DESIGN CONSIDERATIONS FOR AN X-BAND SPACED ANTENNA WEATHER RADAR

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Abstract – Having been routinely employed for ionospheric sounding and boundary layer profiling, the spaced-antenna method has recently attracted interest in the weather radar community. This paper presents design considerations for an X-band spaced-antenna phased array weather radar. The approach is based on a dual-polarized phased-array antenna currently in development at the University of Massachusetts, with phase scanning in azimuth and mechanical actuation in elevation.

Index Terms— Dual-polarized, phased-array, Spaced Antenna (SA), weather radar.

I. INTRODUCTION

The need for wind vector measurement has long been met by dual-Doppler and velocity-azimuth-display (VAD) methods in the weather radar community. The spaced-antenna (SA) method has recently attracted interest as a means to measure cross-beam (tangential) velocities in addition to the more traditional Doppler (radial) velocities routinely measured with scanning weather radars. While SA techniques have been successfully employed up to UHF frequencies [1] for wind profiling, the lack of successful demonstrations beyond these frequencies is in large part due to difficulties in synthesizing appropriate antenna systems. Additionally, weather radars also differ from their wind-profiler counterparts in that they introduce the additional complexity of scanning.

In this paper, we describe a concept for SA implementation on an X-band phased-array weather radar at the University of Massachusetts. We begin by describing the physics of the SA-concept (section II.) and the challenges of SA wind-estimation at microwave frequencies (Section III.). We demonstrate that the SA baseline needs to be short so as to satisfy the restriction due to turbulent decorrelation at X-band. At the same time, the SA baseline needs to be long enough to allow discrimination of lags to cross-correlation peaks. We then describe an intended spaced-antenna implementation and the X-band linear phased-array antenna subsystem (Section IV. and V. respectively).

II. BACKGROUND

Fig. 1 shows a typical SA configuration, wherein a single transmitter antenna is flanked on either side by two receive antennas [3]. A collection of scatterers advect with a velocity v_x, the along-baseline velocity. For the purposes of this illustration, we assume that the advection is strictly in the x-direction and in the absence of turbulence.

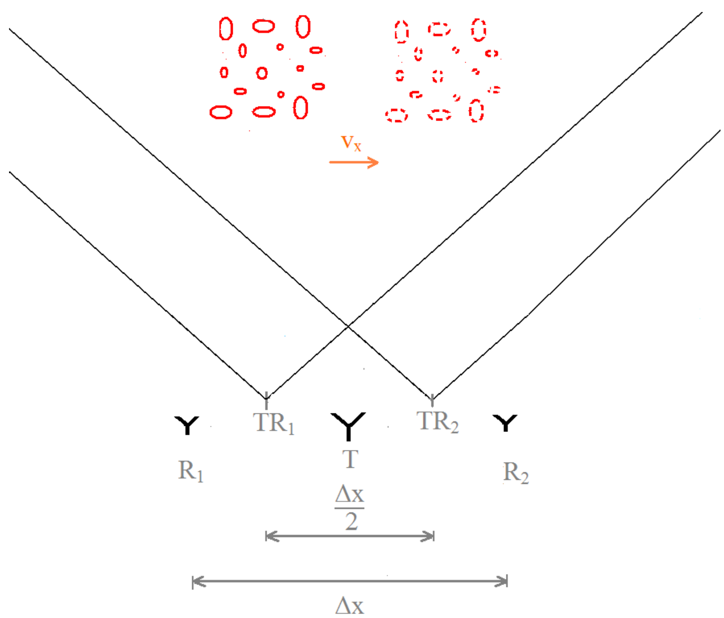

Fig. 1: Illustration of the spaced-antenna concept. The positions of the scatterers at initial time t_1 are shown in solid red. The positions at time t_2 (corresponding to a displacement $\Delta x/2$) are shown in dotted red. TR_1 and TR_2 denote the phase centers.

The scatterers are illuminated by the transmitter T_1 and echoes are received by the antennas R_1 and R_2. The effective phase centers of the transmit-receive combinations are located at TR_1 and TR_2. As this system of scatterers advect, the positions of scatterers relative to T and R_1 change, thereby influencing the received time-series at R_1 and R_2. Consequently, the time-series received at receiver R_2 is the same as that received at R_1, except that it is delayed by a lag $\Delta x/2v_x$.

