# Terminal Doppler Weather Radar Enhancements

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***Abstract*—The design of an open radar data acquisition system for the Terminal Doppler Weather Radar is presented. Adaptive signal transmission and processing techniques that take advantage of the enhanced capabilities of this new system are also discussed. Results displaying data quality improvements with respect to problems such as range-velocity ambiguity and moving clutter are shown.**

## I. Introduction

In response to a series of commercial aviation accidents caused by low-altitude wind shear, the Federal Aviation Administration (FAA) initiated a program in the 1980s to develop the Terminal Doppler Weather Radar (TDWR) that detects and warns against this hazard at major airports. Massachusetts Institute of Technology (MIT) Lincoln Laboratory (LL) played a major role in developing the automated wind-shear detection algorithms for TDWR, demonstrating these operationally on a transportable test bed, and transferring key technology elements to industry. After more than a decade of highly successful operational use, the FAA initiated activities to extend the operational service life of TDWR beyond 2020 and to enhance its wind-shear detection capabilities.

The TDWR was manufactured by Raytheon Corporation using technical specifications developed by the FAA and MIT LL [1]. It operates at 5-cm wavelength on a 0.55° antenna beam and transmits uncoded, 1 μs, 250-kW pulses. It is employed operationally at forty-six large U.S. airports. Although its primary mission is wind-shear detection, TDWR data are also inputs to other systems such as the FAA's Integrated Terminal Weather System (ITWS) [2] and the National Weather Service (NWS) Advanced Weather Information Processing System (AWIPS). ITWS enhances TDWR's airport safety mission by providing short-term forecasts of the occurrence of hazardous microbursts. ITWS also generates a high-resolution gridded wind product [3] that facilitates sequencing and merging operations during approaches to major airports in adverse wind conditions. NWS has established a program to access data from all TDWRs and to process these data in their Weather Forecast Offices as an adjunct to NEXRAD [4]. Researchers developing advanced algorithms for forecasting future thunderstorm impacts on aviation 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.

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## II. Radar Data Acquisition (RDA) Retrofit

Although TDWR has performed its mission extremely well, operational experience over the last decade has exposed data quality issues that can adversely affect the performance 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 estimates. A second major data quality assurance challenge is the extraction of low-altitude Doppler velocity estimates in the presence of strong clutter signals, particularly those associated with moving automobile traffic and biological targets (e.g. birds).

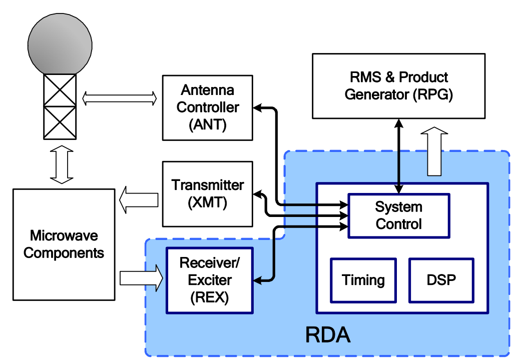


Figure 1. TDWR legacy system block diagram.

The FAA has asked MIT LL to develop a modern replacement for the TDWR's Radar Data Acquisition (RDA) subsystem (Fig. 1). 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. The RDA utilizes a Quad Intel Xeon processor to perform both signal processing and system control functions, running under the Linux operating system [5]. The commercially built Vaisala Sigmet RVP900 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 through additional Linux processor nodes interconnected using gigabit Ethernet (Fig. 2).

This capability will support ongoing enhancements to the TDWR's signal processing algorithms such as those discussed later in this paper. 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 transmitting the base data to downstream clients. All of the software employs standards-based interfaces and is thus transportable essentially unchanged to enhanced commercial off-the-shelf (COTS) processors as these become available.

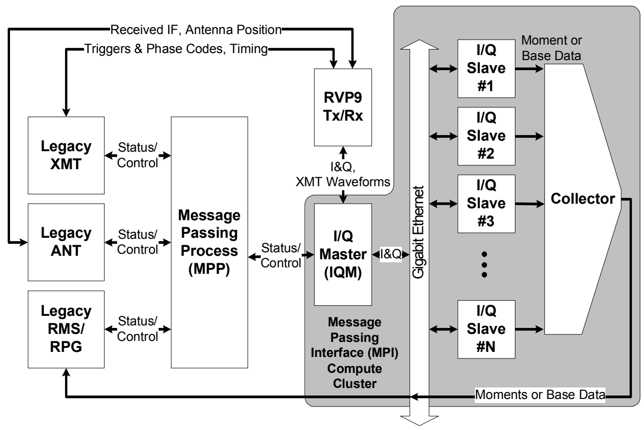


Figure 2. Overview of the new RDA software architecture.

