BEYOND PHASED ARRAYS – DESIGN PRINCIPLES FOR AN IMAGING RADAR

Charles C. Kidder III[1,3]*, M. B. Yeary[1,3], R. D. Palmer[2,3]

[1] School of Electrical and Computer Engineering, University of Oklahoma, Norman, Oklahoma, USA
[2] School of Meteorology, University of Oklahoma, Norman, Oklahoma, USA
[3] Atmospheric Radar Research Center, University of Oklahoma, Norman, Oklahoma, USA

Abstract

Over the next few years, the Atmospheric Radar Research Center (ARRC) of the University of Oklahoma (OU) is building an Atmospheric Imaging Radar (AIR). An imaging radar uses much of the same technology as phased array radars, and is one in many respects, but with a greater portion of the radar operating digitally to provide advanced functionality to the user. An example of this advanced functionality is the use of digital beamforming techniques to image a volume without scanning the transmit beam. Multiple receive beams are created to simultaneously image a larger transmit beam. This paper discusses some of the differences between the AIR and other traditional radars, such as a dish based radar or phased array. Justification for using subarrays which are spaced several wavelengths apart are given. The changes to the RF portion of the receiver are discussed. Particular attention is paid to the differences in antenna and array patterns, signal processing, and received power.

1. INTRODUCTION

To further the capabilities available to radar meteorologists, and those who depend on their data, the University of Oklahoma decided to undertake the design of the atmospheric imaging radar (AIR) to allow the simultaneous imaging of a small sector of the atmosphere. The initial AIR design images a sector approximately 15°by 15°. This allows the imaging of a small-scale phenomena without having to physically scan the radar. Furthermore, the AIR is designed to be mobile and compliment existing mobile radars. This limits the radar face size to about 2 m by 2 m to fit on roadways in the United States. To compliment existing mobile radars, the AIR will operate at X band. Besides the advances in imaging of a volume, the digital architecture of the AIR allows advanced techniques in clutter mitigation (Cheong et al. [2006]) and resolution enhancement (Palmer et al. [2005]) to be used in refining the received signal.

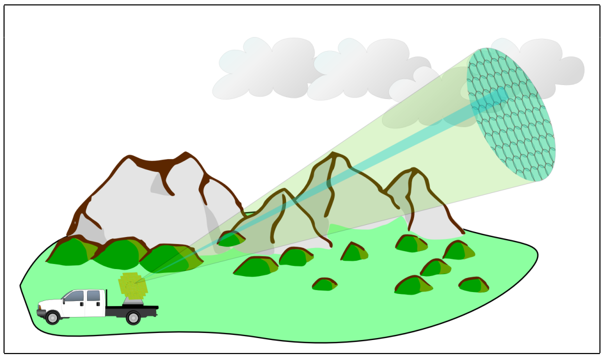

Figure 1: Illustration of the AIR with large transmit beam (yellow) and smaller receive beams (blue).

2. DESIGN CHANGES

An imaging radar uses much of the same technology as phased array radars, and is one in many respects, but with a greater portion of the radar operating digitally to provide advanced functionality to the user. It uses digital beamforming techniques to image many locations simultaneously. At a minimum, an imaging radar needs multiple receive subarrays and a transmitter. Advanced designs may utilize multiple transmitters as well. The initial design of the AIR focused on using a single, monolithic transmitter to illuminate a volume of space. The transmitter can be one used for a conventional dish-based radar, if desired. The transmit antenna must have a wider main beam than a traditional dish. A wide antenna radiation pattern, referred to as a spoiled or spotlight beam, is used. This transmitter and antenna combination was chosen to save cost and complexity of the initial model. Figure 1 depicts the AIR in the lower left corner with the wide, spoiled beam, in yellow with the smaller receive beams overlaid for a specific range.

