10A.4 A METEOROLOGIST EMBEDDED WITH ENGINEERS: BRINGING NWS PERSPECTIVES TO THE DESIGN OF FUTURE OPERATIONAL WEATHER RADAR SYSTEMS

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1. INTRODUCTION

The Weather Surveillance Radar-1988 Doppler (WSR-88D) network is expected to continue to support the National Weather Service (NWS) mission beyond 2030, while work toward determining a potential replacement system is underway. Extensive involvement of the system's users is typically lacking in research and development of complex systems. That is not the case for the Advanced Radar Techniques (ART) team at the National Severe Storms Laboratory (NSSL). A meteorologist with extensive NWS forecasting and WSR-88D training experience, the lead author, was brought to the team in 2017 to support a study of impacts on radar data quality from differing potential future weather radar designs. Specifically, we focused on the aspects of radar design that have the greatest effect on data quality (e.g. the antenna radiation patterns) and the resultant impact on data interpretation (e.g. antenna pattern sidelobe contamination) for NWS forecasters in the domain of hazardous weather forecasting and warning. By directly connecting key radar design parameter settings to the resultant impacts on forecasters' data interpretation, this work has greater salience to support NWS mission-critical operations (NOAA/NWS 2019).

This paper presents the significant benefits of this unique two-way learning environment resulting from embedding a meteorologist within the team of engineers. A high efficiency workflow was developed, as the engineers received feedback on the qualitative fidelity of the radar data they were simulating. Our partnership also resulted in the most relevant data analysis process, which differed depending on the specific radar parameter studied.

In addition to our workflow process, the parameters of radar design studied are presented, with a specific focus on the challenge of antenna sidelobes. What is often referred to as "vertical" sidelobes (i.e. elevation sidelobes) presents itself in the high stakes NWS warning environment of severe convection. One of our studies related antenna patterns with differing sidelobe levels to the degree of "distraction" to the data interpretation process from the NWS forecaster perspective. This paper also presents some qualitative lessons learned by Boettcher about how this type of sidelobe contamination presents in the data. We introduce a more descriptive identifier, and include ideas for potential future work.

2. WEATHER RADAR ENGINEERS AND METEOROLOGISTS

Weather radars are complex systems, both in hardware and software. The better a meteorologist can appreciate this complexity, the easier it is to accept the fundamental trade-offs with weather radar design and performance. Prior to coming to the ART team, Boettcher worked for the NWS for many years developing and delivering training on the WSR-88D, with a focus on the signal processing upgrades, the most significant of which was Dual Polarization (Figure 1).


Dual-Polarization Radar Operations Course

Dual-Polarization Radar Principles
RDA Build 12.0 Lesson 1

*AKA The **Really** Cool Stuff About Weather Radar*

Figure 1. Title slide from one of Boettcher's NWS WSR-88D Dual Polarization Training Course modules.

This was excellent preparation for the transition to NSSL. A challenging but rewarding learning experience began, as there are many aspects of radar design which are not present with the WSR-88D. A particularly surprising example was learning about range sidelobes resulting from pulse compression waveforms (Bluestein et al, 2014), which are discussed in Section 4.2.

Members of the ART team, based in Norman, Oklahoma, are some of the global experts on advanced weather radar design and signal processing techniques. They inhabit a world of waveforms, phase coding, antenna patterns, beamforming, pulse compression, and so much more, that is largely invisible to operational meteorologists. Figure 2 provides a glimpse of their domain of expertise, the details of which are beyond the scope of this paper.

Our collaboration and learning is mutually beneficial: the meteorologist's perspective guides the work, keeping it grounded in the reality of operational needs. Meanwhile, engineering concepts such as antenna pattern design must be understood sufficiently by the meteorologist for appropriate weather case selection for our studies.

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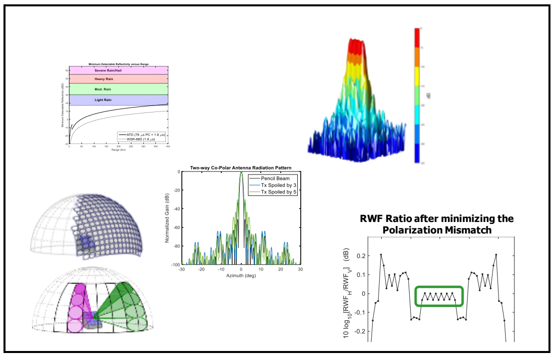


Figure 2. A glimpse into the domain of the ART team weather radar engineering expertise.

