The Atmospheric Imaging Radar: Simultaneous Volumetric Observations Using a Phased Array Weather Radar

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ABSTRACT

Mobile weather radars often utilize rapid-scan strategies when collecting observations of severe weather. Various techniques have been used to improve volume update times, including the use of agile and multibeam radars. Imaging radars, similar in some respects to phased arrays, steer the radar beam in software, thus requiring no physical motion. In contrast to phased arrays, imaging radars gather data for an entire volume simultaneously within the field of view (FOV) of the radar, which is defined by a broad transmit beam. As a result, imaging radars provide update rates significantly exceeding those of existing mobile radars, including phased arrays. The Advanced Radar Research Center (ARRC) at the University of Oklahoma (OU) is engaged in the design, construction, and testing of a mobile imaging weather radar system called the atmospheric imaging radar (AIR). Initial tests performed with the AIR demonstrate the benefits and versatility of utilizing beamforming techniques to achieve high spatial and temporal resolution. Specifically, point target analysis was performed using several digital beamforming techniques. Adaptive algorithms allow for improved resolution and clutter rejection when compared to traditional techniques. Additional experiments were conducted during two severe weather events in Oklahoma. Several digital beamforming methods were tested and analyzed, producing unique, simultaneous multibeam measurements using the AIR.

1. Introduction

Close proximity to quickly evolving severe weather phenomena for high-resolution data collection is difficult to achieve with traditional fixed-site radars. Thus, mobile weather radar systems are used to increase the likelihood of near-storm observations. Mobile radars are a common sight in midwestern regions when the potential for high-impact weather events is significant. One of the original mobile systems was the Center for Severe Weather Research (CSWR) Doppler on Wheels (DOW) (Wurman et al. 1997) followed by the Shared Mobile Atmospheric Research and Teaching (SMART) radar (Biggerstaff et al. 2005). Additional systems, such as the University of Massachusetts—Amherst (UMass) X-band, polarimetric Doppler radar (X-Pol) (Venkatesh et al. 2008) and the National Severe Storms Laboratory (NSSL) and the University of Oklahoma X-band dual-polarimetric radar (NO-XP) (Schwarz and Burgess 2010), improved mobile radar measurements by incorporating dual-polarization capabilities, which allow for attenuation correction and hydrometeor classification (Ryzhkov and Zrnić 1994) among other benefits. Other systems advance mobile radar performance by enhancing spatial resolution through the utilization of higher frequencies and pulse compression techniques. The Texas Tech University Ka-band (TTUKa) radar (Weiss et al. 2009) and the UMass W-band radar (Bluestein et al. 1995) are two such systems. One common feature of all of the systems mentioned thus far is their use of a traditional parabolic dish. In other words, the systems utilize a pencil beam to gather volumetric storm data. Temporal resolution is thus limited and has prompted further exploration for technological advancement in the mobile radar community.

To improve the update time of volumetric storm data, mobile radars have employed various techniques.
Electronic beam steering and frequency hopping are two, somewhat unrelated techniques that aim to improve temporal resolution. Electronic steering can be accomplished in a fraction of the time it takes to mechanically steer the dish of the radar. The CSWR rapid-scan DOW (Wurman and Randall 2001) makes use of multiple frequencies to generate several beams fixed in elevation while mechanically scanning in azimuth. The rapid-scanning X-band polarimetric radar (RaXpol) employs a frequency-hopping technique to allow for high-speed antenna rotation, thus reducing the time required to collect volumetric storm data (Pazmany and Bluestein 2009). The Meteorological Weather Radar 2005 X band (MWR-05XP) uses both phase and frequency scanning to steer the beam in elevation and azimuth, respectively, but it also relies on mechanical steering to a large extent (Bluestein et al. 2010).

Many significant experiments have been completed with these systems, including the second Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX2) project (Wurman et al. 2012), where a fleet of radars, including those mentioned above, were deployed over several weeks and two spring seasons, primarily in search of tornado events. Data collected during these experiments have improved the understanding of tornado life cycles, which in turn has enhanced radar tornado detection algorithms and can potentially lead to a reduction in lives lost to severe weather through the construction of structures better able to withstand the force of tornadic winds (Metzger et al. 2011).

While the aforementioned techniques are valid in the attempt to improve the temporal and spatial resolution of Doppler weather radars, additional approaches exist. As an example, this work presents the atmospheric imaging radar (AIR), developed by the Advanced Radar Research Center (ARRC) at the University of Oklahoma (OU), which employs imaging techniques to simultaneously gather volumetric data on a mobile platform. The AIR is similar to the MWR-05XP phased array radar, in that it electronically steers its receive beams in the vertical dimension by adjusting the phase to each of the 36 receive elements. However, each beam that is generated is done so simultaneously in software and without a physical phase switching network. Also, like the aforementioned radars, mechanical scanning is necessary for azimuthal steering. Temporal resolution of volumetric data collection is improved by gathering a range–height indicator (RHI)-type scan with each radar pulse, the boundaries of which being defined by a broad transmit beam, a feature unique to the AIR. Further, with the use of digital beamforming, additional algorithmic versatility is available with the AIR, allowing for improved spatial resolution and clutter suppression.

In the following section, a discussion of imaging radars and the technology they employ is given. Section 3 contains a detailed system description of the AIR, while a summary of beamforming techniques is presented in section 4. Results from initial calibration and testing are given in section 5, and examples of weather data collected with the full system are presented in section 6. Finally, a summary of the findings and a discussion of future experiments are given in section 7.

2. Imaging radars

Multichannel radar systems, specifically phased array radars, have gained much notoriety in the weather radar community over the last few years largely due in part to the research performed at the National Weather Radar Testbed (NWRT) (Forsyth et al. 2005). Beam agility achieved through electronic beam steering is one of the features that makes systems like the NWRT so attractive (Yu et al. 2007; Zrnčić et al. 2007). Beam multiplexing allows the phased array system to perform multiple tasks simultaneously by eliminating the need to physically move the antenna. Additionally, phased array systems are able to utilize specific elements to reduce the impact of clutter signals (Le et al. 2009; Yeary et al. 2011).

