

Aircraft Jet-Noise Diagnosis Using Massive Acoustic Camera

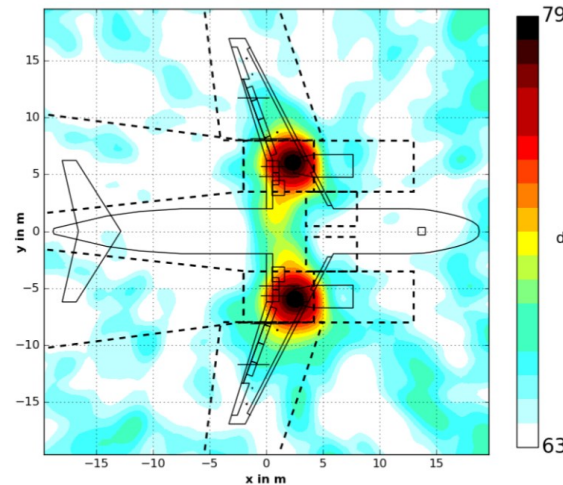
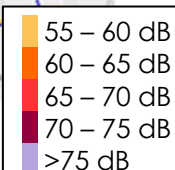
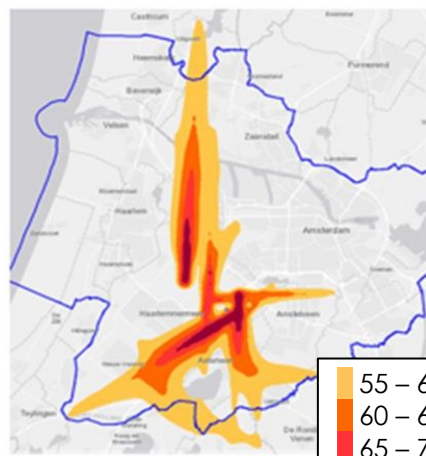
Ricardo Moreno

Supervisors: Marco Raiola and Luis A. Azpicueta Ruiz

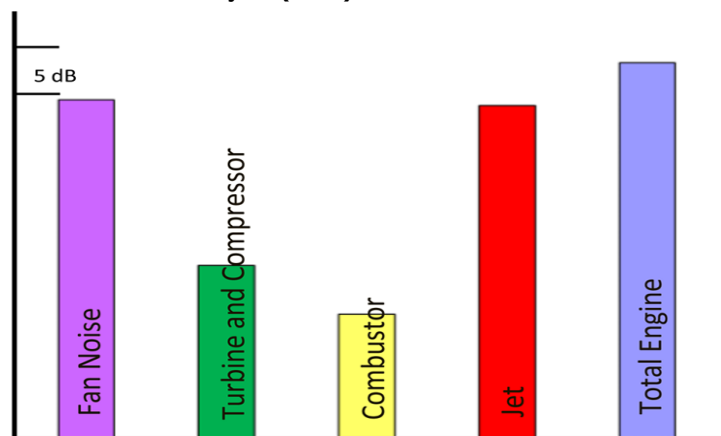
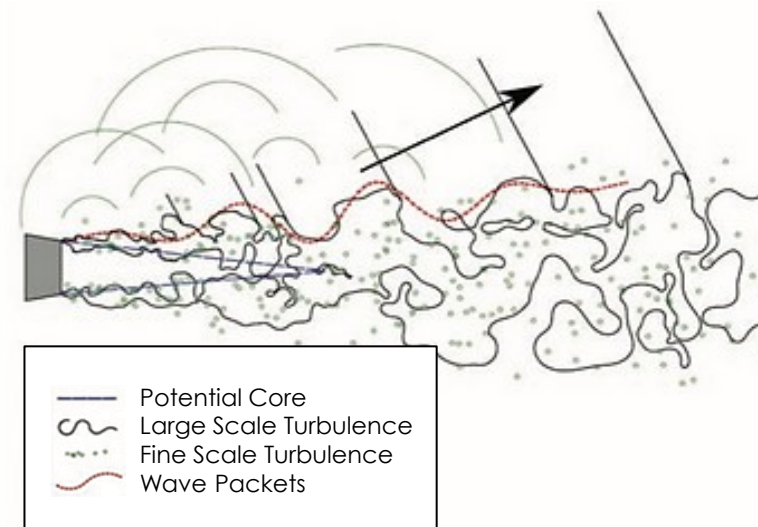
Aircraft Jet-Noise



