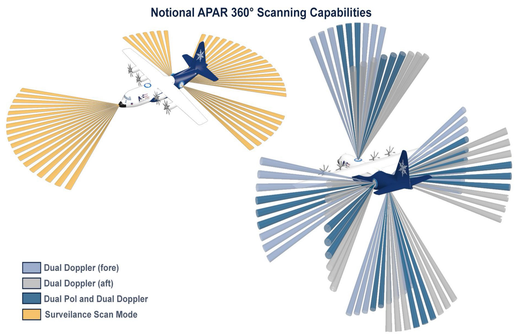
Digital Beamforming Radar Applied in Atmospheric Observation by Event-Driven Simulation Framework

Yuan-Pin Cheng[1] William Blake[1]

[1] NSF NCAR / Earth Observing Laboratory

What is APAR?

Airborne Phased Array Radar (APAR)[3]. Operating at C-band frequency, it is designed to provide single and dual-polarization moments and dual-Doppler analyses, enabling coincident measurements of winds, microphysics, and particle information within a whole storm structure. The full APAR system will consist of four active electronically scanned arrays (AESAs) mounted on the NSF NCAR C-130. To accomplish community science objectives, APAR is designed to have flexible scanning capabilities. As the scanning ability in elevation and azimuth, APAR will provide a Range Height Indicator (RHI) from all four panels to make up a full 3-D volume. Due to the agile scanning capabilities, APAR will provide a 3-D volume in a short time period.[1]

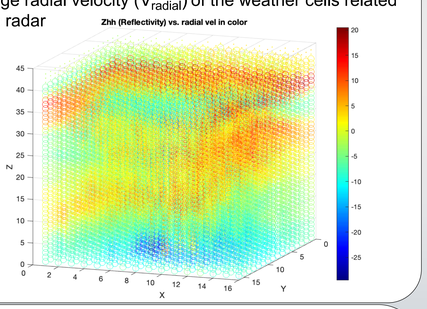


APAR Observing Simulator

While the APAR system is being built, a tool known as the APAR Observing Simulator (AOS) was developed by investigators at NSF NCAR with the intent of operating hypothetical APAR missions into simulated storms.

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 to process beam scheduling and data-loading flow to generate IQ data accordingly. The emulating weather data are generated in series by an electromagnetic backscattering simulation of weather models.

Below: The cells are presented in circles with the size associated with the reflectivity (Z_{hh}) generated by the high-fidelity weather model simulator. The color bar indicates the average radial velocity (V_{radial}) of the weather cells related to the radar



Experiment Design and Description

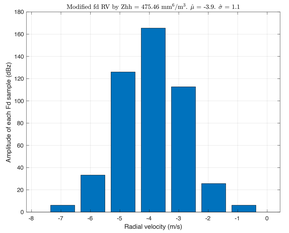
The emulating weather data are generated in fixed time-step granularity, which contains the temporal-varying response of weather models in range, velocity, angle, and amplitude with polarimetric diversity coordinated to the observative radar site.

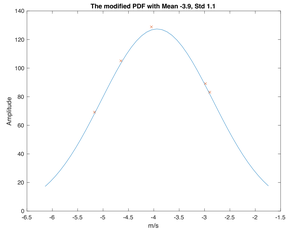
In radar signal processing (RSP) simulation, however, the data-reception period is varied based on the system configuration in pulse repetitive interval (PRI), scanning rate (SR), and numbers and angles of beamforming, which are assigned to the waveform configurations.

To access these emulated datasets efficiently in RSP, an efficient discrete-event simulation (DES) 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.

