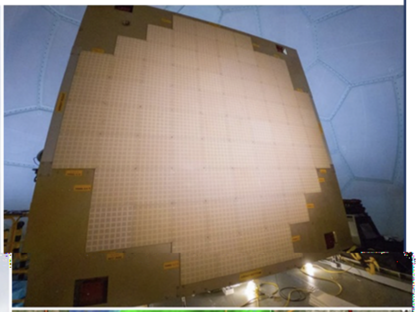
# Advanced Technology Demonstrator System Testing Summary

## National Severe Storms Laboratory Report

*prepared by:* **Stephen Gregg, Christopher Curtis, and Sebastian Torres**



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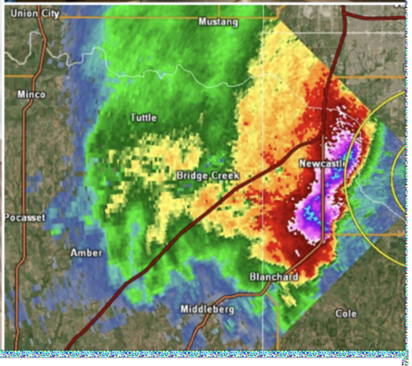

National Oceanic and Atmospheric Administration
**National Severe Storms Laboratory**
Norman, Oklahoma 73072

# Executive Summary

The National Severe Storms Laboratory's (NSSL) Advanced Technology Demonstrator (ATD) is the first full-scale, S-band, dual-polarization, active, electronically scanned phased-array radar (PAR) for weather observations. This report summarizes the processes and results from ATD System Testing, which was the final phase of the project before reaching one of the most crucial project milestones: the ATD's Initial Operating Capability (IOC). ATD System Testing consisted of a comprehensive collection of tests aimed at establishing readiness of the system to support engineering and meteorological research at NSSL. The 70 tests developed for ATD System Testing were classified as *subsystem* tests or *end-to-end* tests. The subsystem tests were divided into three major categories based on the subsystem being tested: Application Software, Backend, and Facilities. These tests validated the performance of each subsystem before end-to-end system tests were conducted. The end-to-end tests were designed to validate the performance of the ATD system as a whole. Based on the functionality being tested, the end-to-end tests were divided into three categories: Core, Operations, and Research.

Nearly 500 pages of technical documentation, including detailed analyses of test results, descriptions of formal testing procedures, and the recording of system performance under a variety of conditions, were produced as part of ATD System Testing. Important outcomes from this effort include

- A comprehensive demonstration of initial operating capabilities,
- A demonstration of the effectiveness of safety features,
- A verification that the performance of the system agrees with its design expectations,
- Documentation of system limitations at the time of reaching IOC,
- Documentation of configuration, testing, and operational procedures,
- Facilitation of staff training on configuration, testing, and operational procedures, and
- The implementation of fixes and the development of improvements needed to address departures from expectations.

While ATD System Testing demonstrated that the ATD can be properly calibrated (i.e., the functionality required to perform and apply calibration data is in place), it did not confirm that the polarimetric calibration of the ATD can be maintained over time. In the upcoming months, our focus will be on improving the robustness and repeatability of polarimetric calibration processes and on quantifying the performance of these processes in terms of producing good-quality dual-polarization data. Additionally, a second phase of ATD System Testing has been planned and will be executed in the near future. This phase consists of Research tests that cover more advanced ATD sampling and scanning capabilities that are not part of IOC.

# Background

The Advanced Technology Demonstrator (ATD) is the first full-scale, S-band, dual-polarization, active, electronically scanned phased-array radar (PAR) for weather observations. The ATD was developed by the National Oceanic and Atmospheric Administration (NOAA) in partnership with the Federal Aviation Administration, MIT Lincoln Laboratory, and General Dynamics. It leverages several prior investments to provide a flexible and affordable weather radar system with which to demonstrate and evaluate the PAR polarimetric performance. The ATD is owned and operated by the National Severe Storms Laboratory (NSSL) and is located at the National Weather Radar Testbed (NWRT) in Norman, Oklahoma.

The integration and testing of the radar subsystems at the NWRT began in June of 2018 and culminated with the ATD reaching its Initial Operating Capability (IOC) in April of 2021. The testing was done in two phases. Phase one consisted of a comprehensive evaluation of the performance of the antenna subsystem led by MIT Lincoln Laboratory, referred to as Antenna Design Verification Testing (DVT). Phase two consisted of a holistic testing of the radar system, referred to as ATD System Testing, and led by the Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) at the University of Oklahoma.

ATD System Testing consists of a collection of hardware and software tests aimed at establishing readiness of the system to support engineering and meteorological research. The tests were developed by a team of engineers from CIMMS, NSSL and General Dynamics. Testing began in November of 2020 and concluded[1] in April 2021 when the ATD officially reached its IOC. Personnel who performed the tests were from CIMMS, NSSL, and General Dynamics and included radar engineers, software developers, and radar meteorologists. All system test descriptions and results are documented in great detail in the ATD System Testing Report. In addition to carrying out the procedures outlined in the tests and determining whether the system worked as expected, a significant amount of documentation was produced in the process; this documentation characterized previously undocumented and/or unknown performance limitations and formalized technical procedures, which are now available for future reference. This document presents a summary of the tests conducted and important takeaways from the results.

