Advances in Operational Weather Radar Technology

Mark E. Weber

■ The U.S. aviation system makes extensive use of national operational Doppler weather radar networks. These are critical for the detection and forecasting of thunderstorms and other hazardous weather phenomena, and they provide dense, continuously updated measurements of precipitation and wind fields as inputs to high-resolution numerical weather prediction models. This article describes recent Lincoln Laboratory activities that significantly enhance the operational effectiveness of the nation's Doppler weather radar networks. An open radar controller and digital signal processor has been developed for the Terminal Doppler Weather Radar (TDWR), which provides safety-critical low-altitude wind-shear warnings at large airports. This processor utilizes a small computer cluster architecture and standards-based software to realize high throughput and expansion capability. Innovative signal processing algorithms—enabled by the new processor—significantly improve the quality of the precipitation and wind measurements provided by TDWR. In a parallel effort, the Laboratory is working with engineers in the National Weather Service to augment the national NEXRAD Doppler weather radar network's algorithm suite. Laboratory staff develop and test enhancements directed at the aviation weather problem. Then they provide plug-and-play software to the NEXRAD second-level engineering support organization. This effort has substantially improved the operational value of NEXRAD data for the aviation system. Finally, we discuss nascent efforts to define a future multifunction radar network using an active-array architecture, which could realize the capabilities of today's multiple weather and air traffic control radar networks.

Lincoln Laboratory has played a significant role in the development and application of U.S. operational weather radar networks. Early efforts addressed the then-under-development Next Generation Weather Radar (NEXRAD) and included analyses of ground-clutter suppression requirements [1] and experimental evaluation of Doppler spectrum-based turbulence estimators [2]. In response to a series of commercial aviation accidents caused by low-altitude wind shear, the Federal Aviation Administration (FAA) initiated a fast-track program to develop a Terminal Doppler Weather Radar (TDWR) that detects and warns against this hazard at major airports. The Laboratory's role in developing automated wind-shear detection algorithms for TDWR, demonstrating these operationally on a transportable testbed, and transferring key technology elements to industry was critical to the successful deployment of this system [3].

A complementary wind-shear detection system utilizing deployed Airport Surveillance Radars (ASR-9) was developed by the Laboratory [4] and is now operational at thirty-four airports that did not receive the

TDWR. Finally, Laboratory researchers have played a significant role in validating and refining industry-developed weather reflectivity processing channels for U.S. terminal air traffic control radars ASR-9 and ASR-11 [5].

Other Laboratory programs have exploited these Doppler weather radars as key inputs to integrated weather processing systems focused on reducing commercial aviation delay caused by adverse weather. The Integrated Terminal Weather System (ITWS) [6] and Corridor Integrated Weather System (CIWS) [7] utilize NEXRAD, TDWR, and ASR-9 measurements to detect and forecast thunderstorm impacts on runways, terminal gateposts, and high-altitude jet routes.

Key aspects of the processing algorithms in these systems derive from insights gained during the Laboratory's development of their input weather radar systems. Data quality control—for example, robust ground-clutter suppression and suppression of interference from distant range-ambiguous thunderstorm returns—is critical if Doppler weather radar data are to be used effectively in automated warning and forecasting algorithms. Likewise, detailed understanding of the differing and often complementary characteristics of storm measurements obtained from these multiple radar systems has been important in developing effective decision support information for FAA and airline operational personnel.

This article describes recent Lincoln Laboratory activities that enhance the nation's current operational Doppler weather radar networks, and nascent efforts to define a next-generation multifunction replacement network. The next section describes current operational weather surveillance radar networks and the aviation-sector uses of each system. A subsequent section discusses a signal processor enhancement for the TDWR, which significantly improves both supportability and operational capabilities. We then describe our use of NEXRAD open-processing systems to implement algorithms that substantially improve the value of this radar to FAA operational systems. Finally, we describe a concept definition study for a multifunction phased-array radar that could replace current weather and aircraft surveillance radar networks, potentially realizing both performance enhancements and cost reductions.

U.S. Operational Weather Radar Networks

The Weather Service Radar 88-D (WSR-88D, or NEXRAD) was developed by Unisys Corporation in the 1980s, using technical specifications developed by scientists at the National Severe Storms Laboratory and other organizations. The radar operates at 10 cm wavelength, utilizes a 1° transmit and receive beam, and transmits uncoded 750 kW pulses with selectable durations of 1.6 or 4.7 μsec. NEXRAD is fully coherent to support ground-clutter suppression and weather Doppler spectrum moment estimation. One hundred forty-three NEXRADs are deployed within the Conterminous United States (CONUS).

NEXRAD data and derived products are disseminated to National Weather Service (NWS) personnel at Weather Forecast Offices and a variety of private and media weather service providers. The Laboratory's engagement with this radar has been primarily in relation to its important role in providing thunderstorm location, intensity, characterization, and movement information to FAA and airline personnel through systems such as the ITWS, CIWS, and Weather and Radar Processor (WARP) [8]. The NEXRAD network's key attributes include national-scale coverage, operation at a non-attenuating wavelength, and connectivity to essentially all operational weather personnel dealing with public and aviation weather services.

Terminal Doppler Weather Radar was manufactured by Raytheon Corporation in the late 1980s using technical specifications developed by the FAA and Lincoln Laboratory. Because spectrum availability at 10 cm wavelength was limited by in-place Airport Surveillance Radars and NEXRAD, TDWR operates at 5 cm. TDWR generates a 0.5° pencil beam and transmits uncoded, 1 μsec, 250 kW pulses. Its sensitivity to volume-filling precipitation particles is essentially identical to NEXRAD. TDWR is deployed operationally at forty-five large U.S. airports.

Currently, TDWR is used primarily for wind-shear detection services at the airports where it is deployed. It is also an input to the ITWS, which uses TDWR data for wind-shear prediction and a high-resolution gridded wind diagnosis [9] that enhances capacity at major airports during high wind conditions [10]. Because of TDWRs siting near major metropolitan areas, its twofold angular resolution improvement relative to NEXRAD, and its aggressive ground-clutter suppression algorithms, there is increasing interest in use of its data for applications beyond the immediate airport vicinity. NWS has established a program to access data from all TDWRs and to process these data in the appropriate Weather Forecast Offices as an adjunct to NEXRAD. Researchers developing advanced algorithms for forecasting future thunderstorm impacts on the airspace system view TDWR data as important, because of the ability of its high-resolution beam to capture boundary-layer wind structures that lead to new storm initiation. Future configurations of the CIWS will include TDWR data ingest and processing for this purpose.

In addition to these meteorological radars, the U.S. Government operates two distinct surveillance radar networks for Air Traffic Control (ATC) services. Airport Surveillance Radars (ASR) operate at 10 cm wavelength and utilize a doubly curved reflector to detect aircraft returns in range-azimuth space by using a 1.4° (azimuth) by 5° (elevation) cosecant-squared beam. Modern ASRs—the Westinghouse-manufactured ASR-9 and the Raytheon-manufactured ASR-11—provide parallel data processing chains that display to terminal controllers calibrated maps of the intensity of precipitation as sensed by their vertically integrating beams. Thirty-four ASR-9 radars are equipped with the Lincoln Laboratory–developed Weather Systems Processor (WSP), which additionally detects low-altitude wind shear and provides zero-to-twenty-minute forecasts of thunderstorm future location.

Air Route Surveillance Radars (ARSR) provide national-scale primary aircraft surveillance. The ARSRs currently in operation date back to the ARSR-1 and ARSR-2 systems deployed in the 1960s. The Departments of Defense (DoD) and the Department of Homeland Security (DHS) have recently assumed responsibility for operation, sustainment, and upgrades to the ARSR network, although technical support is still subcontracted to the FAA. The most modern ARSR—the Westinghouse-developed ARSR-4—employs a phased primary feed that supports the formation of an elevation receive stack of 2° pencil beams. A weather processing channel derives quantitative precipitation reflectivity estimates from these beams. The NWS is actively pursuing ingest of ARSR-4 weather data as a gap filler for the NEXRAD network.

Terminal Doppler Weather Radar Processor Enhancement

TDWR provides a unique capability for high-quality precipitation and wind measurements, particularly in the planetary boundary layer where most significant weather conditions have their roots. The radar features very high angular resolution, high sensitivity to weak clear-air meteorological signals, and a highly stable Klystron transmitter that supports robust Doppler clutter filtering. Operational experience over the last decade with fielded TDWRs has, however, exposed data quality issues that can reduce the reliability of automated applications that utilize its data. Most significant are the impacts of range-ambiguous thunderstorm echoes, which can overlay operationally significant Doppler wind signatures at close range, and challenges associated with aliased Doppler velocity. A second major data quality assurance challenge is the extraction of low-altitude Doppler velocity estimates in the presence of strong ground clutter, particularly that associated with moving automobile traffic.

In 2002, the FAA asked Lincoln Laboratory to develop a modern replacement for the TDWR's Radar Data Acquisition (RDA) subsystem. The RDA is responsible for transmitter and antenna control, signal reception, and signal processing. Its outputs are range-azimuth-elevation fields of precipitation reflectivity, mean Doppler velocity, and Doppler spectrum width (so-called base data). These base data are processed by the TDWR's internal wind-shear detection algorithms as well as the external systems mentioned in the preceding section. A team led by Gabriel Elkin and Nathan Parker in the Weather Sensing group at the Laboratory has developed a contemporary, open RDA subsystem that will support substantially more effective algorithms for the generation of high-quality base data. Of particular note is the capability to adapt transmitted waveforms and processing algorithms on a radial-by-radial basis to the characteristics of the weather and clutter environment.