Imaging technology has been used for many years in the mesosphere–stratosphere–troposphere (MST) radar community (Farley et al. 1981; Röttger and Ierkic 1985; Palmer et al. 1990). Similar to phased array radars, imaging radars also possess the ability to steer the beam electronically. However, unlike phased arrays, imaging radars instantaneously generate many simultaneous beams, removing the need to electronically steer as data are collected. Instead, the beam formation is performed through postprocessing techniques via software, called digital beamforming (DBF) (Skolnik 2001), which greatly improves the temporal resolution of the data collected. An illustration of an imaging radar wide transmit beam and simultaneous receive beams is given in Fig. 1. As the illustration indicates, the AIR provides continuous coverage of the atmosphere over the transmitter-defined field of view (FOV). The illustration greatly exaggerates the 20° FOV (green) for the purpose of depicting the multiple simultaneous receive beams (red) that are produced with each radar pulse. Improvements in spatial resolution, specifically in range, are generally achieved through pulse compression techniques (Skolnik 2001). Interestingly, altering transmit frequencies pulse to pulse allows imaging techniques to be applied in the range dimension and results in improved range
resolution, known as range imaging (Palmer et al. 1999). Combinations of range imaging and DBF yield high spatial resolution, both in angle and range (Yu and Palmer 2001).

Imaging radars also possess the ability to reduce the impact of clutter signals present in the radar sidelobes through the use of adaptive beamforming techniques (Cheong et al. 2006; Yu et al. 2010). Also, simultaneous beam generation allows great flexibility in data processing schemes. Different dwell window lengths can be applied to independent beams, creating versatility in the production of radar images. Long dwells can be used for stationary clutter mitigation, while shorter dwells can be implemented to examine quickly evolving phenomena.

Historically, imaging radars have been used to study the upper atmosphere (Farley et al. 1981; Röttger and Ierkic 1985; Palmer et al. 1990; Kudeki and Sürüçü 1991). More recently the boundary layer has been studied using imaging techniques through a radar at UMass called the turbulent eddy profiler (TEP) (Mead et al. 1998). Studies have shown the versatility of the TEP and its use in meteorological applications (Palmer et al. 2005; Cheong et al. 2006). TEP operates at 915 MHz and is a vertically pointing radar, thus limiting its use in precipitation studies, though hydrometeors are detected with the system.

A focused phased array imaging radar (FOPAIR) was developed at UMass, and high-resolution sea surface measurements were examined (McIntosh et al. 1995; Frasier and McIntosh 1996). The X-band, multichannel radar utilized a single receiver and recorded data through a high-speed switching network, which facilitated sequential scanning similar to synthetic aperture radar (SAR). A single-wide transmit beam was used to illuminate the FOV, and beamforming techniques were utilized to form the receive beams.

The success of TEP and FOPAIR provided validation for the use of imaging technology in environmental observations and prompted the creation of the AIR. Unlike many of the imaging predecessors, excluding FOPAIR, the AIR operates at X band, providing a balance between sensitivity, attenuation, physical size, cost, and is used solely as a precipitation radar, whose primary focus is that of rapidly evolving weather phenomena—namely, severe storms.

3. AIR

Composed of 36 separate antenna elements arranged along a linear baseline, the AIR simultaneously creates a flexible number of beams in a single dimension. The primary mode of operation is the RHI mode, meaning the DBF occurs in the vertical dimension. A photograph of the completed AIR is given in Fig. 2, while
A summary of the AIR technical characteristics is given in Table 1. As with the aforementioned mobile radar systems, mechanical steering is necessary for azimuthal scanning in this mode. The capability to rotate the array $90^\circ$ along the array plane allows the AIR to perform DBF in a plan position indicator (PPI) style and can be achieved with relatively minor mechanical adjustments.

Sensitivities associated with the AIR are defined in terms of minimum detectable reflectivity, or the maximum range at which a particular class and/or density of hydrometeors can be detected. In this case, a sensitivity of no worse than 10 dB at 10 km was determined to be an achievable goal, given the loss of directive gain due to the wide FOV and the attenuation expected at X band. The sensitivity calculation was derived from the weather radar equation (Doviak and Zrnić 1993), and parameters specific to the AIR found in Table 1 are used to determine the equivalent reflectivity at 10 km. It is important for the AIR to attempt to match standard mobile radar range and angular resolutions of 30 m and $1^\circ$, respectively. Pulse compression will be necessary to meet the sensitivity and range resolution requirements, as longer pulses must be utilized to increase the sensitivity of the AIR.

Pulse compression techniques are well documented, specifically for weather radar applications (Mudukutore et al. 1998; Bharadwaj and Chandrasekar 2012). Distributed targets are known to degrade the performance of pulse compression techniques, and the degree of degradation is directly related to the decorrelation time of the volume scatterers (Gray and Farley 1973). It is necessary to design a pulsed waveform that is short relative to this decorrelation time, which can be estimated from the expected velocity spread, or spectrum width, of the volume. Knorr (2005) estimates that a spectrum width of 1 m s$^{-1}$ indicates a decorrelation time of 10 ms. The longest pulse width anticipated by the AIR is less than 10 $\mu$s, and thus should not suffer from significant degradation due to the distributed targets. Experiments examining the use of pulse compression techniques were not completed at the time of the data collections presented in this paper, but they will be explored in future works.

A high-level block diagram of the major system components is given in Fig. 3, and the following sections summarize the various components and subsystems of the AIR.

### Truck and pedestal

The pedestal has a variable rotation rate with the capability of scanning at $45^\circ$ s$^{-1}$, and a linear actuator allows the array panel to point at various elevation angles. The transmitter and upconversion systems are located in a temperature-controlled enclosure mounted behind the array panel. Additionally, interelement spacings can be changed, allowing for alternative antenna arrangements to be explored for future experiments, possibly improving angular resolution and providing a solution to undesirable DBF artifacts like grating lobes. A slotted waveguide array is fixed above the antenna elements at the top of the panel and produces the transmit beam that defines the radar FOV.