The Phenomena Project (2021)

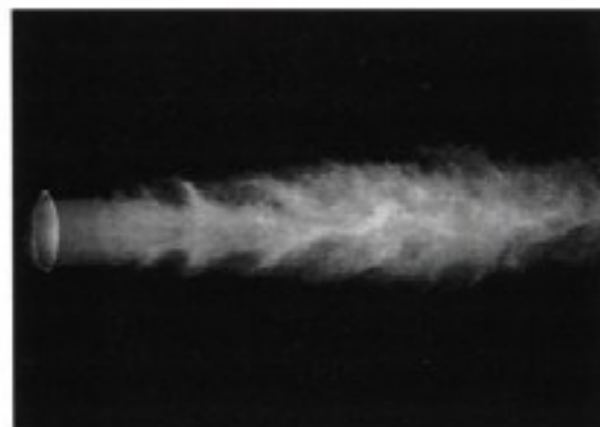


Siller, H., Schumacher, T., & Hage, W. (2020).

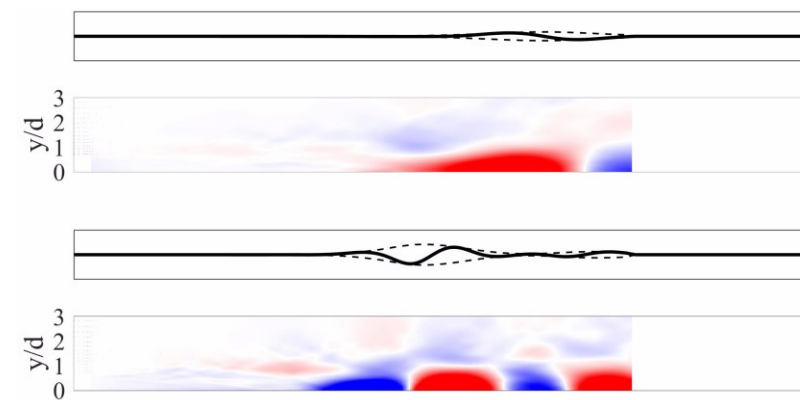


“Typical” Departure Noise Distribution

Nesbitt, E. (CEAS - 2019).



