BLIND CO-CHANNEL SOURCE SEPARATION IN SPARSE INTERFEROMETRIC ARRAYS

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Introduction to Blind Source Separation

- Blind Source Separation (BSS) is an approach to isolating signals of interest in the presence of interference
- In the RF world, BSS enables the separation of the signal of interest from co-channel radio frequency interference (RFI) sources without *a priori* knowledge of the RFI source's location or waveform
  - Furthermore, BSS does not require knowledge, nor precise calibration of the array
- Several approaches to BSS, including (but not limited to):
  - Finite alphabet
  - Self-coherence
  - Cyclostationarity
  - Independent Component Analysis (ICA) algorithms:
    - FastICA
    - Infomax
    - Natural Gradient
    - Joint Approximate Diagonalization of Eigenmatrices (JADE)

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    - Natural Gradient
    - Joint Approximate Diagonalization of Eigenmatrices (JADE) — Selected approach for this paper
- JADE was selected for its robust performance, minimal algorithm configuration, and minimal assumptions levied on the source signal distributions

Summary Of The JADE Algorithm*

Provided $\mathbf{x}(t)$, a $M(\text{number of sensors}) \times T$ $(\text{number of time samples, with } T \geq M)$ data matrix representing the N observed (received) signals at the array

1. Whiten and reduce dimensionality of the data by removing the noise subspace, $\mathbf{z}(t) = \mathbf{R}\mathbf{x}(t)$
   - Signal subspace order is estimated from the eigenvalues of the covariance matrix using an Information Theoretic Criteria approach
   - For the paper, the covariance matrix was diagonally loaded to focus on the significant sources
   - The resulting data matrix should be of dimension $N \times T$
2. Compute the sample fourth-order cumulant of $\mathbf{z}(t)$ as a $N^2 \times N^2$ matrix: $\mathbf{Q}_i$
3. Compute the eigendecomposition of $\mathbf{Q}_i$ and store the most significant N eigenpairs, $\left\{\hat{\lambda}_n, \hat{\boldsymbol{\mathcal{E}}}_n \middle| 0 \leq n < N\right\}$ as an eigenmatrix: $\hat{\mathbf{E}}_n = \hat{\lambda}_n \hat{\boldsymbol{\mathcal{E}}}_n$
4. Jointly diagonalize $\hat{\mathbf{E}}_n$ by a unitary matrix, $\mathbf{Z}$ using Givens rotations
5. The estimated mixing matrix is: $\widehat{\mathbf{A}} = \mathbf{R}^H\mathbf{Z}$ and the estimated de-mixing matrix is thus:

$$\mathbf{A}^{-1} \approx \widehat{\mathbf{W}} = \mathbf{Z}^H\mathbf{R}$$

- Computational Complexity:
  - The pre-whitening algorithm is $O(M^3)$
  - JADE is $O(N^6)$ (after dimensionality reduction)

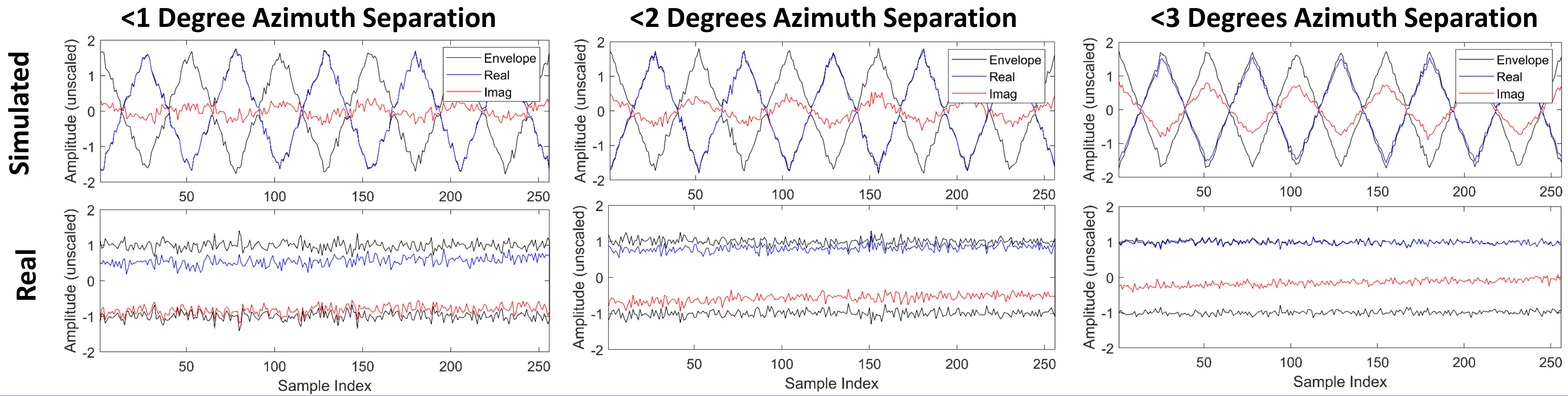
* - J.-F. Cardoso and A. Souloumiac, “Blind Beamforming for non Gaussian Signals,” Proc. Inst. Elect. Eng. F, vol. 40, pp. 362–370, 1993.