## III. 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. A frequent scenario involves the outflow, or gust front, from a thunderstorm complex that may propagate 100 km or more ahead of the generating storm. As the front passes over an 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 configuration. Experience has shown, however, that the gust front may not be detected by TDWR because the overlaid signal power from the range-ambiguous thunderstorm cells significantly exceeds the echo strength of the gust front. The thunderstorm's radar reflectivity (cross section per unit volume) typically exceeds the reflectivity of the precipitation-free air through which the leading gust front propagates by 35 dB. Since echo strength for beam-filling precipitation decreases only as the inverse-square of range, 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 [6]. 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. The TDWR must be range-unambiguous over its required 90-km coverage on the surface scan that is critical for low-altitude wind-shear detection, which results in a maximum PRF of 1670 Hz at the surface with a corresponding unambiguous Doppler interval of ±22 m/s. 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 dealias Doppler wind estimates. The current approach to dealiasing utilizes a combination of signal processing, data continuity arguments, and constraints imposed by a continuously updated wind-field model [7]. 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 more complex pulse transmission and signal processing schemes developed to mitigate the impacts of range- and Doppler-ambiguous weather returns. Two techniques are utilized—multi-PRI [8, 9] and pseudorandom pulse phase coding (e.g., [10]). 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 μs to 936 μs. 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 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 dealiasing 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 [11], 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 pseudorandom variation to the phase of pulses transmitted within a coherent processing interval. 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. This selective cohering technique allows one to filter out unwanted signals from trips other than the first in the spectral domain, thus suppressing 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. 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 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.

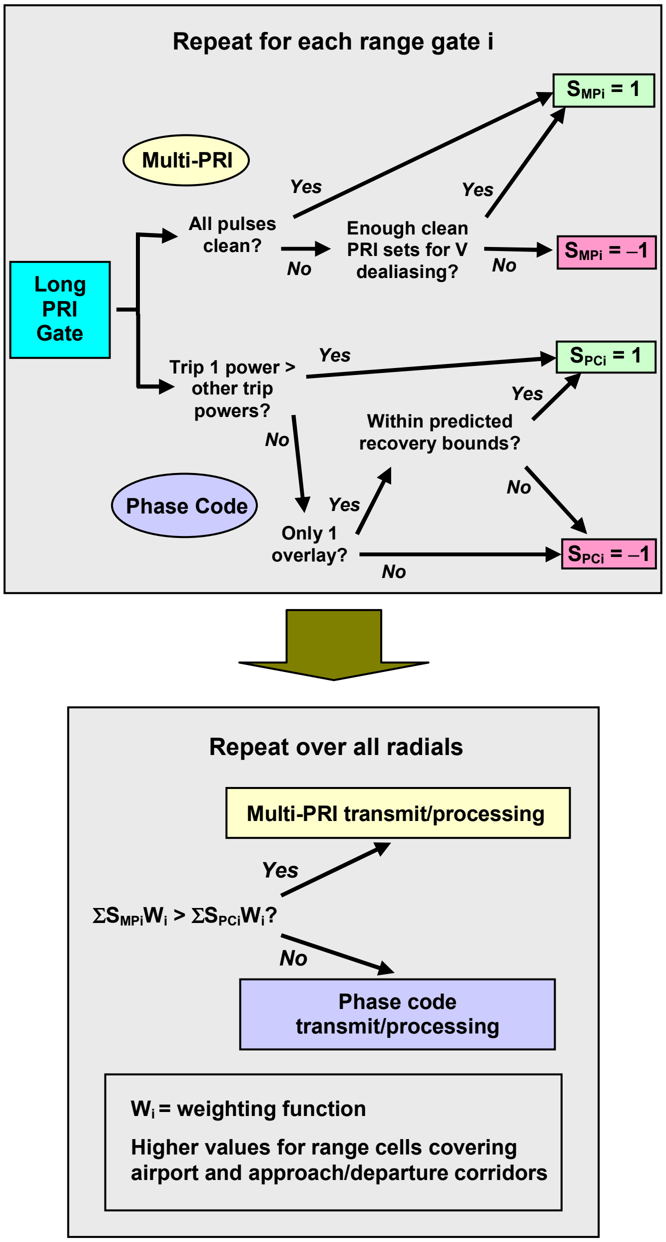


Figure 3. Flow diagram for adaptive waveform and signal processing algorithm.