There is inevitable tension given the desires of meteorologists, who want "clean" radar data, at fast update rates, without artifacts, except for the rare ones that are informative. For example, a Three Body Scatter Spike (TBSS) is usually easy to notice and enhances confidence of the existence of large hail (Lemon 1998). Meanwhile, engineers understand very well the trade-offs for achieving acceptable data quality for operational use vs. faster update rates or finer spatial sampling.

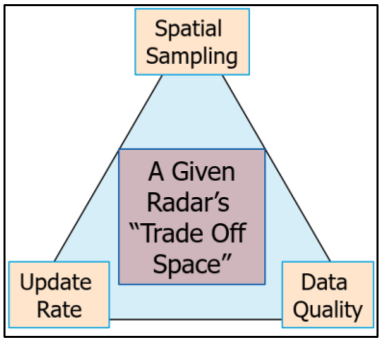


Figure 3. For a given radar, the "trade off space".

Figure 3 captures the "trade off space" for any given radar, which reflects where the engineers and meteorologists must meet to achieve the best possible performance. For example, a desired update rate may not be achievable unless the dwell time is sufficient for acceptable data quality. Or, sampling the data using a finer azimuthal grid has a computational impact that can lower the data quality and/or result in a slower update rate.

3. DATA QUALITY STUDIES AND THE SPARC SIMULATOR

A high fidelity tool developed by members of the ART team simulates a given weather event as if it were sampled by the engineers' chosen weather radar design, with realistic results. It is the Signal Processing and Radar Characteristics (SPARC) simulator (Schvartzman and Curtis 2019), and Figure 4 has an example of the quality of SPARC simulations for a case, with Reflectivity (*Z*) and Storm Relative Velocity (*SRV*) presented. The goal of our team was to make the simulated data indistinguishable from native WSR-88D data. This does not mean identical, pixel by pixel, but that the quality of the image is comparable with that produced from WSR-88D radar data.

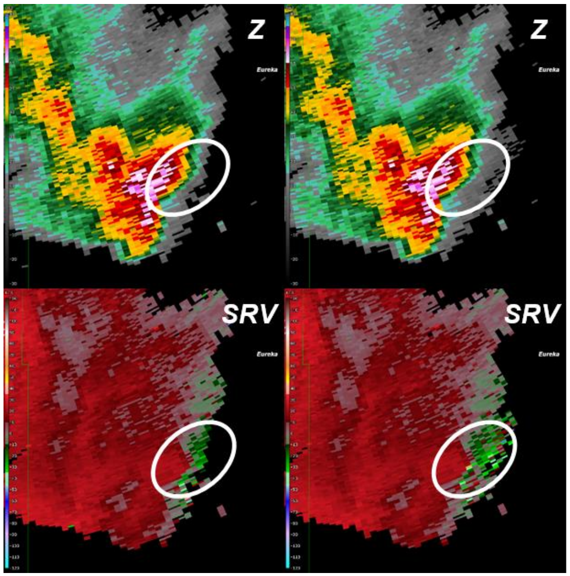


Figure 4. SPARC simulated reflectivity (Z) and Storm Relative Velocity (SRV). Z and SRV in the right column were simulated with higher sidelobe levels than the left column.

For the case in Figure 4, the difference between the simulated *Z* and *SRV* for the left column vs. the right column is due to higher antenna pattern sidelobe levels for the right column. All the other radar base data, spectrum width and the dual polarization variables (not shown) also met this standard of baseline (left column) and degraded (right column) data quality with respect to the WSR-88D. All radar images presented in this paper are captured from the Gibson-Ridge Level 2 Analyst (GRLevel2) radar data viewer, which was used throughout all of our studies.

The SPARC simulator ingests archived radar base data from any WSR-88D, providing high flexibility for case selection for our studies. These data are then converted to simulated in-phase and quadrature (IQ) time-series data for that same time and elevation. Then the IQ data are processed as if the event had been sampled by a different radar, such as a dish antenna or a Phased-Array-Radar (PAR), with adjustable parameters such as sidelobe levels or sensitivity. All the PAR simulations in this study represented a PAR with a stationary (non-mobile) antenna.

The radar parameters studied are:

1. Sensitivity,
2. Resolution (i.e. beamwidth),
3. Spatial Sampling (i.e. pixel size on the radar image),
4. and Sidelobes.