When using a monolithic transmitter, a separate receive array must be used. The receive subarrays differ from a traditional phased array in that the received signal is

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* *Corresponding author address:* Charles C. Kidder III, University of Oklahoma, 120 David L. Boren Blvd., Rm 5900, Norman, OK 73072-7307; e-mail: ckidder@ou.edu

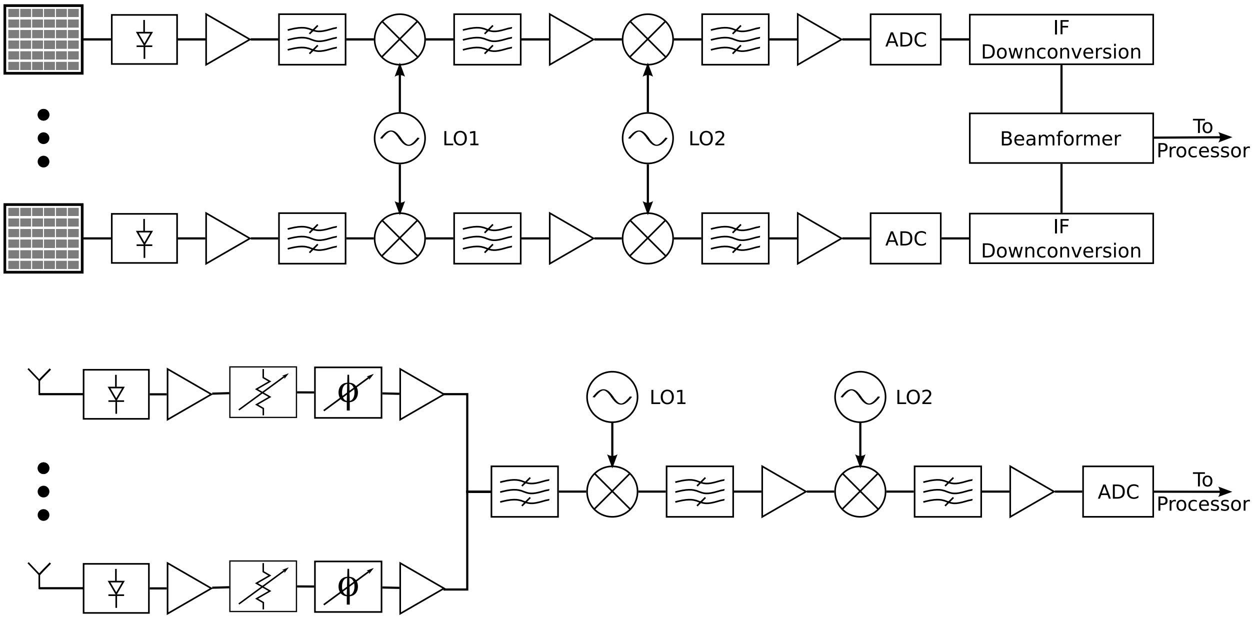

Figure 2: Block diagram of receivers for the AIR (top) and a typical phased array (bottom).

not summed in analog, but summed digitally. Figure 2 shows the simplified block diagrams of the AIR and a typical phased array receiver. In a phased array (Fig. 2, bottom), each antenna has a limiter, low noise amplifier (LNA), phase shifter, attenuator and amplifier. The signal is then summed and filtered before mixing down to baseband where it is digitized. For simplicity, only one of the I & Q channels is shown for the phased array. In the AIR (Fig. 2, top), the output from each subarray is summed together. The phase shifters and attenuators are then removed from the design since the beamformer performs those tasks. After summing the antennas in a subarray, a limiter is placed in the circuit, followed by a LNA. The signal is then mixed down to a IF frequency, using two local oscillators (LO), where it is digitized. By digitizing the signal at an IF frequency instead of baseband, only one analog-to-digital converter (ADC) is needed per channel. After the ADC, conversion to baseband I & Q signals is accomplished using a digital signal processor (DSP) or field programmable gate array (FPGA). At this stage there is I & Q data for each subarray. This data is sent to the beamforming computer which digitally applies complex beam weighting coefficients (phase shifts and attenuation) to the data from each subarray to do beamforming.