Figure 1 depicts the Laboratory-developed RDA replacement system. A Quad Intel Xeon processor performs both signal processing and system control

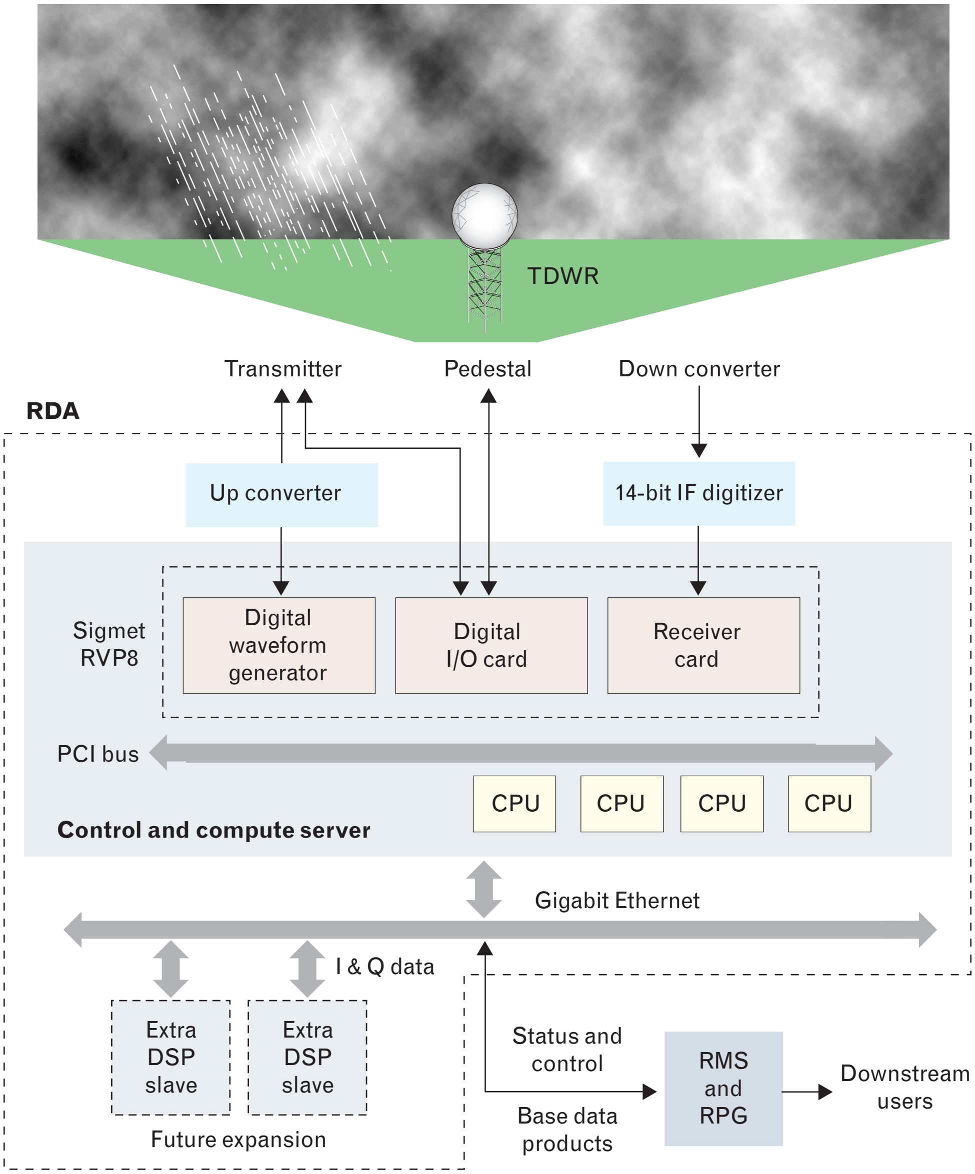


FIGURE 1. Hardware and software architecture of Terminal Doppler Weather Radar (TDWR) radar data acquisition (RDA) subsystem replacement. A commercial off-the-shelf computer with four Intel Xeon processors performs both signal processing and system control functions. The SIGMET RVP8—three PCI cards utilizing field programmable gate array chips—provides digital waveform generation, high-dynamic range digital intermediate frequency signal reception, and system timing. The RDA can be scaled to handle larger processing loads by adding additional processor nodes, interconnected using gigabit Ethernet.

functions. The processor operates under the Linux operating system. The commercially built SIGMET RVP8—three PCI cards, utilizing field programmable gate array chips—provides digital waveform generation, high-dynamic-range digital intermediate frequency signal reception, and system timing. As shown in the figure, the RDA can be scaled to handle larger processing loads by adding additional Linux processor nodes, interconnected using gigabit Ethernet. This capability will support ongoing enhancements to the TDWR's signal processing algorithms such as those discussed later in this section. A software standard called Message Passing Interface can distribute in-phase and quadrature (I&Q) signals to a cluster of digital signal processor slaves. These process the data in parallel and recombine their outputs prior to trans-

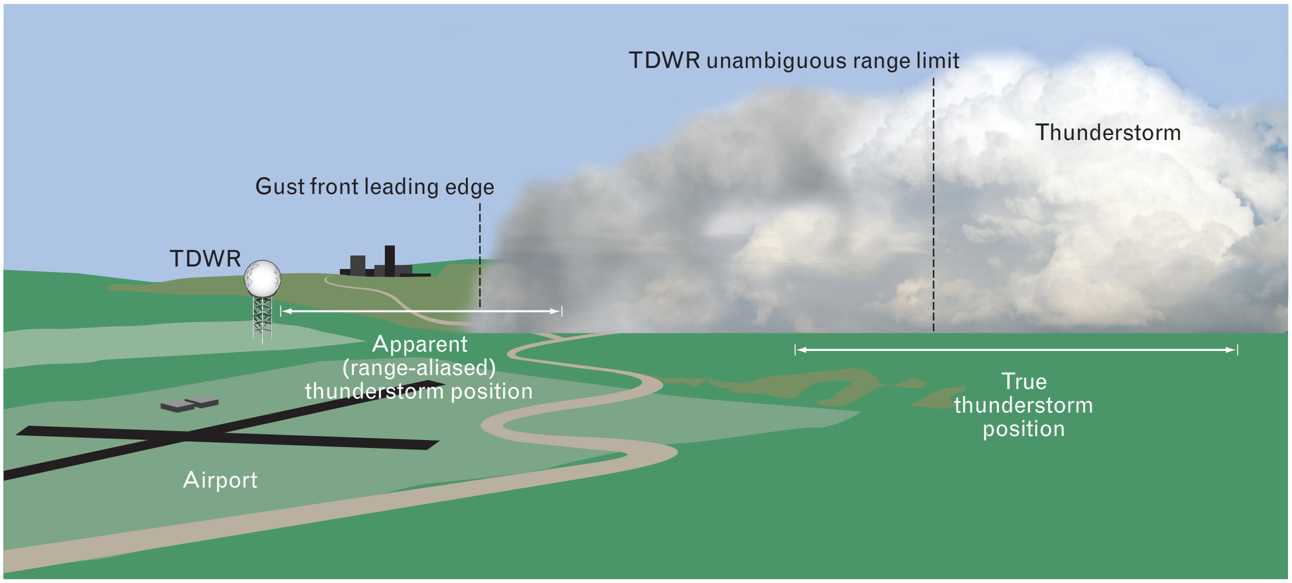


FIGURE 2. Illustration of TDWR range-overlay challenge. In this notional scenario, the outflow boundary, or gust front leading edge, from a thunderstorm complex has propagated well ahead of its parent thunderstorm. Because a portion of the parent storm is beyond the radar's unambiguous range limit, its echo from the preceding transmitted pulse is coincident with first-trip echoes from the gust front. The resulting range overlay interference may prevent detection of the gust front.

mitting the base data to downstream clients. All the software employs standards-based interfaces and is thus transportable essentially unchanged to enhanced commercial off-the-shelf (COTS) processors as these become available.

Range-Doppler Ambiguity Mitigation

Signals from thunderstorms at ranges greater than the unambiguous range—$cT/2$, where c is the speed of light and T is the pulse repetition interval (PRI)—may overlay lower-power Doppler wind signatures of operational significance near the TDWR. Figure 2 illustrates a frequent scenario in which the outflow boundary, or gust front, from a thunderstorm complex propagates 100 km or more ahead of some of the storm cells. As the front passes over a TDWR-protected airport it produces a sudden, potentially hazardous shift in wind speed and direction, turbulence, and a sustained change in wind direction that may require air traffic controllers to change the airport's runway usage configuration. In the illustrated scenario, however, the gust front is not detected because the overlaid signal power from distant thunderstorm cells significantly exceeds the echo strength of the gust front. The thunderstorm's radar reflectivity (cross section per unit volume) typically exceeds by 35 dB the reflectivity of the precipitation-free air through which the leading gust front propagates. Since echo strength for beam-filling precipitation decreases only as $1/\text{range}^2$, the distant thunderstorm echo is often substantially stronger than the close-in gust front return. Current TDWR processing utilizes range-unambiguous data from an occasional low pulse repetition frequency (PRF) scan to recognize the occurrence of this situation. However, because the system does not have waveforms and algorithms to suppress the interfering range-ambiguous echoes, data from affected range gates must simply be censored.

A related data-quality problem is Doppler velocity aliasing in areas of high wind speed. TDWR must be range-unambiguous over its 50 nmi instrumented range. The highest PRF available to the system is 1931 sec^{-1}, which results in an unambiguous Doppler interval of ±26 m/sec. Wind speeds in the atmosphere frequently exceed this limit. In order to ensure detection and accurate strength characterization of strong low-altitude wind-shear events, the TDWR must de-alias Doppler wind estimates. The current approach to de-aliasing utilizes a combination of signal processing, image continuity arguments, and constraints imposed by a continuously updated wind field model [11]. The method, however, has proven to be problematic in many scenarios, resulting in adjusted Doppler velocity estimates over large areas, which may be off by multiples of the Nyquist interval. The most frequent manifestation of de-aliasing errors is wind-shear false alarms caused by the artificial velocity discontinuities that result.

The enhanced RDA will exploit substantially more complex waveforms and signal processing approaches developed by John Cho in the Weather Sensing group to mitigate the impacts of range- and Doppler-ambiguous weather returns. Two techniques are utilized: multi-PRI and pseudo-random pulse phase coding. With the multi-PRI waveform, the radar coherent processing interval is divided into a sequence of pulse batches at different PRIs. A typical multi-PRI coherent processing interval would consist of 64 total pulses, subdivided into eight batches of eight pulses. Within each batch, the PRI is constant but the PRIs of the different batches might range from 600 μsec to 936 μsec. Range-ambiguous thunderstorm echoes from the different pulse batches fold onto different sets of range gates in the operationally important 'first trip,' that is, the range interval from 0 to $cT/2$. Reflectivity and Doppler velocity estimates are formed by using the auto-covariance, or 'pulse-pair' algorithm [12] applied to those pulse batches that are free of range overlays. Thus interference-free weather parameter estimates can be generated as long as some of the different PRI pulse batches are 'clean.' Velocity de-aliasing is accomplished with this waveform by determining the true velocity that is consistent with the aliased velocity estimates from the different PRI pulse batches. The unfolded-velocity cluster method [13], applied to all PRI batches that are free of range overlays, is used to determine the true wind velocity.

A second approach to range-overlay protection is to apply a pseudo-random variation to the initial phase of pulses transmitted within a coherent processing interval. As Figure 3 illustrates, returns from any unambiguous range interval—or 'trip'—can be selectively cohered by appropriately shifting the pattern of the complex weights applied to the echo time samples. Signals returned from trips other than the one selected are whitened in Doppler space. The figure illustrates how this selective cohering technique can be used to suppress range-overlaid weather returns. This approach requires that the PRI within the coherent processing interval be constant so that the requisite forward- and inverse-Fourier transforms can be computed. To accomplish Doppler velocity de-aliasing, the PRI is varied on alternate radials and the cluster method referenced above is applied.

