Digital Beamforming Radar Applied in Atmospheric Observation by Event-Driven Simulation Framework

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1. INTRODUCTION

A hybrid analog-digital beamforming (ADBF) architecture of active electronic scanning array (AESA) provides a balance between increasing degrees of freedom in digital beamforming (DBF) strategy design and also achieves the desirable receiver sensitivity. ADBF mitigates the complexity of the hardware structure compared to the full DBF structures by retaining the partial advantage of the analog beamforming gain. An illustration of antenna configuration vs. weather-emulated echo in a specific range is shown in Figure 1. An ADBF AESA architecture was designed in Airborne Phased Array Radar (APAR) that provides 56 row-wise analog feed networks. It allows a 20° fan beam in elevation to the sharpest 2.2° pencil beam with DBF capability in elevation and steerable in azimuth to process select high-impact weather cases by an advanced space-time adaptive process (STAP).

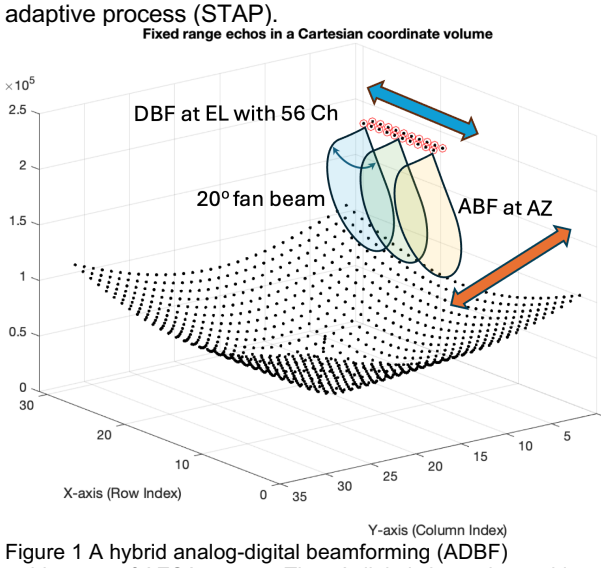


Figure 1 A hybrid analog-digital beamforming (ADBF) architecture of AESA system. The 56 digital channels provide the capability of the DBF process in the azimuth of a fixed-range weather model.

A radar emulator ingests simulated source weather radar data observations and generates a pseudo real-time, multi-channel digital, radar time-series IQ data stream which is powered by a heterogeneous structure HPC with CPUs to process beam scheduling and data-loading flow, GPUs to generate IQ data accordingly, and is followed by Field Programmable Gate Arrays (FPGAs) to emulate the receiver process of demodulation of the multi-channel signals [1].

The pseudo-real-time simulator generates an emulated time series echo response based on the observed ground-truth reference echo data that are set up and processed by the HPC with tremendous computational power and processing time. The emulating weather data are generated in series by an electromagnetic backscattering simulation of weather models using fixed time-step granularity, which contains the temporal-varying response of weather models in range, velocity, angle, and amplitude with polarimetric diversity coordinated to the observative radar site.

In radar signal processing (RSP) simulation, however, the data-reception period is varied based on the system configuration in pulse repetitive interval (PRI), scanning rate (SR), and numbers and angles of beamforming, which are assigned to the waveform configurations.

To access these emulated datasets efficiently in RSP simulations, an efficient event-driven simulation framework is introduced to associate the physics-based precalculated weather-model responses with the radar-processing event without rerunning the emulator to resolve the computational complexity and retain the fidelity of the echo data in RSP.

An event-driven simulation structure processes the echo data based on the waveform configuration design. The time granularity will not be given in fixed increments but rather invoked by the associated PRI, SR, and the aspect angle between the weather model and the designated beams. The designated simulation events vs. the overall emulator simulation time stamps are shown in Figure 2. This RSP in discrete event simulation (DES) architecture utilizes the physics-based weather emulation model. It processes the data on the event invoked by the radar configuration settings regardless of the dataset which is not matched to this specific radar configuration [3].

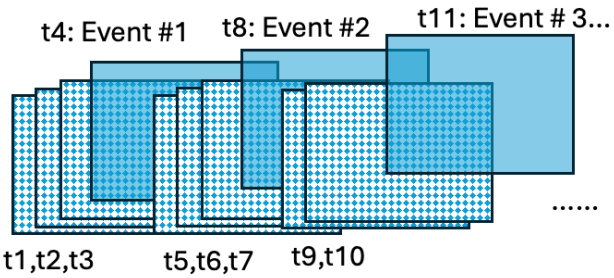


Figure 2 An even-driven simulation architecture processes the emulator data based on the arithmetic event schedule of radar configurations rather than a fixed time-step increment.

The DES RSP generates high-fidelity results based on the genuine weather emulator. The architecture maintains

the simulation efficiency and accuracy by invoking only the events and datasets associated with the time and perspective angle that are aligned with the radar configuration.

The weather-model response is modified as the following form associated with the hydrometeors' spectrum calculated by the emulator.