As mentioned before, the goal of ATD System Testing was to exercise critical functions of the subsystems that were not fully validated by other phases of formal testing leading up to the ATD's IOC as well as to validate the ATD system as a whole. In particular, there was an emphasis placed on developing tests that covered aspects that have a significant impact on the performance of the ATD, on the system's capabilities expected to be completed before the ATD's initial operation, and on the ability to eventually implement new functionality as part of the ATD's Future Operating Capabilities (FOC). A secondary, but still very important goal of ATD

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[1] The Research tests, which involve advanced operating capabilities, have not been executed as of the date of this report. Three Facilities tests that are waiting on improvements to the building that the ATD is housed in, have also not been executed.

System Testing was to facilitate the transfer of knowledge about hardware/software developed by personnel at General Dynamics to engineers and software developers at CIMMS and NSSL. Because of the extensive testing performed as part of other phases in the development and deployment of the ATD, the completion of ATD System Testing enabled the use of the ATD to support PAR research at NSSL.

# Overview

There were 70 tests developed for ATD System Testing, and each belonged to one of two main groups: *subsystem-specific* tests and *end-to-end* tests.

The subsystem tests focused on the ATD's subsystems, including the calibration tower, the mechanical positioner, the facility's HVAC system, the safety interlocks, the antenna motion controller, the beam-steering generator, the digital beamformer, the digital receiver, the digital exciter, the radar controller, the air-traffic-control signal processor, the weather-surveillance signal processor, and the user interface. The subsystem tests were divided into the following major categories: Application Software, Backend, and Facilities. These tests validated the performance of each subsystem before end-to-end system tests were conducted.

The end-to-end tests were designed to validate the ATD system as a whole. These tests were divided into three categories: Core, Operations, and Research. The Core tests were designed to verify the basic functionality of the ATD as a weather radar. The Operations tests were designed to ensure that common operational tasks work as expected. The Research tests explore advanced aspects of the radar that were not needed for IOC but are critical to support future research.

Each test was written in a common format with the following elements:
- The overall objective of the test,
- A set of any prerequisites/conditions required by the test,
- A set of any special hardware/software configurations required by the test,
- A step-by-step set of instructions that the tester must follow,
- A list of requirements used to evaluate the success of the test,
- A history of any revisions made to the test procedures,
- A history of when testing was performed and who was involved in the testing, and
- A detailed report of the test results, including analysis of data, limitations/benchmarks discovered about the hardware/software, documentation about performance, procedures followed, screen captures of interesting phenomena, and/or recommendations for additional considerations.

A formal procedure was implemented in order to carry out, document, and perform additional work based on the outcome of each test. First, after all test procedures were written, they were extensively reviewed by the ATD System Testing coordinators to ensure that the test instructions were clear, that the same terminology and style were used for all tests, and that the set of requirements used to evaluate each test were known prior to running the test. Next, tests were assigned to specific personnel based on expertise, availability, and training opportunity. Testers were responsible for scheduling time to carry out the test at one of the weekly coordination meetings. Where possible, any software issues uncovered during testing were corrected, and a series of software release cycles were scheduled in order to ensure that all tests could be carried out successfully. Lastly, after each test was carried out and documented, the System Testing coordinators reviewed the results and either recommended additional work be performed or accepted the test as having achieved its objective.

# Summary of System Tests

## Application Software Tests

The Application Software tests (referred to as the “A tests”) consist of applications that carry out specific tasks for end users, such as designing scanning strategies, moving the antenna, starting and stopping data collection, monitoring the status of radar subsystems, processing weather and air-traffic-control data, or displaying information to a user. The applications run on multiple computers on the same network. Many of these tests involve the use of one of two different human machine interfaces (the GD HMI, developed by General Dynamics and the Weather HMI, developed by CIMMS and referred to as the Wx HMI), which are both software applications that allow users to interact with the ATD. These tests were designed to ensure that the applications not only function as expected, but that they work together and are robust enough to handle common problems that might occur during normal operation of the radar.

Shown below is a summary containing each of these tests, their primary objectives, the main requirements[2] necessary for the execution of the test to be considered successful, and the outcome of the execution[3] of the test (pass or fail). Additional information about the failed tests is presented in the section on the Impact of Unsuccessful Tests.

| Test | Objective | Requirements | Outcome |
|---|---|---|---|
| **A1.** Base Data Panel Accuracy | Verify that the Base Data panel in the Wx HMI accurately displays base data. | Qualitative comparison shows agreement between GRAnalyst and the Wx HMI for all six of the different radar variables. | FAIL |
| **A2.** Base Data Panel Functionality (Aircraft Components) | Verify that the user interface of the Base Data panel in the Wx HMI functions properly for aircraft-specific user interface controls. | The aircraft track data that is displayed is consistent with the display in the GD HMI. | PASS |

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[2] The requirements shown here are summarized versions of what is stated in the ATD System Testing Report document.

[3] Some tests failed initially due to software issues; where possible, these issues were resolved, and the tests were executed again. The outcomes listed in the table represent the latest execution of the given test.

