8B.2 DISTRIBUTED BEAMS: A TECHNIQUE TO REDUCE THE SCAN TIME OF AN ACTIVE ROTATING PHASED ARRAY RADAR SYSTEM

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1. INTRODUCTION

Key requirements for a future generation of weather surveillance radars include improvements in data quality, a more rapid update of volumetric data, and the ability to perform adaptive weather observations. Although the operational U.S. Weather Surveillance Radar – 1988 Doppler (WSR-88D) network exceeded its expected life span, its intrinsic architecture limitations prevent it from attaining the performance levels required to meet the set of next generation requirements.

Phased Array Radar (PAR) is a candidate that may provide the required functionality by exploiting its unique capabilities. The National Oceanic and Atmospheric Administration (NOAA) is considering an affordable rotating PAR (RPAR) architecture to exceed the capabilities of the current reflector-based WSR-88D network (Weber 2019). To achieve current and future needs to support the National Weather Service (NWS) mission, a concept of operations (CONOPS) for weather surveillance using the RPAR has to be developed.

The RPAR architecture has been used for air surveillance and defense applications since the late 1970's (Palumbo and Cucci 1977, Palumbo 1996, Brookner 2002), but was only introduced for weather surveillance in recent years (Yoshikawa 2013, Ushio 2014, Orzel and Frasier 2018). The CONOPS for these weather RPAR systems consisted of either imitating the operation of conventional reflector radar or performing a straightforward electronic scan in elevation while mechanically rotating in the azimuthal direction. These limited operational concept modes do not fully exploit RPAR's unique capabilities and are not likely to meet demanding functional requirements such as the more rapid update volumetric data.

The NOAA Radar Functional Requirements document (NOAA/NWS 2015) specifies the functionality expected for a future weather surveillance radar system. The *threshold* functional requirements define the minimum expected performance, while the *optimal* functional requirements define the desired performance. One

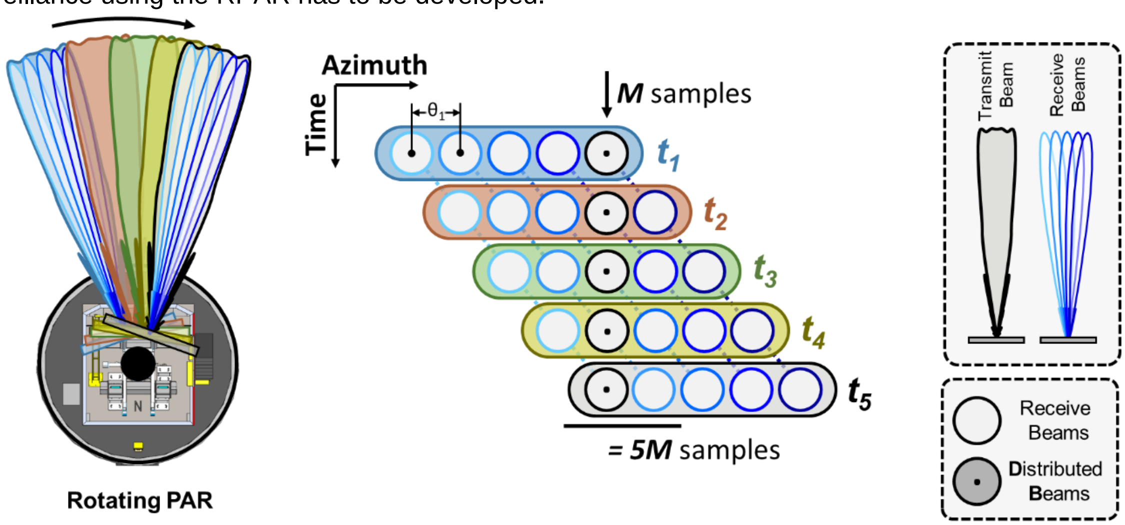

***Fig. 1. Illustration of the Distributed Beams (DB) technique*.**

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of the most demanding optimal requirements is the 1-minute update time to complete a volume scan "*with no degradation of the sensitivity, spatial resolution or standard deviation of measurement for radar variable estimates"*. To achieve this volume-update-time requirement, sophisticated scanning and digital signal processing techniques that exploit RPAR's unique capabilities are likely to be needed.

This paper introduces a novel *distributed beams* (DB) technique which provides a way to reduce scan update times. It is accomplished by synthesizing a wide (*spoiled*) transmit beam and using digital beamforming on receive as the radar rotates. Returns from subsequent receive beams pointing in the same direction are then grouped coherently. Specifically, the azimuthal rotation rate of the platform is matched to the desired sampling (spatial and temporal) such that the coherent processing interval (CPI) for a given beam position is *distributed* over several overlapping receive beams. In this manner, the scan time can be reduced by a factor equal to the transmit beam spoil factor (herein *F*). This exploits the use of spoiled transmit beams in azimuth and allows a faster rotation rate, leading to more rapid updates without degradation in data quality. A schematic of this technique is shown in Fig. 1.

This introduction section provided justification and the concept of a way to reduce the scan times of RPAR architecture. The rest of the paper is structured into four more sections. Section 2 provides an overview of the Distributed Beams CONOPS introduced and offers two DB applications. Section 3 describes DB practical implementation and calibration methods. Section 4 takes the theoretical analysis of the DB technique further by capturing and presenting real data collection using DB. Data are collected by scanning a fixed target (for calibration), and an actual weather front for a comparative demonstration of the DB CONOPS to that of a conventional weather radar. Section 5 summarizes the paper.