The multi-PRI and phase code techniques have complementary strengths and weaknesses, as described by Cho et al. [14]. Multi-PRI signals provide robust overlay protection as long as the distant weather does not span such a large range interval that none of the different pulse batches are free from overlays. For the range of PRIs available in the TDWR system, this restriction corresponds to a range-extent limit for the distant

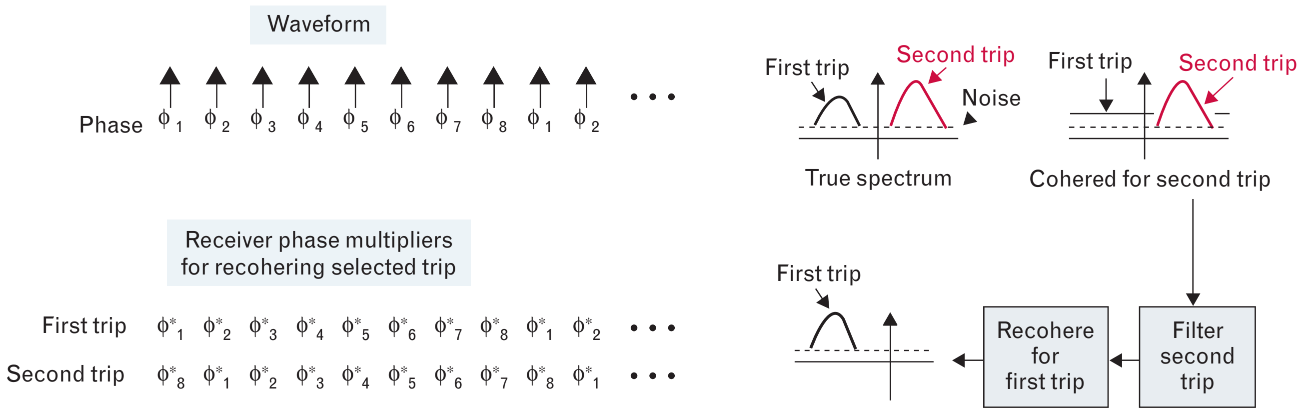


FIGURE 3. Illustration of pulse phase code processing. The transmitted signal waveform and receive sample complex weights required to recohere first-trip or second-trip returns are illustrated on the left. The overlay suppression algorithm is sketched on the right, as applied to a range gate where a strong, second-trip return overlays a first-trip echo.

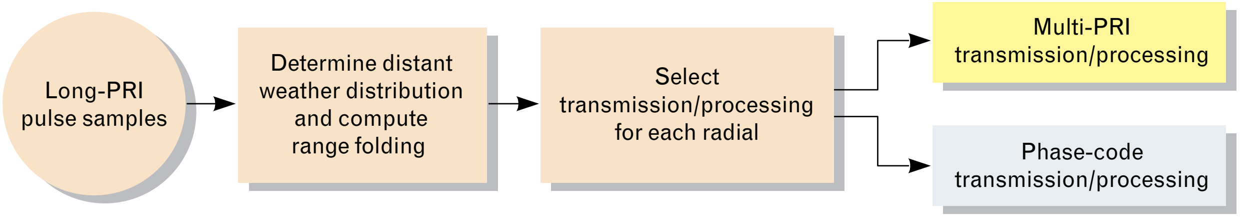


FIGURE 4. Adaptive waveform selection algorithm that uses data from a range-unambiguous low PRF tilt to select the processing approach for subsequent high-PRF scans.

weather of approximately 60 km. The phase-code technique is not affected by the radial extent of the range-overlaid weather echoes, but breaks down in cases of strong and/or spectrally wide overlays.

By adaptively selecting the waveform to be transmitted and processed on each radial, the complementary characteristics of these two techniques can be exploited. At the beginning of each volume scan, a range-unambiguous, low-PRF (326 Hz) scan is transmitted to determine the distribution of weather power with range along each radial. For subsequent high-PRF Doppler scans, a score is determined for each radial and is used to select the best performing waveform for that radial, as illustrated in Figure 4. A set of multi-PRI waveforms is available to optimize performance for this waveform class. Interrupt-driven software and field programmable gate array code allow the enhanced RDA to change waveforms on a radial-by-radial basis as required.

The Lincoln Laboratory RDA prototype is being developed and tested on two non-operational TDWRs at the FAA's Monroney Aeronautical Center in Oklahoma City, Oklahoma. In-phase and quadrature (I&Q) signals recorded with the test systems allow us to intercompare the legacy algorithms and the enhanced algorithms described above. A typical data collection for this purpose involves multiple near-horizon (0.3°) elevation tilts—where range overlays are most problematic—while cycling through each of the pulse transmission options available to the adaptive algorithm.

Data collected on 14 May 2005 illustrate the data quality improvements realized by using the data-adaptive algorithms. The left-side image in Figure 5—plan position indicator reflectivity and radial velocity images processed with the legacy algorithms—depicts a thunderstorm gust front south of the radar. Strong range overlays from distant thunderstorms obscure major portions of this front. It is unlikely that the TDWR's automated gust front detection algorithm would have detected the front under these circumstances.

The right-side image in Figure 5 shows the same data processed with the adaptive algorithm. In this case, the waveform selection algorithm chose to process most of the radials by using the phase-coded waveform because the out-of-trip weather patches were generally extensive in the along-radial direction. First-trip data obscuration from the range-overlaid weather is significantly reduced by using the enhanced algorithms. The resulting reflectivity and Doppler velocity images are of sufficient quality to permit automated detection of the gust front.

Figure 6 shows examples of velocity de-aliasing. Except in regions of very low signal return, the velocity de-aliasing performance is robust.

Implementation Status

Lincoln Laboratory staff worked with FAA engineers at the Monroney Center to finalize the configuration of the RDA replacement and to install it in the two national support TDWRs in their facility. The Lincoln Laboratory–FAA team is currently conducting a multi-month evaluation and test program covering the system's hardware, processing functions, built-in test and fault diagnosis functions, and maintenance procedures. This evaluation will ensure that all legacy system requirements are maintained with the new RDA in place. This team is developing the system, software, and algorithm documentation packages needed for long-term government support.

At the completion of this acceptance testing at the Monroney Center, the RDA engineering prototype will be deployed on an operational TDWR to demonstrate system performance and maintainability in an operational environment. We anticipate that this

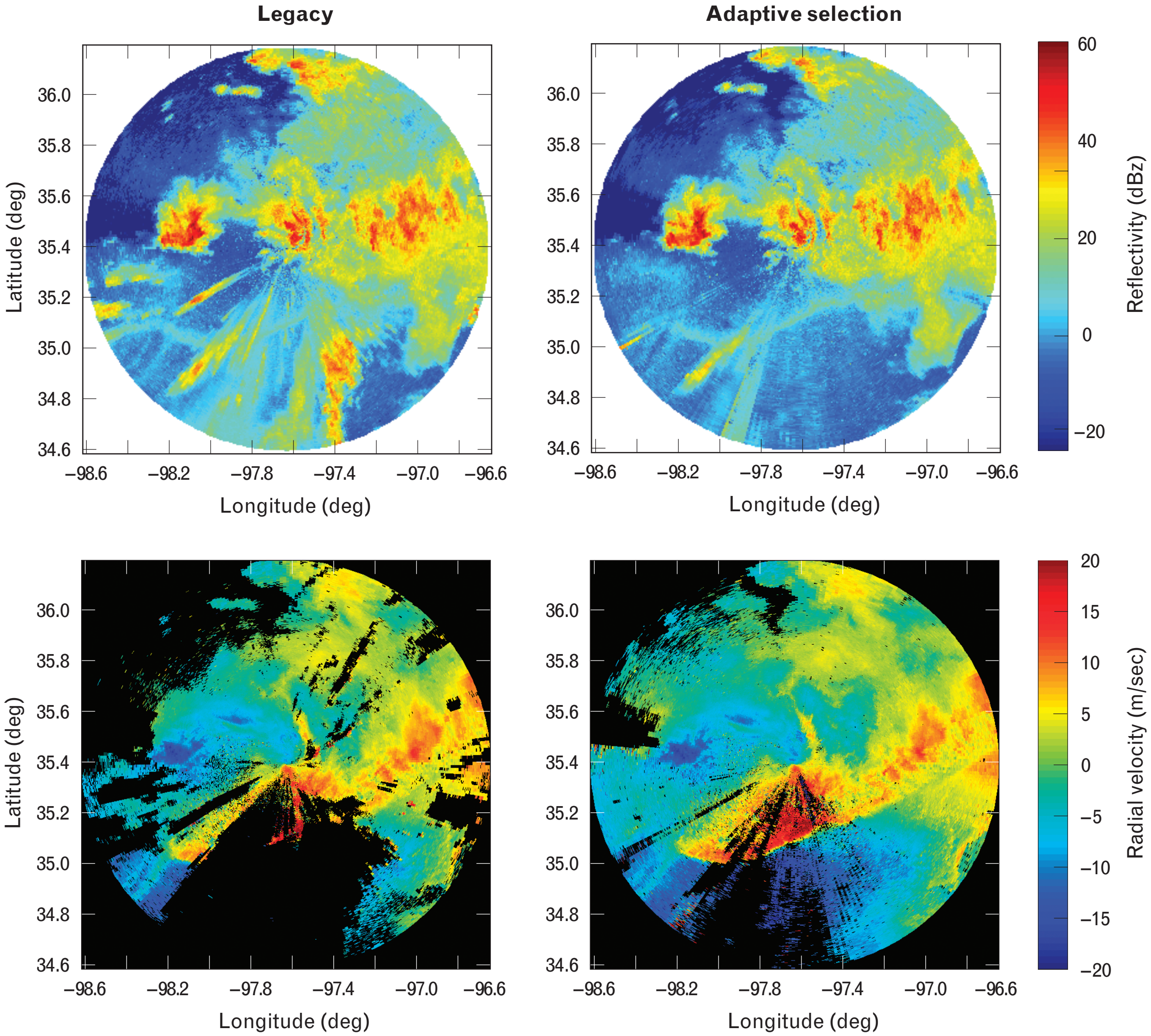


FIGURE 5. Reflectivity images (upper) and radial velocity images (lower) of a strong gust-front passage, measured with the FAA Monroney City TDWR in Oklahoma City. The left-side images were generated by using the legacy TDWR processing algorithms that censor data (black areas in the radial velocity image) when distant thunderstorm overlays are –5 dB or greater relative to the first-trip signal. The right-side images were generated by using the adaptive selection algorithm. First-trip data obscuration from the range-overlaid weather is significantly reduced with this algorithm. Censoring criteria for the algorithm are described elsewhere by J.Y.N. Cho [14].

demonstration will take place in Salt Lake City, Utah, so that I&Q data can be collected to facilitate development of additional processing enhancements addressing the challenging environment at this site. Salt Lake City is representative of several western U.S. TDWR sites (e.g., Denver, Las Vegas, Phoenix) where improved capabilities for measuring radar signatures associated with very low cross-section, dry wind-shear phenomena in the presence of strong ground clutter are needed. The sidebar entitled "Low Reflectivity Wind Shear" provides additional information on this topic. These challenges have prevented the legacy TDWR system from meeting its performance requirements at those sites, and have resulted in associated user dissatisfaction. The RDA prototype will be deployed to Salt Lake City in the summer of 2006, and the test program is anticipated to last for two years.