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|---|---|---|---|
| **A3.** Base Data Panel Functionality (Non-aircraft Components) | Verify that the user interface of the Base Data panel in the Wx HMI functions properly for non-aircraft-specific user interface components. | The ability to control the display of map overlay data (e.g., Oklahoma county lines), spectral moment data, and polarimetric variable data functions properly; information summarizing the currently-displayed data is shown correctly. | PASS |
| **A4.** Calibration Product Update | Verify that custom radar calibration values can be generated and used properly. | The metadata associated with the IQ data that is produced after applying a given calibration recipe contains the correct calibration value. | PASS |
| **A5.** Cycle Entire System | Verify that the system is stable across restart cycles. | The system is able to be restarted 10 times back-to-back, such that after each restart cycle, the following holds: the overall system is ready to run a weather collection, all software applications start without issues, the software that allows network communications establishes connections with every computer on the network, and the system is able to collect, process, display, and record weather data. | PASS |
| **A6.** Cycle Subsystems | Verify that the ability to run a weather collection is not impacted by cycling subsystems off and back on prior to running a collection. | Individual subsystems are able to be restarted, such that the following holds: each software application associated with the given subsystem restarts successfully, and the system is able to collect, process, display, and record weather data. | PASS |
| **A7.** DSP Control Options | Test the ability to operate with different combinations of DSP control options. | The ground clutter filter, point clutter filter, noise estimator, and all censoring modules (SNR, coherency, clutter-residue) function properly. | PASS |
| **A8.** DSP Status Panel Functionality (Disk Utilization Alert) | Verify that the Wx HMI accurately reports disk space utilization and alerts the user whenever a computer is low on disk space. | For each computer on the ATD network, the reporting of disk space is responsive enough to alert the user of any changes as soon as they occur. | PASS |
| **A9.** DSP Status Panel Functionality (Task Failure) | Verify that the Wx HMI alerts the user whenever a software application fails. | The current running state of each software application that runs on the system is monitored and shown to the user. | PASS |
| **A10.** Face-relative Scan | Verify that a weather data collection can be executed with a face-relative-elevation scan. | The elevation values of the weather data produced by running face-relative scans changes appropriately as the mechanical elevation position of the antenna changes. | PASS |
| **A11.** IQ Recording/Playback | Verify that IQ data can be recorded and played back through the ATD's weather DSPs and that the base data produced by playback matches the original base data. | For each of the 6 radar variables, a bin-by-bin, quantitative comparison of the original base data file and the base data file produced through the playback process shows no differences in data values. | PASS |

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| **A12.** Playback with Different Calibration Data | Verify that different radar calibration values can be applied to archived IQ data through the ATD's playback process. | The weather data produced by playing back IQ data with a different set of radar calibration values is adjusted by the application of the new set of calibration values. | PASS |
| **A13.** Scan Panel Functionality | Verify that the user interface of the Scan panel in the Wx HMI functions properly. | A summary of the characteristics of the current scan is shown, the mechanical position of the antenna is shown, the ability to change the scanning strategy works, and the plot that displays a 2-D animation of the transmitted beams matches the beams in the current scan. | PASS |
| **A14.** System Panel Functionality (Client Control) | Test the ability for multiple users to control separate Wx HMIs without the HMIs interfering with each other. | At most one user at a given time is allowed to change the state of any subsystem, change the mechanical position of the antenna, or make any other system-wide change; each user is shown whether they have the ability to make these changes. | PASS |
| **A15.** System Panel Functionality (System Log) | Compare log messages reported in the GD HMI to those reported in the Wx HMI. | For each subsystem, after triggering an event that generates a log message in the GD HMI, a corresponding log message is generated in the Wx HMI. | PASS |
| **A16.** Verifying Archiving Weather Scan | Verify that the Archive function for collecting raw I/Q (beam) data operates as designed and works with weather scans. | The Archive function produces MATLAB files which can be processed to show strong returns when pointed at a calibration tower. | PASS |
| **A17.** Deleting and Recovery of Calibration Sequence | Verify that the proper notifications occur when deleting a Calibration Sequence and that the sequence is backed up and can be recovered. | All edits made to a given calibration sequence are discarded when the backup is restored. | PASS |
| **A18.** Cal Sequence Abort and Resume | Verify that the Abort command for a calibration sequence functions properly. | The command stops the currently running calibration sequence, and subsequently-run sequences can be started without any issues related to the previously stopped sequence. | PASS |
| **A19.** Data Visualization | Verify that the Data Visualization feature on the GD HMI operates as designed. | The user is able to view, pan, and zoom in on the visualization of waveforms. | PASS |
| **A20.** ATC DSP Internal Data Tap | Verify that the Data Tap (collection) mechanism of the ATC DSP operates as designed. | The data produced by the mechanism is validated by the Data Visualization tool in the GD HMI, showing that the data in the files is pulse-compressed and is at the expected range. | PASS |
| **A21.** Register Read and Write | Verify that the read and write register function on the GD HMI operates as designed. | Each of the control and status registers in the FPGAs of the backend components can be read from and written to. | PASS |
| **A22.** EMI Filter | Verify that the EMI filter in the ATC DSP performs as expected. | The ATC DSP EMI filter is effective at removing pulsed interference while preserving the uncontaminated weather data. When combined with the Wx DSP EMI filter, there are no artifacts. | PASS |

# Backend Tests

The main goal of the Backend tests was to exercise critical functions of the backend subsystems that were not fully validated by the testing done during Antenna DVT but still have significant impact on the performance of the ATD. The subsystems covered by these tests include the digital exciter and the digital beamformer. Many of these tests involve using the GD HMI in order to operate in special operational modes that are not supported by the Wx HMI; as such, the limitations of these modes were previously unknown. Other tests verify that the portions of the backend are functional and that the different types of data that can be collected by the ATD are free of signal corruption and are accurate.