| TABLE 1. System characteristics of the AIR. |
|-----------------|-----------------|-----------------|
| **General**     |                 |                 |
| Frequency       | 9.55 GHz        |                 |
| Power           | 3.5-kW TWT      |                 |
| Duty cycle (max)| 2%              |                 |
| Sensitivity     | 10 dBZ at 10 km |                 |
| Typical pulse width | 8 $\mu$s     |                 |
| Range resolution| 30 m (pulse compression) | |
| **Antenna elements** |            |                 |
| 3-dB beamwidth  | $1^\circ \times 20^\circ$ | |
| Gain            | 27 dBi          |                 |
| Voltage standing wave ratio | 2:1 |                 |
| Polarization    | Horizontal (RHI mode) | |
| **Transmit array** |               |                 |
| Gain            | 28.5 dBi        |                 |
| 3-dB beamwidth  | $1^\circ \times 20^\circ$ | |
| **Array**       |                 |                 |
| Beamwidth       | $1^\circ \times 1^\circ$ | |
| No. of elements | 36              |                 |
| **Pedestal**    |                 |                 |
| Rotation rate   | 20$^\circ$ s$^{-1}$ | |

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**Fig. 3.** A block diagram depicting the radar system components. Coherent measurements are attainable due to a master oscillator distribution network and scan-to-scan calibration. A detailed description of each subsystem is given in section 3.
b. Antenna elements and array design

Each antenna element is itself an array of patch antennas, and was designed and built by Micro-Ant, LLC. Data flow and storage limitations restrict the total number of antenna elements. This, coupled with the desired antenna beamwidth, determined the overall size of each antenna element, which is 1.2 x 0.05 m. By combining the signals from each antenna element, an effective two-way 3-dB beamwidth of 1° x 1° can be achieved. A depiction of the AIR two-way beam pattern is given in Fig. 4.

Simulations of the full array were performed utilizing a Gaussian approximation for the transmit beam (blue) and a reconstructed antenna element pattern (green) made from real measurements provided by Micro-Ant. Note that both the transmit and antenna element patterns are approximately 20° wide. By combining all 36 of the wide antenna element patterns together using one of the beamforming techniques discussed in the subsequent sections, a more traditional, narrow beam pattern can be generated (red). The two-way pattern shown in Fig. 4 is so named because both the transmit and receive beam patterns are combined to produce the image.

Sidelobe levels depicted in Fig. 4 are quite high and certainly undesirable; however, advanced beamforming techniques can be applied to reduce the impact and will be discussed in the next section. Additionally, grating lobes are observed at approximately ±33° from broadside.

Grating lobes appear when the array element spacing is wider than λ/2, where λ is the carrier signal wavelength. For the AIR, the antenna element spacing is approximately 1.8λ. When pointed at broadside, the grating lobes exist at greater than 70 dB below the main beam, thus ambiguities caused by their presence are minimal. However, steering the main beam to ±10°, the extent of the FOV for the AIR, attenuates the main lobe slightly and increases the strength of the grating lobes to 34 dB below the main lobe.

Interference and ambiguities due to grating lobes can potentially be a problem in RHI mode if the radar is close to a deep storm with strong reflectivity at upper levels. Interference from grating lobes is expected to primarily affect the lower edge of the FOV. As the beam steers to the lowest elevation angles, the upper grating lobe will be at its closest approach to any scatterers at high elevation angles (>23°). As a result, any large signals falling within the grating lobe beam will appear to be located within the main lobe, producing discontinuities in the lower portion of the FOV. Techniques involving irregular array spacing will be explored in the future to help resolve this issue (Bray et al. 2002); however, significant influence of the grating lobes on weather data collected by the AIR has not been observed to date.

c. Downconversion and data storage

Each antenna element has an individual downconversion enclosure mounted on the back of the structure. A photograph of the enclosure is shown in Fig. 5a. Each unit weighs approximately 3.18 kg fully populated and is sealed from the outside environment. Heat accumulation within the enclosures is not a significant concern; however, powered components are seated directly against the wall of the enclosure and the outer wall is embedded with heat fins at these locations. Additionally, desiccant is utilized within the enclosure to absorb any condensation that may form.

The downconversion units are responsible for transferring the received radio frequency (RF) signal from 9.55 GHz to the 50-MHz intermediate frequency (IF) and are composed of a mix of connectorized and printed circuit board (PCB) components. This hybrid design was used primarily to reduce costs of the total system given the large number of channels. The downconversion units each accept an 80-MHz stable reference signal that is distributed from a master oscillator within the truck cab. Phase-locked oscillators within each unit allow the system to maintain a high level of coherency between elements. Direct current (dc) power is distributed to all 36 channels from three large power supplies also housed within the truck.
Computer software aided in the initial design of the downconversion units and allowed for parameters like linear dynamic range (LDR) and 1-dB compression points (P1dB) to be considered prior to prototyping and production purchasing. Implemented designs were able to achieve 86-dB LDR with typical gain values of 24 dB and a noise figure of 2.6 dB. Phase noise measurements revealed that the downconversion units were able to achieve $-80$, $-85$, $-105$, and $-133$ dBc Hz$^{-1}$ at 1, 10, 100, and 1000 kHz, respectively. Overall, the performance of the downconversion units is adequate for use on the AIR.

IF signals produced by the downconversion units are then passed to 1 of 5 eight-channel digital receivers, also designed and built at OU and shown in Fig. 5b (Meier et al. 2012). The sampling rate is 40 MS s$^{-1}$ and utilizes the latest in software-defined radio technology to produce 14-bit in-phase and quadrature (IQ) data streams. Each digital receiver is reconfigurable over the ethernet and has the capability to adjust the decimation rate and compensation filter coefficients. The baseband IQ streams are then stored on three 7-TB servers for postprocessing.

d. Transmitter and upconversion

A model 174X 3.5-kW traveling wave tube (TWT) amplifier purchased from Applied Systems Engineering, Inc. is responsible for generating the output transmit signal and is capable of producing an 8-μs pulse at a 2500-Hz pulse repetition frequency (PRF). The long pulse capability provided by the TWT helps to recover the loss in sensitivity incurred through the wide transmit beam. However, a long pulse also produces large range gates, reducing spatial resolution. To achieve the desired 30-m range resolution while maintaining radar sensitivity, pulse compression must be performed. Initial tests have illustrated the capability of the AIR to achieve good range-sidelobe performance while utilizing appropriately tapered linear-frequency-modulated (LFM) waveforms; however, a full implementation was not available during the data collection discussed in this paper. More thorough analysis of the pulse compression capabilities of the AIR will be included in subsequent publications. Waveform flexibility is achieved through an arbitrary waveform generator that produces a 50-MHz IF signal, which is then converted via connectorized components to the 9.55-GHz transmission frequency. The high-frequency signal is then amplified by the TWT and a slotted waveguide array is used to transmit the $1^\circ \times 20^\circ$ FOV beam. Both receive and transmit subsystems are driven by the same 80-MHz reference signal, which is distributed to all components to maintain coherency.