By adaptively selecting the pulse sequence to be transmitted and processed on each radial (Fig. 3), the complementary characteristics of these two techniques can be exploited [12]. 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. 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.

An example of how this adaptive waveform transmission and signal processing improves the data quality is shown in Fig. 4. Note how a gust front that had to be mostly censored due to range-overlaid distant storm signals becomes distinguishable with the new technique.

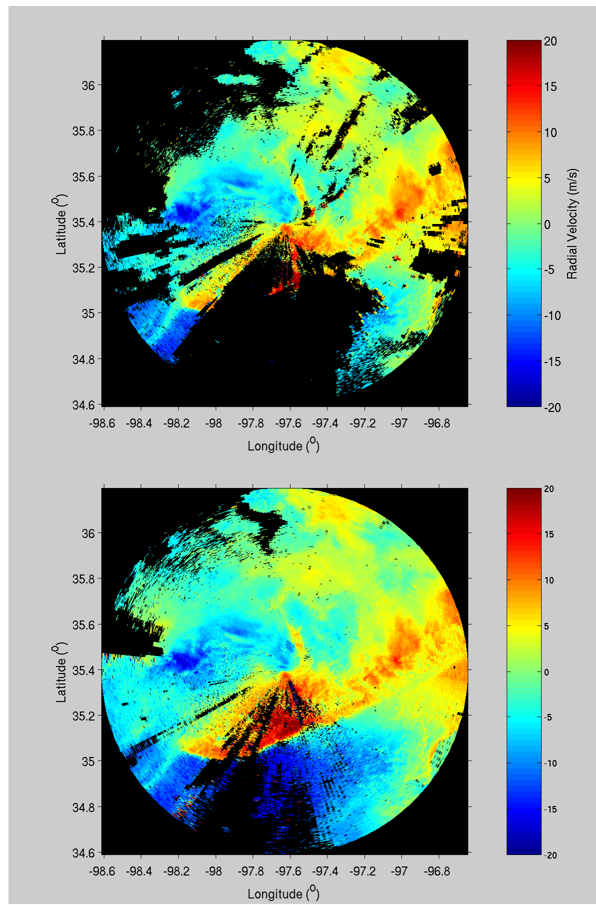


Figure 4. Radial velocity estimated from single-PRI and constant pulse phase transmission data (top) and adaptive selection algorithm data (bottom). Regions of censored data are shown in black.

## IV. Spectral Filtering of Moving Clutter Returns

Although stationary ground clutter can be removed by a high-pass filter, moving clutter such as birds and roadway traffic cannot be attenuated using the same technique because their signal power can exist in the same part of the Doppler velocity spectrum as the weather returns of interest. The moving clutter problem is exacerbated at Western sites with dry microbursts, because their low signal-to-noise ratios (SNRs) are more easily masked by unwanted moving clutter. For Las Vegas (LAS), Nevada, the offending clutter is traffic on roads that are oriented along the radar line of sight near the airport. The radar is located at a significantly higher altitude than the airport, increasing the visibility to the roads, and giving LAS the worst road clutter problem of all TDWR sites. The Salt Lake City (SLC), Utah, airport is located near the Great Salt Lake, which is the biggest inland staging area for migrating seabirds in the country. It, therefore, suffers from bird clutter, which not only can obscure wind shear signatures but can also mimic them to trigger false alarms [13].