| Test | Objective | Requirements | Outcome |
|---|---|---|---|
| **B1.** Burst Mode Validation | Verify that the backend components (along with DSP Data Collection) support the "burst" mode where multiple pulses are scheduled within a single Radar Event. | Burst mode operates without error messages, signal corruption, or large pulse-to-pulse phase differences, and the data produced contain the expected number of IQ samples. | PASS |
| **B2.** Maximum PRT and Receive Window Validation | Using an iterative test method of increasing the PRT and receive-window parameters, document the maximum PRT and receive window for data collection purposes. | For each mode (burst, multi-pulse and single pulse) and a variety of receive windows and number of pulses, the PRT is increased to the point of a failure; the results for each combination tested are well-documented. | PASS |
| **B3.** Exciter Spectral Characterization | Characterize the spectrum of signals from the Digital Exciter to verify that there is no significant signal corruption. | The ripple across any passband does not exceed 2 dB. | PASS |
| **B4.** Down Converter Spectral Characterization | Characterize the spectrum of signals through the Down Converter to verify that there is no significant signal corruption. | The ripple across any passband does not exceed 2 dB. | PASS |
| **B5.** Receiver Spectral Characterization | Characterize the Digital Receiver's Spectral Response, and verify that there is no significant signal corruption. | The ripple across any passband does not exceed 2 dB. | PASS |
| **B6.** Beamformer Spectral Characterization | Characterize the Digital Beamformer Spectral Response, and verify that there is no significant signal corruption. | The ripple across any passband does not exceed 2 dB. | PASS |
| **B7.** Max Number of Beams Supported | Verify that 24 beams per sub-band can be produced by the DBF and captured in the DSP; verify the process of generating the necessary beamformer coefficients and loading them. | There are no errors/warnings when processing 24 beams, data is processed without any signal corruption, and the procedure for generating the beamformer coefficients is up-to-date. | PASS |

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| **B8.** Receiver Filter Coefficient Modification | Verify the ability to create filter coefficients and load them into the Digital Decimation Filters in the receiver, and validate the documented procedure. | The effects of the different coefficients are evident by examining frequency/power plots that show the desired outcomes of the filters; the process of updating coefficients is well-documented. | PASS |
| **B9.** Receiver Noise Floor | Verify the noise floor for each channel; validate the process for calculating the attenuator settings to achieve the desired noise floor. | The magnitude of the min/max/mean noise floor for all 48 channels is calculated and documented. | PASS |
| **B10.** ADC Data Collection | Verify the ability to capture ADC data for debug support and/or to examine the use of a wider receive spectrum. | Plots show returns with 80 MHz spectrum and sub-bands are centered around 40 MHz. | PASS |
| **B11.** FPGA Load Process (From HMI) | Validate the process to load a new FPGA build via the GD HMI. | The loading completes successfully, and no errors/warnings are shown. | PASS |
| **B12.** FPGA Load Process (Manual) | Validate the process to manually load a new FPGA for those not supported by GD HMI. | The loading completes successfully, and no errors/warnings are shown. | PASS |

## Facilities Tests

The Facilities tests address the performance of the ATD in various environmental conditions, the safety mechanisms that are in place at the ATD site, and the proper functioning of the azimuth control unit and the calibration tower. Tests F1, F2, and F4 were not carried out due to necessary improvements to the ATD building’s HVAC system but will be carried out at a future date.

| Test | Objective | Requirements | Outcome |
|---|---|---|---|
| **F1.** Environmental Control I (High Temperature) | Validate that the air conditioning system is able to exchange the amount of heat generated by outdoor temperature, array operation, and solar loading. | During operation of the radar, the temperature and humidity of each zone in the building remain stable. | NA |
| **F2.** Environmental Control II (High Humidity) | Validate that the HVAC system is able to maintain a stable maximum humidity and that the dehumidification demand on the air conditioning system does not result in a runaway cooling cycle. | A consistent humidity of 45% must be maintained during a test in which the outdoor humidity is greater than 75%. | NA |
| **F3.** Environmental Control III (Low Temperature) | Validate that the heating system is able to maintain interior temperatures in cold outdoor conditions, independent of the heat generated by the array. | Building temperatures must remain stable when set to 60° and 65° during a test in which the outdoor temperature is less than 32°. | PASS |

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| **F4.** Environmental Control IV (Low Humidity) | Validate that the HVAC system is able to maintain a minimum relative humidity under dry outdoor conditions. | The building humidity must remain stable when set to 30% and 40% during a test in which the outdoor humidity is less than 20%. | NA |
| **F5.** Power Continuity (UPS, Transfer Switch, and Generator) | Demonstrate smooth failover from commercial to generator power. | Upon power failure at the ATD building, the equipment must transition to backup power using a generator, and the generator must support the most taxing power conditions that are to be expected during operations. | PASS |
| **F6.** Safety Circuit I (Motion Interlock Logic) | Validate proper operation of interlocks and red annunciator lights to warn on-site personnel that remote users can initiate motion of the radar within the building. | Warning lights are shown for all of the hatches, gates, and doors that are open during conditions in which motion can be initiated, and they are not shown otherwise. | PASS |
| **F7.** Safety Circuit II (Motion Interlock Effect) | Validate that motion is disabled when the safety interlock circuit is open to ensure the safety of on-site personnel. | Motion of the radar within the building is possible only when the indicator lights are on, and is not possible only when the indicator lights are off. | PASS |
| **F8.** Safety Circuit III (Radiation Interlock Logic) | Validate proper operation of interlocks and blue annunciator lights that warn on-site staff that remote users have the ability to cause the radar to emit radiation. | Both aural and visual indicators correctly warn on-site personnel based on the state of the interlocks whenever the radar is able to emit radiation and whenever it is not. | PASS |
| **F9.** Safety Circuit IV (Radiation Interlock Effect) | Validate that radiation is disabled when the safety interlock circuit is open. | Radiation of the radar is possible only when indicated and not possible otherwise. | PASS |
| **F10.** Safety Circuit V (Emergency Shutoff Operations) | Validate that the controls that are in place to perform an emergency shutoff work properly. | When pressing the emergency stop button or activating the kill switch, the appropriate breakers are de-energized properly. | PASS |
| **F11.** ACU/Pedestal (Rate, Position, and Halt Commands) | Validate the performance and actions for the Rate, Position, and Halt commands of the azimuth control unit. | When commanded, the rotation rate reaches the commanded value and is stable, the actual positions of the pedestal match the command values, and the rotating deck stops abruptly. | PASS |
| **F12.** Calibration Tower | Test the power levels through attenuators, the delay line loss and timing, and operation of continuous-wave source mode. | Any difference in power levels matches the amount of attenuation that was commanded, the losses in the delay line are within expected tolerances, and a flat signal response in relative power is seen for the continuous-wave mode. | PASS |