The radar receiver architecture of the AIR is designed for producing multiple simultaneous beams. As the processing speed of FPGAs and DSPs continue to increase along with the speed of ADCs, they will become closer to their intended sensor. The AIR is a step in that direction with digital conversion to baseband. This fosters an environment in which digital systems replace analog ones, thus mitigating many non-ideal effects, while reducing weight and lowering economic cost. Digital beamforming allows the signal to be split to n beamformers without incurring a $1/n$ signal loss that would occur if done in analog. To make this possible, the digitization of the received signal must occur at each subarray. This requires a receiver for each subarray, instead of one per radar for traditional radars. The differences in the antenna patterns, signal processing opportunities, and implementation challenges will be discussed in the following sections. More detail on the RF design of the AIR can be found in Kidder III et al. [2007].

3. RECEIVE ARRAY PATTERNS

The effective antenna pattern of the AIR is the composite of several patterns. The first antenna pattern that is considered is the individual receiving element. Next, the array pattern at the subarray level is taken into account. The physical location of the subarrays is then taken into account as the array level pattern is formed. These multiple patterns allow for good control over the composite receive pattern of the AIR. The individual patterns, the element, subarray and array patterns, will be discussed below. While any of these patterns, on their own, are not ideal for a radar, together they are able to produce a very narrow beam.

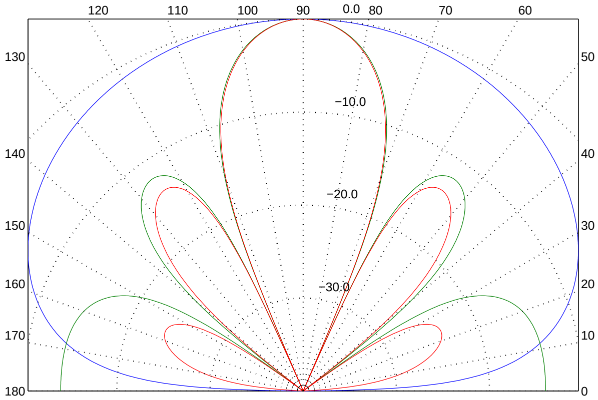

Figure 3: Normalized antenna power patterns for an idealized patch antenna (blue), subarray pattern (green), and composite subarray pattern (red).

3.1. Element Pattern

For the AIR, the ideal antenna element is one that is slightly wider than the main beam of the illumination pattern, with nulls located in the transmit antenna sidelobes. This maximizes the return from the transmitted signal main beam while minimizing the return from the transmit antenna sidelobes. A correctly designed antenna element will also act as a bandpass filter, attenuating signals outside the desired range. This is especially beneficial in an environment which is electromagnetically crowded. An example of a patch antenna pattern is given in Fig. 3 as the blue trace. This is an idealized patch antenna pattern simulated by a $\cos^2\theta$ pattern.

3.2. Subarray Pattern

After the individual antenna element is chosen, the subarray pattern is designed. The main beam needs to be slightly wider than the transmit beam, so that the multiplication of the antenna element pattern and the subarray pattern yield a 3 dB beamwidth equal to the transmit beam. Nulls can be placed outside of the main beam to compliment the sidelobes present in the antenna element and transmit antenna. Nulling can take place to further reduce ground clutter. Once the subarray is fabricated, the antenna element and subarray pattern are set unless each element of the subarray has phase shifters and attenuators. This hybrid approach of analog and digital phase shifting is not used in the AIR. For the subarray pattern in Fig. 3, a square subarray was formed with 25 patch antennas spaced 0.5λ apart. Figure 3 shows just the subarray pattern, in green, with the composite subarray pattern in red.

