (VORTEX2) experiment in June 2009. In addition, Rapid-Scan data has been collected in a landfalling hurricane and there are plans to use it to study boundary layer thermals, microbursts, and other rapidly evolving phenomena.

Many studies of small-scale phenomena require microphysical information that can be obtained through dual-polarization radar measurements. However, traditional dual-polarization radar must scan slowly to obtain data from alternating H and V pulses, or employ 45° transmissions, which do not permit a full matrix of observations (no LDR, for example) and are subject to cross-polarization errors. Collecting fine temporal-scale and dual-polarization data have long been incompatible objectives. During VORTEX2, for example, scientists had to make daily choices between 'dual-pol days' when radar would scan slowly and 'dual-Doppler days' when radar would scan fast. A new dual-polarization scheme, which permits much faster scanning, is being implemented in the DOWs for early 2010. Two transmitters, with frequencies separated by 150MHz, pulse synchronously.

In fast full-matrix (H/45) mode, one transmitter transmits H, while H and V are received, resulting in measurements of linear depolarization radio (LDR), reflectivity and velocity. The second transmitter transmits at 45°, while H and V are received, resulting in independent measurements of reflectivity, velocity, and so on, as well as the cross-polar correlation coefficient (Rho-HV), Differential Reflectivity (ZDR), and Differential Phase (Phi-DP).

In an even faster 45° (45/45) only mode, both transmitters transmit with receipt at H and V, resulting in independent measurements of reflectivity, velocity, cross-polar correlation coefficient (Rho-HV), Differential Reflectivity (ZDR), and Differential Phase (Phi-DP) at each frequency, permitting very fast scanning. In all these modes, high pulse repetition frequencies (PRF), staggered PRF, clutter filtering, full-time series recording, and other modern techniques are being implemented.

A new DOW, using the dual-frequency, dual-polarization approach, but at C-band (about 5.5GHz), has been proposed. This system will employ a 4.3m folding antenna (deployment/undeployment in less than a minute) to obtain a 1.0° beam.

Observing near Earth's surface

To understand how severe weather, including hurricanes, microbursts, mountain windstorms, and tornadoes, causes damage to objects, and to answer basic questions such as 'how strong are the winds very near the surface, at house height?', observations of winds near these objects are necessary.

Unfortunately, no matter what radar technologies are used, there are practical restraints to radar observations near the ground. Ground-skimming 1° DOW beams are centered at 25m AGL (above ground level) at a range of only 3km. Narrower radar beams in specialty radar operating in the mm-wavebands are still unable to observe near the surface because of terrain, trees and man-made objects, which are common below 20m AGL. To put it

succinctly: radar are blind to conditions near the ground.

To explore this shadowed region, the DOW program has deployed an array of surface instrumentation within hurricanes and tornadoes. Pods, which are very stable, and hardened 50kg weather stations, are dropped in the path of tornadoes and at forward locations along the coastline during hurricanes to collect measurements at 1m AGL.

A manned armored vehicle is able to penetrate inside tornadoes and collect measurements at 3m AGL, at least until the exposed instrumentation is destroyed by flying debris. A fleet of 'mobile mesonet' automobiles is used to collect observations in the severe environment. Point measurements reveal conditions only at specific locations, so they are combined with three-dimensional DOW radar data collected from 25-2,000m AGL to create comprehensive maps of surface wind fields at the all-important house level of 1-15m AGL.

Mobile radar

The DOW program has demonstrated that ambitious radar technology can be implemented on highly mobile platforms, and that radar can be deployed quickly and adaptively to study a wide range of phenomena in a variety of environments, ranging from landfalling hurricanes, to wintertime mountaintops, to alpine valleys, to tornadic supercells.

Since the DOWs were invented, several universities and research laboratories have developed mobile radar systems based on the DOW concept. These include radar operating at C-band, X-band, Ka-band, and W-band, with dual polarization and a phased-array system. DOW-like radar are now operational in China, Japan, Taiwan, Greece and the USA, and systems are planned in other countries.

One can imagine a fleet of mobile radar (and other inexpensive ground-based instrumentation) forming the core of an adaptable/targetable observing network in Europe, Asia, the Americas, or elsewhere where there is a developed road network. A fleet of, say, 50 DOWs could be deployed to pre-site-surveyed locations in a region forecast to be at risk of severe weather in 24-48 hours' time. For example, if a severe weather system is forecast to impact a 200 x 200km area of Europe, the DOWs would establish a fine-scale observing network in the region. This array could be adapted and tightened as the event approached and the forecast became more precise. Data from this dense array of radar and other instrumentation could be assimilated into short-period forecast models to provide one- to six-hour predictions and warnings of floods, high winds, hail, tornadoes, high-impact snowfall, and so on.

Such an array of instruments could also be deployed to regions of natural or man-made disasters, including wildfires, terrorist attacks, and pollution accidents. ◗