8a.1 TARGET TRACKING AT THE NATIONAL WEATHER RADAR TESTBED: A PROGRESS REPORT ON DETECTING AND TRACKING AIRCRAFT

Mark Yeary[1*], **Blake McGuire**[1], **Yan Zhai**[1], **Doug Forsyth**[2],
William Benner[3], **Garth Torok**[3]
[1] School of Electrical & Computer Engineering – Univ. of Okla., Norman, OK
[2] National Severe Storms Laboratory – Norman, OK
[3] Federal Aviation Administration – WJHTC, NJ

1. Abstract

This paper describes point target detection with the new Phased Array Radar (PAR) at the National Weather Radar Testbed (NWRT) in Norman, Oklahoma. Differing from conventional radars, such as the WSR-88D, the NWRT is designed to be multi-function. That is, it can detect both volumetric and point targets (such as aircraft). This paper also outlines the design of a cell averaging (CA) constant false alarm rate (CFAR) algorithm for enhanced target detection. This paper will be geared towards point target detections and how these can be incorporated into a tracker.

2. Introduction

On a national basis, airport capacity has increased by only 1 percent in the past 10 years, while air traffic increased 37 percent during that time, as reported by the American Society of Civil Engineers (ASCE 2003). It is clear that America's infrastructure is aging. Providing discipline specific solutions will be extremely costly. However, by working together, a diverse group of scientists and engineers can develop the individual radars that have a multi-function capacity to provide both weather and target tracking data. This strategic alliance greatly reduces costs, while providing enormous benefits to the public.

Severe and hazardous weather such as thunderstorms, downbursts, and tornadoes can take lives in a matter of minutes. In order to improve detection and forecast of such phenomena using radar, one of the key factors is fast a scan capability. Conventional weather radars, such as the NEXRAD (Next Generation Radar developed in the 1980's), are limited by mechanical scanning and thus limited in improved scanning speed. Approximately 175 of these radars are in a national network to provide the bulk of our weather information. Under the development for weather applications, the electronically steerable beams provided by the phased array radar can overcome these limitations of the current NEXRAD radar. For this reason, the phased array radar was listed by the National Research Council as one of the two candidate technologies to supercede the NEXRAD (NRC 2002). By definition, a phased array radar is one that relies on a two-dimensional array of small antennas. Each antenna has the ability to change its phase characteristics, thus allowing the overall system to collectively locate specific interesting regions of weather. The National Weather Radar Testbed (NWRT) is the nation's first facility dedicated to phased array radar meteorology. Figure 1 depicts the system components of the new radar (Forsyth et al 2002). In addition, the demand for students trained in this area will be high as new radar technologies replace the ones designed 20 years ago, and as weather radar usage extends into areas such as homeland security. The phased array radar technology developed at the NWRT will be used enhance the safety and capacity of the National Airspace System. Moreover, this project is consistent with the *Joint Action Group for Phased Array Radar* (JAG 2006) and NOAA's *Mission Goals for the* 21^{st} *Century*: to serve society's needs for weather information (NOAA 2003).

Long-term warnings have improved greatly over the last five years and are now being used for critical decision making (NRC 1999). Further improvements are being aimed at providing longer warning lead times before severe weather events, better quantification of forecast uncertainties in hurricanes and floods, and tools for integrating probabilistic forecasts with other data sets.

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[*] Corresponding Author: M. Yeary (yeary@ieee.org), School of Electrical and Computer Engineering, University of Oklahoma, Norman, OK 73019, USA, & Atmospheric Radar Research Center at the National Weather Center, Norman, OK.