The FAA has programmed funding to deploy the

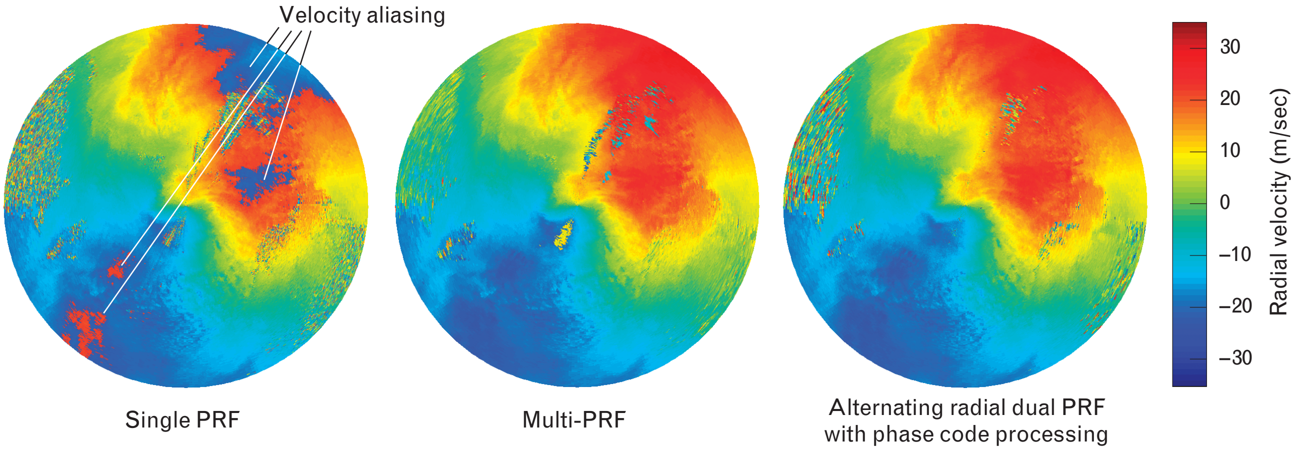


FIGURE 6. Velocity images illustrating the de-aliasing performance of the enhanced RDA algorithms. Velocity estimates using the legacy system single PRF waveforms (left) must be de-aliased by using image continuity-based post-processing algorithms that have proven to be problematic. The middle and right images show de-aliased velocity fields generated by using the two waveform classes employed in the enhanced RDA. Data are from the Monroney Center TDWR.

RDA replacement nationally during the period 2007 through 2009. The components of the Laboratory-developed prototype system will be procured by the U.S. Government (with COTS technology refreshes where appropriate), then integrated and installed at all sites by the FAA engineers from the Monroney Center. In parallel, Lincoln Laboratory staff will continue to develop and transition processing enhancements that address operational needs at fielded TDWR sites. As noted, improved ground-clutter suppression and low-reflectivity wind-shear signature retrieval algorithms are expected to be fielded as a second major enhancement following the range-Doppler ambiguity mitigation improvements. Additional algorithm builds will be delivered as needed.

NEXRAD Algorithm Enhancements

The triagency (NWS, FAA, and DoD) NEXRAD Program Management Council has implemented an ongoing improvement program to ensure that NEXRAD hardware, processors, and scientific algorithms remain current. Figure 7 shows a timeline for major NEXRAD system hardware and processor upgrades. Each upgrade enables significant functional enhancements through the insertion of new or more capable data processing algorithms. The first major upgrade was the Open Radar Product Generator (ORPG), the NEXRAD subsystem that processes radial-format reflectivity, mean Doppler velocity, and Doppler spectrum width base data to generate meteo-

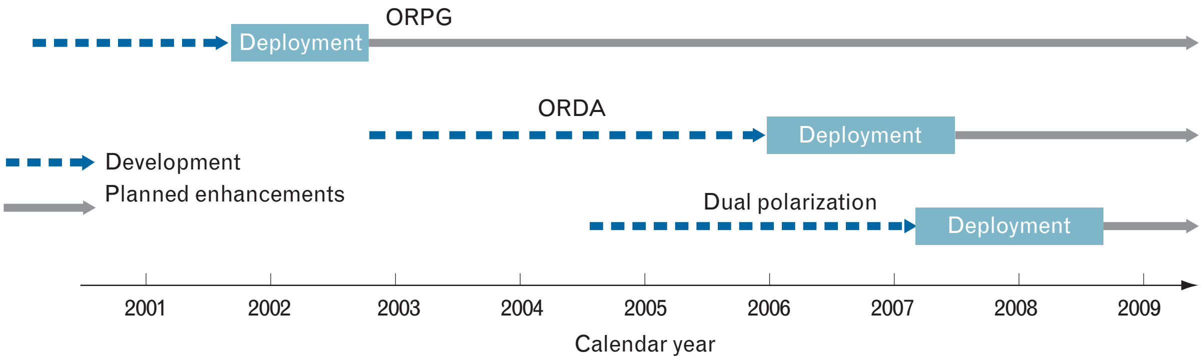


FIGURE 7. Timeline for NEXRAD processor upgrades and hardware enhancements. The Open Radar Product Generator (ORPG) is already deployed, the Open Radar Data Acquisition (ORDA) subsystem is in the process of being deployed, and the dual polarization upgrade is in development and on target for deployment in 2007.

LOW REFLECTIVITY WIND SHEAR

The radar cross section per unit volume for meteorological targets is specified by the reflectivity factor *Z*. Rayleigh scatterers (e.g., raindrops) contribute to the reflectivity factor in proportion to their number density and to their diameter raised to the sixth power. Reflectivity factors for meteorological targets vary from –40 dBz for non-precipitating clouds to in excess of 70 dBz in severe storms containing large hail. The minimum detectable signal (MDS) of the Terminal Doppler Weather Radar (TDWR) is –26 dBz at a range of 10 km. For pulse-volume filling atmospheric targets, this limit increases with range as R^2 (6 dB per octave).

At most TDWR-equipped airports, the wind-shear phenomena the system is designed to detect occur in association with reflectivity factors well above the MDS. However, at four western U.S. airports—Denver, Salt Lake City, Las Vegas, and Phoenix—operationally significant wind shear may be associated with very low radar cross section. Two factors contribute to this circumstance.

First, the precipitation that forces the downdrafts and surface outflows responsible for low-altitude wind shear may completely evaporate as it falls through the warm, dry boundary-layer characteristic of the western United States during summer months.

Second, the background reflectivity of precipitation-free air in the high plains and mountain states is significantly lower than the summertime background reflectivity in the eastern and central United States. This is due to the lower density of biological targets such as insects and in some cases the soaring birds that feed on the insects. Figure A plots representative daily variations in near-surface clear-air reflectivity measured using the TDWRs at Dallas/Fort Worth, Newark, and Las Vegas. The pronounced diurnal varia-

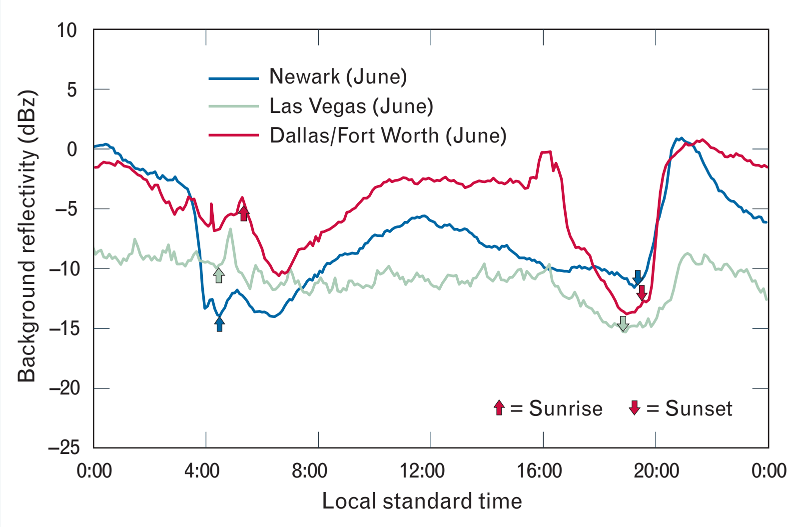
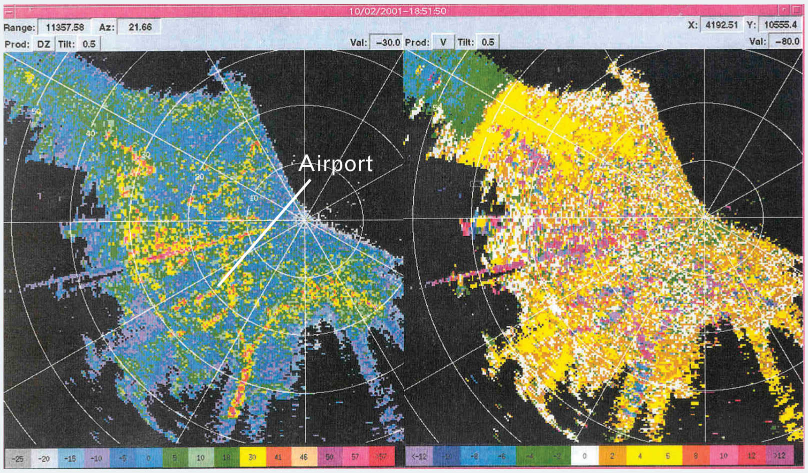


FIGURE A. Representative daily cycles of the low-altitude clear-air reflectivity factor, measured with TDWRs at Dallas/Fort Worth, Newark, and Las Vegas.

rological products and disseminate these to NEXRAD operational users. The Open Radar Data Acquisition (ORDA) subsystem is analogous to the enhanced TDWR RDA described above and will support corresponding improvements to the base data it feeds to ORPG. The dual-polarization upgrade will insert microwave components and a second receiving chain to support simultaneous transmission and reception of horizontally and vertically polarized signals. Radar meteorologists have shown that polarimetric measurements can significantly improve quantitative rainfall estimates, discriminate between different hydrometer types (rain, snow hail, and graupel), identify non-meteorological biological targets (birds and insects), and augment Doppler-filtering-based clutter suppression techniques [15].