## Core Tests

The Core tests address the basic functionality of the ATD as a weather radar. The goal was to use these end-to-end tests to verify as much of the overall system as possible while verifying radar functionality. One way that this was achieved was by using the weather base data produced by the ATD since it is the final product created by the system.

Four of the tests focused on the resolution volume, both its shape and location; these tests confirm that the resolution volume has the proper shape and size in both the angle and range dimensions, and ensure that the resolution volume is accurately located in space.

Other Core tests examined the calibration and proper estimation of the meteorological radar variables; in particular, these tests confirm that angular-dependent calibrations are being properly corrected and that the radar variables are consistent with those produced by data from the nearby KOUN radar.

The remaining Core tests verified that the system can properly impose the pulse-to-pulse phase codes that are needed for accurate radar-variable estimation, and ensure that the overall sensitivity of the system as a whole meets the expected design specifications.

| Test | Objective | Requirements | Outcome |
|---|---|---|---|
| **C1.** Antenna Pseudo-pattern | Verify that the azimuth beamwidth and sidelobes of the pencil-beam antenna pattern meet specifications. | Measured azimuth beamwidth is within 0.1° of the specified beamwidth of 1.58°, and first sidelobe levels are no more than 3 dB above the specified antenna sidelobe levels of -48.35 dB. | PASS |
| **C2.** Coverage | Verify that the coverage of the ATD data meets expectations. | The signal-to-noise ratio (SNR) of the data being censored is less than the SNR threshold used for censoring. | FAIL |
| **C3.** Phase Coding | Verify that the system can impose the needed pulse-to-pulse phase codes for an IOC weather scan. | The RMS error of the differences in phases due to the imposed phase codes is within 2° of the commanded phase for both channels. | FAIL |
| **C4.** Pointing Accuracy | Verify that the calculations used to measure pointing directions used in weather scans are accurate. | Differences in azimuth do not exceed 0.5°, and differences in maximum and minimum elevation values do not exceed 0.5°. | PASS |
| **C5.** Radar Variable Self-Consistency | Verify the calibration of reflectivity and all dual polarization variables using self-consistency testing. | RMS differences of variables from different electronic scanning angles (but the same direction in space) are within ±1 dBZ for reflectivity, ±0.1 dB for differential reflectivity, ±1° for differential phase, and ±0.006 for correlation coefficient. | FAIL |
| **C6.** Radar Variables | Compare all six radar variables from an ATD weather scan to a KOUN weather scan. | The RMS differences (over at least 25 gates) should be less than 4 dBZ for reflectivity, 1.5 m/s for radial velocity, 1 m/s for spectrum width, 0.07 for correlation coefficient, 2 dB for differential reflectivity, and 30°/km for differential phase. | FAIL |
| **C7.** Range Accuracy | Validate the distance from a fixed tower for a normal weather scan to validate the accuracy of the range calibration correction. | The absolute difference between estimated and true tower range is within 18.75 m, and the range of the tower in the base data is consistent with the results from the IQ data. | PASS |

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| **C8.** Range Weighting Function | Verify that the range-weighting function shape, including range sidelobes, is acceptable, measured using the weather scan and a fixed tower. | The estimated range-weighting functions for both the short pulse and long pulse from the fixed tower collected with a weather scan are within 18.75 m of the expected 6 dB width, and the first sidelobe is not more than 3 dB above the first sidelobe measured in DVT 6. | PASS |
| **C9.** Sensitivity | Verify that the sensitivity of the ATD meets expectations. | The relative sensitivity of the ATD and KOUN are within ±2 dB of the theoretically computed difference. | PASS |

## Operations Tests

The Operations tests ensure that the day-to-day operational radar tasks can be carried out as expected. The most common tasks are separated into simple tests that verify the functionality and robustness of the system. These tasks include customizing scanning strategies and producing weather data that can be used in offline processing.

| Test | Objective | Requirements | Outcome |
|---|---|---|---|
| **O1.** Archiving | Verify that the controls and processes for long-term storage of IQ and base data work as expected. | Data archiving on the archive server is successful when archiving is enabled, and no data is recorded when archiving is disabled. | PASS |
| **O2.** Changing Antenna Azimuth Position | Verify the ability to accurately change the mechanical azimuth position of the antenna. | Data collected at different commanded azimuth positions corresponds to the correct azimuth positions, and the time required to change azimuth positions does not exceed 5 seconds. | PASS |
| **O3.** Changing Antenna Elevation Position | Verify the ability to accurately change the mechanical elevation position of the antenna. | Data collected at different commanded elevation positions corresponds to the correct elevation positions, and the time required to change elevation positions does not exceed 3 seconds. | PASS |
| **O4.** Long-term Weather Collection | Demonstrate the ability to run an extended (8 hour) weather collection test. | There are no more than 2 dropped base radials, no significant system warnings/errors are encountered, and all of the expected IQ and base data files are produced. | FAIL |
| **O5.** Multifunction | Ensure that the system can run in multifunction mode (aircraft and weather detection) and that the allocation of time spent in the aircraft mode can be configured. | Data from both modes can be collected without any issues, and the time between weather scans is consistent with the configured values. | PASS |
| **O6.** New Weather Scans | Test all components of the weather scan definition by verifying that users can create/run new weather scans with different scanning parameters. | There are no errors in the design or collection of the new scans, the Scan panel in the Wx HMI reflects changes to the scan, and the collected data match the definition of the scan. | PASS |