2. DISTRIBUTED BEAMS (DB) RPAR CONOPS OVERVIEW

Active PAR technology allows the synthesis of arbitrary antenna beam patterns on transmission by varying the magnitude and phase of transmit signals at each individual array element level (also referred to as *tapering*). This capability can be used to produce a wider transmit beam, effectively increasing the beam coverage. This comes at the expense of increased antenna pattern sidelobe levels, reduced sensitivity, and slightly increased beamwidth. For example, an active PAR antenna with an intrinsic radiation pattern that produces a narrow *"pencil"* beam (as defined by the one-way 3 dB width), can also be used to synthesize transmit beams that are wider than the intrinsic narrow beam of the system. Examples of these pencil and spoiled transmit patterns are presented in Fig. 2. Transmission of spoiled beams has been proposed

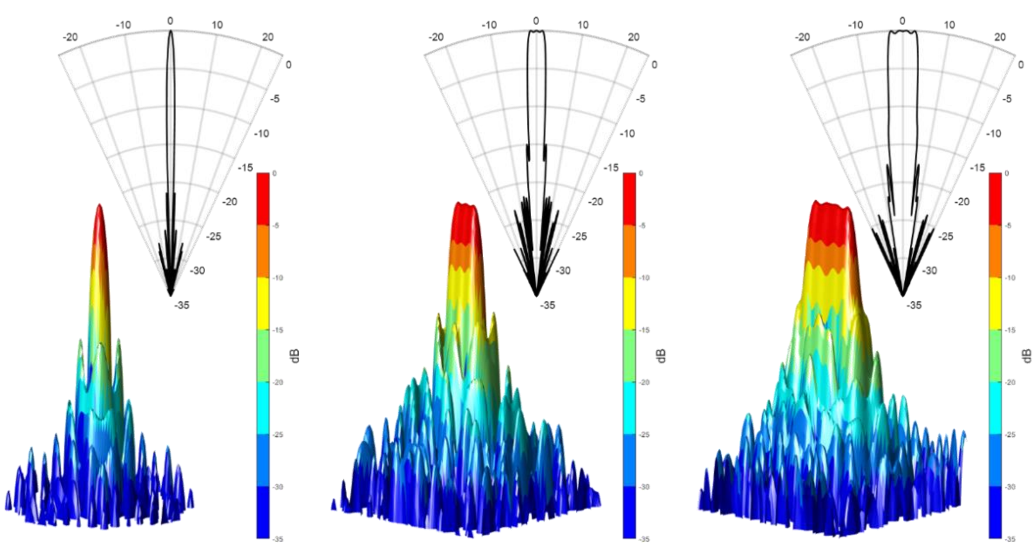

Fig. 2. Simulated one-way antenna radiation patterns for a narrow pencil beam (left), a beam spoiled by a factor of three (center), and a beam spoiled by a factor of five (right). Sectors correspond to azimuthal cuts of the antenna patterns.

for stationary PAR systems to reduce the scan time (Weber et. al, 2005). Depending on the PAR architecture, several receive beams can be simultaneously formed digitally within the transmit beam. The digitally formed receive beams use the full antenna aperture to produce a narrow *pencil* beam. However, these narrow receive beams combined with the wide transmit beam result in lowering sidelobe levels of the two-way antenna pattern.

A scan strategy for the RPAR using the DB technique is now defined. Assume the antenna is rotating in azimuth at a constant speed of ω °/s, the broadside transmit beam is spoiled by a factor F, and F beams are simultaneously formed within the transmit beam on receive to sample with a one-beamwidth (θ_1) spacing in azimuth (as illustrated in Fig. 1 for a factor F = 5). The beamwidth is defined as the angular width within which the microwave radiation is one-half of its peak intensity (Doviak and Zrnić 1993). Finally, let us define the CPI as a set of M pulses at a pulse repetition time (PRT) of T_s seconds. With this, the rotation speed can be set to

$$\omega = \frac{\theta_1}{MT_s}\ °/s,$$

to transmit the desired CPI (MT_s) over the angular sampling of θ_1. There are two applications considered here for the DB CONOPS. The two possibilities with the DB technique are: 1) *Scan Time Reduction* and 2) *Data Quality Improvement*. Both are now briefly described, followed by a comparison to conventional parabolic-reflector radar and tradeoff considerations in the context of a practical implementation.

1. ***Scan time reduction***: The number of pulses per CPI is reduced $M_{DB}=M/F$, and the rotation speed is increased to $\omega_{DB} = F\omega$. As the PAR rotates at ω_{DB}, M_{DB} pulses are received on each receive beam. In a continuous rotation regime, the centers of resolution volumes sampled by F beams received every $M_{DB}T_s$ seconds (coming from distinct transmit beams) are coming from the same azimuth location. Samples received on these beams are combined to recover the $M_{DB}F=M$ pulses required to obtain the desired data quality. Operating the radar under this concept results in reducing the scan time by a factor F.
2. ***Data quality improvement***: The number of pulses per CPI and the rotation speed are maintained at M and ω. Similar to the previous scenario, F beams received every MT_s seconds (coming from distinct transmit beams) are coming from the same azimuth location. Samples received on these beams are combined to obtain MF pulses. Increasing the number of samples by F results in a significant reduction in the variance of radar-variable estimates.