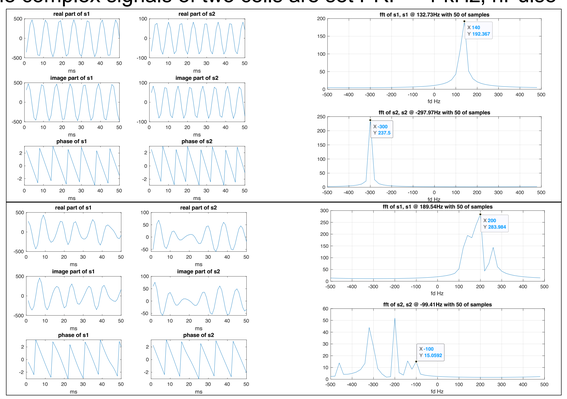
The modified random normal variable $\tilde{v}$ based on the V_{radial} (v), spectrum width (σ) is defined as: $\tilde{v}(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-v)^2}{2\sigma^2}}$

Normalized the probability of density function (PDF) by Z_{hh} with the 5 sample PDFs (bottom left) of $\widetilde{Z_{hh}}$ in linear scale to present the stochastic distribution of the hydrometeor cell. The summation of the five $\widetilde{Z_{hh}}$ equals to Z_{hh} from the hydrometeor cell without introducing scaling offsets (bottom right).

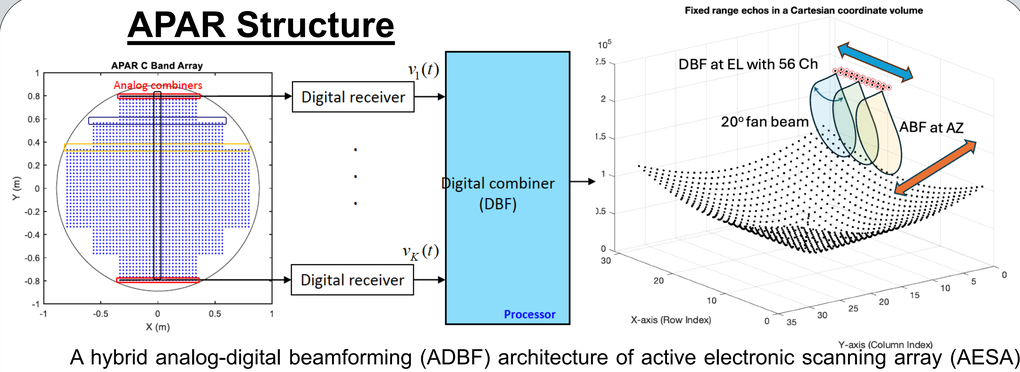




The complex form of the cell with one(**top**)/five(**bottom**) $\widetilde{fd}$s calculated by $\tilde{v}$ are derived and resolvable in the spectrum:
$S = \widetilde{Z_{hh}} * \exp(i * 2\pi * \widetilde{fd}^* \Delta t + \tilde{\phi})$, where Δt = nPulse*PRI, [3]
$\phi \in U(0,2\pi)$ to represent the random initial phase of detection.[4]
The complex signals of two cells are set PRF = 1 kHz, nPulse = 50



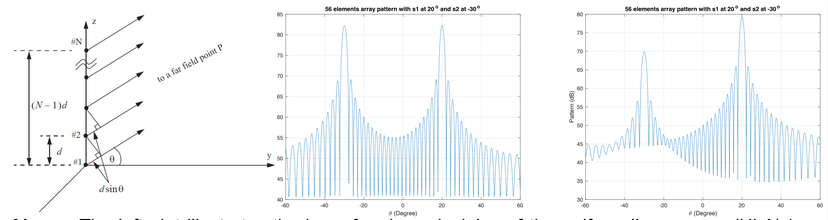
APAR Structure



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.[2]

An illustration of antenna configuration vs. weather-emulated echo in a specific range. An ADBF AESA architecture was designed in 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 super-resolution Direction of arrival (DOA) estimation and space-time adaptive process (STAP).