In the presence of turbulence, the scatterers are re-arranged as they advect in the x-direction. As a result, the scatterers occupy different relative positions with respect to R_2 at time t_2 and a reduction in peak of the cross-correlation function is brought about. Since these relative positions are scaled by the radar wavenumber, an increase in radar frequency makes the effect of turbulence more pronounced.

III. SPACED-ANTENNA WIND ESTIMATION

The generalized form of the normalized cross-correlation of the received electric field, *E(x,t)*, in space and time is given by:

$$\rho_{12}(\Delta x,\tau)=\frac{E(x,t)E^{*}(x+\Delta x,t+\tau)}{\left|E(x,t)\right|^{2}} \qquad (1)$$

Following Doviak et al. [4], the normalized correlation functions $\rho(\Delta x,\tau)$ of echoes received at spaced-antennas due to a random distribution of scatterers is given by (2).

$$\rho(\Delta x,\tau)=\exp[-\left(a_h(v_x\tau-\frac{\Delta x}{2})\right)^2] \\ \exp[-(a_h v_y\tau)^2] \\ \exp[-2(k\sigma_v\tau)^2] \qquad (2)$$

Here k is the radar wavenumber, $\Delta x/2$ is the spaced-antenna baseline for the geometry in Fig. 1, a_h is an antenna parameter that is a function of T/R antenna beamwidths and k, σ_v is the rms radial velocity due to turbulence in the resolution volume, v_x and v_y are the along- and cross-baseline components of velocity. The first gaussian is a function of along-baseline winds alone and is what we are primarily interested in. In the absence of cross-baseline winds and turbulence, this gaussian ensures that the peak of the cross-correlation function occurs at a lag $\Delta x/2v_x$. The second gaussian captures the effect of cross-baseline winds. Both these gaussians describe the effect of the mean wind traversing the finite beamwidth of the antenna. The third gaussian captures the effect of turbulence. Being centered at zero-lag, turbulence and cross-beam winds shift the cross-correlation towards zero-lag and bring about a reduction in peak.

In order to understand the effect of frequency on the correlation functions, we recognize that the only term having any sort of frequency dependence, other than the radar wavenumber (k), is a_h (given by (3)).

$$a_h=6.56\times10^{-2}\,\frac{\theta_{1R}^2}{\theta_{1R}^2+\theta_{1T}^2}\,\frac{\theta_{1T}}{\lambda} \qquad (3)$$

where, θ_{1T} and θ_{1R} are the 3-dB beamwidths of the transmit and receive antennas in degrees. The second term in (3) captures the effect of different antenna configurations. For spaced-antenna systems where the transmit and receive antennas have identical 3-dB beamwidths, this term is typically 0.707 (unitless). As the 3-dB beamwidth of the receive antenna becomes broader than the transmit antenna, the value of this term approaches unity. Recognizing that the transmit antenna beamwidth is inversely proportional to the electrical aperture size, we see a_h that has no strong dependence on frequency.

The third term in (2) has a strong dependence on frequency and rms turbulence intensity. While picking an SA-baseline, it is important that the turbulent term not dominate cross-correlation function. Fig. 2 plots the variance of the third Gaussian (given by (4)) for different rms turbulence intensities.

$$\exp[-2(k\sigma_v\tau)^2]=\exp\left[-\frac{\tau^2}{2\tau_{pat}^2}\right]$$

$$\text{where,}\qquad \tau_{pat}=\frac{1}{\sqrt{2(2k^2\sigma_v^2)}} \qquad (4)$$

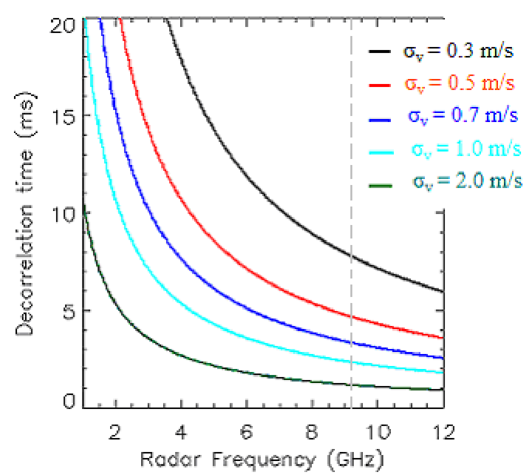

Fig. 2: The decorrelation time of the radar echo due to turbulence only plotted against Radar Frequency in GHz (X-axis). All curves are plotted for cross-baseline winds of 0 m/s. A dashed line indicates our radar frequency.