Validating JADE Performance With a Real Sparse Interferometric Array

- To validate the performance of the JADE algorithm, we use a data set collected from an airborne interferometric array
- Each collection includes an emitter at a known location, transmitting a continuous wave (CW) signal with a high SNR (approximately 30 dB)
- The data set included approximately 300 collections for every frequency of interest, spanning the full azimuth of the airborne array
  - Each collection is approximately 20 milliseconds, with a 50 kHz sample rate
- The environment contains co-channel emitters of unknown quantity, design, and location
  - These emitters present an opportunity to demonstrate JADE performance, but without the ability to measure performance against clairvoyant metrics
- To measure JADE against clairvoyant metrics with a broader set of relative geometries, we supplemented the environment by injecting a simulated emitter in some datasets

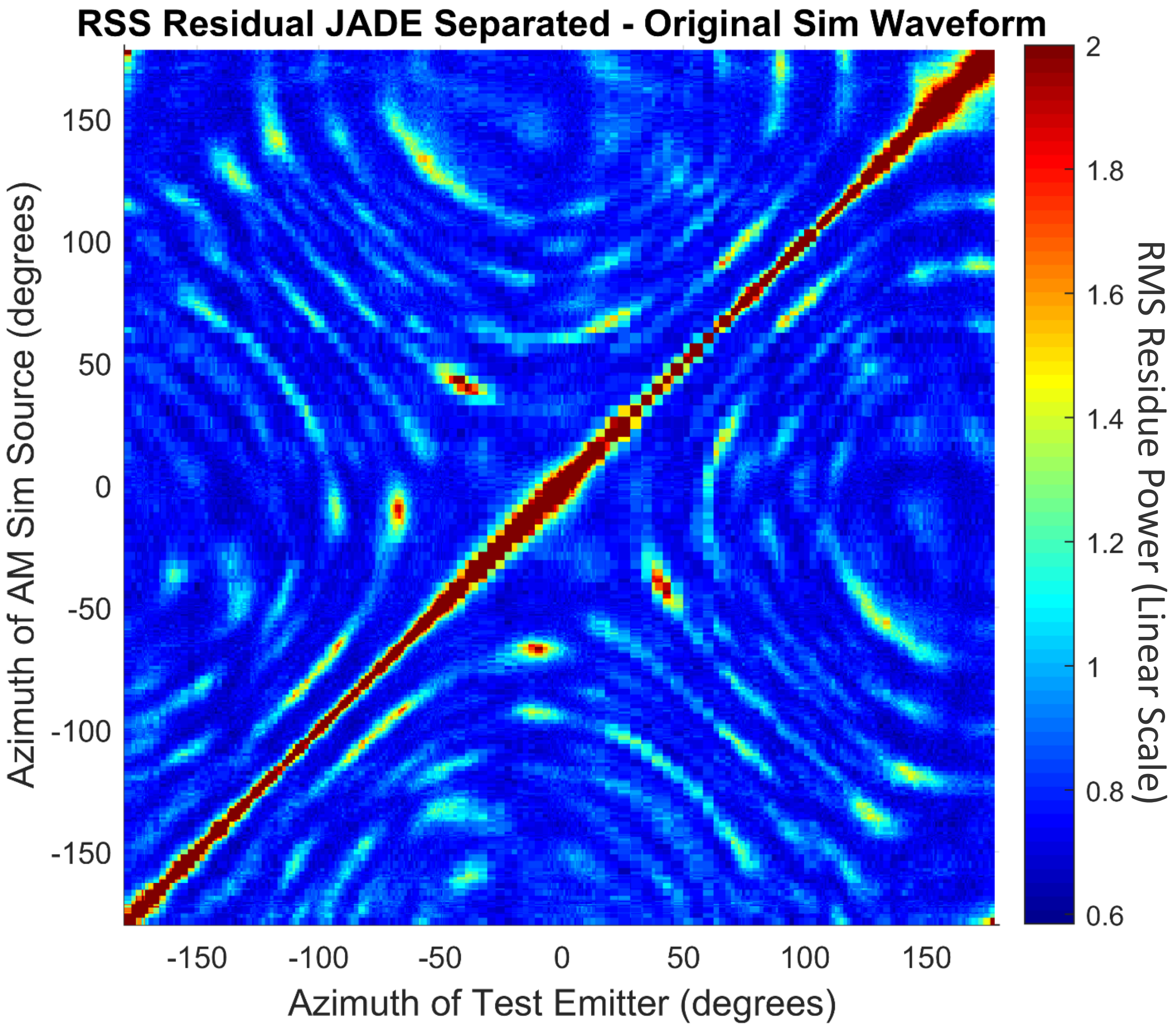
JADE Results Using Real + Simulated Sources