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| **O7.** System Readiness | Verify that a procedure exists that documents all steps needed in order to fully operate the system during daily testing. | The procedure, *as documented*, allows a user to complete all aspects of daily testing. | PASS |
| **O8.** Weather Collection | Verify the ability to collect and display data from at least two different weather scans. | The reporting in the Wx HMI is consistent with the properties of each scan, and base data is accurate and can be displayed in offline tools. | PASS |

# System Testing Results

## Main Takeaways

Nearly 500 pages of documentation has been produced as part of ATD System Testing, including the detailed analysis of test results, establishment of formal testing procedures, and the recording of system performance under a variety of conditions. During testing, five software release cycles were completed, addressing important issues uncovered during the execution of the tests. In addition to accomplishing the objectives outlined in the tables in this document, there was a significant transfer of knowledge, staff were cross-trained, and fourteen comprehensive system procedures were written and included in an appendix of the ATD System Testing Report document for future reference. Much of the knowledge transferred was from engineers at General Dynamics to engineers/software developers at CIMMS and NSSL through training with the GD HMI, which is a user interface that allows greater control over the ATD's advanced capabilities. Additionally, by systematically carrying out so many test procedures after all hardware and software had been integrated, expectations concerning the ATD's capabilities were demonstrated empirically to either be met or not be met; that is, relying on design specifications alone was no longer necessary.

Aside from some issues mentioned below, the tests performed as part of ATD System Testing show that the ATD is ready to be used as a weather radar in support of engineering and meteorological research. Many of the Application Software and Operations tests showed that the radar can be customized to scan in a wide variety of ways (with accurate reporting in the human-machine interface). A number of tests, having required the use of the two types of data produced by the ATD (raw received signals/IQ data and fields of radar variables/base data), showed that the applications that process, produce, record, and archive these data are functioning well. These tests also showed that the system itself is stable; the applications, in general, were shown to be robust and to be free of errors/warnings during the most common operational use cases. The Core tests verified that some physical properties, such as the antenna beamwidth, measurement of radar variables, and the accuracy of pointing the antenna, all meet design specifications. Many of these tests reflect the ability to perform accurate polarimetric calibrations, which were done prior to their executions. The Backend tests were important in not only demonstrating the ability to use the system near its limits but also in documenting those limits so that future work can be planned accordingly; additionally, these tests were crucial in showing that there was no signal corruption, and that data integrity is preserved when operating under conditions other than what are currently being used in routine weather-data collections. Finally, the Facilities tests demonstrated that, one, there are sufficient safeguards in place so that the personnel occupying the ATD building are protected from mechanical movement and radiation produced by the antenna through the use of alarms and mechanisms that disable these functions; two, that the equipment can be operated safely under extreme weather conditions and power failures; and that three, that the hardware that controls movement and that allows for calibrations to be performed are functioning as expected.

## Impact of Unsuccessful Tests

In the event that a test failed to meet one of its requirements, attempts were made to resolve the issues that prevented its successful completion. Often, the test was placed on hold, the issue was investigated, a fix was developed and implemented, and the test was executed again; however, there were tests for which this procedure was not sufficient.

For the Application Software test **A1. Base Data Panel Accuracy**, there was an issue with the spatial consistency of the display of weather base data in the Wx HMI. When a side-by-side comparison was performed using commercial display software, a discrepancy in the geographical position of the weather data was observed; the data in the Wx HMI's display was off by approximately 4 range bins (about 1 kilometer). The geographical display code used in this application is tied to a deprecated infrastructure, so the issue was documented so that operators are aware of it. In addition, as part of planned ATD software improvements, a completely redesigned Wx HMI is being developed, which includes an updated base data display that corrects the issue revealed through this test.

The second failure occurred with one of the Operations tests, **O4. Long-term Weather Collection**. This test had a strict set of requirements that had to be met during the entire duration of the test. This test was executed seven times over the course of five months, and each test exhibited one or more issues, which prevented it from being considered successful. These issues included: too much data lost while operating; errors/warnings reported by the digital receiver subsystem that could not be tracked to a specific cause; issues related to the status of the array's panels reported by the beam-steering generator subsystem; freezes with the software that allows for communication between network components; and freezes during the execution of system health checks. Significant time was spent troubleshooting these issues, and some of them were resolved. After resolving these issues and because there was such a wide range of issues present in the first few attempts of executing this test, the test instructions were updated to require that two successful back-to-back 8-hour collections be performed. However, some issues were still encountered during at least one of the two 8-hour tests. Even though this test was considered unsuccessful, the most important of the issues initially encountered with this test occurred only after hours of operation, and when they did occur, the operator was able to restart the system and return to an error-free operational state within just a few minutes.