e. Array calibration

Array calibration is an important issue for phased array radars, including imaging systems. It is typical for such systems to receive periodic calibration adjustments over time. However, this process is time consuming and is not suitable for time-sensitive data collection during severe storms. Instead, a technique that could be employed while processing the data was desired so as not to interrupt data collection. A technique based on the cross correlation between adjacent antenna elements is used for each dwell (Attia and Steinberg 1989). The performance of this calibration method matches that used during the single- and dual-source tests, and its functionality has been tested with weather cases successfully. Phase drift between antenna elements is slow, thus recalibration is only required on the order of minutes.
Typically, the calibration is performed at the start of data processing and the values are used for the remainder of the fileset, normally 1–3 min of data. It is known that by utilizing this technique, uncertainties in the angle of arrival can manifest. These linear angle offsets can easily be corrected by utilizing the ever-present ground clutter signals, with some discretion, as in the angle of arrival can manifest. These linear angle remainder of the fileset, normally 1–3 min of data. It is data processing and the values are used for the re-

Typically, the calibration is performed at the start of APRIL 2013 I S O M E T A L . 661 AIR and the benefits of each.

desired direction controlled by \( \mathbf{w} \), gives a complex voltage corresponding to the desired direction controlled by \( \mathbf{w} \):

\[
y(t) = \mathbf{w}^H \mathbf{x}(t),
\]

where \( H \) indicates a Hermitian operator. By selecting different weight vectors, the array scans across the FOV, sampling different points in angular space. As with traditional weather radars, power and velocity estimates improve as the sample size increases. Thus, \( N \) temporal samples are gathered from each array element and the vector \( \mathbf{x}(t) \) becomes an \( M \times N \) matrix, \( \mathbf{X} \). Likewise, a set of pointing vectors is developed for each of the \( L \) desired sampling angles, creating a matrix \( \mathbf{W} \), which is \( M \times L \). Power and velocity can then be estimated utilizing a variation of the pulse-pair processing technique discussed in Doviak and Zrnić (1993) and derived in Cheong et al. (2004) through the calculation of the autocovariance of the array output signals:

\[
R_{yy}(\tau) = E[y(t)y^H(t-\tau)] = E(\mathbf{W}_l^H \mathbf{X} \mathbf{X}^H \mathbf{W}_l) = \mathbf{W}_l^H R_{xx}(\tau) \mathbf{W}_l.
\]

where \( \mathbf{W}_l \) represents the \( l \)th column of the steering vector matrix. Thus, \( R_{yy}(\tau) \) is a scalar value and \( R_{xx}(\tau) \) is an \( M \times M \) matrix at lag \( \tau \). Typically, the weight matrix is given by

\[
\mathbf{W} = \frac{1}{\sqrt{M}} \begin{pmatrix}
    e^{j(2\pi\lambda)\sin\theta_1 d_1} & e^{j(2\pi\lambda)\sin\theta_1 d_2} & \cdots & e^{j(2\pi\lambda)\sin\theta_1 d_M} \\
    e^{j(2\pi\lambda)\sin\theta_2 d_1} & e^{j(2\pi\lambda)\sin\theta_2 d_2} & \cdots & e^{j(2\pi\lambda)\sin\theta_2 d_M} \\
    \vdots & \vdots & \ddots & \vdots \\
    e^{j(2\pi\lambda)\sin\theta_M d_1} & e^{j(2\pi\lambda)\sin\theta_M d_2} & \cdots & e^{j(2\pi\lambda)\sin\theta_M d_M}
\end{pmatrix},
\]

where \( \theta_l \) is one within the set of \( l = (1, 2, \ldots, L) \) desired sampling angles, \( \lambda \) is the radar operating wavelength, and \( d_m \) is the position of the \( m \)th radar element from the phase center of the array. Utilizing the pulse-pair processor concept (Cheong et al. 2004), power and radial velocity can be obtained via

\[
P(\theta_l) = R_{yy}(0) = \mathbf{W}_l^H R_{xx}(0) \mathbf{W}_l
\]

\[
\nu_r(\theta_l) = -\frac{\lambda}{4\pi T_s} \arg[R_{yy}(T_s)],
\]

where \( T_s \) is the pulse repetition time (PRT).

b. Weighted Fourier beamforming

Variations of the pulse-pair beamforming technique are explored on the AIR with the goal of improving the accuracy and performance of the radar. The first and most straightforward variation is to perform a weighted Fourier beamforming by simply augmenting the weight matrix through a Hadamard product with a matrix of scalar values, \( \mathbf{A}_{\text{win}} \):

\[
\mathbf{W}_{\text{win}} = \mathbf{W} \circ \mathbf{A}_{\text{win}}
\]

\[
= \mathbf{W} \circ \begin{bmatrix} (a_1, a_2, \ldots, a_M) \end{bmatrix}^T \begin{bmatrix} 1 & 1 & \ldots & 1 \end{bmatrix},
\]

where \( a_m \) is the \( m \)th value of any window function (Hamming, Hann, etc.) arranged in a column vector, which is then multiplied by an \( L \)-length row vector of ones. The columns of \( \mathbf{A}_{\text{win}} \) are selected such that the amplitude of each array element is weighted by a value \( a_m \), thus reducing the impact of sidelobes in the beamforming dimension at the expense of a deterministic loss in angular resolution and gain.

c. Capon beamforming

Data-dependent techniques alter the weighting function adaptively and are able to minimize the impact of
sidelobes while improving the angular resolution. One such technique, known as Capon’s method or the minimum variance method, attempts to minimize the power output of the beamformer while maintaining unity gain in the desired pointing direction (Capon 1969). The resulting beam pattern attempts to place nulls over points of strong interference or clutter. Expressed mathematically,

$$\min_w P(\theta) \text{ subject to } e^H w = 1,$$

where \(e_i = [e_i(2\pi/\lambda)^n d_1 e_i(2\pi/\lambda)^n d_2 \ldots e_i(2\pi/\lambda)^n d_d]_n\).

By examining the mathematical statement of Capon’s method, it is apparent that little control of the beam pattern is maintained at angles other than the direction of interest. It is possible that, for areas other than the pointing direction with low signal strength, high gain values can result. The impact should be minimal since the signal strength is low.