- To test against a broader array of controlled geometries, a simulated sawtooth amplitude modulated signal was overlaid on the real collected CW signal at the same RF and SNR.
- The simulated target uses a phase and gain profile derived from the CW emitter at a different collection time and direction of arrival (DoA). This is done to allow a realistic simulated waveform with selective difference of arrival angle in the absence of calibrated knowledge of the array manifold.
- The JADE results of three different simulated-to-collected DoA offsets are shown here:
  - Signal separation performance visibly improves as the angular separation of the sources increases



JADE Performance Vs. Direction Of Arrival

- Using the full set of measured phase fronts from the real emitter, the performance of JADE for the full range of relative DoAs was simulated and shown in the figure.
- Higher residue is observed primarily when the sources obscure one another (i.e. the sources have nearly identical DoAs)
  - This is a limitation of all spatial separation techniques, and is subject to the resolution of the array



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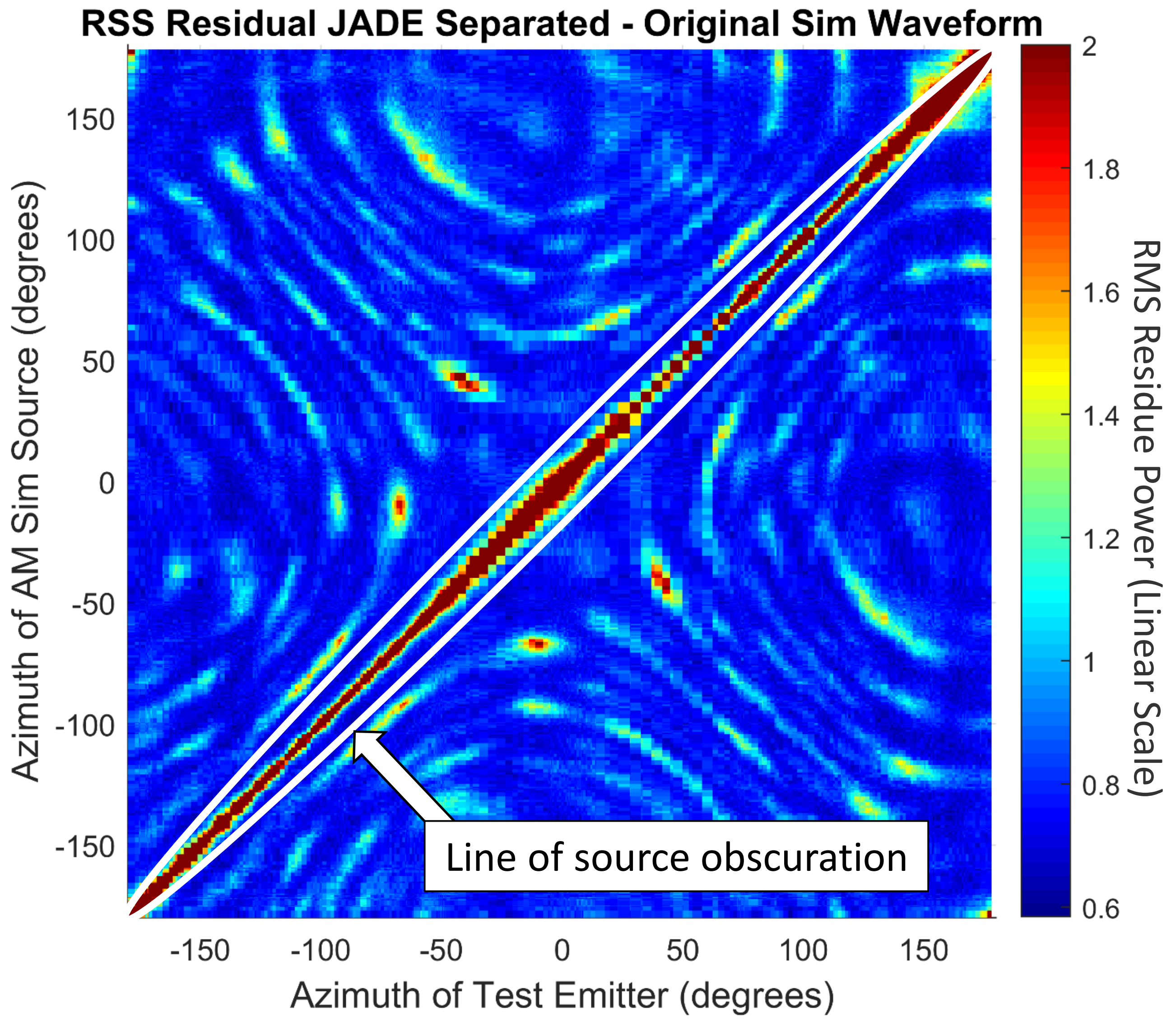