Cases were selected for each of these studies, finding weather events that stress each parameter. For example, the "footprint" of winter weather on a radar image is directly related to that radar's sensitivity. The antenna sidelobe studies were particularly informative for both the engineers and the meteorologist, as we found that our perceptions differed greatly. The sidelobe study also involved the most significant engineering upgrade to the SPARC simulator, by expanding the antenna pattern into the elevation dimension. This mean the antenna pattern was simulated as it actually is, a volume. Our "coming together" on sidelobes is described in Section 5.

4. OUR FEEDBACK LOOP, INITIAL PROCESS

In this section, we describe how our two-way learning produced a highly efficient "pre-analysis" process for each of the radar parameters studied. Once weather cases were selected, initial simulations were run to determine if we were ready for analysis of all the cases. There were three initial questions to be answered before the simulations on all the cases could be produced and the full analysis could proceed.

4.1 *Do the data look real?*

The setup for each simulation requires an extensive number of engineering "settings" within the SPARC MATrix LABoratory (MATLAB) software. Sometimes, the setting change needed was obvious, such as the appropriate level of clutter filtering, while sometimes one setting had unintended consequences. Figure 5 has an example of an early simulation that had to be rerun. The *Z* data are excessively noisy (note the circled area), and the fields (especially SRV) appear to be smoothed, though no smoothing was applied with GRLevel2.

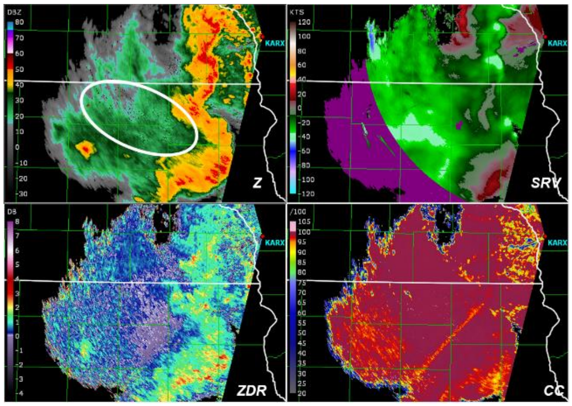


Figure 5. An early "do the data look real?" simulation with upper left Z, upper right SRV, lower left differential reflectivity (ZDR), and lower right correlation coefficient (CC).

4.2 *Do the simulations support the study?*

Once the data fidelity was sufficient, the next step in our feedback loop was to ensure that the radar design parameter we wish to study was the only feature changing from one simulation to another. We will use an example from the range sidelobe study. Due to its Klystron amplifier, the WSR-88D is capable of transmitting a short, high-power pulse, which minimizes range sidelobes. Thus WSR-88D users (including the lead author before the study began) may not be familiar with the data quality issue of range sidelobes. For other radar designs, such as a relatively low-powered PAR, the use of pulse compression waveforms may produce range sidelobes that require mitigation (Schvartzman and Torres 2019). This contamination presents as the name implies: for strong *Z* gradients in the range direction, there is an extension of weak echo into the clear air down-radial. Figure 6 provides two examples of simulated data with differing range sidelobe levels (6a compared to 6b). The radar products are upper left, *Z*, upper right, *SRV*, lower left, *ZDR*, and lower right *CC*.

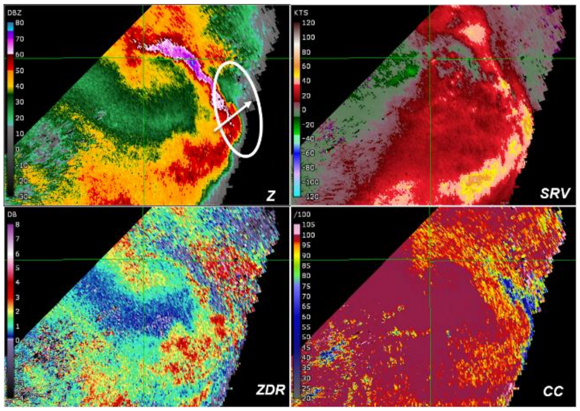


Figure 6a. One simulation with very low range sidelobes.