Lagrangian methods are used to solve the well-known minimization problem and a solution for the Capon weight vector follows:

$$w_c = \frac{R_x^{-1}(0)e_i}{e^H R_x^{-1}(0) e_i}.$$  \hspace{1cm} (8)

The Capon weight vector is then substituted for \(W_i\) in both Eqs. (4) and (5) for high-resolution estimates of power and radial velocity.

While the angular accuracy of Capon’s method is often superior to that of Fourier beamforming, small errors present in the steering vector, \(e_i\), can reduce the accuracy of amplitude estimations. Small errors can arise due to uncertainties in the array element positions, which result in an offset between the point of interest and the unity constraint location, thus allowing Capon’s method to attenuate or skew the power measurement at the desired angle. A robust version of Capon’s method exists that makes assumptions regarding the uncertainty weighting vector and iteratively converges toward an optimal solution (Li et al. 2003; Li and Stoica 2006; Stoica and Moses 2005).

d. Robust Capon beamforming

As previously mentioned, robust Capon beamforming (RCB) makes an assumption that the true steering vector, \(e_0\), lies within an uncertainty set of ellipsoidal shape, or

$$[e_0 - e_i]^H C^{-1} [e_0 - e_i] \leq 1,$$  \hspace{1cm} (9)

where \(e_i\) is the initial estimate of the steering vector, as previously defined, and \(C\) is a positive definite matrix. In the previous subsection, the Capon beamformer was viewed as a spatial filtering problem. For the robust Capon beamformer, the problem is viewed from a covariance fitting standpoint and attempts to find the largest possible power at the signal of interest while keeping the residual covariance matrix positive semi-definite (Li and Stoica 2006). At the same time, only steering vectors within the previously defined uncertainty ellipsoid are considered. Thus, the beamforming optimization is formulated as

$$\max \sigma^2 \text{ subject to } R_{xx} - \sigma^2 ee^H \succeq 0$$

for any \(e\) satisfying \([e - e]^H C^{-1} [e - e] \leq 1\), \hspace{1cm} (10)

where \(\sigma^2\) is the power in the direction of interest. A complete and thorough derivation of the solution to the above formula can be found in Li et al. (2003). However, a summary of the steps involved is given in pseudocode format below:

(i) Select a value for \(\epsilon\) (related to the ellipsoidal search space).

(ii) Perform the eigendecomposition of \(R_{xx}\) and find \(U, \Gamma\), where \(U\) is the set of eigenvectors and \(\Gamma\) is a diagonal matrix containing the corresponding eigenvalues, \(\gamma_m\), with \(m = 1, \ldots, M\).

(iii) Set a new vector \(z = U^H e_0\).

(iv) Solve \(g(\lambda) = \sum_{m=1}^M |z_m|^2 (1 + \lambda \gamma_m)^2 = \epsilon\) for \(\lambda\) using Newton’s method knowing the solution is unique and lies in the range \([\|e_0\| - \sqrt{\epsilon}/(\gamma_1 \sqrt{\epsilon}) \leq \lambda \leq \min(\|e_0\| + \sqrt{\epsilon}/(\gamma_1 \sqrt{\epsilon}), (\|e_0\| + \sqrt{\epsilon})/(\gamma_1 \sqrt{\epsilon})\)]\).

(v) Use the determined value of \(\lambda\) to find \(e_0 = e_i - U (I + \lambda \Gamma)^{-1} U^H e_i\).

(vi) Compute the estimated signal power from \(\bar{\sigma}^2 = (\|e_0\|^2 / M) (1/e_i^H U \Gamma (\lambda^2 - I + 2\lambda^{-1} \Gamma + \Gamma^2)^{-1} U^H e_i)\).

(vii) Calculate the new RCB weights \(w_{\text{RCB}} = \{[R_{xx} + (1/\lambda) I^{-1}] e_i]/[e_i^H [R_{xx} + (1/\lambda) I^{-1}]^{-1} R_{xx} (1/\lambda) I^{-1}] e_i\}.

(viii) Use \(w_{\text{RCB}}\) for \(W_i\) in Eqs. (4) and (5).

The result of the algorithm are high-angular-resolution estimates that do not suffer from uncertainties in the steering vector.

RCB was chosen because it is relatively inexpensive computationally and is known to improve errors due to steering vector uncertainties, which greatly enhances the data quality of the beamformer. The user parameter \(\epsilon\) is an important factor in the performance of the RCB algorithm and is directly related to the steering vector error. Utilizing small values for \(\epsilon\) causes the RCB algorithm to approach that of Capon, while values larger than what are required reduce the ability of...
RCB to suppress interferers and thus $\epsilon$ should be chosen as small as possible (Li and Stoica 2006).

The following sections describe the implementation and testing of the aforementioned beamforming techniques. Results from initial tests are examined first, followed by real weather data examples.

5. Initial tests

Receive subsystem validation was achieved through a series of experiments involving two signal sources separated in both frequency and space with the goal of evaluating the AIR angular resolution and the viability of potential beamforming algorithms. To do so, two sources were placed approximately 125 m from the array and time series data were collected for each antenna element. One source was placed on the balcony of a nearby building, and the other source was placed on the roof. This physical arrangement gave an angular separation of approximately 2.85°. Each source transmitted a continuous wave signal, and data were collected passively by the antenna element/receive subsystems. Initially, only one source was activated, followed by subsequent tests that utilized both sources transmitting simultaneously.

Preliminary results of the single- and dual-source tests are shown in Fig. 6. Standard Fourier beamforming was applied to 500 temporal samples from all 36 antenna elements and generated images with the application of a Hann window function (Fig. 6a). Additionally, Capon and RCB techniques were used to evaluate the functionality of the AIR and are shown in Figs. 6b and 6c, respectively. Both adaptive algorithms are known to perform well when the number of samples exceeds the number of array elements (Li and Stoica 2006) and thus 500 samples are an appropriate number for accurate beamforming calculations. The mean noise level was calculated using a technique similar to Hildebrand and Sekhon (1974) and was determined to be $-80.02$ dB.