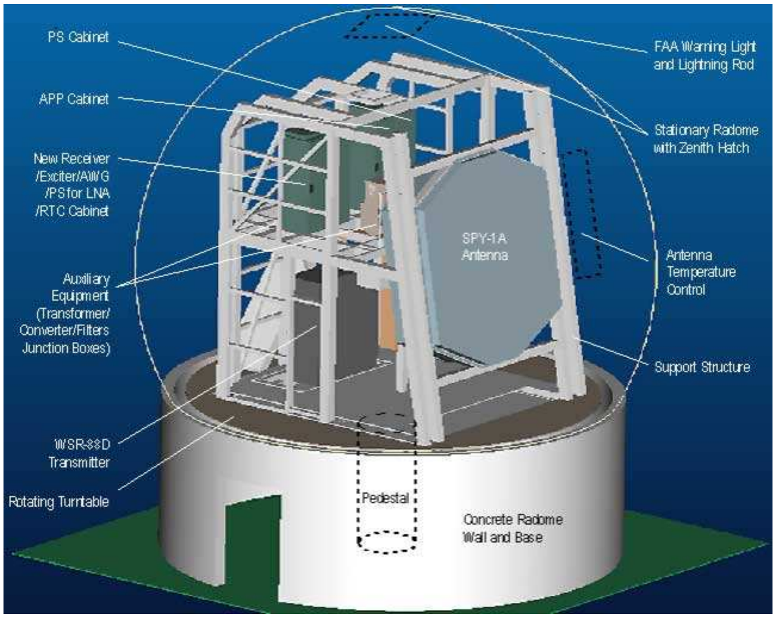

Figure 1: *Face of the SPY-1 phased array radar inside its dome, citation: (Forsyth et al 2002) .*

a. *Target Dectection*

As one of the tasks under the MPAR Program, the FAA's William J. Hughes Technical Center (WJHTC) in New Jersey developed the Track Processor (TP) to complement the weather processing capability of the NWRT. This Track Processor system is designed to be an independent corollary to NWRT though the data can be overlaid with weather data for display. It is designed to receive the same raw radar data that is processed by the weather detection processing algorithms and to locate targets within that data. Air surveillance target detection and track processing algorithms are resident in a separate/parallel signal processor computer suite for operator display at the National Severe Storms Laboratory (NSSL) in Norman, Oklahoma or remotely at the WJHTC. The initial testing of this system was performed in September 2005 at the NWRT and illustrated that the digital signal processor used for the track processor was successful using a track while scan approach at NWRT. Tracks were correlated against the tracks reported by a local ASR-9 radar from Oklahoma City, Will Rogers Airport. The results illustrated that data from the Track Processor display could be accurately overlaid on the ASR-9 display to demonstrate that the same tracks had been detected in range, azimuth and altitude. When completed, the Track Processor will be capable of providing a very rapid and accurate air traffic picture of targets including non-cooperative aircraft since it does not rely on a transponder for any positional information. Figure 2 illustrates the tracks detected in a Track and Scan process during the Track Processor test (track data was correlated against ASR-9 data in range and azimuth). It should also be noted that various clutter sources also are clearly apparent since no clutter filtering was applied for this prototype version. Track history is shown and can be seen as straight line connectivity on the display.

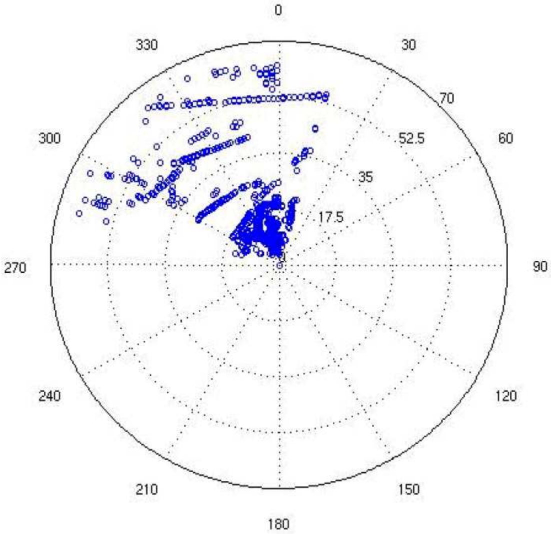

Figure 2: *Tracks detected in a Track and Scan process during a NWRT Track Processor test.*