Crow & Champagne, JFM, 1971



Raiola, AIAA/CEAS Aeroacoustics 2024

**If we want to represent noise
emissions with images,
we need a microphone array**

Massive Microphone Array

General design criteria

16 microphones per data line

4 serializers per module

64 microphones per module

Module **synchronization**

Side-viewing array **placement**

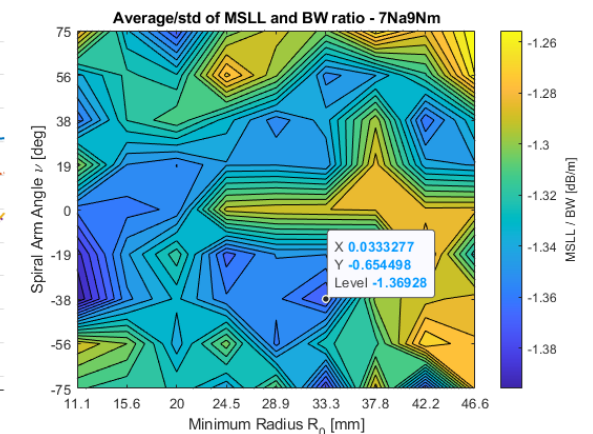
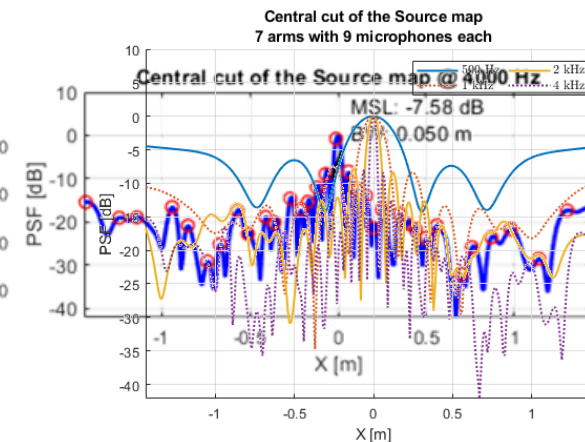
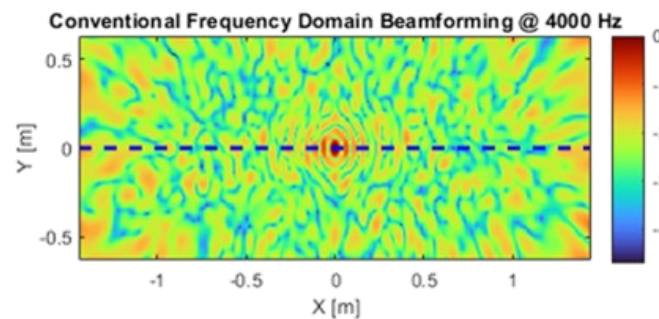
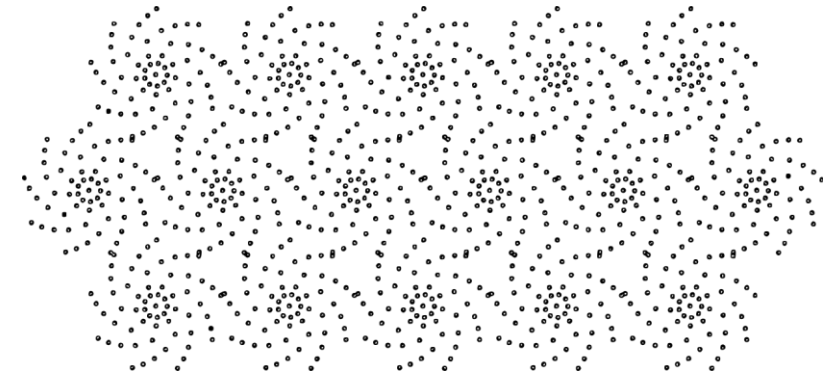
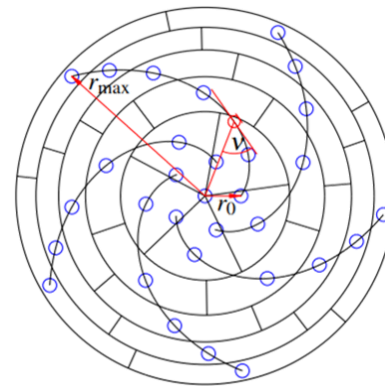
Anechoic chamber **cut-off frequency**