![Fig. 6. Results of the single- and dual-source tests using (top) windowed Fourier beamforming, (middle) Capon beamforming, and (bottom) RCB. A Hann window was selected for comparison in the windowed Fourier beamforming case. Note that the array is able to resolve the two signal sources separated by 2.85° in elevation in all cases; 500 samples were used as input to the beamformers. The RCB image was produced using $\epsilon = 9$ and was necessary to produce appropriate power levels. The flat shape of the signal sources is an artifact of the large $\epsilon$ value.](image)

### Table 2. Isolated cell parameters on 8 Aug 2011.

<table>
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<th>Value</th>
</tr>
</thead>
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</tr>
<tr>
<td>Lon</td>
<td>97°46′461″W</td>
</tr>
<tr>
<td>PRT</td>
<td>0.8 ms</td>
</tr>
<tr>
<td>Dwell</td>
<td>500 samples</td>
</tr>
<tr>
<td>$\tau$</td>
<td>1 $\mu$s</td>
</tr>
<tr>
<td>Bearing</td>
<td>60°</td>
</tr>
<tr>
<td>Time</td>
<td>0227–0235 UTC</td>
</tr>
</tbody>
</table>

Without the application of the Hann window function (results not shown), the two-way beamwidth is 0.77° and the first sidelobe is located at 1.25° with a sidelobe level...
(SLL) of $-13.24$ dB. After the application of the window function (shown in Fig. 6a), the beamwidth increases to $1.3^\circ$ and the first sidelobe is located at $2.12^\circ$ with an SLL of $-31.5$ dB. As expected, the addition of the window function to the windowed Fourier beamforming algorithm resulted in the lowering of sidelobes at the expense of angular resolution. The benefit of windowed Fourier beamforming is the reduced leakage from off-target angles to the main lobe, thus diminishing the ambiguity of measurement values. However, the 3-dB width of the main beam also is enlarged, making it more difficult to distinguish targets separated by small distances. Additionally, the application of the window function weights results in a deterministic reduction in signal power. In general, the sacrifice in resolution is acceptable given the sidelobe performance.

Traditional beam-shape figures of merit, like beamwidths and SLLs, are more difficult to quantify for the Capon case due to the nature of the experiment. It is apparent that the Capon beamforming technique suffers from a discrepancy between the expected steering vector and the true steering vector, for example, $\mathbf{e}_0 - \mathbf{e}_1 \neq 0$. Thus, the algorithm attenuates the signal of interest instead of leaving it unchanged [see Eq. (7)] and accounts for the low power levels observed in these initial tests. However, it is important to note, qualitatively, the improvement in performance with the use of Capon beamforming on the point target measurements.

To mitigate the uncertainty in the steering vector, the RCB algorithm discussed in the previous section was applied. Benefits obtained by utilizing the robust Capon algorithm are readily observed in Fig. 6c, as an improved power estimate is regained while achieving improved point-resolving capabilities. It is important to note that the adaptive algorithm performance will differ when distributed targets are analyzed. A distributed field of targets will force the beam to amplify some regions while attenuating others, ideally where sources of interference lie. Unfortunately, weather is a somewhat
homogeneous medium and adjacent angular cells contain power levels similar to the cell of interest, making attenuation of multiple near-in cells difficult. However, the improvement in angular resolution is expected to outperform the windowed Fourier technique and the removal of nonmeteorological interference sources is superb. RCB is thus presented as an additional technique for DBF weather radars.

The user-chosen value of $\epsilon$ directly affects the accuracy of the power estimates as well as the flat shape of the source returns presented in Fig. 6c. As mentioned previously, the value of $\epsilon$ should be chosen to be as small as possible while still achieving improved power estimates over Capon beamforming. If $\epsilon$ is too large, then the ability to remove interference targets is greatly diminished and the return signals become unusable. A value of 9 was used in this case.

6. Weather data collection

a. 8 August 2011

The first operational test of the AIR occurred on the evening of 8 August 2011. The deployment area was near the Westheimer Airport in Norman, Oklahoma, and a spotlight mode RHI scan strategy was employed. The RHI scan mode simplified the subsequent data processing and provided a quick validation of the system functionality. The location of the AIR together with the scanning parameters are given in Table 2.
Early that evening, a line of thunderstorms formed along a cold front passing through central Oklahoma. The 0000 UTC OUN sounding (not shown) reveals temperatures at the surface exceeding 40°C and dewpoints of less than 20°C, indicating the presence of a dry layer extending from the surface to approximately 3000 m. Because of this scenario, high wind gusts with large damage potential were a strong possibility. An image of a scan collected with a nearby Weather Surveillance Radar-1988 Doppler (WSR-88D) radar, KTLX, is given in Fig. 7, providing an overview of the weather scenario. The image was produced using the Unidata Integrated Data Viewer. The location of the AIR is denoted by the white cross, while KTLX is centered beneath the intersection of the two heavy white lines. Comparison reflectivity and radial velocity RHI scans reconstructed from KTLX volumetric data are given in Fig. 8. The black line in the images represents the AIR FOV. While the images are of coarser quality than will be presented with the AIR, a qualitative comparison can be made.

The AIR was located approximately 20 km bearing 240° from KTLX. Spotlight-mode RHI scans were collected with the beam pointing 60° from north. A series of storm cells proceeded through the beam, and several minutes worth of data were collected with each of the three computers storing IQ samples at a rate of approximately 160 MB s⁻¹. For all scans, $T_s = 0.8$ ms and a pulse width of 1 μs was used, thus no pulse compression was implemented during this test. Return power and radial velocity measurements censored for signal-to-noise ratios greater than 3 dB are displayed in Figs. 9 and 10, respectively. A windowed Fourier beamforming algorithm was employed, and 500 samples were used to...
process each image. The range and height extent of each individual image is 3–11 and 0–4 km, respectively. Approximately 50 s worth of data were collected with a $\Delta t$ between each image of 6.25 s. Because of the high temporal resolution of the AIR, the images presented in Fig. 9 represent a decimated view of the true temporal resolution of $\Delta t = 1.25$ s.

By comparing the scans in Figs. 9 and 10 with the images in Fig. 8, it is apparent that the AIR is able to observe the target storm at a very high resolution, both temporally and spatially. Fine details within the cell and subtle changes scan-to-scan visible to the AIR would not be available on systems like KTLX or other traditional scanning dish radars. Granted, some of the motion visible in the AIR images is due to advection of the cell through the fixed radar beam position; however, the temporal scale of the RHI images exceeds that of KTLX. Because of this fact, it is difficult to perform a direct comparison between the two radars; however, general agreement can be observed. The cell of elevated reflectivity visible in the KTLX data (Fig. 8) located from 12 to 16 km in range and from 0 to 1.5 km in height roughly matches the shape of the cell observed with the AIR. Note that the AIR and KTLX beams are opposing, so the sign of the radial velocity values are reversed between the two radars. Also, the AIR PRT limits the maximum ambiguous velocity to 9.6 m s$^{-1}$ and radial velocities have been unwrapped at the midlevels.