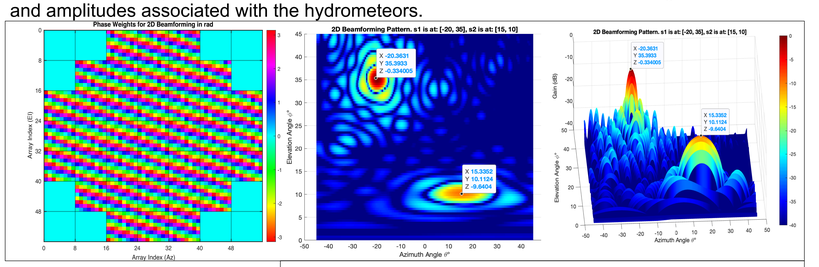
1D ULA beamforming with 56 channels



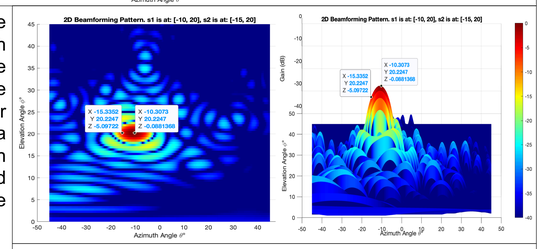
Above: The left plot illustrates the beamforming principles of the uniform linear array (ULA) by determining the phase difference between each element caused by the DOA of the object. The center plot shows examples of 1D 56-channel ULA with two directions at 20° and -30°. The right plot demonstrates the two hydrometeor signals extended to 56 channels with phase difference associated with the spatial path difference. The DOAs of the signals were resolved with the amplitude associated with the reflectivity of hydrometeor.

2D ULA beamforming with 56 channels

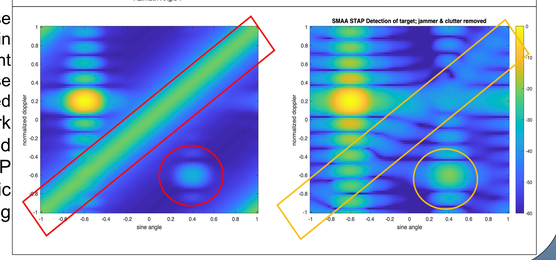
Below: The 2D ULA directional coefficients were shown in the left plot with APAR configurations. The center and right plots showed the two cells were resolved with their designated directions and amplitudes associated with the hydrometeors.



Right: The example shows the two undiscernible objects with 5° difference in azimuth. The stronger echo dominated the beamforming response under the current antenna configuration. Super-resolution DOA algorithms are introduced into APAR RSP to improve angular resolution.



Right: A DBF-based STAP denoise example is shown. With the DFs in spatial and time domains, efficient space, time, and waveform denoise processes [5,6] can be introduced into RSP. This DES framework provides a high-fidelity and efficient architecture for RSP simulation to reuse the generic data of AOS without repeating the simulator.



References

1. Lee, W.-C., B. Klotz, J. Vivekanandan, et al. 2024: Implementation of the Airborne Phased Array Radar (APAR) Observing Simulator (AOS) Prototype, 104th AMS Annual Meeting, Session 13 - Emerging Measurement Technologies, Low-Cost Sensors, and Data Visualization Methods, Paper 13.5.
2. Karboski, Adam, et al. "Airborne Polarimetric Doppler Phased Array Weather Radar: Digital Twin of the Active Electronically Scanned Array." 2022 IEEE International Symposium on Phased Array Systems & Technology (PAST). IEEE, 2022.
3. Doviak, Richard J., and Dusan S. Zrnic. Doppler radar & weather observations. Academic press, 2014. Ch.4, pp.67-69.
4. Cheng, YuanPin, et al. "Hybrid High-Fidelity Modeling of Radar Scenarios using Atemporal, Discrete Event, and Time-Step Simulation." Proceedings of the World Congress on Engineering and Computer Science. Vol. 2. 2016.
5. Nieh, Jo-Yen, and Yuan-Pin Cheng. "Innovative multi-target estimating with clutter-suppression technique for pulsed radar systems." Sensors 20.9 (2020): 2446.
6. Mahafza, Bassem R. Radar systems analysis and design using MATLAB. 3rd Ed. Chapman and Hall/CRC, 2013. Ch.16, pp.633-639.

Acknowledgements

Most of this work was supported by the National Science Foundation through the Mid-Scale Research Infrastructure (MSRI-2) Program Award for APAR (AGS-2153337). The authors would like to thank Dr. W.-C. Lee, Dr. J. Vivekanandan , and Mr. A. Karboski for the conceptual review and inspiration.