We see that the turbulent decorrelation time at X-band is an order of magnitude below that at UHF. Fig. 3a and 3b show the corresponding reduction in the peak of the cross-correlation function. From the σ_v =1.0 m/s curve (typical of the day-time boundary layer) in Fig. 3b, we see that the spaced antenna baseline needs to be shorter than 30 cm for the peak of the cross-correlation function to be atleast 0.5.

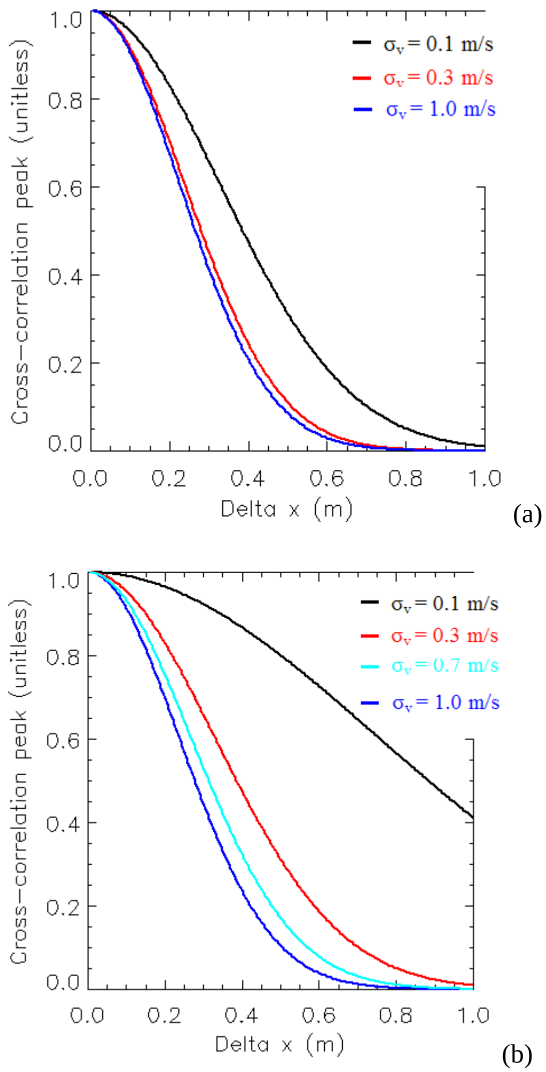

Fig. 3: The peak of the cross-correlation function as a function of SA-baseline. All curves are plotted for a radar frequency of 10 GHz, 3° transmit and 15° receive antennas, cross-baseline-velocities of 0 m/s and infinite SNR.

(a) Along-baseline velocity of 5 m/s
(b) Along-baseline velocity of 15 m/s

As the physical dimension of antennas for satisfactory SNR is far greater in comparison, having an SA-baseline appropriate for X-band frequencies is not straightforward. This embodies the first design challenge for X-band SA weather radars. In order to make measurements of cross-beam velocities, antenna systems that permit baselines smaller that their dimensions have to be synthesized.

The product of the three gaussians in (2) is also a gaussian, given by (5)-(6). Here, τ_p is the time-lag to the peak of the gaussian cross-correlation function, τ_c the width of the gaussian, exp ($-\eta$) is the relative value of the peak of the cross-correlation with respect to the autocorrelation function.

$$\rho_{12}(\triangle x,\tau) = \exp(-\eta)\exp\left(-\frac{(\tau-\tau_p)^2}{2\tau_c^2}\right) \quad (5)$$

$$\tau_c = \frac{1}{a_h\sqrt{v_x^2+v_s^2}} \quad (6a)$$

$$\tau_p = \frac{\triangle x}{2}\frac{v_x}{v_x^2+v_s^2} \quad (6b)$$

$$\eta = \left(\frac{a_h\triangle x}{2}\right)^2 \frac{v_s^2}{v_x^2+v_s^2} \quad (6c)$$

$$v_s^2 = v_y^2 + 2\left(\frac{k\sigma_v}{a_h}\right)^2 \quad (6d)$$

The Full Correlation Analysis (FCA) now estimates the along-baseline wind using estimates of τ_p, τ_c and η in (7). Consequently, in order to have a reasonable estimate of the along-baseline wind v_x, we need to be able to estimate each of these parameters accurately.

$$v_x = \frac{\triangle x}{2}\frac{\tau_p}{2\eta\tau_c^2+\tau_p^2} \quad (7)$$

Fig. 4 shows the shift in the lag to cross-correlation peak due to turbulence by plotting (6b) for different values of Δx. From the Δx=5 cm curve, we see that changes in τ_p become imperceptible for the chosen range of velocities. This embodies the second challenge for SA weather radar design at X-band, the SA-baseline has to be long enough to allow discrimination of lags to cross-correlation peaks.