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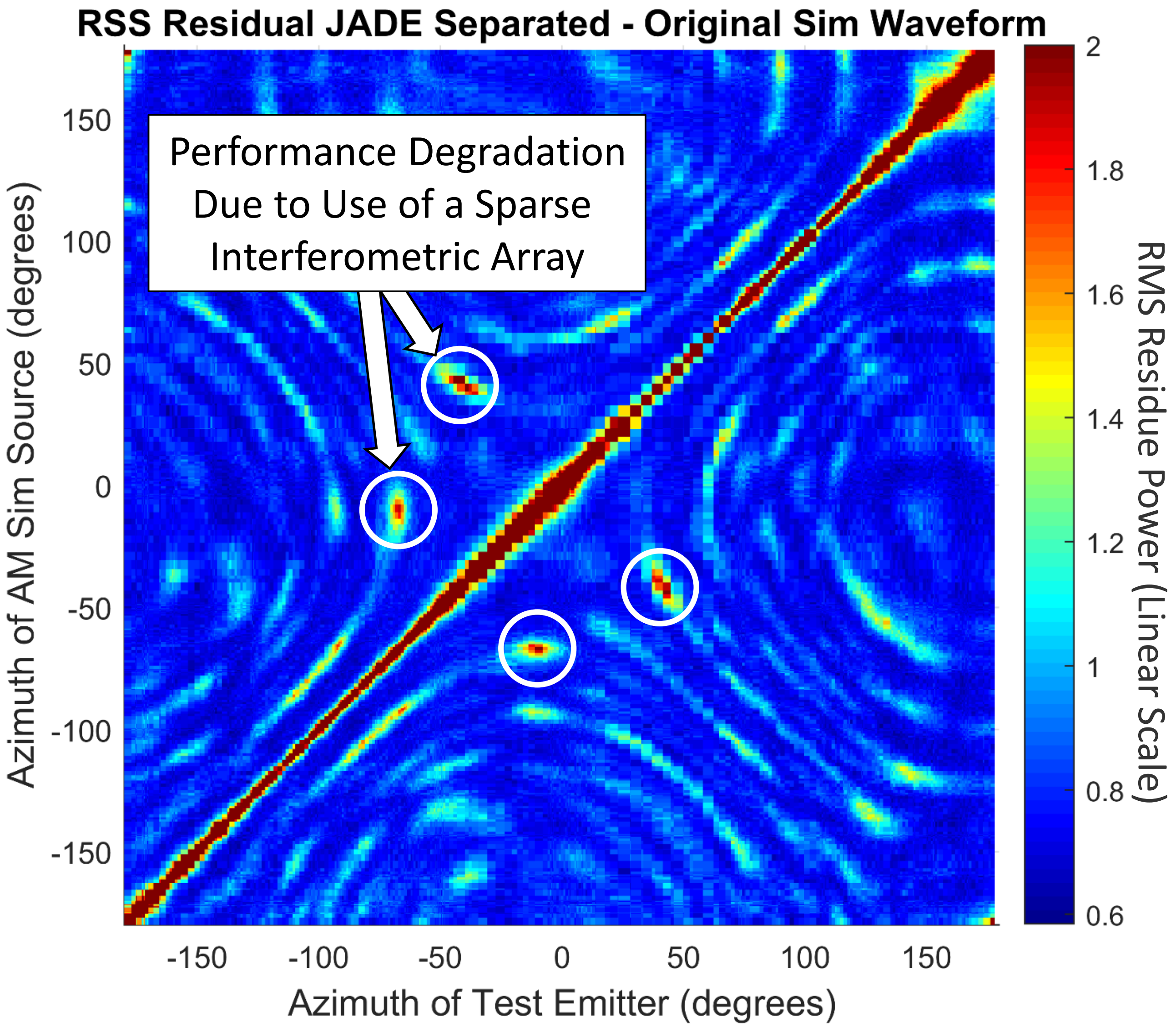
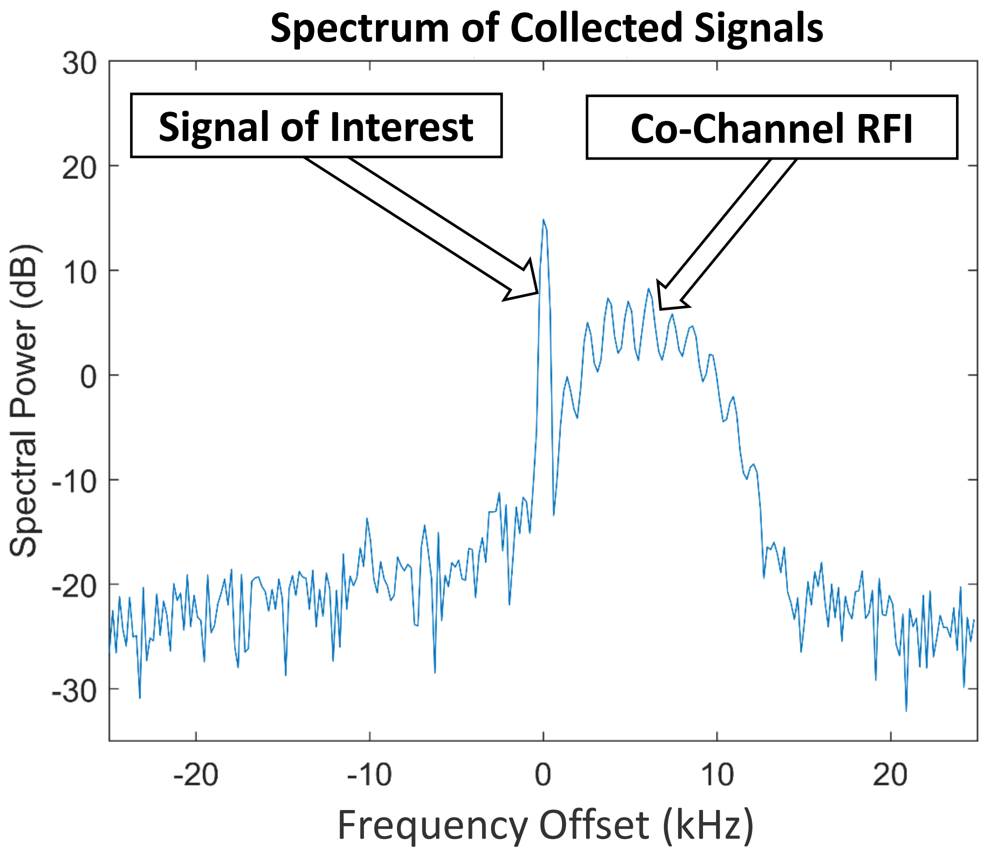