Acoustically and aerodynamically **transparent**

Spatial aliasing -> Inter-mic spacing

Microphone dimensions & pin connections

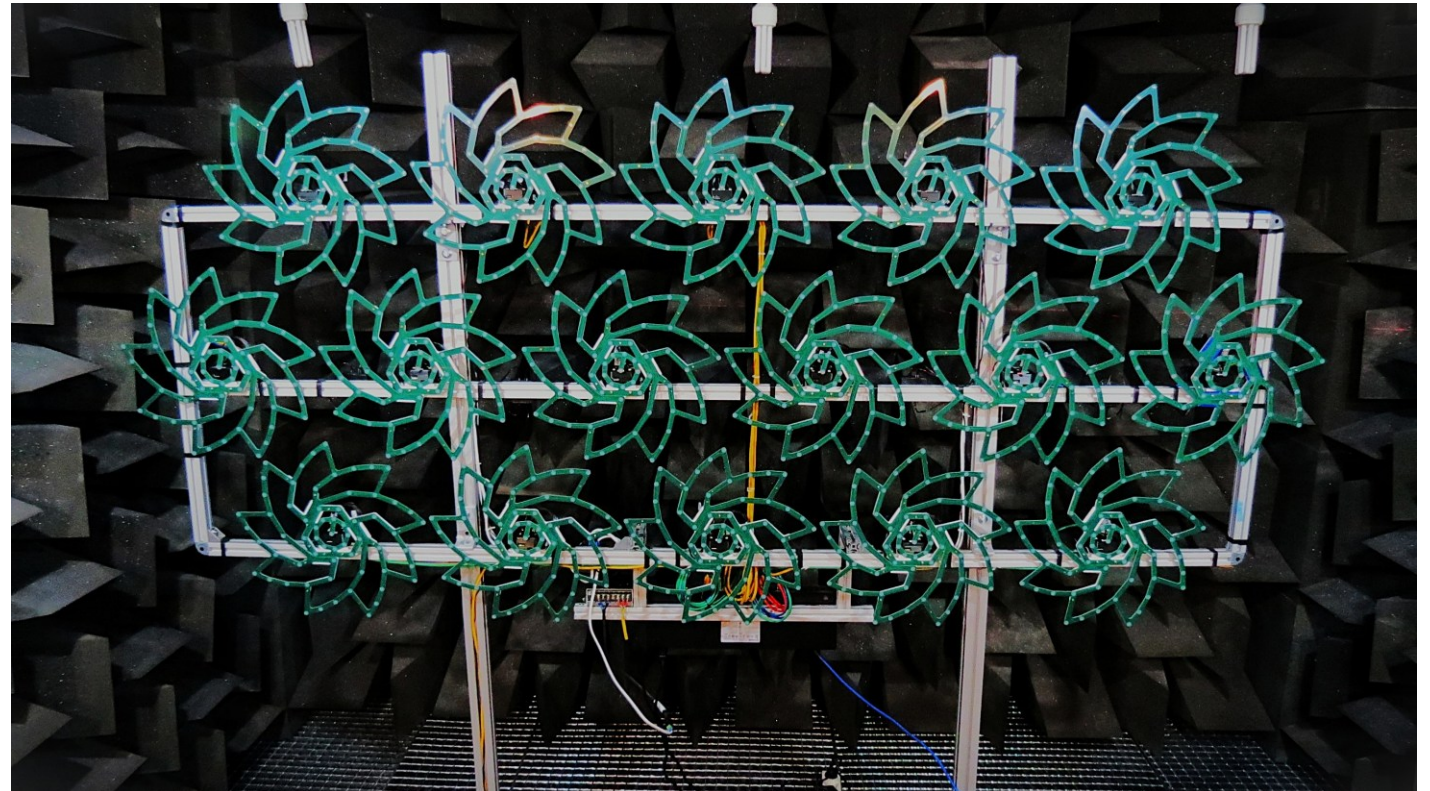
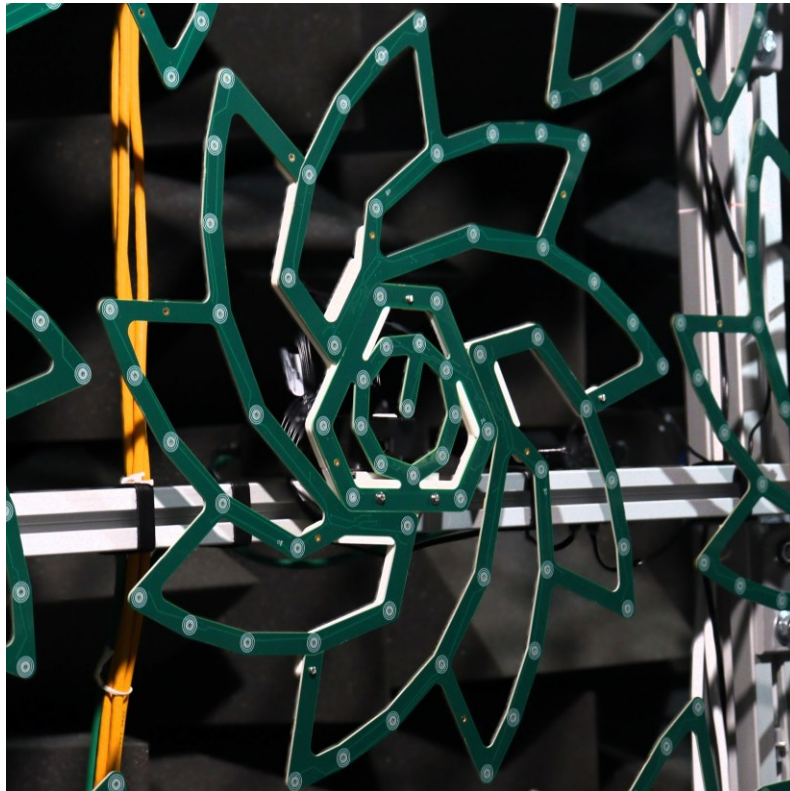
Underbrink spiral design