In addition to the comparisons of temporal resolution, sensitivity can also be examined. With the 1-$\mu$s pulse width, the dynamic range of the AIR is limited to 20 dB due to the low average power of the transmitted pulse. As such, the high temporal resolution results in a trade-off between speed and sensitivity. By gathering data over a FOV simultaneously, the time between samples is reduced, as is the minimum detectable signal. It is expected that with the utilization of pulse compression, sensitivity of the AIR can be improved, though the trade-off still remains.

With the increased temporal resolution, the AIR can examine features of storms that would not be visible with traditional radars. For example, a region of high relative power located within the images presented in Figs. 9 and 10 appears to descend through the AIR FOV as the scan progresses. A magnified view of this rain shaft is given in Fig. 11. A horizontal black line in each image indicates the base of the core of elevated relative power. A rough estimate of the vertical motion of the descent can be obtained simply by taking the difference between the height value for each black line. For the example shown, a vertical velocity of $-9$ and $-7$ m s$^{-1}$ is calculated between the three images. More rigorous image processing techniques could be used to monitor

![Fig. 11. Magnified view of the range-corrected relative power collected during the 8 Aug 2011 event. The horizontal black lines represent the height of the base of a descending core of elevated power. Calculating the rate of change between the images represents an estimation for the vertical velocity of the core. In this case, an average value of $-8$ m s$^{-1}$ is calculated.](image-url)
the motions of particular features within the cell and would increase the accuracy of these estimates. As previously mentioned, it is difficult to determine if horizontal advection into the FOV is responsible for the appearance of descending rain. However, this exercise serves as an illustration of the additional dynamic insight obtained via the AIR.

For completeness and to fully exploit the capabilities of the imaging system, all four of the beamforming techniques discussed earlier were applied to the 8 August 2011 data and the results of the power estimates were analyzed qualitatively. A single set of 500 pulses was used to illustrate the outcome of the experiment and an image summarizing the results is given in Fig. 12. The standard Fourier beamforming results are omitted from the image. Ground clutter sidelobe artifacts are visible in the first 2 km for the windowed Fourier case. The addition of the window function to the Fourier beamformer reduces the effect of the sidelobes but also produces deterministically lower power estimates due to the tapered weight values. The reduction in angular resolution is not obvious in these images. Capon beamforming removes nearly all of the sidelobe artifacts; however, power estimates are also biased due to potential errors between the estimated and true steering vector. These errors are corrected through the use of RCB, which provides some improvement to the relative power estimates. Note the ground clutter is still visible at the lowest elevation, but the sidelobe arcs present in the windowed Fourier case are reduced in strength.

Though no ground truth exists for these experiments, it is believed that RCB provides the most detailed and accurate depiction of the weather scenario due to the improved resolution, sidelobe suppression, and corrected power estimates. Thus, the scans illustrated in Figs. 9 and 10 are recalculated using RCB and presented in Figs. 13 and 14. One limitation of RCB is determining the appropriate $\epsilon$ value. Values that are too large can cause the overestimation of signal power, while values that are too small suffer from Capon-like power underestimation. Comparisons of the RCB results to those obtained via Fourier beamforming can aid in determining the validity of the chosen $\epsilon$ value. In this case, a direct comparison between the power estimate images reveals that the RCB algorithm yields power estimates similar to those obtained with Fourier beamforming (not shown).
Although the temporal resolution of 1.25 s is sufficient for most scenarios, improvements made to the AIR data processing system designed to enhance the temporal resolution were tested on a later weather event and the results are given in the next section.

b. 17 October 2011

A cold front passing through Oklahoma initiated a line of thunderstorms in the late evening hours of 17 October 2011. The location and scan parameters are presented in Table 3. The AIR was positioned approximately 6 km east of Wynnewood, Oklahoma, and to the north of a squall line, which was traveling in an east-southeasterly direction. Again, RHI scans were collected using a PRT of 0.8 ms and a pulse width of 1 μs. For this experiment, however, alterations to the data digitization process allowed for more rapid data updates.

Using 300 pulse dwells, an RHI image is generated every 0.33 s, a significant improvement over the previous experiment. To illustrate the extremely high temporal resolution achieved by the AIR, Fig. 15 depicts 9 images from the October squall line with a Δt = 16.5 s, meaning 1 out of every 50 available images is shown. At this reduced data rate, it is possible to see minor changes in the storm structure between images. Over the course of the entire scan, the main region of elevated relative power within the storm splits and a second core develops farther downrange at approximately 7 km in height. In the event that changes such as these occur on the coarser time scale, the AIR allows for a more in-depth look at the storm evolution by viewing the data at any interval.

Fig. 13. As in Fig. 9, but RCB is used. Note the difference in the range-corrected relative power levels between the two images. RCB is able to recover the loss in beam sensitivity due to the application of the window function and appears to eliminate errors due to uncertainty in the steering vector.
greater than or equal to the full temporal resolution of 0.33 s. For instance, Fig. 16 illustrates what occurred between the $t + 16.5$ and $t + 33$ s images in Fig. 15, an action analogous to magnifying a high-resolution picture. For this particular case, as the time scale decreases, it becomes more difficult to see any appreciable evolution in the storm. However, it is advantageous to have the capability to collect a large volume of data at sub-second intervals, particularly during events in which large changes are expected on short time scales (e.g., tornadoes, hurricanes). Again, the sensitivity of the 1-$\mu$s pulse data collected by the AIR is lower than is desired for deep analysis of storms but sufficient for instrumentation analysis. Further experiments utilizing longer pulse widths will improve the sensitivity of the weather radar product estimates.