JADE Performance With Real Environmental Co-Channel Sources

- In one collection, the array collected a high power, co-channel FM emitter (at an unknown DoA) along with the original source emitter (at a known DoA)
- JADE demonstrated successful separation against this real dataset without relying on a priori information such as the known DoA of the CW emitter.



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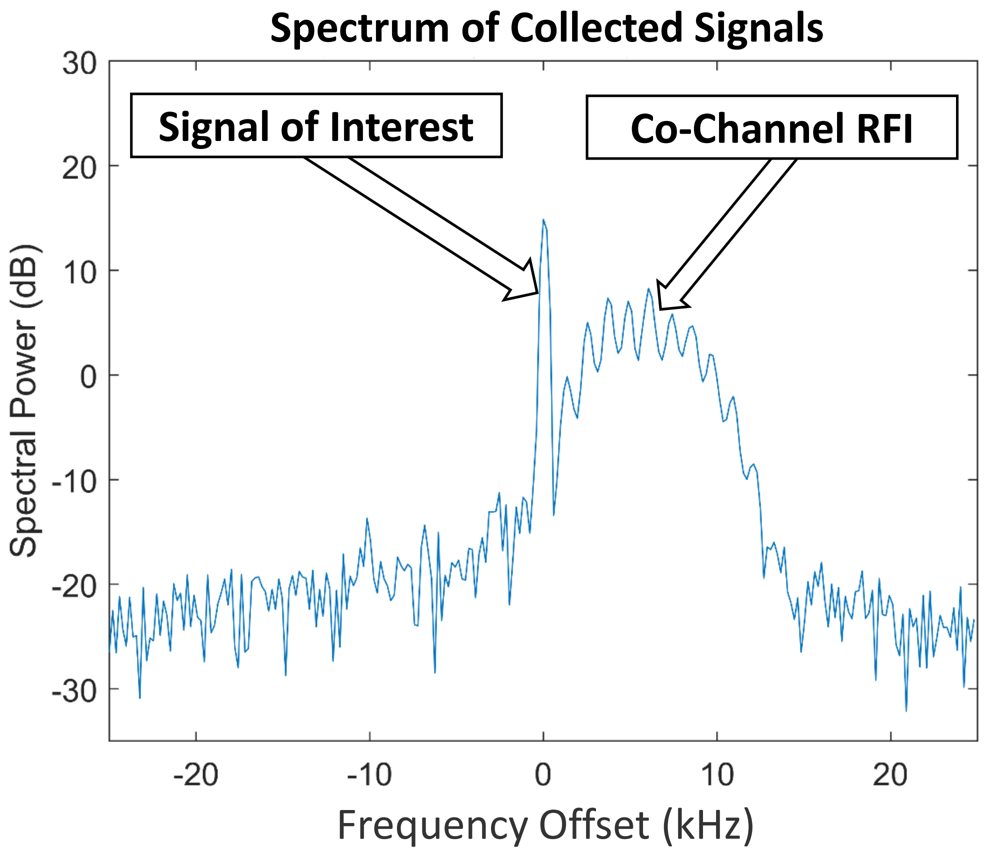