Comparing the process described in the first application to conventional radar with a parabolic-reflector antenna, the DB technique exploits the PAR beamforming capability to reduce the scan time. This increases rotation speed, but comes at a price of increased rotation speed, increased sidelobe levels (i.e., for the same antenna aperture), reduced sensitivity, and slightly increased beamwidth. Nevertheless, some of these limitations can be mitigated. As argued by Leifer et al. (2013), the rotating machinery has been around for a long time and has a high technology-readiness level, which reduces the risk of deploying PAR pedestals capable of rotating at higher rates. The sidelobe levels of the two-way pattern could be reduced to the desired levels by increasing the aperture size by a small amount, which would also improve the beamwidth. The sensitivity loss can be recovered by increasing the power radiated by each array element.

Section 3 advances the theoretical aspects of DB by presenting a practical implementation of the technique and by discussing important antenna calibration considerations.

3. DB IMPLEMENTATION ON THE ATD

The Advanced Technology Demonstrator (ATD) is an active S-band planar dual-polarization PAR that is funded jointly by the National Oceanic and Atmospheric Administration (NOAA) and the Federal Aviation Administration (FAA). It is being developed by the National Severe Storms Laboratory (NSSL), the Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) at the University of Oklahoma, MIT Lincoln Laboratory, and General Dynamics Mission Systems (Stailey and Hondl 2016, Conway et al. 2018, Torres et al. 2019). This proof-of-concept system makes use of pulse compression waveforms to meet sensitivity and range-resolution requirements (Schvartzman and Torres, 2019). The antenna is composed of 76 panels, where each panel consists of an 8×8 set of radiating patch-antenna elements with dual linear polarization (H and V), for a total of 4864 elements. This arrangement of antenna elements spaced by λ/2 results in a ~4×4 m aperture that produces a beam that is ~1.58° wide at broadside. On receive, the antenna is partitioned into overlapped subarrays (consisting of 8 panels each) to produce lower sidelobes and suppress grating lobes outside of the main beam of the subarray pattern (Herd et al. 2005). The operating frequency band of the antenna is 2.7-3.1 GHz. Through element-level control of the magnitude and phase of transmitted signals, this system is capable of synthesizing arbitrary beam patterns on transmission.

The spoiled transmit beams produced by the ATD are synthesized using phase-only coefficients to maximize the power on transmit (Brown et. al., 2006). The co-polar main lobes of these antenna patterns were measured using the calibration infrastructure installed in the vicinity of the ATD (Ivić et al, 2019), and are shown in Fig. 3 (axes were scaled to enhance visual interpretation). These measurements play an important role for the calibration and successful implementation of the DB technique. That is, not only the magnitude of the two-way patterns has to be calibrated, but also their phases to ensure a coherent transition across the *F* receive beams to be coherently processed.

The DB technique was implemented on the ATD using a transmit beam spoiled by a factor of five and forming a set of nine simultaneous receive beams sampled at ½ θ_1 (sampling similar to super-resolution on the WSR-88D). The uncalibrated two-way beam patterns were measured for all receive beams. Measurements were used to calibrate the gain and phase of the beams. Gain calibration was straightforward; that is, signal power was compensated digitally by the relative difference between the peak gain of the two-way broadside beam (TW #5 in Fig. 4) and each other receive beam (Ivić and Schvartzman 2019). This is shown in the next set of panels in Fig. 4. Achieving phase calibration required two considerations: (1) similar to the gain calibration, instantaneous phases of the two-way peaks were measured and digitally corrected, and (2) a constant phase compensation was also needed to align the phase centers for the two-way distributed beams. Note that the second phase calibration is a result of the mechanical rotation of $\omega M T_s$ degrees, which shifts the phase centers of the two-way distributed beams because the center of rotation is not exactly the center of the antenna.