The third issue occurred due to the **C2. Coverage** Core test failing to meet initial expectations about the distribution of the signal-to-noise ratios of the data on the verge of being censored by the signal processor. Based on simulations, expectations about the distribution of SNR for all gates “near extinction” beyond the clutter region were used in the test definition. This test failed its first execution due to problems with the base-data metadata (NEXRAD Message 31) that was used to compute the SNR values. Fixes to this problem were included in one of the System Testing software releases, and the test was executed again. After adjusting simulation parameters to better reflect the signal characteristics in the data, the results obtained through testing were more consistent with the expectations produced by the more accurate simulation results. Despite the failed outcome of this test, the analysis of the data collected was critical to correct the formatting of the base data files, which is required in order to use conventional tools for offline processing/display of the weather base data.

The fourth test that was unsuccessful was due to an issue with unexpected behavior in phase coding that was seen during the execution of the Core test **C3. Phase Coding**. This test was designed to show that when imposing certain pulse-to-pulse phase codes for each polarization channel, the RMS error of the differences between the commanded and measured phase codes are within an acceptable range (2°). It was seen that the RMS error of the phase differences for the horizontal channel were almost 6°. The accumulation of error in the horizontal channel across pulses could largely be attributed to the change in phase of the other channel (the vertical channel); this is speculated to have been caused by contamination due to depolarization from the external tower used in this test (the same phenomenon has been observed in the analysis of other test data). While this hypothesis was not confirmed, if true, it would point to a limitation of the measurement approach. However, a similar test performed during Antenna DVT also revealed unexplained phase coding errors, which could be attributed to errors in array calibration or inherent limitations of the antenna. Although this issue does not significantly impact the ATD’s IOC, it should be investigated further to accurately characterize the performance of the system when imposing various phase codes.

The fifth issue occurred during the **C5. Radar Variable Self-Consistency** test, which verifies that electronic beam-steering calibration values are accurate. This is achieved by capturing the same weather event from three different mechanical positions and then computing the RMS error of the differences in radar variables at the same spatial locations. Calibration values for this test are used to compute estimates for reflectivity, differential reflectivity, differential phase, and correlation coefficient and to account for biases in electronic beam-steering; this test also checks for potential mismatches between the horizontal and vertical polarizations as a function of beam-steering angle. Although multiple sets of calibration values were considered, the test was severely limited by the number of widespread weather echoes that were available from the weather event that was captured. As such, the results obtained were inconclusive. As is mentioned in the future work in the Conclusions section, achieving robust and repeatable radar calibration will be a priority in the upcoming months; so, achieving a positive result with this test will become a higher priority once more progress is made with respect to demonstrating the polarimetric calibration of the ATD.

The sixth unsuccessful test occurred because not all of the variables in the **C6. Radar Variables** test met the expectations when compared to a neighboring radar. With this test, weather data was collected at the same time for both the ATD and a neighboring radar (KOUN), and estimates from the same radar variables of each radar were compared; the expectation with this comparison is that the RMS differences obtained are small enough to conclude that both radars measure each variable similarly. In particular, the following table shows the expected maximum RMS error (over a set of at least 25 gates) and the actual RMS error.

| Radar Variable | Z dBZ | V m s$^{-1}$ | W m s$^{-1}$ | ZDR dB | KDP ° | RHO (unitless) |
|---|---|---|---|---|---|---|
| Expected Max RMS Error | 4.00 | 1.50 | 1.00 | 2.00 | 30.00 | 0.07 |
| Actual RMS Error | 4.93 | 2.43 | 1.29 | 1.84 | 15.18 | 0.05 |

As shown, reflectivity (Z), radial velocity (V), and velocity spectrum width (W) failed to meet the requirements, while differential reflectivity (ZDR), specific differential phase (KDP), and correlation coefficient (RHO) met the requirements. There were some differences between the two radars that could be responsible for some of the increased error, including differences in signal quality between the ATD and KOUN (since the ATD uses pulse compression and range averaging and KOUN does not), in beamwidths, and in the exact times that data were collected by each radar (differences for the collection time of individual cuts in each scan varied between 2 and 45 seconds between the radars). Some differences specific to a particular radar variable were shown to be responsible for a significant portion of the RMS error. For the radar variables that did not meet expectations, there was a disproportionately higher amount of error attributed to the lowest and/or the highest cuts in the scan; for reflectivity, the RMS error of the middle five cuts was near the expected maximum (and the extreme low and high cuts had a much higher RMS error), for velocity, the RMS error was near the expected maximum except for the last three cuts, and for spectrum width, the RMS error was near the expected maximum only for three of the middle cuts (though the highest cuts contributed significantly more error to the overall RMS error). For the ATD, the reflectivity field was smoother than the field for KOUN due to the use of pulse compression and range averaging, which was seen in regions where KOUN reported more high and low values. There was also a bias in reflectivity with some lower reflectivity values that were higher for the ATD than for KOUN. For radial velocity, there were differences in values that were near the Nyquist velocity due to the way in which aliasing was handled by each radar; by removing these values from the error calculation, the RMS error dropped from 2.43 m s$^{-1}$ to 1.6 m s$^{-1}$, which is much closer to the expected maximum. For spectrum width, there was a strong influence from errors in the higher cuts. Additionally, the number of samples and the Nyquist velocity differ significantly between the ATD and KOUN, and these values greatly affect the quality of the spectrum width estimator. By restricting the set of values used in the RMS error calculation to only those that are between 1.6 m s$^{-1}$ and 6 m s$^{-1}$ (taking into account the estimator performance), the RMS error is very close to the expected maximum expected RMS error. Because of the elevation-related differences in errors and the mismatches between the ATD and KOUN scans, we will revisit this type of test in the future to better understand the discrepancies in radar-variable estimates.