Reflectivity

Velocity

FIGURE B. Low-elevation-angle plan-position indicator data taken in precipitation-free conditions from the TDWR at Las Vegas. The strong linear returns exhibiting large non-zero Doppler velocities are from automobile traffic.

tion at Newark and Dallas/Fort Worth reflects the activity levels and vertical mixing of the biological targets. Note that background reflectivity at Las Vegas remains below –10 dBz throughout most of the day.

Given the intrinsically low reflectivity of some wind-shear events in these environments, challenges associated with ground-clutter suppression are also exacerbated. As an example, Figure B is a plan position indicator reflectivity image, recorded during clear conditions with the Las Vegas TDWR. The radar at Las Vegas is sited on elevated terrain east of the airport and as a result is subject to strong returns from automobile traffic on roadways surrounding the airport. These returns exceed the background atmospheric reflectivity factor, and often fall outside the stop band of the TDWR's high-pass Doppler clutter suppression filters.

Techniques to be assessed to improve TDWR performance at the 'dry' western sites include:

(1) Range oversampling and signal whitening [1] to reduce signal parameter estimate variance at low signal-to-noise ratios.

(2) Estimation of near-surface water-vapor content using the 'refractivity from clutter' technique [2] that does not rely on backscatter from atmospheric targets. The leading edge of thunderstorm outflows (i.e., the gust front) should be marked by a pronounced water-vapor gradient. Examples of this signature are shown elsewhere [3].

(3) Comparison of signal Doppler spectra on and immediately adjacent to roadways to recognize and suppress spectral components resulting from automobile traffic. This capability will reduce or eliminate the need for 'road editing' maps currently used to censor data over roadways, as illustrated in Figure C.

In addition to enhancing the performance of TDWR, the Laboratory is working with the FAA to assess complementary sensing technologies. One promising approach is the use of a commercially manufactured pulsed, infrared Doppler lidar that could be sited on airport property. The lidar detects returns from atmospheric aerosols, and normally has high signal-to-noise in the conditions associated with 'dry' wind shear. In addition, the lidar's very nar-

In the remainder of this section, we focus on the Laboratory's exploitation of ORPG to implement NEXRAD algorithm enhancements that significantly improve the product quality of FAA systems that use NEXRAD data. We anticipate that in the future Laboratory engineers will interact with the multi-agency NEXRAD enhancement community to develop application algorithms that exploit ORDA and the dual-polarization upgrade to improve aviation weather systems performance.

Open Radar Product Generator Technology Insertion Approach

The ORPG—a COTS scientific workstation resident on each NWS Weather Forecast Office local area network—provides data input/output and meteorologirow beam essentially eliminates interference from ground targets.

The Laboratory analyzed data collected by this sensor in 2003 during wind-shear events in Denver [4], and showed that the lidar measurements complement those from Doppler weather radar. Lidar measurements of thunderstorm outflows without precipitation typically exhibited substantially higher data quality than coincident measurements with the Denver TDWR or NEXRAD radars. Although wind shear occurring in precipitation was problematic for the lidar because of high signal attenuation, these events are well measured by the microwave radar systems.

The Laboratory assisted the FAA in collection of lidar and TDWR data in Las Vegas during a three-week period in the summer of 2005. As an example of data collected, Figure C [5] compares TDWR and lidar measurements of a gust front approaching the airfield (the two sensors are not collocated). The FAA analysis of the Las Vegas data concludes that, if integrated, the complementary sensing characteristics of the TDWR and pulsed Doppler lidar would provide wind-shear detection performance that fully meets requirements even in this very challenging environment. The FAA's technology planning organization is currently evaluating the technical and economic merits of pulsed Doppler lidar as an adjunct to Doppler radar at select U.S. airports.

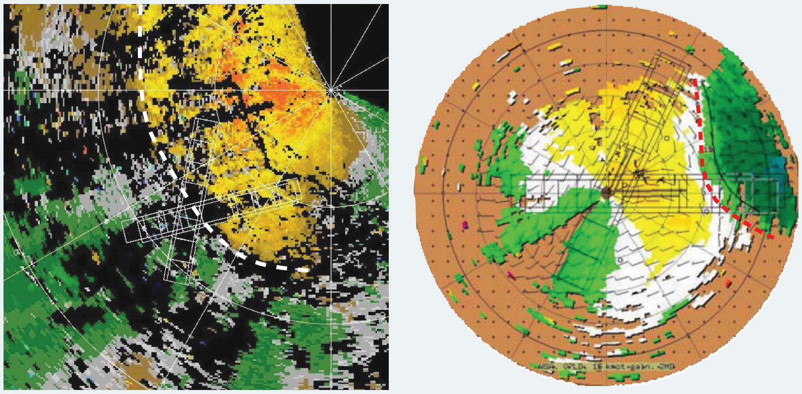


FIGURE C. Near-coincident radial velocity images of a gust-front passage at Las Vegas on 30 July 2005, as measured with the airport's TDWR (left) and a 2 μm pulsed Doppler lidar (right). TDWR radial velocity censoring (shown in black) is due to clutter and automobile returns, and it contributed to a missed gust front (white dashed line). The lidar (right) detects the gust front (red dashed line) approaching the airport from the east. Green indicates wind toward the radar or lidar, while yellow indicates wind away from the radar or lidar.

References

1. S.M. Torres, C.D. Curtis, and J.R. Cruz, "Pseudowhitening of Weather Radar Signals to Improve Spectral Moment and Polarimetric Variable Estimates at Low Signal-to-Noise Ratios," *IEEE Trans. Geosci. Remote Sens.* **42** (5), 2004, pp. 941–949.
2. E. Fabry, "Meteorological Value of Ground Target Measurements by Radar," *J. Atmos. Oceanic. Technol.* **21** (4), 2004, pp. 560–573.
3. T.M. Weckwerth, C.R. Pettet, F. Fabry, S. Park, M.A. LeMone, and J.W. Wilson, "Radar Refractivity Retrieval: Validation and Application to Short-term Forecasting," *J. Appl. Meteor.* **44** (3), 2005, pp. 285–300.
4. G. Perras, "A Comparison of Coherent Technologies, Inc. Wind Tracer Pulsed Lidar Data to NEXRAD and Terminal Doppler Weather Radar at the Denver International Airport," Lincoln Laboratory Project Memorandum 43PM Wx-0102 (13 Apr. 2005).
5. C. Keohan, K. Barr, and S.M. Hannon, "Evaluation of Pulsed Lidar Wind Hazard Detection at Las Vegas International Airport," *12th Conf. on Aviation, Range and Aerospace Meteorology, Atlanta, Ga., 29 Jan.–2 Feb. 2006,* http://ams.confex.com/ams/pdf papers/105481.pdf.

cal processing for the associated NEXRAD. ORPG is currently implemented on a Sun Ultra 10 workstation; in 2007 it will be rehosted on a significantly faster PC-Linux computer to accommodate ever-increasing processing demands. ORPG utilizes a Common Operations Development Environment (CODE) to facilitate rapid algorithm technology insertion. CODE insulates ORPG algorithm developers from low-level data input/output details, system timing constraints, and system resource allocation issues so that externally developed scientific algorithms can be inserted by using a plug-and-play paradigm.

Under FAA sponsorship, a Laboratory team led by Dave Smalley and Betty Bennett has been the first NEXRAD algorithm development group to extensively exploit the CODE paradigm. Laboratory staff interacted with the NWS organization that developed CODE to fully understand how to utilize it. We worked with the NEXRAD Radar Operations Center—the radar network's second-level engineering support organization—to establish a technology transfer process involving algorithm description, software documentation, and system compatibility testing. Finally, we have interacted regularly with the NEXRAD oversight organizations—the Technical Advisory Committee responsible for algorithm scientific oversight and the System Resource Evaluation Committee responsible for maintaining the overall integrity of NEXRAD processing resources—to coordinate the insertion of Lincoln Laboratory–developed software and algorithms.

An important infrastructure for enhanced algorithm development and validation is a network of ORPG workstations that we have connected to data feeds from nine operational NEXRADs. Input base data from these radars are obtained in real time over Internet, Internet-2, and leased networks operated in conjunction with other Lincoln Laboratory aviation weather programs. The developmental ORPG network allows us to process these data in real time with the enhanced algorithms developed by the Laboratory. By continuously monitoring their output over extended periods of time, and at environmentally diverse locations, we are able to validate that the new algorithm implementations are robust and identify residual product-quality issues that may occur only infrequently.

ORPG Algorithm Enhancements

Using this technology transfer process, we have successfully implemented four major ORPG algorithm enhancements and are completing development of a fifth. These are listed in Table 1, which also indicates the FAA aviation weather systems that take advantage of the improved products.

NEXRAD layer-average or layer-maximum composite reflectivity products are two-dimensional representations of the measured precipitation field, generated either by averaging the radar reflectivity values at each range-azimuth cell over multiple elevation angle tilts, or by choosing the maximum reflectivity across the set of tilts. The FAA's Weather and Radar Processor (WARP) mosaics composite reflectivity products from multiple NEXRADs and displays resulting storm location/intensity information to en route controllers on their radar scopes. In terminal airspace, the Integrated Terminal Weather System (ITWS) displays NEXRAD composite reflectivity products in its long-range storm location/movement windows. Ground-clutter breakthrough, particularly during super-refractive or anomalous propagation conditions, has been a significant data-quality issue in the FAA's operational usage of NEXRAD composite reflectivity products. The intensity and spatial extent of the clutter breakthrough have frequently been sufficient to present significant false storm indications on the operational displays, thereby reducing user confidence in the validity of the weather presentation from WARP and ITWS.

After providing an initial patch to the clutter editing logic in the legacy composite reflectivity product, Lincoln Laboratory developed a significantly more robust two-dimensional representation of storm intensity—the high-resolution vertically integrated liquid water (VIL) product. Inter-tilt reflectivity interpolation is first applied to fill data gaps; reflectivity is then converted to equivalent liquid water density and integrated over each range-azimuth vertical column to generate the VIL field. A data quality-assurance module was developed to precondition the base data input to the high-resolution VIL algorithm. This module exploits signal discriminants in the spatial, spectral, and elevation angle domains to differentiate between ground-clutter breakthrough and meteorological echoes [16]. In addition, it detects and censors constant-power interference introduced by the occasional inappropriate injection of calibration signals into operational data streams by NEXRAD maintenance personnel, and strobes when the antenna scans past the sun.