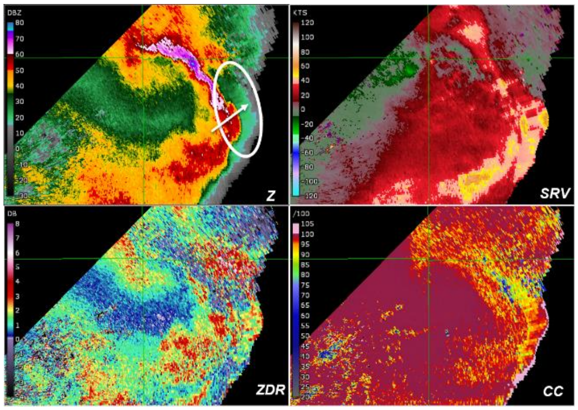
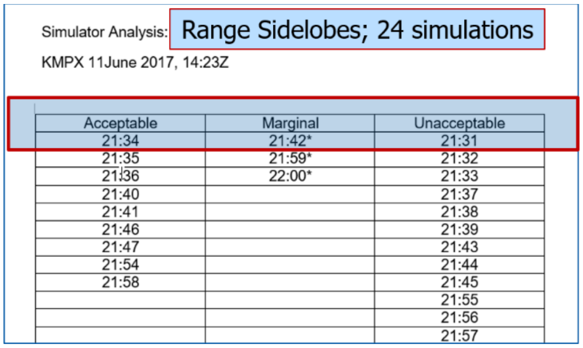


Figure 6b. A second simulation of the same case as 6a, but with much higher range sidelobes.

When comparing the images from Figures 6a and 6b, note that the change is limited to the extent of the range sidelobes down-radial (arrow) from the strong *Z* gradient. Meeting the condition of isolating the radar parameter to be studied allowed for the final step before all the cases were analyzed.

4.3 *Is the analysis approach sufficient?*

This step involves the granularity of the analysis. It is obviously important to extract as much meaning as possible from the analysis of the simulations. Each radar parameter investigated presented a different type of result in the radar data. There were also significant differences in the ease of identification of the impacts. For range sidelobes, the analysis was based on the areal extent of the contamination with the understanding that, like azimuthal (horizontal) sidelobe contamination, the *Z* gradient that produces it is readily apparent on the image. Range sidelobes were scored as *Acceptable, Marginal, or Unacceptable*. See Figure 7 for an example analysis for one of the six cases simulated for range sidelobes. Each entry labeled (using time strings) is a separate simulation, for a total of 24. The time stamp was used only to separate one simulation from the other.



Simulator Analysis: Range Sidelobes; 24 simulations

KMPX 11June 2017, 14:23Z

Acceptable	Marginal	Unacceptable
21:34	21:42*	21:31
21:35	21:59*	21:32
21:36	22:00*	21:33
21:40		21:37
21:41		21:38
21:46		21:39
21:47		21:43
21:54		21:44
21:58		21:45
		21:55
		21:56
		21:57

Figure 7. One of the analysis summary sheets for the range sidelobe study.

Another example of the granularity difference from one radar parameter to another was the study on spatial sampling. The cases for this study were four winter events, four non-tornadic severe convection events (e.g. bow echoes), and eight potentially tornadic supercell circulations. The goal for the circulation cases was not based on whether the supercell produced a tornado. It was to have a diversity of circulation sizes and intensities. All these cases were simulated to compare for potential differences between varying spatial sampling configurations.

One example was a parabolic reflector (i.e. dish) antenna with constant azimuthal sampling vs. a PAR antenna. For the PAR antenna, 0.5° azimuthal sampling from the beam steered at the broadside angle (perpendicular to the face of the array) changes to 0.7° azimuthal sampling at a steering angle that is 45° from broadside (described as the "edge"). The PAR antenna sampling used for comparison is described as "sine space" sampling, with 0.5° at broadside, varying to 0.7° at the edge. Figure 8 presents this sine space sampling concept for a PAR antenna.

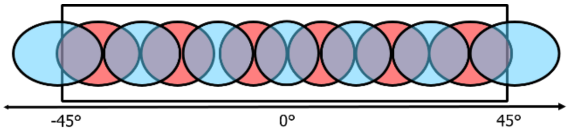


Figure 8. Sine space sampling for a PAR antenna with 0.5° at broadside varying to 0.7° for a beam steered at 45° from broadside.

For the sampling study, any differences, where they existed, were very subtle. Figure 9 has a storm scale example, with a hail core adjacent to an area of big drops. *Z* and *ZDR* in the right column (Sim 2) were simulated as a PAR antenna viewing this storm at broadside sampling at 0.5° in azimuth, while the left column (Sim 1) is simulated as a dish antenna sampling at 0.7° in azimuth everywhere. Note the subtle, but overall sharper appearance of the *Z* and *ZDR* in the right column, with the interface between big drops and hail in *ZDR* more apparent.