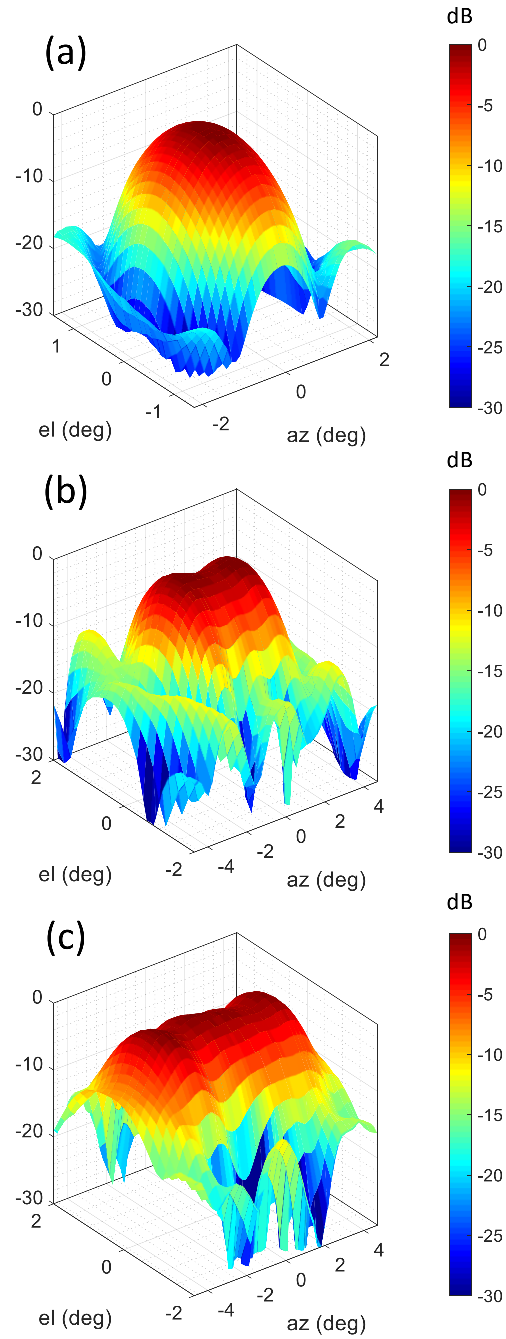

Fig. 3. Measured one-way normalized ATD antenna mainlobe patterns (a) pencil beam (b) beam spoiled by a factor of three, and (c) beam spoiled by a factor of five.

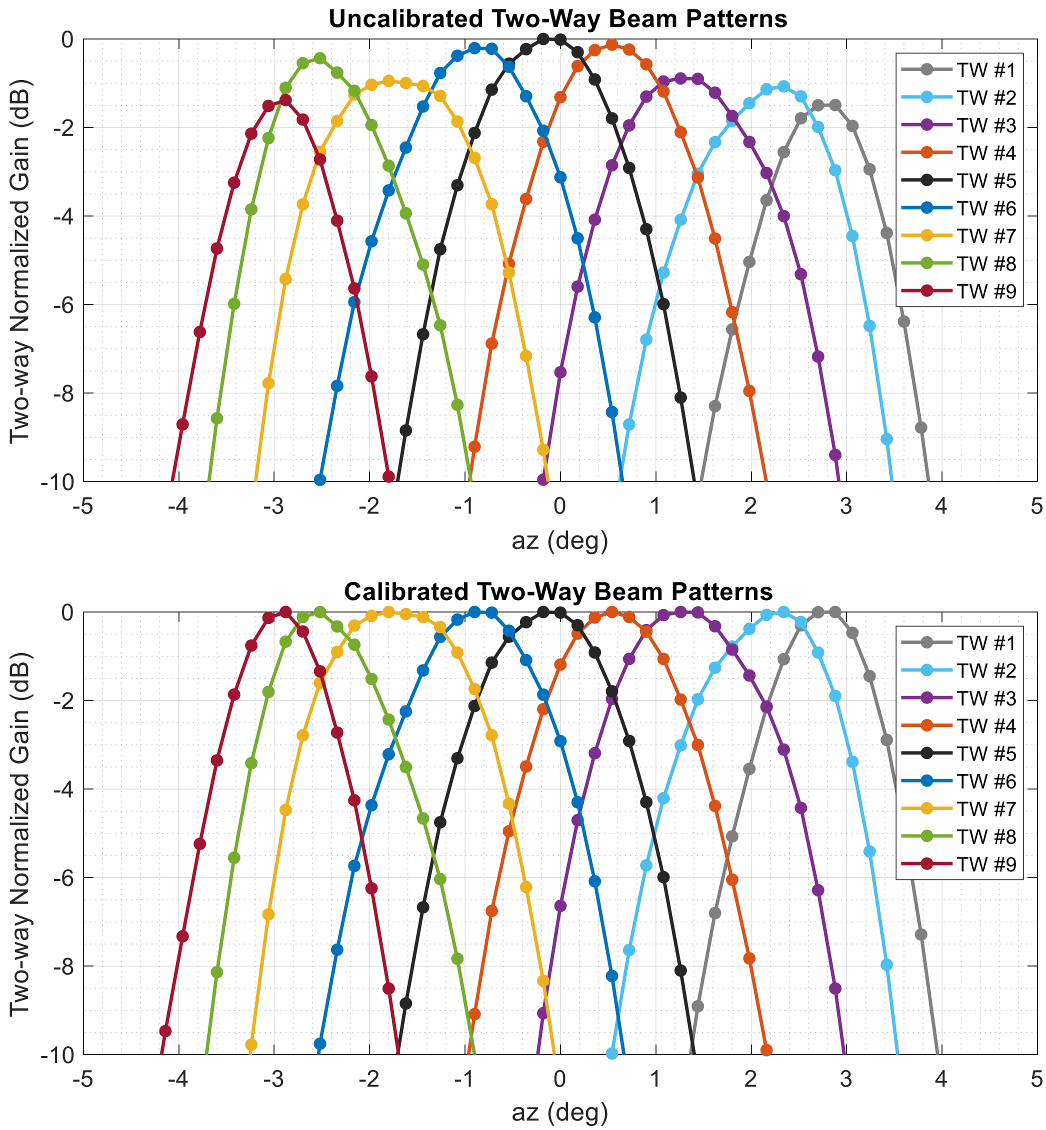

Fig. 4. Azimuthal slice of the measured two-way normalized ATD antenna patterns at 0.5° elevation: uncalibrated (top), calibrated (bottom).