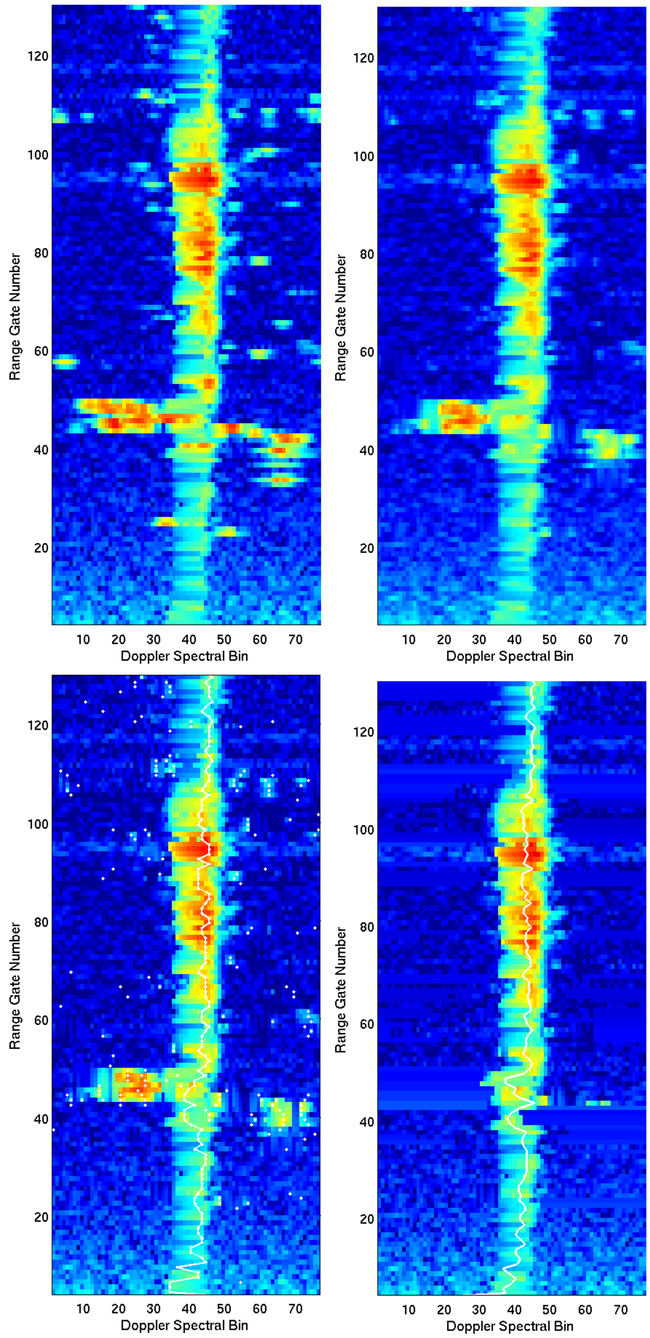


Figure 5. Stationary ground clutter is removed (top left). Isolated spectral peaks are removed (top right). Spectral modes (white dots are identified at each range gate, and the shortest path (white line) connecting them in range is determined (bottom left). Undesirable spectral modes are eliminated. The first moment (white line) is shown for reference (bottom right).

In order to mitigate these problems, we developed a moving clutter spectral filter (MCSF) [14]. We first form a Doppler velocity power spectrum at each range gate with the usual window-and-DFT approach. These spectra are stored in a 2D matrix. Stationary ground clutter is removed using a suitable low-pass spectral filter. We then remove positive power anomalies along range at each spectral bin in a manner similar to a point target filter. Clutter signals that are not continuous in range are thereby removed. Next the number and location of spectral modes (statistically significant peaks) at each range gate are determined. A measure called the normalized circular excess mass (NCEM) is used to winnow out "insignificant" peaks in the spectra. One mode is then selected at each range gate such that the path connecting the modes has the shortest possible overall distance. This process favors retaining globally continuous (in range) signals over only locally continuous features. The assumption is that atmospheric signals will be continuous over longer ranges than moving clutter features. For modes other than the ones selected by the shortest connecting path, the number of "extra" modes is then reduced using a stricter NCEM threshold. This step is needed to reduce the incidence of these "extra" modes being part of the atmospheric spectrum. Any leftover "extra" modes are deemed to be moving clutter and are removed by filling in with the computed spectral "noise" floor. The various steps in the MCSF process are illustrated in Fig. 5.