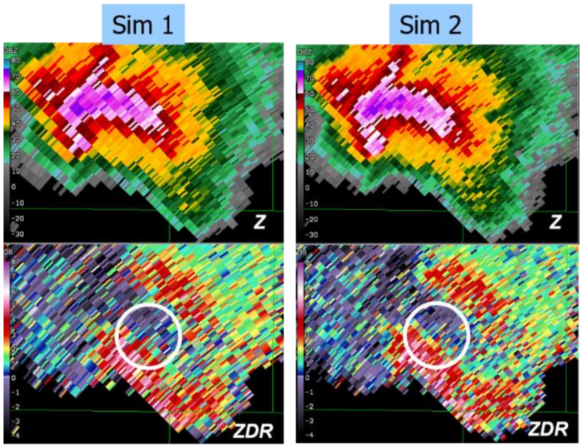
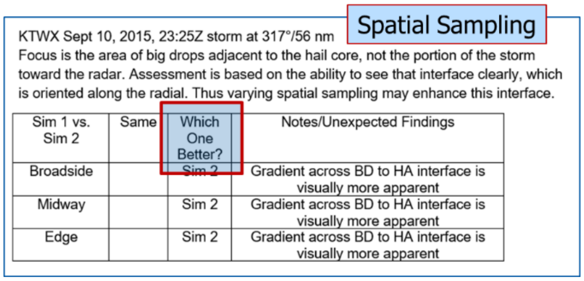


Figure 9. A comparison of storm scale features for a PAR antenna steering at broadside (right column), and a dish antenna (left column).

Thus for the spatial sampling study, the analysis was limited to a comparison (the same or is one of them better?) of one simulation against the other. Figure 10 shows the results for three PAR antenna angles compared to the dish antenna. The key point for this study is the subtlety of differences, where they do exist.



KTWX Sept 10, 2015, 23:25Z storm at 317°/56 nm

Spatial Sampling

Focus is the area of big drops adjacent to the hail core, not the portion of the storm toward the radar. Assessment is based on the ability to see that interface clearly, which is oriented along the radial. Thus varying spatial sampling may enhance this interface.

Sim 1 vs. Sim 2	Same	Which One Better?	Notes/Unexpected Findings
Broadside		Sim 2	Gradient across BD to HA interface is visually more apparent
Midway		Sim 2	Gradient across BD to HA interface is visually more apparent
Edge		Sim 2	Gradient across BD to HA interface is visually more apparent

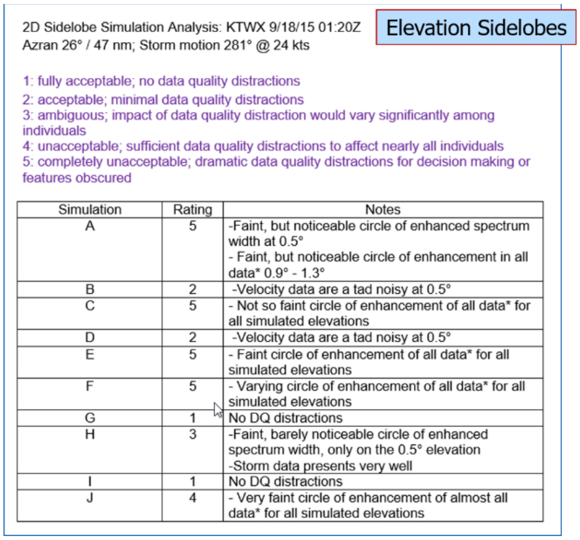
Figure 10. One of the analysis summary sheets for the Spatial Sampling study.

The most robust analysis granularity was applicable to the antenna pattern sidelobe study, specifically what the team ultimately came to identify as "elevation" sidelobes instead of "vertical" sidelobes. The justification for this naming convention is discussed in Section 5.

Elevation sidelobe contamination unfortunately presents itself in one of the most demanding NWS domains: severe local storm convection. The type of storms that produce Z gradients that change in height sufficiently to result in sidelobe contamination are also potentially tornadic. Depending on storm geometry with respect to the radar antenna pattern, elevation sidelobe contamination can appear as a circulation (Piltz and Burgess 2009). Diagnosing a circulation as potential sidelobe contamination requires significant cognitive resources, and is extremely difficult for NWS warning forecasters to do in real time.