The high-resolution VIL product has been shown to convey the operational impact of storms much more reliably than legacy NEXRAD composite reflectivity products [17]. Both the FAA WARP and ITWS systems will transition their NEXRAD input to this product in the future. Figure 8 compares the legacy composite-maximum reflectivity product to the high-resolution VIL product.

A corresponding high-resolution radar echo tops product developed by the Laboratory is also now fielded in the national NEXRAD network. This algorithm

Table 1. NEXRAD Algorithm Enhancements and the FAA Weather Processing Systems That Take Advantage of Them

	Clutter-edited composite reflectivity	*Data quality assurance*	*High-resolution vertically integrated liquid water (VIL)*	*High-resolution enhanced echo tops*	*Machine-intelligent gust-front algorithm*
Weather and Radar Processor (WARP)	Product in use	Planned use	Planned use	Planned use	
Integrated Terminal Weather System (ITWS)	Product in use	Planned use	Planned use	Planned use	Potential use
Medium-Intensity Airport Weather System (MIAWS)		Product in use	Product in use	Product in use	Potential use
ASR-9 Weather Systems Processor (WSP)					Potential use
Corridor Integrated Weather System (CIWS)		Product in use	Product in use	Product in use	Potential use

remedies resolution deficiencies and biases present in the legacy NEXRAD echo tops product [16]. Operational experience with this product's application in the CIWS [7] shows that it reliably indicates whether thunderstorms block high-altitude jet routes, or conversely, whether planes can fly over precipitations cells that might appear impenetrable on the basis of a two-dimensional composite reflectivity or VIL product.

Finally, the Laboratory-developed Machine Intelligent Gust Front Algorithm (MIGFA)—developed originally for the FAA's ASR-9 WSP and TDWR wind-shear detection systems [18]—has been modified to operate with NEXRAD signal parameters and will be inserted into the ORPG. The resulting automated detections of thunderstorm-generated gust fronts will allow FAA and DoD air traffic control personnel to

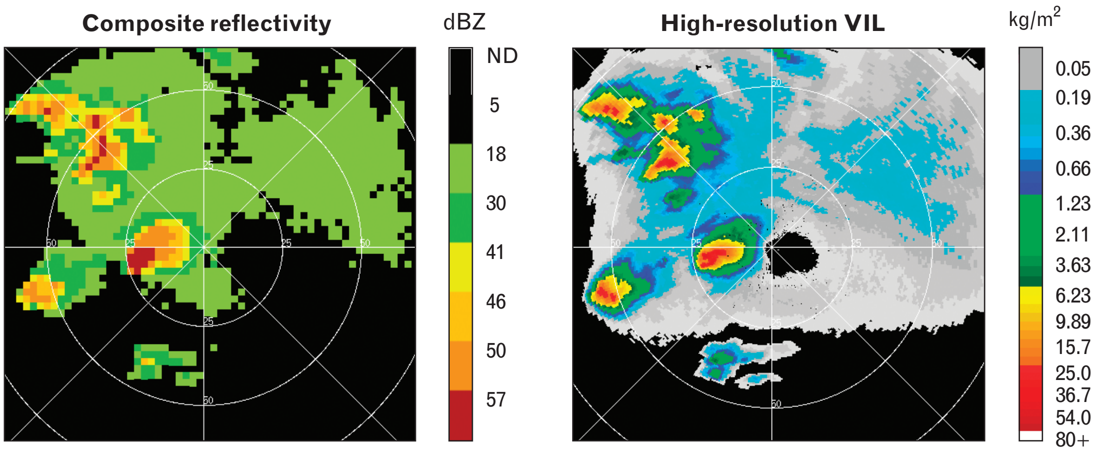

Composite reflectivity **High-resolution VIL**

FIGURE 8. Comparison of the high-resolution vertically integrated liquid water (VIL) product (right) versus a legacy composite reflectivity product (left). The VIL product provides higher spatial resolution and is not as susceptible to single-tilt artifacts such as ground clutter or bright bands at the melting level. Data are from the Norman, Oklahoma, NEXRAD during a severe weather outbreak on 3 May 1999.

anticipate gust-front impacts at smaller airports and military airfields not equipped with the dedicated wind-shear detection systems.

MIGFA will also provide important input to automated thunderstorm forecasting algorithms [19] by detecting and tracking the surface convergence boundaries that are preferred zones for new thunderstorm development. Because of the complexity of this algorithm, and its computational resource requirements, MIGFA was selected by the NEXRAD Radar Operations Center as the test algorithm for its upgraded, Linux-PC based ORPG platform. Lincoln Laboratory engineers are working closely with the Radar Operations Center to quantify MIGFA's processor and memory usage on this platform, and to expose portability and operational stability issues.

Next-Generation Multifunction Radar Study

Current U.S. weather and aircraft surveillance radar networks vary in age from ten to more than forty years. Ongoing sustainment and upgrade programs can keep these networks operating in the near to mid term, but the responsible agencies (FAA, NWS, and DoD/DHS) recognize that large-scale replacement activities must begin during the next decade. In 2005, the FAA asked Lincoln Laboratory to evaluate the technology issues and cost trades associated with a replacement strategy involving multifunction radars utilizing active electronically scanned arrays.

Cost considerations are a key element of this study. The current operational ground radar network is composed of seven distinct radar systems with separate government program offices, engineering support organizations, and logistics lines. A single, national multifunction phased-array radar (MPAR) network could reduce life-cycle costs by consolidating these support functions. The total number of deployed radars could also be reduced, since the airspace coverages from today's radar networks overlap substantially.

Today, a total of 510 weather and primary aircraft surveillance radars operate in the CONUS. To quantify the potential reduction in radar numbers, Steve Maloney in the Weather Sensing group at Lincoln Laboratory developed a three-dimensional database that defines the current airspace coverage of these networks. High-resolution digital terrain elevation data were used to account for terrain effects. Karen Anderson and Jim Flavin in the Air Traffic Control Systems group developed an iterative siting procedure to delineate MPAR locations that duplicate current coverage. Figure 9 shows that 334 MPARs would provide near-seamless airspace coverage above 5000 feet AGL, replicating the national scale weather and aircraft coverage currently provided by the NEXRAD and ARSR networks. The figure also illustrates that these MPARs would provide low-altitude, airport-area weather and aircraft surveillance functions that are today provided by TDWR and ASR-9 or ASR-11 terminal radars. Approximately half of the MPARs are terminal-area gap fillers providing range-limited coverage underneath the radar horizon of the national-scale network. These would be smaller-aperture, lower-cost radars employing the same scalable technology as the full-sized MPAR [20].

MPAR Configuration

If the reduced numbers of MPARs required and their single architecture are to produce significant future cost savings, the acquisition costs of the active electronically scanned array radars must be at least comparable to the mechanically scanned radars they replace. To define the technical parameters of the required MPAR and estimate its costs, we developed a conceptual radar configuration and have commenced detailed design of prototype components that address its key technical challenges.

Figure 10 shows a high-level depiction of the conceptual MPAR architecture. Table 2 lists key parameters. The 2.7 to 2.9 GHz S-band allocation for the current NEXRAD and ASR networks provides a compromise between sensitivity requirements for meteorological targets (whose cross section increases with decreasing wavelength) and challenges associated with precipitation-induced signal attenuation, range-Doppler ambiguities, and precipitation clutter rejection for the aircraft surveillance function. All of these latter challenges are increasingly problematic at shorter wavelengths. In addition, an S-band active array can exploit the low-cost, COTS component base developed for the consumer wireless device market. Maintaining low costs for active electronically scanned arrays dictates the use of commercially available, low-

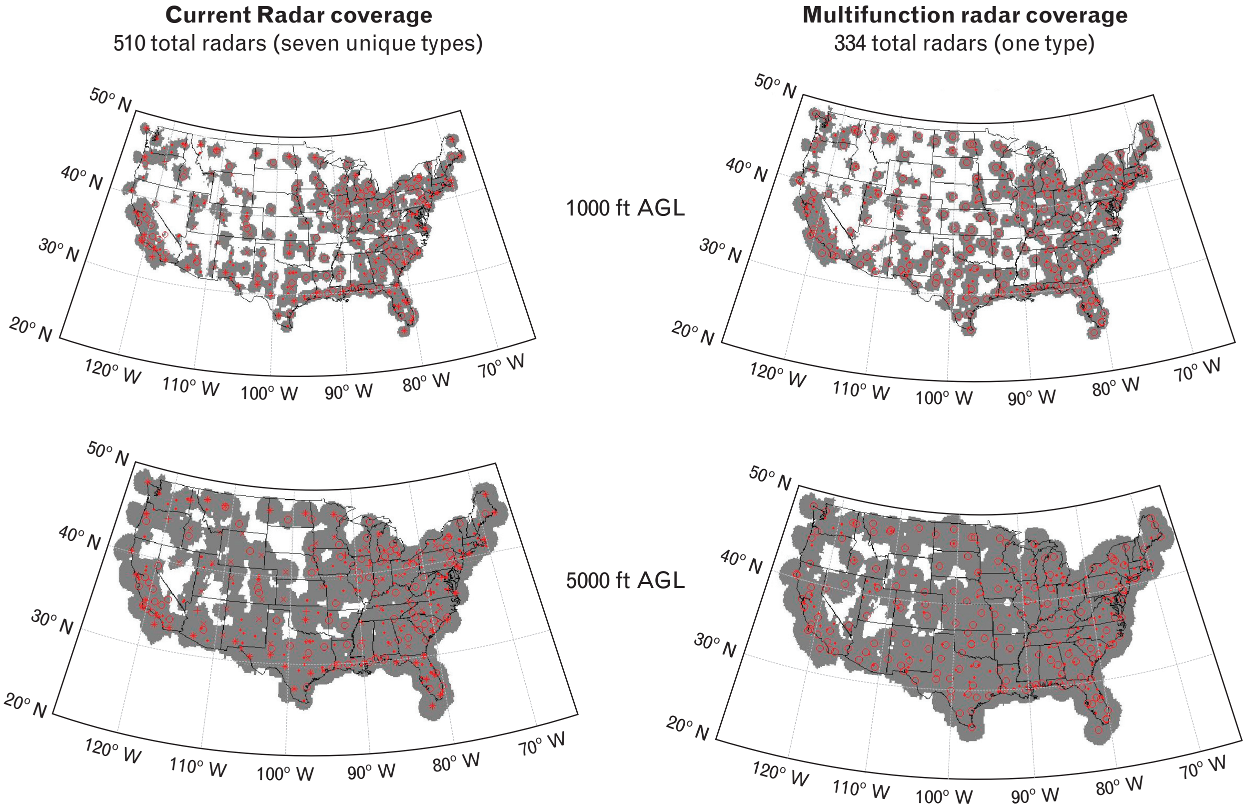


FIGURE 9. Airspace coverage comparisons between current U.S. operational radar networks (left), consisting of 510 radars of seven types (ASR-9, ASR-11, ARSR-1/2, ARSR-3, ARSR-4, NEXRAD, and TDWR), and the conceptual multifunction phased-array radar (MPAR) network (right), consisting of 334 radars of a single type. Coverage at 1000 feet and 5000 feet above ground level (AGL) is depicted for both networks.

peak-power transmit amplifiers (1 to 10 W). This in turn requires the use of long (up to 50 μsec) transmitted pulses to achieve necessary energy on target. Pulse compression to a 1 μsec equivalent pulse length provides the necessary range resolution (150 m).