Phase calibration is critical for the DB technique to achieve the scan-time reduction of *F*. If the phases of the signals of the DB samples are not coherent across two-way beam transitions, the combined time-series data cannot be coherently processed. Any loss of coherency from sample to sample would prevent the use of conventional pulse-pair or spectral processing methods (e.g., clutter filtering). An example of spectral processing will be shown in Section 4.

While the ATD was not designed for operating in a constant rotation regime, it is capable of scanning while rotating to scan in an RPAR CONOPS. This allows us to explore techniques in the context of a RPAR concept of operations. Nevertheless, the pedestal is not prepared to rotate at high speeds and therefore, this proof-of-concept implementation demonstrates the second application described in Section 2 (Data Quality Improvement). Specifically, sets of data were collected with the ATD rotating at ω = 4.1 °/s, with M = 64 at a PRT of T_s = 3 ms over a ~20° sector, and the DB technique was used to improve the quality of estimates (beyond the requirements). The antenna was set at 0° elevation, and the transmit beam was electronically steered to 0.5° in elevation and maintained at broadside on azimuth. Future plans include the implementation of motioncompensated steering, by which beams will be electronically steered by a small angle to maintain pointing on the center of the resolution volume being sampled. This would exploit PARs beam agility and also mitigate beam-smearing effects.

In the next section, illustrations of the DB technique are presented with a scan over a stationary point target (i.e., a radio tower), and a scan of actual weather echoes from a stratiform precipitation system.

4. DATA COLLECTION USING DB

The first illustration of the DB technique was accomplished by combining returns from nine receive beams, as the radar rotates past a stationary point target. The radar boresight was commanded to rotate from 290° to 310° azimuth with respect to North. The target is located at 31.65 km in range, and at 297° azimuth. The purpose of this test was to verify that the radar executed the scan by rotating at the commanded speed, and that the absolute location of the target was the same for all receive beams. In addition, it was verified that

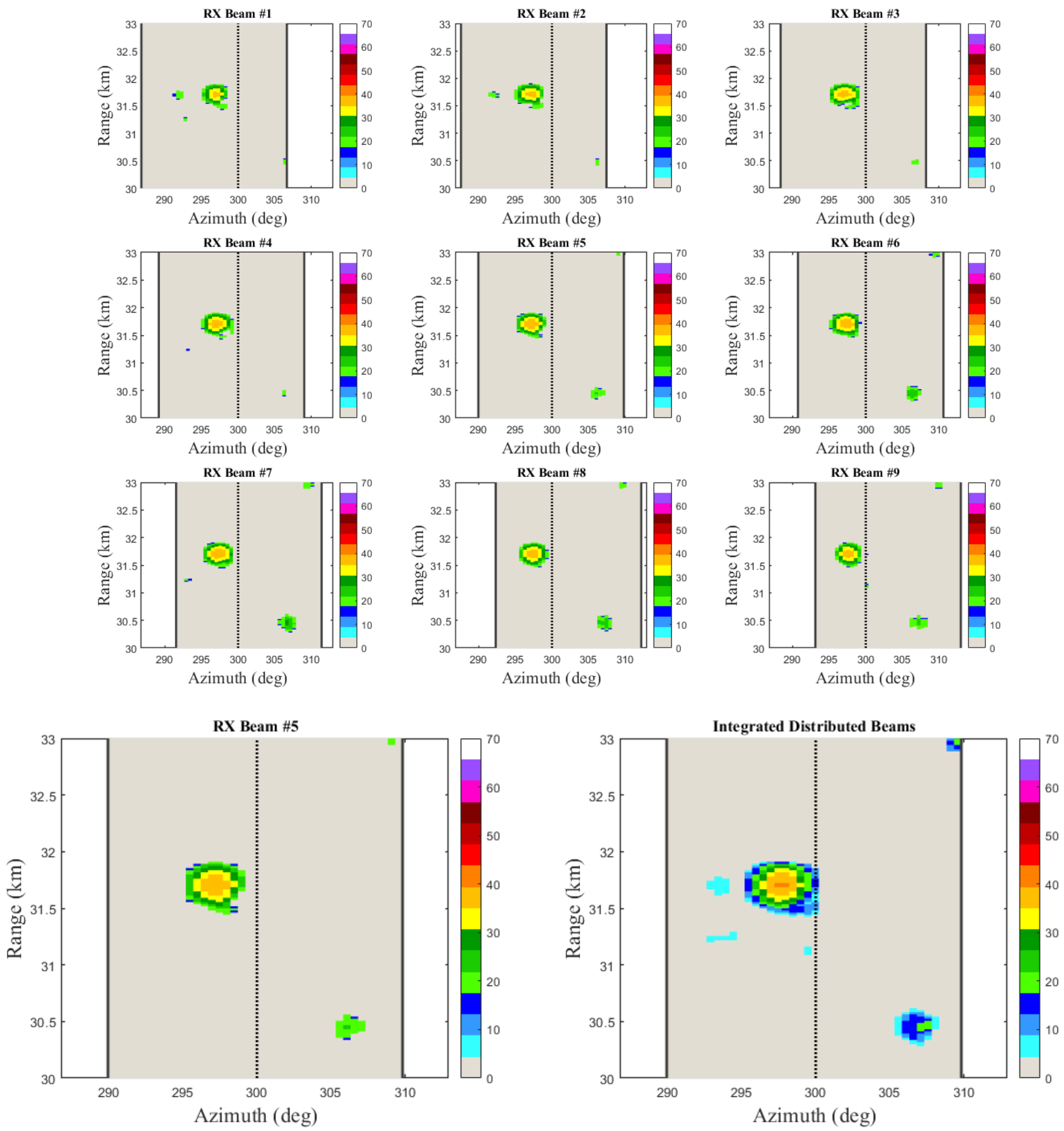

Fig. 5. Reflectivity from a stationary point target collected with the ATD on 12 Nov 2019. The bottom panels show the reflectivity computed from the two-way broadside beam (left, RX Beam #5) and the reflectivity with the DB technique (right).

the spread of azimuth angles for pulses across DB was less than 0.12°.