For this study, thirteen different supercell cases were selected for geographic and mesocyclone depth diversity. The data for each case were simulated with progressively increasing sidelobe levels. The simulations were randomized and presented to the meteorologist (as with all the other studies) blindly, meaning it was unknown which antenna pattern was applied to each simulation. We developed a five-point scoring system, based on the level of "distraction" to the data interpretation process generated by the extent of the sidelobe contamination from multiple elevations.

Figure 11 provides an example analysis for one of the supercell cases, while Figure 12 presents a closer look at the descriptions for the five levels. In real time, the level of "distraction" is directly related to the cognitive resources needed to determine if the data are valid. Note how the language of the differing levels of distraction reflects how the NWS population as a whole would respond to the compromised data.



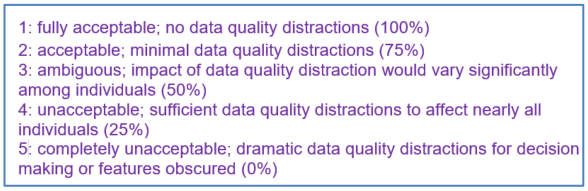
2D Sidelobe Simulation Analysis: KTWX 9/18/15 01:20Z
Azran 26° / 47 nm; Storm motion 281° @ 24 kts

Elevation Sidelobes

1: fully acceptable; no data quality distractions
2: acceptable; minimal data quality distractions
3: ambiguous; impact of data quality distraction would vary significantly among individuals
4: unacceptable; sufficient data quality distractions to affect nearly all individuals
5: completely unacceptable; dramatic data quality distractions for decision making or features obscured

Simulation	Rating	Notes
A	5	-Faint, but noticeable circle of enhanced spectrum width at 0.5° - Faint, but noticeable circle of enhancement in all data* 0.9° - 1.3°
B	2	-Velocity data are a tad noisy at 0.5°
C	5	- Not so faint circle of enhancement of all data* for all simulated elevations
D	2	-Velocity data are a tad noisy at 0.5°
E	5	- Faint circle of enhancement of all data* for all simulated elevations
F	5	- Varying circle of enhancement of all data* for all simulated elevations
G	1	No DQ distractions
H	3	-Faint, barely noticeable circle of enhanced spectrum width, only on the 0.5° elevation -Storm data presents very well
I	1	No DQ distractions
J	4	- Very faint circle of enhancement of almost all data* for all simulated elevations

Figure 11. One of the analysis summary sheets for the elevation sidelobe study.



1: fully acceptable; no data quality distractions (100%)
2: acceptable; minimal data quality distractions (75%)
3: ambiguous; impact of data quality distraction would vary significantly among individuals (50%)
4: unacceptable; sufficient data quality distractions to affect nearly all individuals (25%)
5: completely unacceptable; dramatic data quality distractions for decision making or features obscured (0%)

Figure 12. A closer look at the elevation sidelobe five level scoring.

4.4 *Proceed with the analysis for all the cases*

All the previous steps discussed in Section 4 prepared us to perform the simulations and analysis for all the cases selected for each of the radar parameters studied.

Using the elevation sidelobe study as an example, once steps 4.1 – 4.3 were complete, all the cases could be analyzed. For each of the thirteen supercell cases, ten different antenna patterns were simulated. For each of these antenna patterns, radar base data (legacy and dual polarization) were generated for eight elevations similar to Volume Coverage Pattern (VCP) 12, 0.5° through 5.1° (Brown et al, 2005). The analysis was performed similarly to the NWS storm interrogation process, scanning the elevations up and down for the particular time step selected. The analysis perspective applied by the meteorologist was that the data were being viewed in real time, which is a much more demanding domain than post-storm analysis. Also, based on years of experience interacting with and teaching NWS forecasters, the simulations were viewed from the perspective of the NWS population as a whole, ranging from novices to experts.

5. HOW WE CAME TOGETHER ON SIDELOBES

The SPARC simulator was originally designed for a single elevation of radar data. One of the most important engineering contributions to all of our studies was expanding its capacity to simulate a volumetric antenna pattern that receives returned power from multiple elevation angles. Thus when the main lobe is pointing toward a feature such as a storm inflow on the lowest radar elevation, returned power from sidelobes striking the storm overhang aloft also became present in the time series data from the simulation. This engineering advancement, along with numerous discussions during our collaboration, led to a shared understanding and a novel approach to the language for sidelobes on a given radar image.