3. Preliminaries about the Laboratory Data and Cell Averaging CFAR Design

This section builds on Section 2a by outlining the steps required for data collection and differing from the effort in Section 2a, this section also outlines the design of a cell averaging (CA) constant false alarm rate (CFAR) algorithm for enhanced target detection. It is noted that CFAR techniques are well-known to the radar community, citations are many and do include (Skolnik 2002), (Sisterson et al 1998) and (Barton 1984). A readily deployable form of CFAR was initially developed by (Finn and Johnson 1968), and it relied on cell averaging. As discussed later, a variation of it is employed here in the two diminsional target field. In order to collect data, a series of STIM or “stimulus” packets are defined that contain the details of how, where and when the radar is to operate – more details about the STIM files for the NWRT are in (Katz et al 2003). The data is then packaged into blocks organized by STIM, with the raw I&Q data being appended to its STIM as necessary. Rather than providing absolute voltage readings in decimal form, which some processors cannot handle, the data was provided in terms of an integer ratio between the signal power and a reference voltage. The radar collected data from a 45 degree by 45 degree sector of the atmosphere over a period of several minutes. Thus for this particular experiment, both the azimuth and elevation angles were scanned from 0 to 45 degrees. For each radial, the data was collected at a range between approximately 2.0 km and 117.0 km. 32 pulses were emitted and received along each radial. The received signal was sampled at 5 Mbps, leading to a range gate size of approximately 60 m for a total of 1856 valid range gates. The sector was swept using the tilt and scan strategy, thus rotating the radar’s beams in azimuth from 0 to 45 degrees, increasing the beam’s elevation angle by one increment, and revisiting the same azimuth locations. For this particular experiment, the volume search process was completed 10 times to observe moving point targets. It should be noted that as a result of the tilt and scan strategy and the radar PRF of 1250 Hz, any target detected would not be revisited for approximately 20.5 seconds. Skolnik (Skolnik 2002) and Bar-Shalom (Bar-Shalom 1992) have discussed that a commercial airliner that can turn at rates up to $3°$/s, completing a $90°$ turn in 30 s. A radar with a scan time of 20.5 s will not obtain enough observations during the turn. The future dual-use fractional phased array associated with the MPAR will solve this problem. In the dual-use mode – of collecting weather information while tracking targets of homeland interest – the scan strategy of the radar will need to be devised to accommodate both targets. This implies an adaptive multiplexing operation that visits each target differently. With respect to weather, the radar doesn’t have to radiate the entire volume every sweep of the beams. Weather targets are much larger than aircraft and move at a slower rate. However, one problem for the radar is that weather targets can have a very small reflectivity and the algorithms will require good Doppler resolution (Buckler 1998). This requires longer dwells where improved resolutions are desired.

Typically when the I&Q data are available, all pulses gathered along a particular radial will be integrated together to increase the signal-to-noise (SNR) ratio of the pulses, that turn leads to more reliable detections. Coherent integration utilizes the complex I&Q data to add pulses together both in amplitude and in phase, to increase the overall SNR by a factor equal to the number of integrated pulses. However, as a result of the radar’s low PRF, its lengthy dwell times, and the unknown Doppler shift exhibited by the targets of interest, coherent integration is not appropriate for this data. Instead, a technique known as non-coherent integration was employed, wherein the phase information is discarded and the sums of the magnitudes of the samples are added.

a. *Target Models and CA-CFAR*

The classic Swerling target models are typically employed to analyze the fluctuating cross section of a target. Moving towards a more comprehensive set of models with a variety of underlying distributions, (Shnidman 1995) has provided several strategies for studying fluctuating targets and clutter in CA-CFAR applications. We proceed here with the detection and tracking process by following a methodology detailed in (Shnidman 1995). We begin by defining I_n and Q_n to be the n^{th} sample from the in-phase and quadrature channels, respectively, at the output of an incoherent recevier. Using these definitions, we let $y_n = |I_n|^2 + |Q_n|^2$. Additionally, let E_n denote the maximum signal energy of the n^{th} pulse at the output and let X_t represent the signal-to-noise ratio resulting from the non-coherent integration of N return echos. Ideally, these echos are returned from a completely stationary target and they are corrupted by zero-mean independent and identically distributed (i.i.d.) Gaussian noise with a fixed power. To make detection decisions in this case, a version of the likelihood ratio test is applied, wherein a so called sufficient statistic, based in part on the echo power, can be compared with a fixed threshold to determine the presence or absence of a target. However, since we are interested in non-stationary aircraft traversing an environment characterized by noise with a fluctuating non-zero mean, the aforementioned ideal assumptions are clearly violated. To mitigate these issues, a cell averaging technique is employed to maintain a user specified constant false alarm rate when clutter or noise of unknown or varying power is present. This is accomplished by adaptively generating an estimation of the noise power surrounding a specific cell under test by examing the power in surrounding cells. This estimation and a threshold parameter known as α, are responsible for the adaptive nature of the CA-CFAR algorithm. Thus a two-dimensional false alarm algorithm is employed, which has proven successful by other researchers in the past, including (Sisterson et al 1998; Kabakchiev et al 1996).

It is seen that the application of the CA-CFAR algorithm to the detection of a fluctuating target in the presence of clutter with a varying mean is an example of a Category VIII case (Shnidman 1995). In this model, Gamma density functions take the place of the fixed target and the fixed zero-mean clutter, that affords a great degree of flexibility in modeling our experiment. The first step towards generating the adaptive CA-CFAR threshold is the calculation of the probability of detection, P_D, which is given below and more fully described in (Shnidman 1995). It is a function of N_t, the number of integrated samples; X_t; N_r, the number of reference cells used to estimate of the noise power is based; X_r, the mean of the power in those reference cells; α; and K and L, the fluctuation parameters for the Gamma density function.