3.3. Array Pattern

With the antenna element and subarray patterns formed, the subarrays can be physically laid out. The subarray layout is important as it must be known to calculate the array pattern. To create the composite array pattern shown in Fig. 4, 49 subarrays were arranged in a minimum redundancy configuration (1-3-6-2-3-2) (Moffet [1968]; Pearson et al. [1990]) along both the x and y axes with a minimum spacing of 3λ. The redundancy of an array is defined as

$$R = \frac{N\,(N-1)}{2\sum \text{spacing}}$$

where N is the number of elements in the array and spacing refers to all element spacings in the array, not just the adjacent element. This is a measure of redundancy in the spatial frequencies present in an array. The array pattern, by itself, is the green trace in Fig. 4. Combining the subarray pattern yields the composite pattern with the grating lobes disappearing due to the subarray pattern. Since the signals from each subarray are digitized at each subarray, multiple beams can be formed from the same set of signals. This allows further refinement of the power pattern of the array.

Reprocessing of the subarray signals was used to produce the pattern seen in Fig. 5. The initial broadside composite power pattern is shown as the red trace in Fig. 4. This pattern was taken and had patterns at $\pm 7^\circ$ broadside multiplied with it. This pattern was then normalized before being plotted in Fig. 5. Comparing the pattern in Fig. 5 with the pattern for a dish in Fig. 6 shows a narrower main beam, but with higher sidelobes. Further study of the optimal array processing will yield further refinements in the composite array pattern, and should improve the sidelobe level. This type of reprocessing of the received signal is not practical in a phased array due to the large increase in hardware complexity it would create in a phased array radar.

4. SIGNAL PROCESSING

The ability to reprocess the same set of signals from each subarray allows the creation of a feedback loop on a per-pulse basis for the AIR. In a traditional phased array radar, the weights used to form the array pattern must be determined before the pulse is received and put through the beam forming network. In the AIR, the beam forming network is digital and can operate on the same set of signals repeatedly, as in Fig. 4. In Section

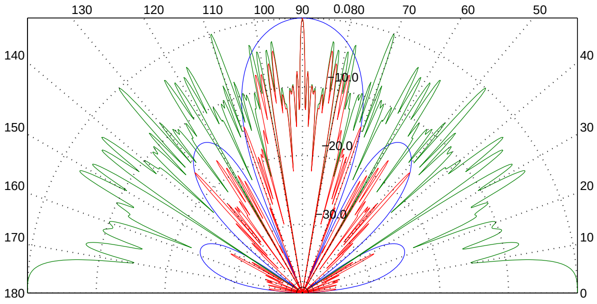

Figure 4: Antenna power patterns for a subarray (blue), from Fig. 3, array pattern (green), and composite array pattern (red).

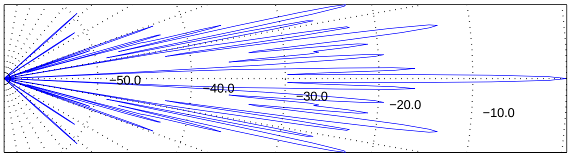

Figure 5: Normalized antenna power pattern for the array in Fig. 4 when three elevations are multiplied (broadside and $\pm 7^\circ$).

3, the example was given of pattern multiplication. With the appropriate amount of processing power this can be done in real-time, or the signals can be captured and post-processed later. Some other examples of improved processing allowed by the AIR are given below.

4.1. Resource Prioritization

By giving a signal processor a priority list of processing tasks, the computing resources can be dynamically reallocated depending on the content of a given set of signals. An example of this would be to only spend the time to recalculate the array pattern if a point target exists with a backscatter cross section above a given value and there is enough time to process it before the next set of signals arrive. This allows real-time processing of radar data without becoming sluggish on non-ideal data sets.