The reflectivity fields for the receive beams collected with the ATD on 12 Nov 2019 are shown in the top nine panels of Fig. 5. A dotted line was drawn at 300° azimuth for reference. The two bottom panels show the reflectivity computed from the two-way broadside beam (left, RX Beam #5) and the reflectivity with the DB technique (right). It is apparent that the increased number of samples obtained with DB processing improved the SNR and the recovery of weaker reflectivity echoes (i.e., recovered sensitivity). Given that the resolution of the target's location did not change after DB processing, it can be inferred that spatial resolution was not degraded.

The Doppler spectrum for the stationary target was computed using all 576 samples combined using DB (9 × 64), both before and after phase correction. The resulting spectra are shown in Fig. 6. It is apparent on the uncorrected spectrum that there was no coherency on the set of pulses, resulting in replicas of a distorted spectrum. After applying the described phase calibration and the correction for the shift on phase centers the spectrum now appears to have been corrected.

Next, Fig.7 shows the reflectivity fields for the receive beams collected with the ATD observing a stratiform precipitation system on 20 Nov 2019. These are shown in the top nine panels of Fig. 7. The radar boresight was commanded to rotate counterclockwise from 100° to 80° in azimuth. The two bottom panels show the reflectivity computed from the two-way broadside beam (RX Beam #5) and the reflectivity with the DB technique. Comparing these two reflectivity fields, note the appreciable reduction in the variance of estimates when using the DB technique. The field looks smoother and with better-defined weather features. This is due to the SNR gain obtained from combining many additional samples. Furthermore, weaker echoes on the edge of the precipitation system closer to the radar are also recovered.

This example illustrates the DB application for improving data quality as described in Section 2. If the radar had been operated at five times the speed (~20.5 °/s), the estimated DB reflectivity field would be similar to that from the two-way broadside beam (RX Beam #5) with the same data quality but in 20% of the time.

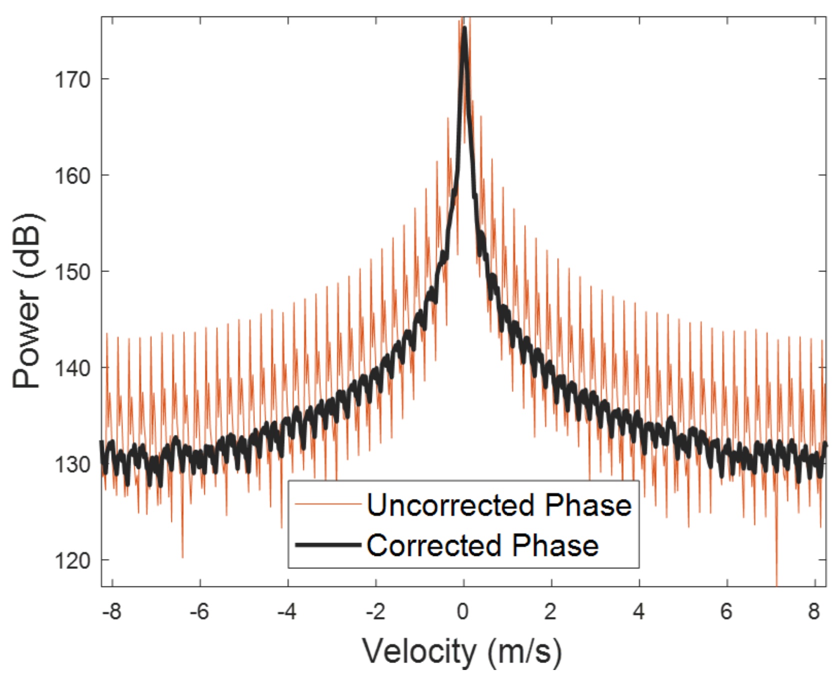

Fig. 6. Doppler spectra for the stationary point-target without phase correction (orange curve) and with phase correction (black curve).