$$
\begin{aligned}
P_D &= \left[\sum_{m=0}^{N_t-1} h(m) + \sum_{N_t}^{\infty}(m)\right] \\
&\quad \times \left[1 - \sum_{i=0}^{m-N_t} \frac{\Gamma(k+i)}{i!\Gamma(k)} \left(\frac{1}{1+X_t/k}\right)^k \left(\frac{X_t/k}{1+X_t/k}\right)^i\right] ,
\end{aligned}
$$

where

$$
\begin{aligned}
h(m+1) &= h(m)\left[\frac{\alpha}{1+\alpha}\right] \\
&\quad \times \left[\frac{N_r + 2m - (N_r + m - L)z}{(m+1)(1-z)}\right] \\
&\quad - \ h(m-1)\left[\frac{\alpha}{1+\alpha}\right]^2 \\
&\quad \times \left[\frac{N_r - 1 + m}{(m+1)(1-z)}\right]
\end{aligned}
$$

and

$$
z = \frac{1}{1+\alpha}\left[\frac{X_r/L}{1+X_r/L}\right] .
$$

Once a closed form expression for P_D has been found, P_{FA} can be found by setting X_t, the SNR of the non-coherently integrated cells, to zero. However, it is important to note that because the cells have a non-zero mean clutter, that even though X_t is set to zero, there is still power reflected back from the cells that must be accounted. This is accomplished by setting X_t to $(N_t \cdot X_r)/N_r$ and letting $K = L$. Thus, the P_{FA} depends only on N_t, N_r, X_r, α, and L. By using an iterative technique, a value for alpha can be found that gives the desired value of P_{FA}. Multiplying α value by the noise estimate X_r generates the threshold for the current cell under test.

It is important to note that one major premise of the algorithm is that the neighboring cells do not contain a target as well. However, since we are dealing with 60 m range gates and aircraft meeting or exceeding this size, this assumption is often violated. To deal with this issue, a number of “buffer” cells are defined around the test cell to prevent any bleed over from influencing the detections. For our data, all cells that can be reached within two steps from the test cell are considered buffer cells, and the noise estimate is calculated by averaging together all cells a distance of three cells away from the test cell. By summing these cells together and dividing by the number of the cells, the estimated noise value is obtained.

To generate tracks, the CA-CFAR algorithm is implemented on the successive sector scans at a particular elevation. For this data set, this meant selecting an elevation angle (2.27 degrees in this instance), then running the algorithm on each of the 10 scans of the volume. Results can be seen by plotting the results on the same graph in MATLAB, as depicted in Figure 3. Future work will involve the application of Doppler processing and the addition of a clutter map to the CA-CFAR algorithm to drastically reduce the clutter seen in the figure. Additionally, the issue of multiple detections of a single target will be resolved with the application of flight path modeling. This takes advantage of the constraints placed on aircraft by the FAA that dictate a minimum allowable vertical and horizontal proximity.

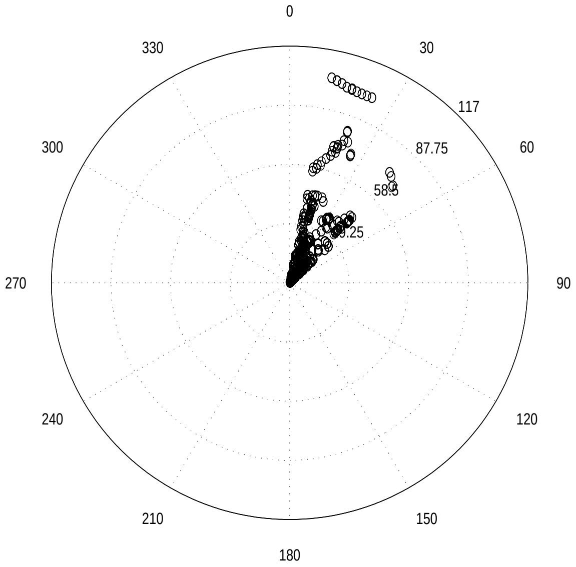

Figure 3: *Tracks detected via the adaptive CA-CFAR process.*

4. Conclusions

The combination of high-performance computing and distributed sensing provide new tools for researchers to observe the natural world at a fidelity that could only be imagined a few years ago. Consequently, improvements can be made to the algorithms that analyze dynamic movements. The cell avaraging CFAR based target detection algorithm presented here provides a technique for tracking hard targets, while simultaneously operating in a weather detection mode. Future efforts will be oriented around carefully defining a balance of radar beam resources to both track these targets and monitor evolving weather patterns. In addition, monopulse based techniques will also be explored for improved point target detection.

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