## Other Issues Found During Testing

Because of the scope of this effort, testers uncovered many issues that were previously unknown, and some of them were unrelated to the tasks being performed in the tests themselves. Most of these issues were software related and were resolved through additional software development and troubleshooting. Not only were the most pressing issues corrected, but the majority of the less-impactful ones were also corrected; so, this effort also served to improve the overall quality of the application software.

Within the Wx HMI, there were issues discovered and resolved related to the process of creating custom scanning strategies with nontraditional azimuth sectors, the calculation of transmit/receive beams, user interface components failing to update after changing scanning parameters, incorrectly shown aircraft track information, inaccurate geographical coordinates of radar locations, and with changing a scan's azimuthal spacing.

Within the Wx DSP infrastructure, there were many issues found and resolved related to the calibration infrastructure, the weather processing modules, and the weather base data that the signal processor produces. For calibration, there was an issue fixed where one of the measured calibration values (the broadside differential reflectivity bias) was not being used in the estimation of differential reflectivity. There was an issue that prevented a subset of the latest calibration values from being applied operationally, and there was an issue such that incorrect calibration values were being applied. There were several issues found and resolved in test **A7. DSP Control Options** when using different processing modules that were previously very difficult to detect; this was because either the consequences of the malfunctioning module were subtle or the issues were only present under certain combinations of enabled modules. There were one or more problems found with the SNR censoring module, the clutter residue module, and the coherency-based thresholding module; the results of these errors included data not being censored properly. By understanding these issues and correcting their implementations, data quality for future weather data is improved, and operating with any (valid) combination of modules enabled produces the desired results. Lastly, there were issues with the weather base data produced, including a mismatch between phase codes and incomplete fields and issues with data quality.

While exercising many of the backend subsystems, there were issues found and resolved related to performing comprehensive testing of subsystems in general and other issues with specific subsystems. There was a lack of procedures to force subsystems to report errors and warnings; this was particularly important because an operator depends on the accurate reporting of advisory messages from each subsystem. Without such a mechanism, there was no way to guarantee that an operator using the operational software (that is, the Wx HMI) would be aware of important information being reported by each subsystem. Not only was a procedure developed to test each subsystem’s reporting, but the accurate reporting of each subsystem to the Wx HMI was thoroughly tested/verified. The digital beamformer was designed to support 48 beams, but was shown in test **B7. Max Number of Beams Supported** to only support 36 beams; the software responsible for the limitations was updated, and the test was performed again to demonstrate that the full set of 48 beams were supported. Also, not only did the test **B2. Maximum PRT and Receive Window Validation** establish limits on the maximum supported PRTs and the maximum dwell times supported by the beam-steering generator, but it helped identify issues with thermal drift causing pulse-to-pulse phase differences to be outside of the expected 1° difference.

# Conclusions

## Future Work: Polarimetric Calibration

Although procedures for the polarimetric calibration of the ATD have been developed and tested, their performance and the repeatability of the calibration data produced need additional improvement in order to show that the ATD can be properly calibrated and that this calibration can be maintained over time. One of the goals with this effort was to ensure that calibration processes can be performed reliably on the ATD and that their results are applied in the real-time signal processing. **A4. Calibration Product Update** ensures that a user can generate their own custom calibration values and have the system apply them in the real-time processing; **A12. Playback with Different Calibration Data** ensures that data that has not undergone signal processing can be processed by the same signal processors used in real-time processing; **A17. Deleting and Recovery of Calibration Sequence** ensures that calibration processes can be deleted, saved, and recovered; and **A18. Cal Sequence Abort and Resume** ensures that calibration processes can be aborted, which is useful because some calibrations can take many hours to complete. So, these tests have demonstrated that the functionality required to perform and apply calibration data is in place, and the focus can shift to improving the robustness and repeatability of calibration processes and to quantifying the performance of the calibration data in terms of producing good-quality dual-polarization data.

## Future Work: Research Tests

Because the Research tests cover advanced functionality, it was decided to complete them during a second phase of System Testing, which allowed the ATD to be brought into operations sooner. Many of these tests are focused on more advanced modes of operation of the ATD that involve different types of scanning, such as using spoiled transmit beams, running RHI scans, using Staggered PRT, and scanning while moving the radar mechanically. The New Calibration test further explores the use of the GD HMI, the ATD calibration tower, and the switch matrix to perform calibrations with different types of transmit and receive modes, as well as to serve as a good means to transfer calibration-specific knowledge from engineers at General Dynamics to those at the Cooperative Institute for Severe and High-Impact Research and Operations (CIWRO) and NSSL.

The following tests involve the use of advanced functionality and are currently considered experimental; however, they all make use of the ATD's current infrastructure, and, at least for their basic use cases, do not require significant changes in hardware/software.

| Test | Objective |
|---|---|
| **R1.** New Calibration | Develop and run a new calibration sequence to test the flexibility and capabilities of the GD HMI's calibration creation tools. |
| **R2.** Scan-while-move | Demonstrate the ability to execute weather scans while the antenna is moving mechanically. |
| **R3.** Spoiled Beam | Demonstrate the ability to use beam spoiling in weather scans, using 3x1 and 5x1 beam spoiling. |
| **R4.** Staggered PRT | Demonstrate the ability to use Staggered PRT mode in weather scans. |
| **R5.** Subarray Recording | Demonstrate the ability to record overlapped subarray data for use in adaptive beamforming research. |
| **R6.** Weather Beam Types | Demonstrate that transmit beam types other than the standard beam type can be used in weather scans. |
| **R7.** RHI Scans | Demonstrate the ability to create, run, and display RHI weather scans. |

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