For radar engineers, sidelobes are an ever-present characteristic of a radar's antenna pattern, existing as a volume, spreading outward from the main lobe for >± 180°. They regard sidelobe contamination as coming from all directions other than the direction of interest. In Figure 13, an example WSR-88D antenna pattern shows the main lobe and sidelobes that fall off in the azimuthal direction. To better grasp this pattern as a volume, the arrow prompts the visualization of rotating the pattern in space.

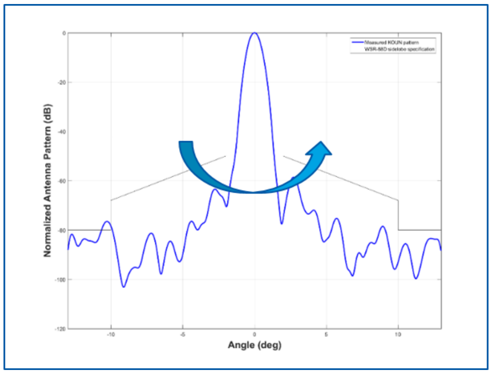


Figure 13. An example WSR-88D antenna pattern with the main lobe and sidelobes. The arrow prompts the viewer to visualize the pattern as a volume.

For meteorologists, "sidelobes" mean the data contamination that appears on the radar images.

Initially, this fundamental difference in perspective made it difficult to fully understand one another in our conversations. We struggled with the need for scientific purity, while communicating effectively to our NWS stakeholders. As we began to understand each other better, the work of our study flowed, and most importantly, the challenge of how best to communicate our work to both engineers and meteorologists became a high priority for us.

5.1 *Azimuthal vs. Elevation Sidelobes*

We came together on a naming convention for the two differing types of sidelobe contamination based on their primary source. This also supports the meteorologist's perception of there being two different types of contamination, because the way these two types manifest in the radar data is quite different.

The first is azimuthal sidelobe contamination, sometimes referred to as horizontal sidelobes. This presents on a single radar elevation, and the strong *Z* gradients that produce the sidelobe contamination are evident on the radar image itself. Figure 14 provides an example, with the extension of weak echo into adjacent radials from the strong azimuthal *Z* gradient. As the main lobe samples the clear air adjacent to the storm core, power returned from the sidelobes is converted to weak reflectivity extending in the azimuthal direction away from the storm core.

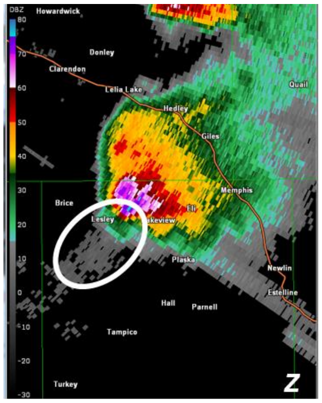


Figure 14. Azimuthal sidelobe contamination (circled), where the associated strong Z gradients are also apparent.

The other type of sidelobe contamination is often referred to as "vertical" sidelobes, or sometimes "velocity shadows". The emphasis on velocity is important because this is the radar product that is most critical during NWS severe storm warning operations. The storm type most likely to produce this type of sidelobe contamination is severe, potentially tornadic, convection. The *Z* gradient for this type exists aloft, across multiple elevations, and the contamination on the low-level velocity data does not have a readily apparent source. Also, the source of this contamination is not limited to the vertical plane. Thinking of the main lobe and sidelobes as a volume, elevations aloft well outside the vertical plane also contribute, hence our naming decision of elevation sidelobe contamination.

Figure 15 provides an example of compromised velocity data in the low-level storm inflow region due to elevation sidelobe contamination. Unlike the more familiar azimuthal sidelobe contamination, the source is not apparent on the same radar image. Diagnosing the validity and the source of this low-level velocity signature requires extensive cognitive resources. However, during real time warning operations, cognitive resources are already significantly stretched.

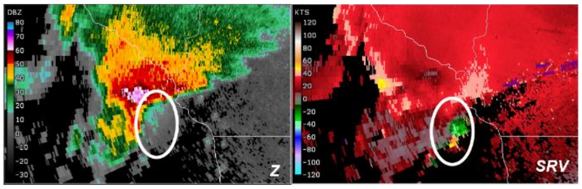


Figure 15. Low level Z and SRV products with compromised velocity data in the storm inflow produced by elevation sidelobe contamination (circled).