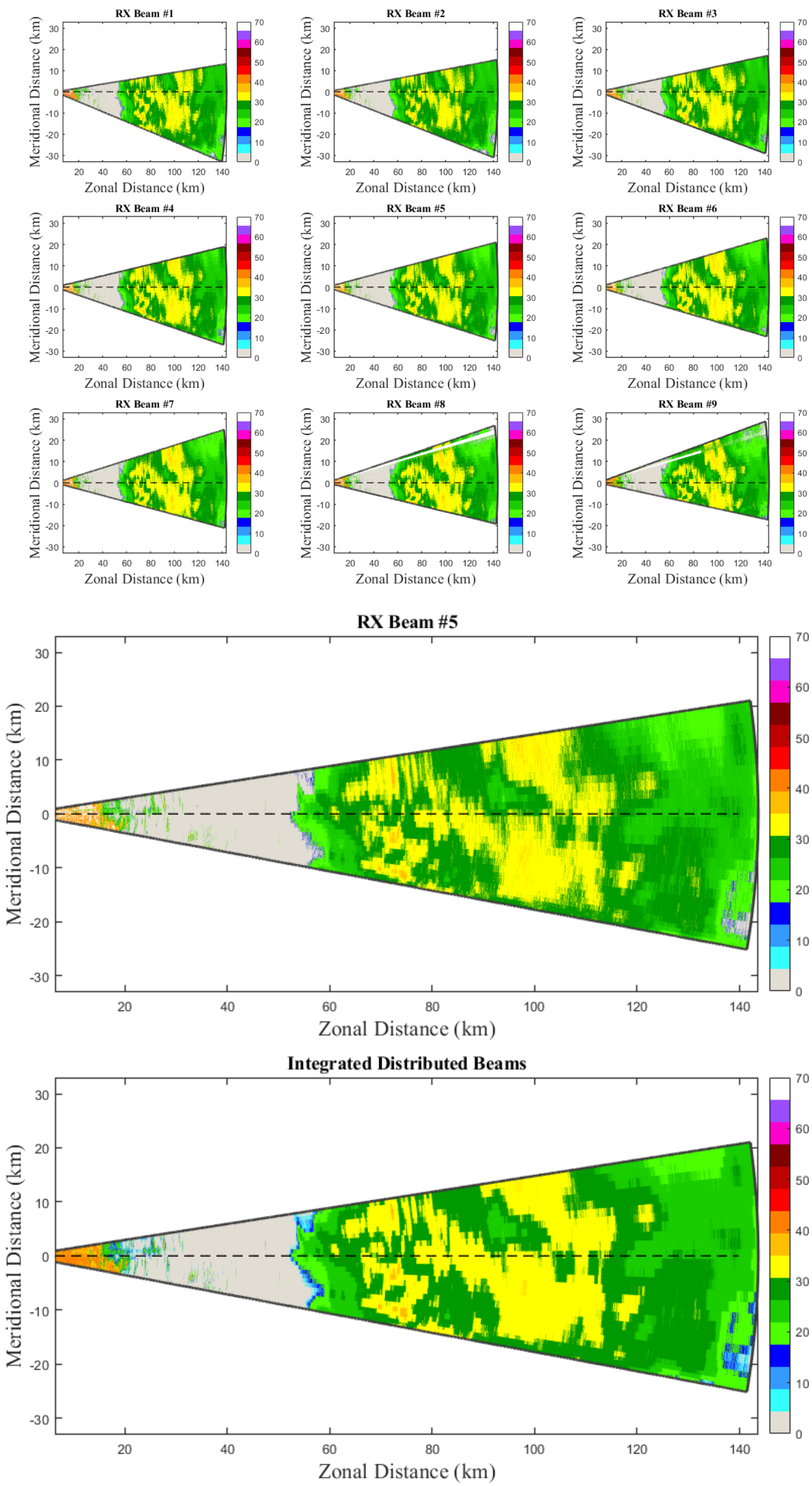

Fig. 7. Reflectivity from weather echoes collected with the ATD on 20 Nov 2019. The bottom panels show the reflectivity computed from the two-way broadside beam (RX Beam #5) and the reflectivity with the DB technique.

5. SUMMARY

Achieving the optimal requirements introduced in the NOAA/NWS Radar Functional Requirements for future weather surveillance radar will likely require exploiting capabilities of advanced radar systems. The RPAR architecture may be an affordable candidate radar to replace the WSR-88D and meet the demanding requirements. By exploiting PARs unique capabilities in conjunction with advanced signal processing techniques, it may be possible to design a CONOPS to meet these requirements.

Further investigation of techniques to exploit PAR's unique capabilities in the context of a rotating CONOPS is ongoing. The novel *Distributed Beams* technique described could be one of the tools that helps the RPAR achieve the required update times (~1 min). In this paper, the DB technique was introduced and two applications of it were described. A discussion on some of its limitations and possible ways of addressing them was given, and illustrations of the technique for a stationary point-target and a weather system were presented through an implementation on NSSL's ATD system. Even though achieving high reduction factors may be challenging due to the high rotation speeds required, an operational implementation with only a small time-reduction factor (e.g., $F = 2$), would still bring a significant improvement in reducing the scan time, and would function at lower rotation speeds (~8-15 °/s).

The preliminary results presented show that the DB technique can be used to reduce the scan time or to improve the data quality (i.e., reduce the variance of estimates) in a RPAR. There are plans to study the performance of the technique to produce polarimetric-variable estimates, and the possibility of integrating it with other techniques to reduce the scan time while maintaining data quality and spatial sampling. It is hoped that the outcome of our research efforts will provide valuable information for the design of a future U.S. Weather Surveillance Radar Network.