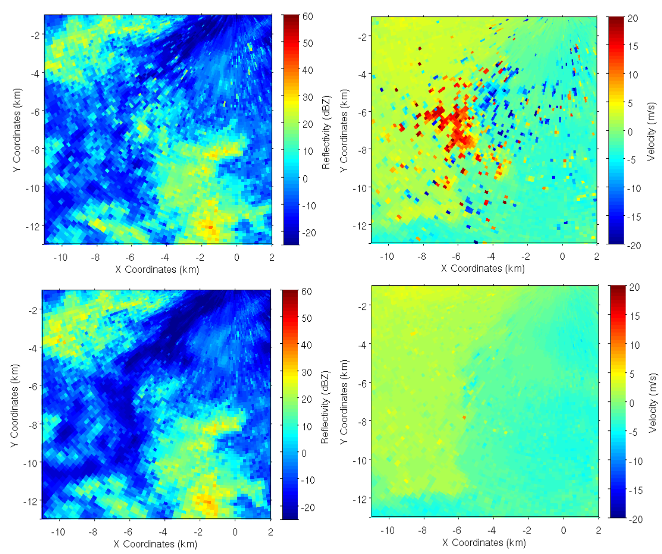


Figure 6. Reflectivity (left) and radial velocity (right) plots for data processed without MCSF (top) and with MCSF (bottom). This was a bird clutter case observed with the SLC TDWR at 0.5° elevation.

Initial testing of the MCSF algorithm has been accomplished using recorded time-series data from the operational TDWR's in LAS and SLC. Cases where widespread bird activity contaminated the data were handled well by algorithm, albeit with small amounts of residual moving clutter in some instances. An example of the improvement in the radial velocity data using MCSF for a SLC bird-contaminated case is shown in Fig. 6. The results for road clutter were only partially successful, with MCSF filtering out traffic returns from roads that were not parallel to the radar line of sight. The roads that lined up with the radar radials, however, were largely not filtered. MCSF fails in these cases, because the moving clutter extends continuously in range for long stretches at a time. Thus, MCSF is not a complete solution for road clutter, but it should reduce the area covered by TDWR Clutter Residue Editing Maps (CREM) where roads currently force data censoring. In cases processed to date, we have not observed instances where MCSF degrades the quality of actual wind shear signatures. An example of microburst data with and without MCSF is shown in Fig. 7.

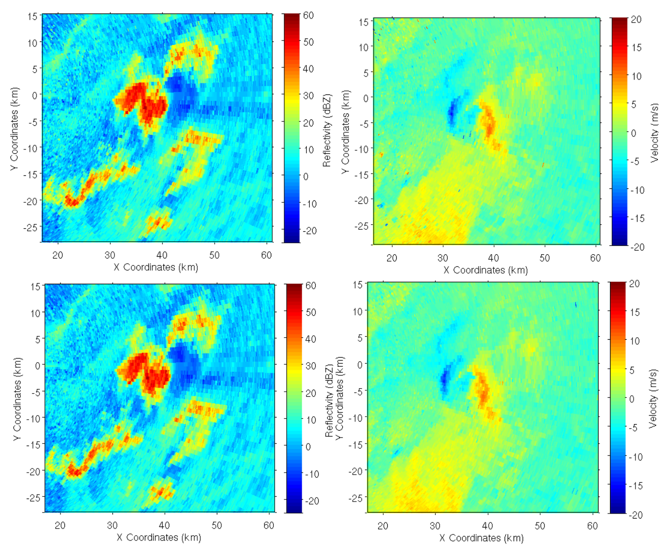


Figure 7. Reflectivity (left) and radial velocity (right) plots for data processed without MCSF (top) and with MCSF (bottom). This was a microburst observed with the MMAC Program Support Facility TDWR at 0.3° elevation.

## V. Implementation Status

MIT LL staff worked with FAA engineers at the Mike Monroney Aeronautical Center (MMAC) in Oklahoma City, Oklahoma to finalize the configuration of the RDA replacement and to install it in the two national support TDWRs in their facility. The MIT LL–FAA team conducted an evaluation and test program covering the system's hardware, processing functions, built-in test and fault diagnosis functions, and maintenance procedures. This evaluation ensured 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 the legacy system requirements validation, the RDA engineering prototype was deployed on operational TDWRs at LAS and SLC to demonstrate system performance and maintainability in an operational environment. Data collected at these sites are facilitating development of additional processing enhancements as described in this paper.

The FAA has programmed funding to deploy the RDA replacement nationally beginning in 2010. The components of the MIT LL-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 MMAC. In parallel, MIT LL 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.

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