5.1 *How Elevation Sidelobes Present in the Data*

Our elevation sidelobe study also revealed something initially unexpected about the differing ways elevation sidelobe contamination presents itself. It was generally understood that velocity values aloft are sometimes mapped to the lower elevations in a way that suggests a circulation. Figure 16 has an example of this type of contamination that suggests a low-level circulation. The red box is used to link the location of the storm inflow region in Z to the center of the potential circulation in SRV. The location of this potential circulation within the inflow region of the storm is often a clue to its validity, but in warning decision making, time for diagnosis is very limited.

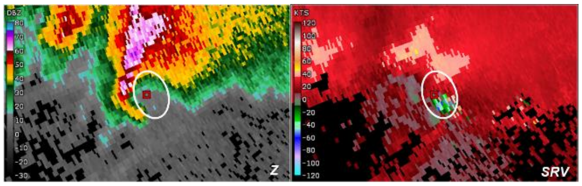


Figure 16. Elevation sidelobe contamination (circled) that suggests a possible circulation.

The second (and more frequent) way that elevation sidelobe contamination presented itself in our study was as noisy velocity in the low-level storm inflow region (Figure 17). Even though this type occurs more frequently, it does not have the salience of a potential circulation. Also, NWS forecasters are highly skilled at visually filtering noisy data, i.e. it is mentally, likely unconsciously, disregarded as unimportant. Most NWS forecasters do not consciously notice it, and likely do not realize this is also elevation sidelobe contamination.

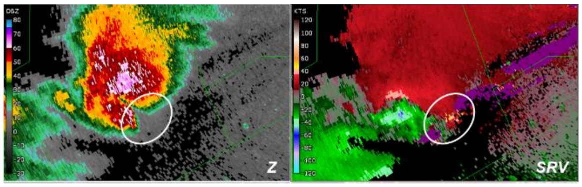


Figure 17. Elevation sidelobe contamination (circled) that presents as noisy velocity data in the low-level storm inflow.

There are other radar data products, particularly spectrum width and the polarimetric variables, which are helpful tools for diagnosing elevation sidelobe contamination (not shown). Reflectivity and storm-relative velocity were heavily weighted during the study analysis, as it is not a given that all NWS forecasters are using spectrum width or the polarimetric variables extensively in real time. More information about these other radar data and potential diagnosing techniques is expected to be provided as part of future work.

6. CONCLUSION

A unique collaboration, resulting from embedding a meteorologist with engineers has greatly enhanced two-way learning, streamlined the investigation process, and found novel results, especially with respect to antenna sidelobe contamination.

Several radar parameters (sensitivity, resolution, spatial sampling, and sidelobes) were studied for impacts on NWS data interpretation, using the robust, high-fidelity SPARC simulator. Following sometimes extensive two-way communications and learning, we first selected weather cases that stressed each parameter. By systematically adjusting the SPARC simulator, differing levels of these parameters (e.g. antenna pattern sidelobes), were applied to the cases, and then analyzed to find the relationship to data interpretation impacts on NWS forecasters.

A crucial element to this study was the meteorologist and engineer partnership. A rigorous pre-analysis process emerged to ensure validity of each study. The simulated data first had to pass the “does it look real?” test, followed by ensuring that the parameter to be studied was the only feature changing from one simulation to the next. Finally, the appropriate granularity for the analysis for each study was developed because the impacts on the data from one parameter studied to the other varied significantly. For example with the spatial sampling study, we were comparing one azimuthal sampling grid to another, thus the analysis was comparative: was there a difference, and if so, which one was better? On the other hand, the sidelobe study involved antenna patterns with progressively increasing sidelobe levels, allowed for a five level scale of distractions to the data interpretation process. The overall goal of finding relationships between differing radar parameter settings and the resultant impacts on NWS data interpretation would not have been possible without this unique collaboration.

The work on sidelobes revealed the most significant difference in perspective between the meteorologist and the engineers, yet ultimately produced the most meaningful results. We came together for a naming convention that is based on the source region for the sidelobe contamination, azimuthal vs. elevation. We also revealed that a great deal of elevation sidelobe contamination does not manifest as potential circulations, but as noisy velocity data in the storm inflow region.

Finally, we look forward to continuing this partnership to combine the best of quantitative (engineering) analysis and qualitative (meteorologist) analysis toward a potential replacement for the exceptional WSR-88D network.

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