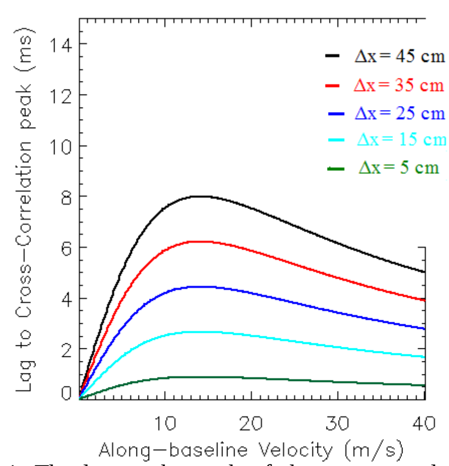

Fig. 4: The lag to the peak of the cross-correlation function plotted as a function of along-baseline velocity. All curves are plotted for a radar frequency of 10 GHz, 3° transmit and 15° receive antennas and cross-baseline-velocities of 0 m/s.

To a first approximation, Fig. 3-4 show that the choice of SA-baseline at X-band is contained in the 5 - 30 cm interval. However, in order to have acceptable SNR at the radar receiver, typical weather radar antennas at X-band have dimensions of the order of D ~1.5 m. Even if two such antennas were placed adjacent to each other, the resulting SA-baseline would be larger than the afore mentioned criterion. Phased arrays permit the needed flexibility in synthesizing various baselines and apertures for SA-configurations (see section IV). Additionally, SA weather radars differ from conventional wind-profilers in that they introduce the complexity of scanning [2]. Phased-arrays allow us to eliminate any relativistic motion between the antenna and the target due to scanning.

IV. PHASED-ARRAY SPACED-ANTENNA IMPLEMENTATION

Fig. 5 depicts our approach to implementing a phased-array spaced-antenna system. The entire phased-array is used upon transmission, while alternating portions of the array are used upon reception. The resulting time-series is of the form T, RL, T, RR, T, and so on. Auto and cross-correlations may be produced with the interleaved time series from separate portions of the array.

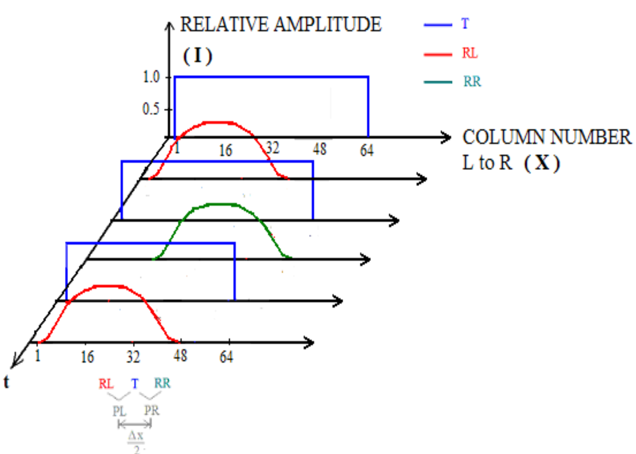

Fig. 5: Time series of transmit/receive aperture weighting indicating alternating left and right receive apertures interleaved with the transmit pulse. The SA-baseline is denoted by |PL – PR| = Δx/2.

This approach is similar to the scheme employed by the MAPR UHF radar [1] and to that described using the NWRT S-band radar [3]. The primary difference lies in the flexibility of our SA-baseline and sub-aperture sizes (see Section V.). Since our phased array is capable of operation with programmable amplitude weighting upon transmit and receive, the receive sub-apertures may overlap.