A four-faced planar array is assumed, although the transmit/receive (TR) element count can most likely be reduced by using cylindrical or quasi-hemispherical array geometries. Angular resolution (1° or less) and power-on-target requirements are set by the weather surveillance function. This dictates an aperture size of eight meters and an associated TR-element count of 20,000 per face (80,000 total). Multifunction aircraft and weather surveillance capability is attained by allocating three 1 MHz sub-bands within the 2.7 to 2.9 GHz interval to the three requisite surveillance functions: (1) terminal area (0 to 60 nmi) aircraft surveillance; (2) long-range (0 to 250 nmi) aircraft surveillance; and (3) weather surveillance (0 to 250 nmi).

Signals are transmitted and received independently in each of these sub-bands. Channelized TR elements with independent phase shifters and attenuators for each sub-band, and a sub-array beamformer architecture [21], allow for the transmission of independently steered transmit beams for each sub-band and the digital formation of associated receive beam clusters.

This architecture supports efficient allocation of energy to the three surveillance functions, as depicted in Figure 11. For each function, the transmit beam is spoiled as appropriate to balance energy-on-target and volume-scan update requirements. For terminal-area aircraft surveillance, a 1° × 5° transmit beam provides more than adequate energy density while supporting the five-second volume-scan update rate required for tracking aircraft in this domain. For weather surveillance of low cross-section clear-air phenomena, maximum sensitivity must be maintained, dictating the transmission of full-resolution (1° × 1°) beams. Long-

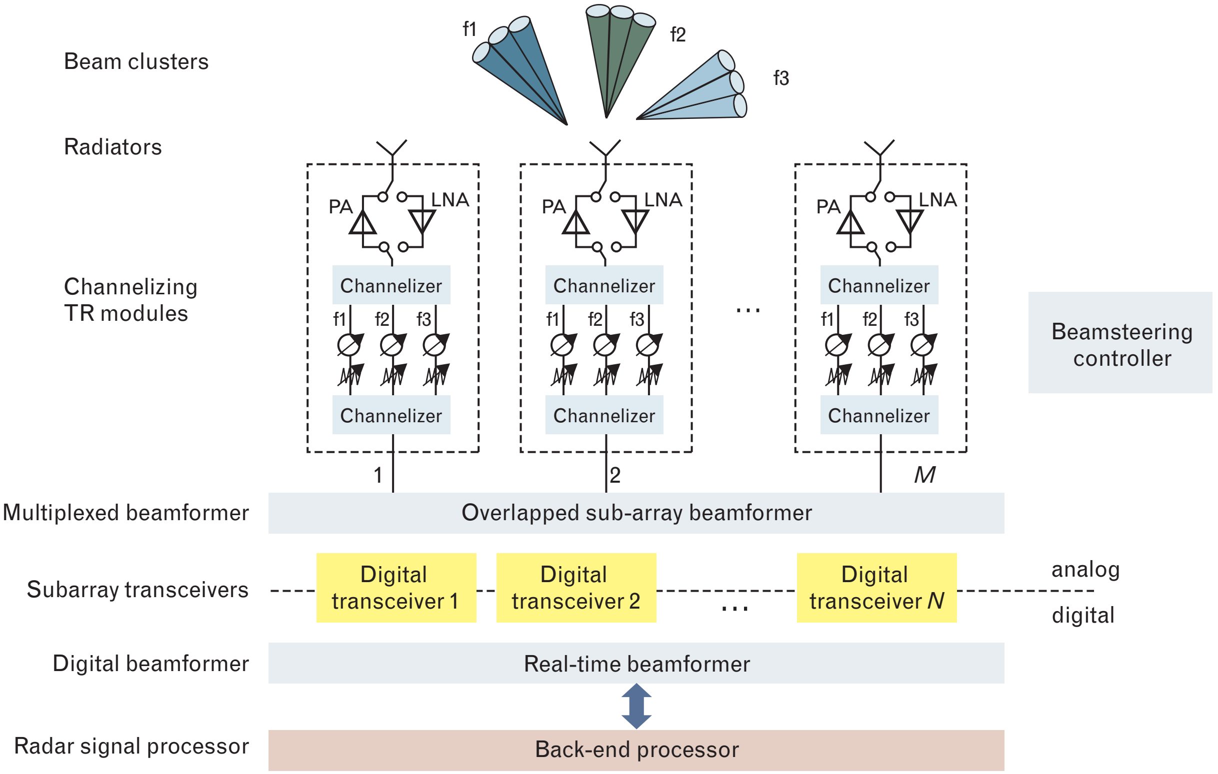


FIGURE 10. Conceptual MPAR architecture. Triple-mode transmit-receive modules and an overlapped sub-array beamformer support independently steered beamclusters for weather and aircraft surveillance functions. A high-capacity digital beamformer generates multiple, simultaneous receive beam channels for each surveillance mode, which are processed by aircraft and weather detection algorithms.

Table 2. Concept MPAR Parameters

Transmit/receive modules	Wavelength (frequency)	10 cm (2.7–2.9 GHz)
	Transmit/receive element peak power	1–10 W
	Bandwidth (per channel)	1 MHz
	Frequency channels	3
	Pulse length	1–50 μsec
Active array (four faced, planar)	Diameter	8 m
	Transmit/receive elements per face	20,000
	Beamwidth broadside	0.7°
	Beamwidth at 45° scan angle	1.0°
	Gain (at 45°)	46 dB
Architecture	Overlapped sub-array	
	Number of sub-arrays	400
	Number of concurrent beams	160

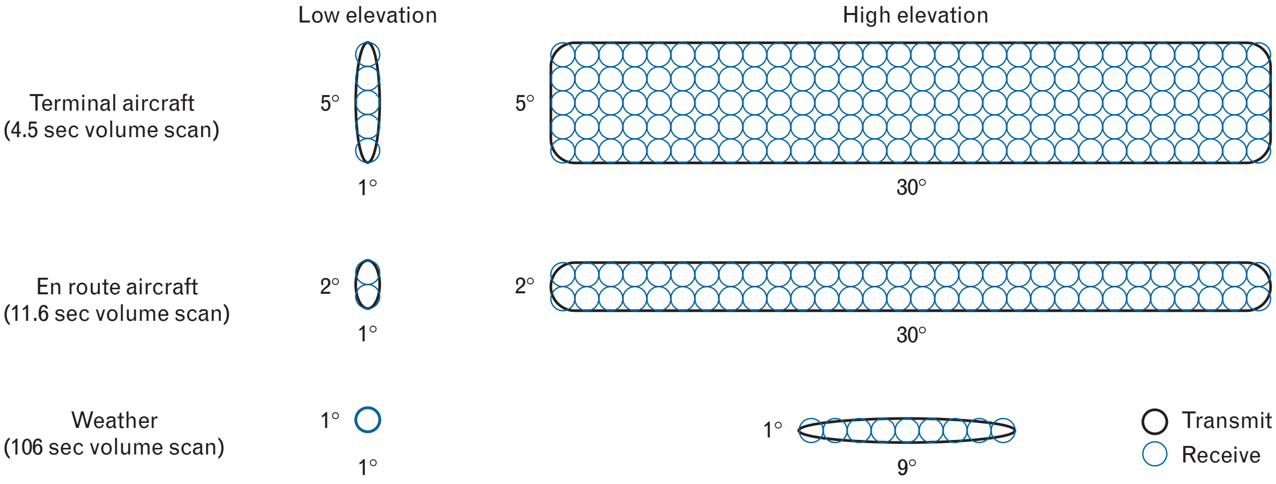


FIGURE 11. Conceptual transmit/receive beam patterns for the three MPAR functions for terminal and long-range aircraft and weather surveillance. The black ellipses represent transmit azimuth-elevation beam shapes for each function. Blue circles are the associated 1° × 1° pencil-beam receive clusters. As described in the text, reduced maximum range requirements at high elevation angles allow for significant increases in the number of concurrent receive beams. This in turn significantly reduces the volume scan period for each surveillance function.

range aircraft surveillance is an intermediate case. For each function, concurrent clusters of full-resolution (1° × 1°) receive beams spanning the angular extent of the transmit beam are formed by using the sub-array beamformer.

As elevation angle increases, the maximum range to altitude-limited weather and aircraft targets decreases as the cosecant of elevation angle. As indicated in Figure 11, the associated reduction in required radiated energy density is exploited by further spoiling the transmit beam pattern at high elevation angles. This significantly increases the volume-scan update rate.

These beam formation and scanning strategies allow MPAR to maintain (for aircraft surveillance) or significantly exceed (for weather surveillance) current volume-scan update rates. Equal or greater power on target would be realized with the defined system parameters. For aircraft surveillance, the capability to resolve target height by using the full-resolution receive beam clusters is significant. (Monopulse processing could provide angular resolution of approximately 0.05° for medium to high cross-section targets.) Target characterization would be substantially improved, and false tracks caused by automobile traffic, birds, and other low-altitude targets could be much more readily suppressed. For weather surveillance, data-quality improvements would be realized by using shaped beam patterns to suppress ground clutter, and by using data-adaptive dwells and scan patterns. Significant speed-ups in volume-scan update rate (from five minutes today to about one minute) would improve the estimation of acceleration terms assimilated into cloud-scale numerical weather prediction models. Improved data assimilation would in turn allow these models to more reliably forecast severe weather phenomena. Finally, by cross-correlating signals received separately on halves or quadrants of the active aperture, the cross-radial wind component can be estimated by using techniques described by R.J. Doviak et al. [22]. This parameter can likewise substantially improve the performance of cloud-scale numerical weather prediction models in providing operational hazardous weather forecasts.

MPAR Cost Model

Based on the conceptual MPAR configuration described above, a team led by Jeff Herd and Sean Duffy in the RF Systems Technology group has commenced detailed design of a scaled pre-prototype active electronically scanned array that incorporates the required technologies. This design work is providing technical and cost details that can be used to evaluate the viability of the MPAR concept.