The modified random normal variable $\tilde{v}$ based on the V_{radial} (υ), spectrum width (σ) is defined as:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\upsilon)^2}{2\sigma^2}}$$

The υ is radial velocity, the σ is the spectrum width of the hydrometeor's samples in this observation cell. Normalized the probability of density function (PDF) by Z_{hh} with the 5 sample PDFs is shown in the left chart of Figure 3. The $\widetilde{Zhh}$ is a random variate of Z_{hh} to present the power of the hydrometeor cell with stochastic distribution in linear scale. The summation of the five $\widetilde{Zhh}$ equals to Z_{hh} from the hydrometeor cell without introducing scaling offsets as shown in the right plot.

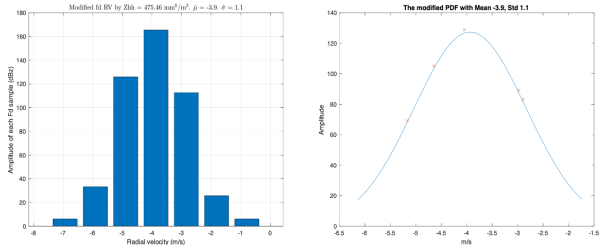


Figure 3 Five samples of a modified normal random variable are used to represent the stochastic parameters of the weather meteor samples with the radial velocity, spectrum width, and reflectivity.

The complex form of the meteor signal is defined as follows:

$S = \widetilde{Zhh} * \exp(i * 2\pi * \tilde{fd} * \Delta t + \tilde{\phi})$, where Δt = nPulse*PRI, $\phi \in U(0,2\pi)$ to represent the random initial phase of detection.[2][3] The complex signals of two cells are set PRF = 1 kHz, nPulse = 50.

Samples represent the weather cell calculated by $\tilde{v}$. The $\widetilde{fd}$s are derived and resolvable in the spectrum and the illustrative signals are shown in Figure 4 top and bottom plots respectively.

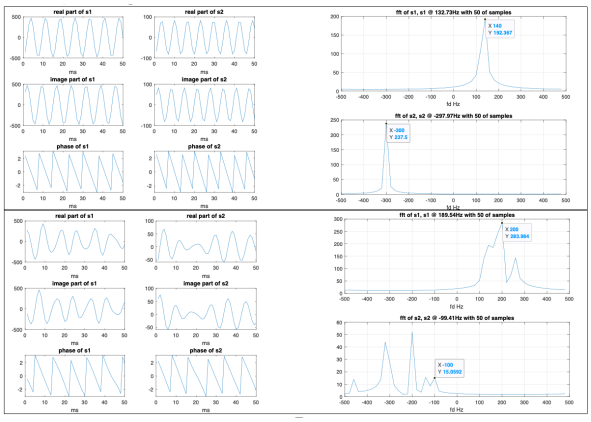


Figure 4 The complex form of meteor signals presented in time series at the left plots and the Doppler frequencies are resolved correctly with the amplitude associated to the Zhh.

The complex form of the cell signal is extended into each element in the array. The signal of each element is modulated by the phase offset associated with the path difference from the cell to each element. The contribution of spatial difference of each element results in the direction of arrival (DOA) estimation in beamforming simulation. A 2D beamforming simulation with two weather echoes is shown in Figure 5. The left plot is the phase of the directional coefficients of each element to perform two data cells at [-20, 35] and [15,10] degrees in azimuth and elevation direction. The center and right plots are the beamforming spectrum of these two echoes with the correct angular estimation and power response associated with the Z_{hh}.

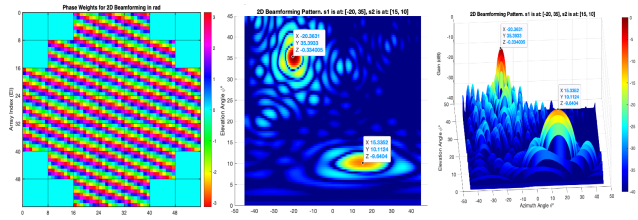


Figure 5 The 2D ULA directional coefficients were shown in the left plot with APAR configurations. The center and right plots showed the two cells were resolved with their designated directions and amplitudes associated with the hydrometeors.

With the DBF architecture of the AESA radar system, the 56 row-wise beamformers provide the degree of freedom (DF) of the special signal process to enhance desired resource direction and suppress potential distortion sources within the radar-searching field of view (FOV). A DBF-based STAP denoise example is shown in Figure 6. With the DFs in spatial and time domains, more efficient denoise processes can be introduced into RSP. A Doppler distortionless waveform design [4] and advanced STAP [5] enhance RSP performance in atmospheric observation applications. This DES framework provides a high-fidelity and efficient platform for RSP simulation.

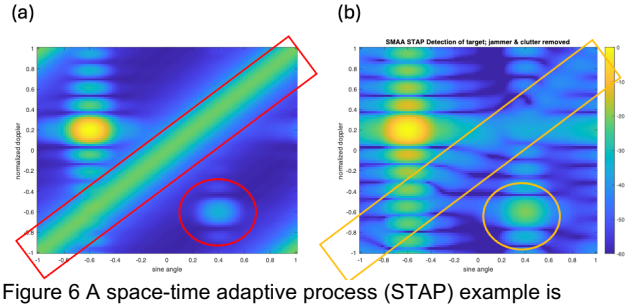


Figure 6 A space-time adaptive process (STAP) example is processed under a DBF structure. In (a), a desired signal was under interference by a time-varying chirping noise (red square) and a signal-tone jamming signal (red circle). In (b) these two interferences were removed after STAP.

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1.1 *References*

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