V. DESCRIPTION OF PHASED-ARRAY ANTENNA SUB-SYSTEM

Through the center for Collaborative Adaptive Sensing of the Atmosphere (CASA), the University of Massachusetts is developing a linear phased-array antenna that is capable of electronic scanning in azimuth and mechanical actuation in elevation [5]. The so-called "phase-tilt" array consists of 64 dual-polarized antenna columns (Fig. 6-7). Each column is a center-fed microstrip patch array capable of both horizontal and vertical polarization excitations. Although the array is capable of dual-polarization operation, only one polarization (H) is intended for use in the SA configuration. The array has a 2° beamwidth in the azimuth plane and a 3.5° beamwidth in the elevation plane at broadside (Fig. 7).

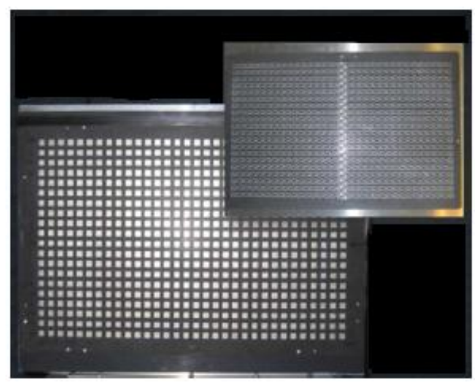

Fig. 6: A panel of the phase-tilt array. Inset: Reverse side of array showing the dual-polarized serpentine transmission line feed-network [5].

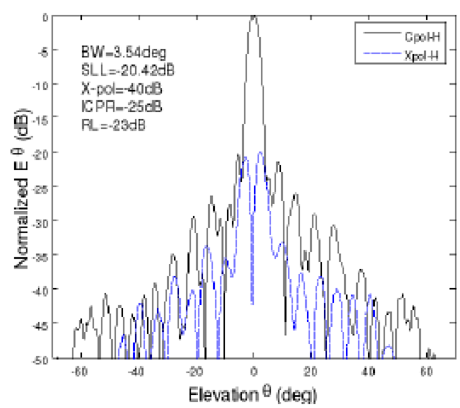

Fig. 7 : Measured H-polarization elevation pattern for the central element in the prototype array [5].

Behind each column, a Transmit-Receive (T/R) module provides independent amplitude and phase control on both transmit and receive (Fig. 8). A beam scheduling application on the computer is able to preload and define several beam configurations and beam sequences that are executed by the state machines residing in the FPGA. It is this flexible control of the aperture, which enables the implementation of the spaced-antenna system we have proposed.

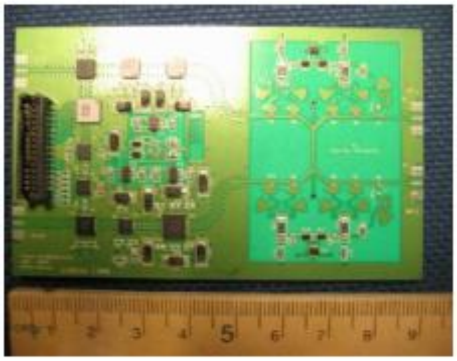

Fig. 8 : A fabricated Transmit-Receive (T/R) module. (Scale in cm shown below) [5].

Prototypes of the array elements and T/R modules were developed and tested in 2008, and the first array antenna panel is being tested. Upon completion of preliminary testing, we intend to duplicate one such panel for usage in the Spaced-Antenna configuration described in section IV.

VI. SUMMARY

At microwave frequencies, the physical dimension of antennas for satisfactory SNR is greater than the restriction on the SA-baseline due by turbulent decorrelation. Consequently, even if two such antennas were placed adjacent to each other, the resulting SA-baseline would be longer than required. On the other hand, the SA-baseline has to be long enough to allow discrimination of lags to cross-correlation peaks.

This paper describes an approach for the design of Spaced-Antenna weather radars at X-band using a linear phased-array being developed at the University of Massachusetts. The array, consisting of 64 dual-polarized antenna columns, has a 2° beamwidth in the azimuth plane and a 3.5° beamwidth in the elevation plane at broadside. It is capable of phase scanning in azimuth and mechanical actuation in elevation. Behind each column, a Transmit-Receive (T/R) module provides independent amplitude and phase control on both transmit and receive.

Flexible control of the aperture upon transmit and receive enables the implementation of a spaced-antenna system. The entire phased-array is used upon transmission, while alternating portions of the array are used upon reception. Auto and cross-correlations may be produced with the interleaved time series from separate portions of the array.

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