The pre-prototype array will be 4.2 m in diameter,

Table 3. MPAR Component Cost Model*

Component	*Pre-prototype*	*Full-scale production*
Antenna element	$1.25	$1.25
Transmit/receive module	$20	$20
Power, timing, and control	$18	$18
Digital transceiver	$12.50	$6.25
Analog beamformer	$63	$15
Digital beamformer	$18	$16
Mechanical/packaging	$105	$25
RF interconnects	$163	$40

* per TR element

providing sufficient radiated power, antenna gain, and angular resolution (2.0° pencil) to demonstrate key weather and aircraft surveillance functions. The array will radiate and receive in two 1 MHz sub-bands, and will utilize a one-dimensional, sixteen-channel sub-array beamformer to digitally form a vertical cluster of eight receive beams for each sub-band. A brick module design is utilized with the major RF subsystems in a 6U Eurocard chassis behind the radiating elements. The dual-channel TR-element design incorporates low-cost COTS components and a Lincoln Laboratory–designed phase shifter to maintain the total parts cost at less than $20 per TR element. Key to maintaining low TR-element cost is the use of a modest peak power (1 to 10 W) COTS high-power amplifier. The sub-array beamformer will initially be implemented by using a multilayer printed circuit board design based on the Laboratory's X-band Space and Airborne Radar Transformational Array (SPARTA) program. We anticipate that current Laboratory efforts to develop an application-specific integrated circuit (ASIC)–based sub-array beamformer will significantly reduce the costs of this MPAR subsystem relative to the printed circuit board design.

The sub-array output receiver design is derived from the Lincoln Laboratory Digital Array Radar program [23], providing high performance at a modest cost. A scalable, high-performance digital beamformer preliminary design was developed by Michael Vai in the Digital Systems group. Workable implementation technologies include field programmable gate arrays, ASICs, multichip module, and mixed signal designs.

Table 3 summarizes MPAR component cost estimates based on this pre-prototype array design. The tabulated numbers are normalized to a per-TR-element basis. Cost reductions indicated in the full-scale production column result from either economies of scale or new technology development expected within the next three to five years. When scaled to the number of TR elements required for the full-scale MPAR, these component costs are consistent with an MPAR that is cost-competitive with current operational radar systems (about $11 million for the MPAR configuration described in the preceding section).

The favorable overall cost picture for MPAR, based on current technology prices, coupled with expectations that essential components derived from the mass-market wireless and digital processing industries, will continue to decrease in price, indicate that active-array, multifunction radar technology is a promising option for next-generation U.S. airspace weather and aircraft surveillance needs. We anticipate that the Laboratory will continue to work with the FAA, NOAA, and industry to refine, prototype, and test next-generation MPAR concepts.

Summary

Government-operated weather radar networks provide essential observations of weather phenomena that vitally affect aviation safety and airspace capacity. In addition, these networks provide wide-area, volumetric precipitation and wind-field measurements essential to the high-resolution diagnosis and forecast algorithms that will underpin future improvements in aviation weather decision support systems. As described in this article, Lincoln Laboratory is providing significant support to the Government in enhancing deployed TDWR and NEXRAD radars to provide more open, sustainable system architectures, higher-quality raw measurements, and user products that improve the capabilities of aviation weather processing systems. Our efforts include the design, implementation, and technology transfer of advanced weather radar processing architectures and the development of innovative data processing algorithms that exploit these high-throughput processors. Effective working relationships with industry and government partners have been essential in the successful implementation of these enhancements.

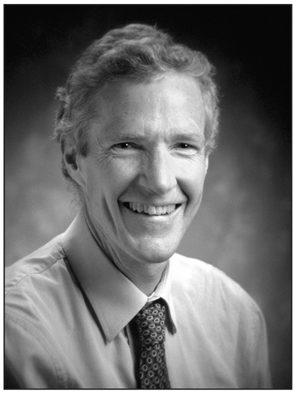
The Laboratory has provided important technical input to a multi-agency evaluation of a next-generation multifunction weather and aircraft surveillance radar concept based on active electronically scanned array technology. Our in-depth experience with weather radar, air traffic control surveillance systems, and advanced array technology has allowed us to develop radar configuration concepts, network requirements, and associated cost models that will be essential in evaluating the viability of this concept.

As described in related articles in this issue of the *Lincoln Laboratory Journal*, weather-related safety and capacity impacts to the nation's aviation system are a major concern today and will become increasingly problematic as airspace demand increases significantly in the coming decade. The Laboratory's multifaceted attack on this challenge commences with the efforts described in this article to provide cost-effective, maintainable radar observing systems that output high-quality raw data and associated 'nowcast' products to downstream forecast algorithms and user decision support systems.

REFERENCES

1. J.E. Evans and W.H. Drury, "Ground Clutter Cancellation in the Context of NEXRAD," *21st Conf. on Radar Meteorology, Edmonton, Alberta, Canada, 19–23 Sept. 1983,* pp. 158–162.
2. M. Labitt, "Coordinated Radar and Aircraft Observations of Turbulence," Lincoln Laboratory Project Report ATC-108 (20 May 1981).
3. J. Evans and D. Turnbull, "Development of an Automated Windshear Detection System Using Doppler Weather Radar," *Proc. IEEE* 77 (11), 1989, pp. 1661–1673.
4. M.E. Weber and M.L. Stone, "Low Altitude Wind Shear Detection Using Airport Surveillance Radars," *IEEE Aerosp. Electron. Syst. Mag.* **10** (6), 1995, pp. 3–9.
5. M.E. Weber, "Assessment of ASR-9 Weather Channel Performance: Analysis and Simulation," Lincoln Laboratory Project Report ATC-138 (31 July 1986).
6. J.E. Evans and E.R. Ducot, "The Integrated Terminal Weather System (ITWS)," *Linc. Lab. J.* 7 (2), 1994, pp. 449–474.
7. J.E. Evans and E.R. Ducot, "Corridor Integrated Weather System," in this issue.
8. J. Johnson, S. Walden, J. Stobie, and R. Graff, "Update on the FAA's Weather and Radar Processor (WARP)," *10th Conf. on Aviation, Range, and Aerospace Meteorology, American Meteorological Society, Portland, Ore., 13–16 May 2002,* pp. 203–205.
9. R.E. Cole and F.W. Wilson, "The Integrated Terminal Weather System Terminal Winds Product," *Linc. Lab. J.* 7 (2), 1994, pp. 475–502.
10. S.S. Allan, S.G. Gaddy, and J.E. Evans, "Delay Causality and Reduction at the New York City Airports Using Terminal Weather Information Systems," Lincoln Laboratory Project Report ATC-291 (16 Feb. 2001).
11. J.G. Wieler and S.-C. Hu, "Elimination of Doppler Ambiguities in Weather Radar Data," *Proc. IEEE National Radar Conf., Lynnfield, Mass., 20–22 Apr. 1993,* pp. 163–166.
12. D.S. Zrnić, "Spectral Moment Estimates from Correlated Pulse Pairs," *IEEE Trans. Aerosp. Electron. Syst.* **13** (4), 1977, pp. 344–354.
13. G. Trunk and S. Brockett, "Range and Velocity Ambiguity Reduction," *Proc. IEEE National Radar Conf., Lynnfield, Mass., 20–22 Apr. 1993,* pp. 146–149.
14. J.Y.N. Cho, G.R. Elkin, and N.G. Parker, "Range-Velocity Ambiguity Mitigation Schemes for the Enhanced Terminal Doppler Weather Radar," *31st Conf. on Radar Meteorology, Seattle, Wash., 6–12 Aug. 2003,* pp. 463–466.
15. D.S. Zrnić and A.V. Ryzhkov, "Polarimetry for Weather Surveillance Radars," *Bull. Amer. Meteor. Soc.* **80** (3), 1999, pp. 389–406.
16. D.J. Smalley, B.J. Bennett, and M.L. Pawlak, "New Products for the NEXRAD ORPG to Support FAA Critical Systems," *19th. Conf. on Interactive Information Processing Systems (IIPS), Long Beach, Calif., 8–13 Feb. 2003,* http://ams.confex.com/ams/pdfpapers/57174.pdf
17. M. Robinson, J.E. Evans, and B.A. Crowe, "En Route Weather Depiction Benefits of the NEXRAD Vertically Integrated Liquid Water Product Utilized by the Corridor Integrated Weather System," *10th Conf. on Aviation, Range, and Aerospace Meteorology, Portland, Ore., 13–16 May 2002*, pp. 120–123.
18. R.L. Delanoy and S.W. Troxel, "Machine Intelligent Gust Front Detection," *Linc. Lab. J.* **6** (1), 1993, pp. 187–212.

19. M.M. Wolfson and D.A. Clark, "Advanced Aviation Weather Forecasts," in this issue.
20. M. Weber, J. Cho, J. Flavin, J. Herd, and M. Vai, "Multifunction Phased Array Radar for U.S. Civil-Sector Surveillance Needs," *32nd Conf. on Radar Meteorology, Albuquerque, New Mex., 24–29 Oct. 2005,* http://ams.confex.com/ams/pdfpapers/96905.pdf.
21. J.S. Herd, S.M. Duffy, and H. Steyskal, "Design Considerations and Results for an Overlapped Subarray Radar Antenna," *Proc. IEEE Aerospace Conf., Big Sky, Mont., 5–12 Mar. 2005,* pp. 1–6.
22. R.J. Doviak, G. Zhang, and T.-Y. Yu, "Crossbeam Wind Measurements with a Phased Array Doppler Weather Radar: Theory," *Proc. IEEE Radar Conf., Philadelphia, 26–29 Apr. 2004,* pp. 312–316.
23. D.J. Rabideau, R.J. Galejs, F.G. Willwerth, and D.S. McQueen, "An S-Band Digital Array Radar Testbed," *Proc. IEEE Int. Symp. on Phased Array Systems and Technology, Boston, 14–17 Oct. 2003,* pp. 113–118.



MARK E. WEBER leads the Weather Sensing group, which develops sensors, forecast algorithms, processing techniques, and decision support tools for the U.S. commercial aviation industry. His research interests have included experimental studies of thundercloud electrification phenomena, active sonar and radar signal processing, radar-based low-altitude wind-shear detection systems, and technologies to improve the management of air traffic during convective weather. He leads the group's efforts to develop enhanced weather surveillance capabilities for deployed FAA and NOAA national radar networks. In addition, he is supporting these agencies in the development of a research and acquisition program for a next-generation multifunction phased-array radar network. He received a B.A. degree in physics from Washington University in St. Louis and a Ph.D. degree in geophysics from Rice University. Before joining Lincoln Laboratory in 1984, he worked at Columbia University's Lamont-Doherty Geological Observatory and the U.S. Naval Research Laboratory.