The cases presented in this study show the preliminary results of the AIR’s capability to collect high-temporal-resolution data, though the observed phenomena evolved on a relatively slow temporal scale. In future deployments, the AIR will focus on meteorological phenomena that evolve at faster temporal scales, such as tornadogenesis. During tornadogenesis, the low-level wind field may change in 15 s or less (Bluestein et al. 1999). Bluestein et al. (2010) observed rapid changes in relative power and velocity associated with the formation of a cyclonic vortex signature. Because the AIR collects data over a $20^\circ$ vertical FOV, it will provide an opportunity to obtain high-temporal-resolution measurements of both the tornado and low-level mesocyclone nearly simultaneously during tornadogenesis and throughout a tornado’s lifetime. Such temporal resolution can help identify how important changes in the intensity of low-level mesocyclone are to tornado formation and how changes in wind speed at one level are transferred vertically.
The AIR can track coherent structures observed in power estimates, which could provide approximations of three-dimensional motion. In the present study, an example was shown in which the data were used to track a descending relative power core and estimates of the rate of descent were obtained. Improved sensitivity obtained via pulse compression will allow the AIR to collect data with other rapid-scan mobile radars (e.g., RaXpol), and dual-Doppler analysis could be used to extract three-dimensional wind fields. The AIR’s capability to collect data over a 180° sector in 9 s would allow the radar to synchronize with other rapid-scan systems and minimize errors caused by advection or temporal evolution during the volume scan.

A future polarimetric version of the AIR could provide numerous additional opportunities for research. Given that the tornadic debris field is rapidly varying in time and large debris resides in the tornado for only a few tens of seconds (Dowell et al. 2005), the polarimetric debris signature also may vary significantly over short time scales. Moreover, changes in the tornado’s

<table>
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<td>1 μs</td>
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<tr>
<td>Time</td>
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</tr>
</tbody>
</table>


Fig. 15. A collection of data from 0039:55 UTC 18 Oct 2011, 6 km east of Wynnewood, OK, using the AIR. RCB and 300 samples were used to generate each image. A 20° vertical RHI is collected in each scan with Δθ = 0.125° and separated by approximately 16.5 s in time. These images do not represent the full temporal resolution achieved by the AIR during this experiment. A higher-temporal-resolution view of the data shown in this figure is presented in Fig. 16.
wind field on small temporal scales could affect debris lofting and centrifuging. Hence, high-temporal-resolution polarimetric radar measurements are needed to understand the characteristics of tornadic debris. Moreover, a polarimetric AIR could aid studies of lightning by observing changes in the orientation of ice crystals in response to changes in the electric field. Such changes have been observed at time scales of 10 s or less (Caylor and Chandrasekar 1996), and scale analyses by Cho et al. (1981) suggest that ice crystal orientation could change on the order of $\approx 10$ ms. Thus, a three-dimensional mapping of ice crystal orientation of a polarimetric AIR would provide a distinct tool to aid studies of ice crystal orientation changes and its relationship to lightning.

Data collections with the AIR illustrate the unique nature of the system. High-temporal-resolution and high-spatial-resolution weather data can be collected utilizing relatively routine scan parameters. Future data collections will incorporate azimuthal scanning capability, improving the scope of volumetric information. While these AIR data are limited by the low aliasing velocity ($9.6 \text{ m s}^{-1}$) and the sensitivity due to the large FOV, some relatively straightforward improvements can mitigate these shortcomings. Employing staggered PRTs, for example, will be essential in the future for the use of the AIR in severe weather events. High aliasing velocities will be necessary if the AIR is to observe tornadoes and produce meaningful data for analysis. Further, the coherent TWT-based system allows the application of pulse compression, which, if properly designed, can improve sensitivity while controlling adverse effects from range sidelobes. Plans are currently underway to implement these improvements.

Fig. 16. As in Fig. 15, but illustrating enhanced temporal capabilities of the AIR. RCB is used to achieve high spatial resolution, and data digitization processes are optimized to achieve 0.33-s update rates for a 20° RHI spotlight scan. Again, a decimated view of the full temporal resolution is shown, but the capability of the AIR to display data on various temporal resolution scales is illustrated.
7. Conclusions

The ARRC at OU designed and built a mobile imaging radar system to explore the use of beamforming techniques for high-speed data collection over large volumes of the atmosphere. Several experiments have shown the ability of the AIR to collect high-spatial-resolution data at extremely rapid rates. Well-known beamforming techniques were tested and evaluated both qualitatively and quantitatively. Fourier and windowed Fourier beamforming techniques suffer from fixed sidelobe interference. Capon beamforming allows the shape of the beam to adapt to the environment but suffers from power inaccuracies due to steering vector uncertainties that can arise in a multichannel system. Robust Capon beamforming mitigates this issue with relatively low computational cost, by improving the accuracy and resolution of estimates. Regardless of the technique used, traditional weather radar parameters of power and radial velocity can be produced through the use of the pulse-pair beamformer.

Weather data collected by the AIR thus far illustrate the applicability of imaging radar technology for meteorological applications. High-resolution images produced by the AIR surpass what is typically achievable with fixed-site radars, though sensitivity is lacking in the current state, a common trade-off for remote sensing systems. What has been provided by the AIR is another technique by which high-temporal-resolution data can be gathered, which motivates future experiments focused on gathering data from events evolving on much shorter time scales. It is believed that with the inclusion of pulse compression, the sensitivity of the AIR can be improved, thus allowing the system to produce research-quality environmental data. The capability to gather subsecond RHI images could lead to a deeper understanding of storm dynamics, including much sought after knowledge regarding tornadogenesis. The addition of azimuthal scanning capabilities will allow the AIR to capture larger volumes of data on a time scale of a few seconds.

Data collection and evaluation of the radar system will continue through the life of the radar. Adaptive beamforming techniques will continue to be applied and evaluated using the weather event data collected thus far and in the future. Currently, experiments exploring the use of pulse compression techniques are being conducted to improve sensitivity beyond current levels. Further, staggered PRT algorithms are being employed to increase the aliasing velocity.

In addition to the waveform modifications, array alterations are also proposed in future iterations of the AIR. Alternative array spacing techniques will be explored as possible mitigating measures for undesired beam artifacts, such as grating lobes. Polarimetric elements can add entirely new applications for the AIR, including debris tracking and hydrometeor classification. Also on the horizon are plans to develop a two-dimensional version of the AIR that would allow for instantaneous volumetric scans on subsecond intervals.

It is hoped that the data collected with the AIR will enhance understanding of tornadogenesis, tornado evolution, and other rapidly evolving phenomena. The rapid updates of the AIR could reveal new information about changes in tornado dynamics and structure occurring in only a few seconds.

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