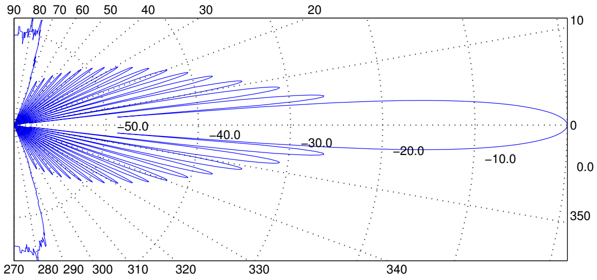

Figure 6: Antenna power pattern for a parabolic dish antenna 20λ in diameter.

4.2. Per Target Signal Summation

The infrastructure of the AIR allows the use of fewer/more pulses for a given target depending on the decorrelation seen in the signal. This can be based upon a lookup table or dynamically calculated from the data taken. This would allow more pulses to be used in calculations for a slow moving system while using fewer pulses for phenomena which decorrelates faster, such as tornadoes.

4.3. Per Target Array Patterns

The weather radar equation assumes that the phenomena being observed are the same size, or larger than the transmit and receive beams of the radar (Doviak and Zrnić [2006]). With the AIR, the assumption that the phenomena being observed is larger than the receive beam may not be true. By dynamically altering the receive array pattern the signal returned from a given phenomena can be maximized, allowing detection of large phenomena with low reflectivity.

5. CHALLENGES

The two greatest challenges to achieving the AIR are the received signal power and in the computing power needed to realize the full potential of the low-level data made available by the radar. Neither of these challenges are insurmountable, but are costly at present. The impact of each challenge is discussed below.

5.1. Transmit Power Density

The wider transmit beam necessary to illuminated the larger volume required by the AIR means that there is less power per square meter at a given range. This can be overcome by using a larger transmitter, or by integrating more received pulses. To illustrate this, two ideal antennas which only transmit in the main beam will be used. The power density at a given range and transmit power can be found by finding the solid angle, in steradians, of the main beam, $\Omega = \theta_3^2/\pi$, and using the following equation, $P_i = P_t/\Omega r^2$. For two antennas with the same transmit power, and different beamwidths, the ratio of incident power becomes

$$\frac{P_{i1}}{P_{i2}} = \frac{\Omega_2}{\Omega_1} = \frac{\theta_{3_2}^2}{\theta_{3_1}^2}$$

For two antennas with beamwidths of 1°and 15°, respectively, $P_{i1}/P_{i2} = 225 =$ 23.5 dB. If the receive antenna patterns are the same, it will take 225 times more pulses integrated to get the same amount of received power. If all other signal power is from thermal noise, there is not much that can be done to overcome the increased number of pulses. If more than the intended signal and thermal noise are present (e.g. reflections from point targets, interfering transmitters), the array pattern can be adapted to remove those signals so fewer pulses need to be integrated. Since the AIR can image a larger volume than a traditional dish based radar, it does not need to scan as fast and can spend the time required to acquire the increased number of pulses while still providing faster volume updates.

5.2. Computing Power

Supercomputers powerful enough to process the stream of data coming off the AIR in real-time do exist. However, having one of these attached to the AIR is not practical. It is desired that all the needed signal processing will be done in real-time so that the provided information will be as timely and accurate as possible. For processing constrained applications, such as a mobile radar, a way must be found to provided the greatest utility in the algorithms run on a given set of signals. Some of this was discussed in Section 4. Finding the correct rule set for optimum processing will be an ongoing exercise as it is not strictly quantitative, but is also subjective and should be based on the cues a given user looks for in the weather being observed.

It is also proposed that work on the algorithms needed for processing the received signals be undertaken to improve the efficiency at which they run on dedicated hardware such as DSPs and FPGAs. DSPs and FPGAs are better suited for series processing of digital signals than a general purpose CPU. Integration of DSPs and FPGAs will improve the overall speed that a given set of operations can occur.

6. CONCLUSION

The feasibility of the Atmospheric Imaging Radar have been shown. The benefits of adaptive array pattern formation coupled with the subarray and element patterns were discussed along with the new signal processing opportunities provided. Further areas for research in minimizing requirements for received power and computational resources were shown.

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