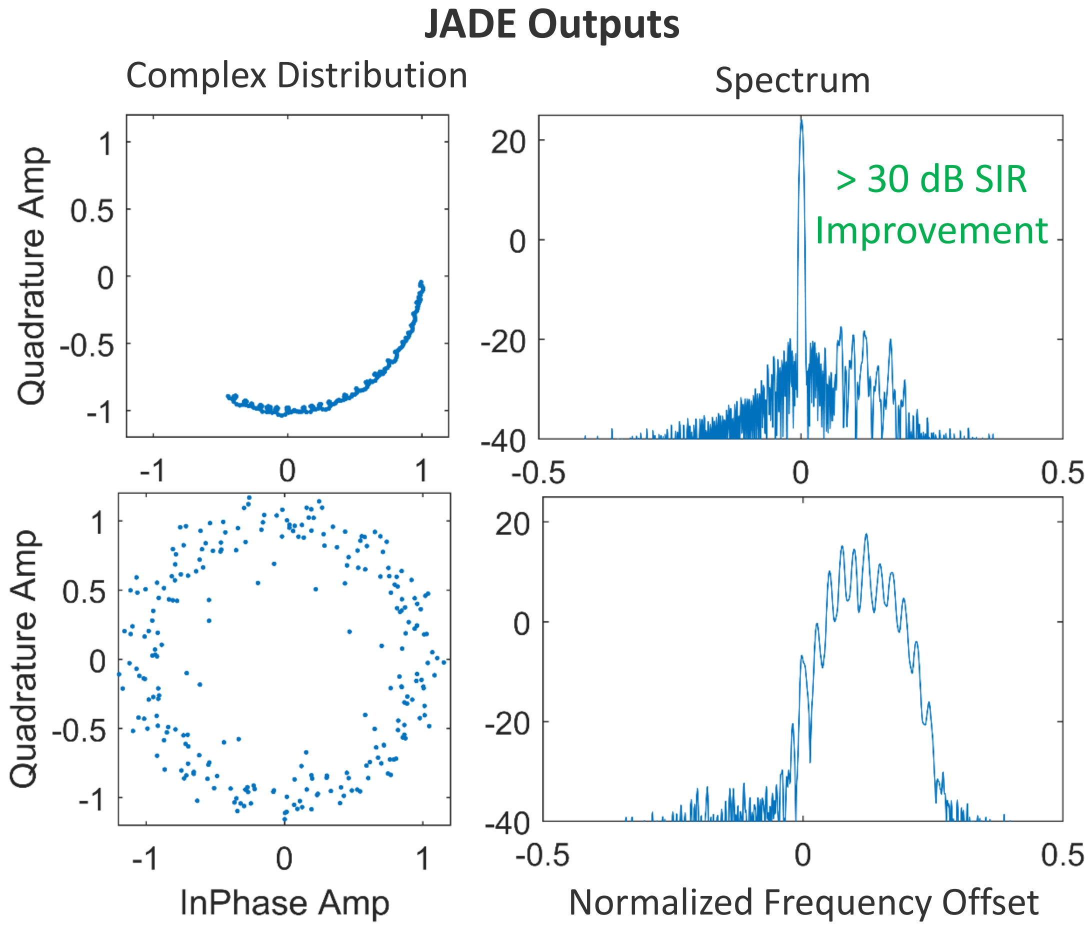

Conclusion

- The separation results against simulated and real signals suggest that JADE can be productively applied to sparse array applications such as RFI mitigation in radio astronomy or signal separation in airborne reconnaissance.
- The JADE algorithm has been shown to provide effective signal separation in the absence of any array knowledge, calibration, or *a priori* assumptions except:
    1. Estimation of the number of sources can be challenging. Focus here was on estimation of number of significant sources, so very low level signals were not separated.
    2. While structured signals can be separated from random (Gaussian-distributed) signals with no higher order statistics, two Gaussian signals cannot be separated by JADE. So at most one random, Gaussian-distributed signal was assumed.
- Failure of the algorithm to separate RFI sources from the signal of interest has been shown to be limited
- JADE provides effective RFI mitigation for almost all geometries, subject to the angular resolution of the array

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