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REFERENCES

E. Brookner, 2002: Phased array radars-past, present and future, *RADAR Conference*, Edinburgh, UK. pp. 104-113. doi: 10.1109/RADAR.2002.1174663

Brown, G., C. Kerce, and M. Mitchell, 2006: Extreme beam broadening using phase only pattern synthesis," *Proc. of the IEEE Workshop on Sensor Array and Multichannel Processing,* Waltham, MA. doi: 10.1109/SAM.2006.1706079

Conway, M. D., D. Du Russel , A. Morris, and C. Parry, 2018: Multifunction phased array radar advanced technology demonstrator nearfield test results. *Proc. of the IEEE,* doi: https://doi.org/10.1109/RADAR.2018.8378771

Doviak, R. J., and D. S. Zrnić, 1993: *Doppler Radar and Weather Observations*. Academic Press, 562 pp.

Herd, J. S., S. M. Duffy, and H. Steyskal, 2005: Design considerations and results for an overlapped subarray radar antenna. Preprints, *IEEE Aerospace Conf.*, Big Sky, MT, USA.doi:10.1109/AERO.2005.1559399

Ivić, I. R., and D. Schvartzman 2019: A first look at the ATD data corrections. Preprints, *39th International Conference on Radar Meteorology*, Nara, Japan. Amer. Meteor. Soc., Paper 2-06. Extended abstract available: https://cscenter.co.jp/icrm2019/program/data/abstracts/Poster2-06_2.pdf

Ivić, I., C. Curtis, , E. Forren, R. Mendoza, D. Schvartzman, S. Torres, D.J. Wasielewski, and F.A. Zahrai, 2019: An Overview of Weather

Calibration on the Advanced Technology Demonstrator. *IEEE International Symposium on Phased Array Systems and Technology*, Waltham, MA. Available: https://www.researchgate.net/publication/338019168_An_Overview_of_Weather_Calibration_on_the_Advanced_Technology_Demonstrator

Leifer, M. C., V. Chandrasekar, and E. Perl, 2013: Dual polarized array approaches for MPAR air traffic and weather radar applications, *IEEE International Symposium on Phased Array Systems and Technology*, Waltham, MA, pp. 485-489. doi: 10.1109/ARRAY.2013.6731876

NOAA/NWS, 2015: Radar Functional Requirements, NOAA/NWS Internal Rep., 58pp. Available: https://www.roc.noaa.gov/WSR88D/PublicDocs/NOAA_Radar_Functional_Requirements_Final_Sept%202015.pdf

K. A. Orzel and S. J. Frasier, 2018: Weather Observation by an Electronically Scanned Dual-Polarization Phase-Tilt Radar, in *IEEE Transactions on Geoscience and Remote Sensing*, **56**, pp. 2722-2734. doi: 10.1109/TGRS.2017.2782480

B. Palumbo and A. Cucci, 1977: Array antenna with multiple, independently scanned beams for a 3D radar, *1977 Antennas and Propagation Society International Symposium*, Stanford, CA, USA, pp. 185-188. doi: 10.1109/APS.1977.1147771

B. Palumbo, 1996: Some examples of systems developments in Italy based on phased array technology, *Proceedings of International Symposium on Phased Array Systems and Technology*, Boston, MA, USA, pp. 444-449. doi: 10.1109/PAST.1996.566134

Schvartzman, D., and S. Torres, 2019: Design of Practical Pulse Compression Waveforms for Polarimetric Phased Array Radar. Preprints, *39th International Conference on Radar Meteorology*, Nara, Japan. Amer. Meteor. Soc., Paper 15A-02. Available at: https://cscenter.co.jp/icrm2019/program/data/abstracts/Session15A-02_2.pdf

Stailey, J. E., and K. D. Hondl, 2016: Multifunction phased array radar for aircraft and weather surveillance. *Proc. IEEE*, **104**, 649–659, doi: https://doi.org/10.1109/JPROC.2015.2491179

Torres, S., T. Buckman C. Curtis E. Forren S. Gregg I. Ivic R. Mendoza D. Schvartzman C. Schwarz D. Wasielewski A. Zahrai, 2019: Towards an operational demonstration of the first full-scale polarimetric phased-array radar. Preprints, *39th International Conference on Radar Meteorology*, Nara, Japan. Amer. Meteor. Soc., Paper 2A-04. Available at: *https://cscenter.co.jp/icrm2019/program/data/abstracts/Session2A-04_1.pdf*

Ushio, T., and Coauthors, 2014: Development and observation of the phased array radar at X band. XXXIth URSI General Assembly and Scientific Symposium (URSI GASS), IEEE. doi:10.1109/URSIGASS.2014.6929643

Weber, M., J. Cho, J. Flavin, J. Herd, and M. Vai, 2005: Multi-function phased array radar for U.S. civil-sector surveillance needs. *Preprint, 32nd Conf. on Radar Meteorology*, Albuquerque, NM, Amer. Meteor. Soc. http://ams.confex.com/ams/pdfpapers/96905.pdf

Weber, M., 2019: Meteorological Phased Array Radar Research at NOAA's National Severe Storms Laboratory, *2019 IEEE International Conference on Microwaves, Antennas, Communications and Electronic Systems (COMCAS)*, Tel-Aviv, Israel. doi: 10.1109/COMCAS44984.2019.8958067

Yoshikawa, E. *et al*., 2013: MMSE Beam Forming on Fast-Scaning Phased Array Weather Radar. *IEEE Transactions on Geoscience and Remote Sensing*, **51**, no. 5, pp. 3077-3088, doi: 10.1109/TGRS.2012.2211607