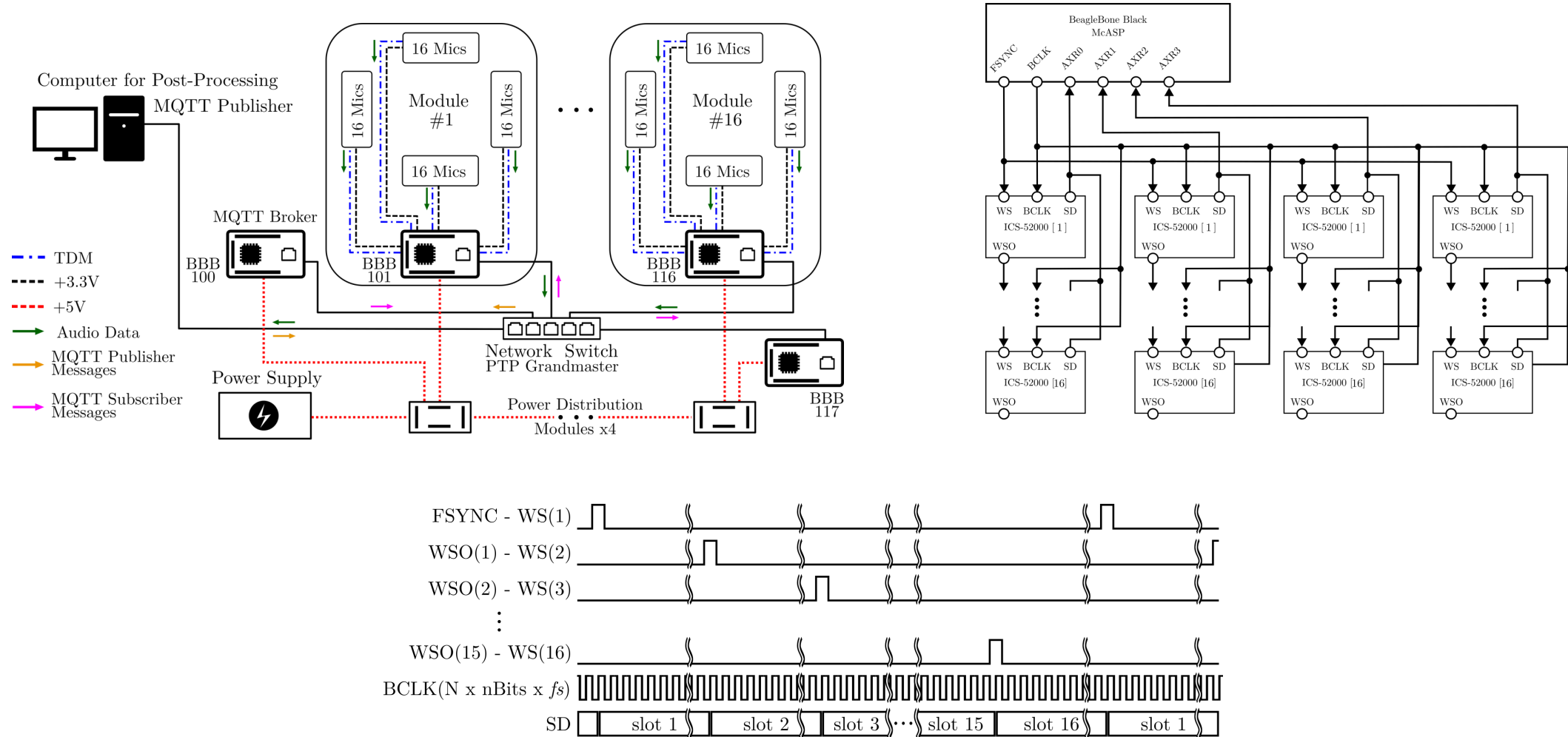
MxArray

A Modular, Multiplexed, and Massive MEMS-based Acoustic Array

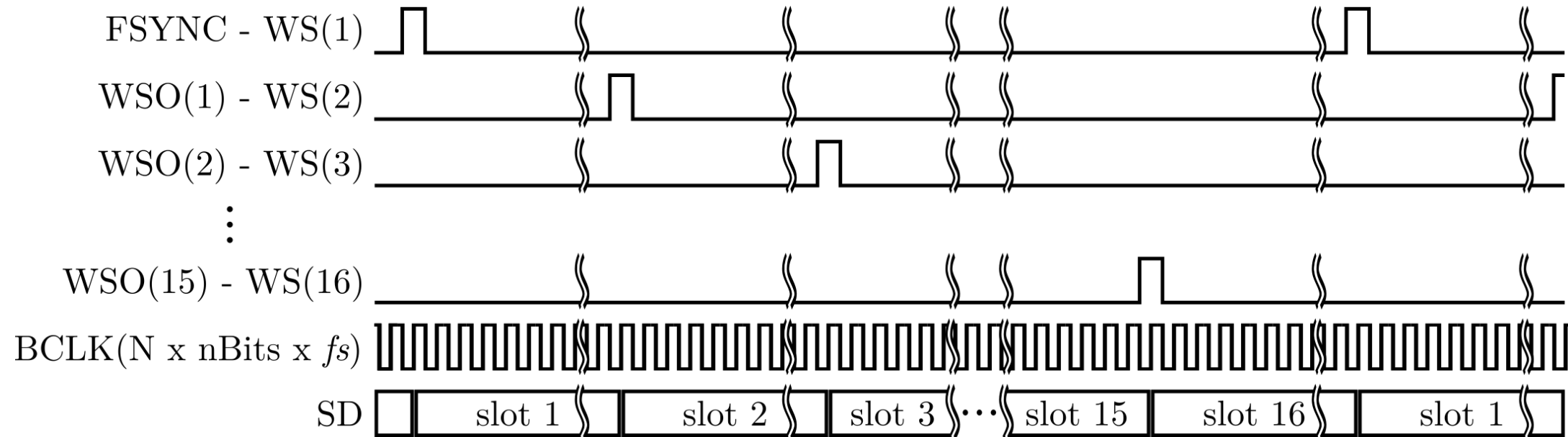
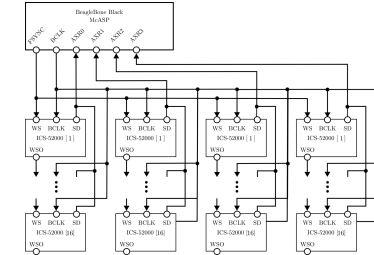
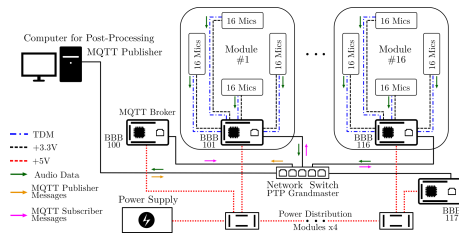
- Embedded Linux System
- Scalable
- Low cost
- PTP synchronized
- IoT commanded
- Preempt_RT patch



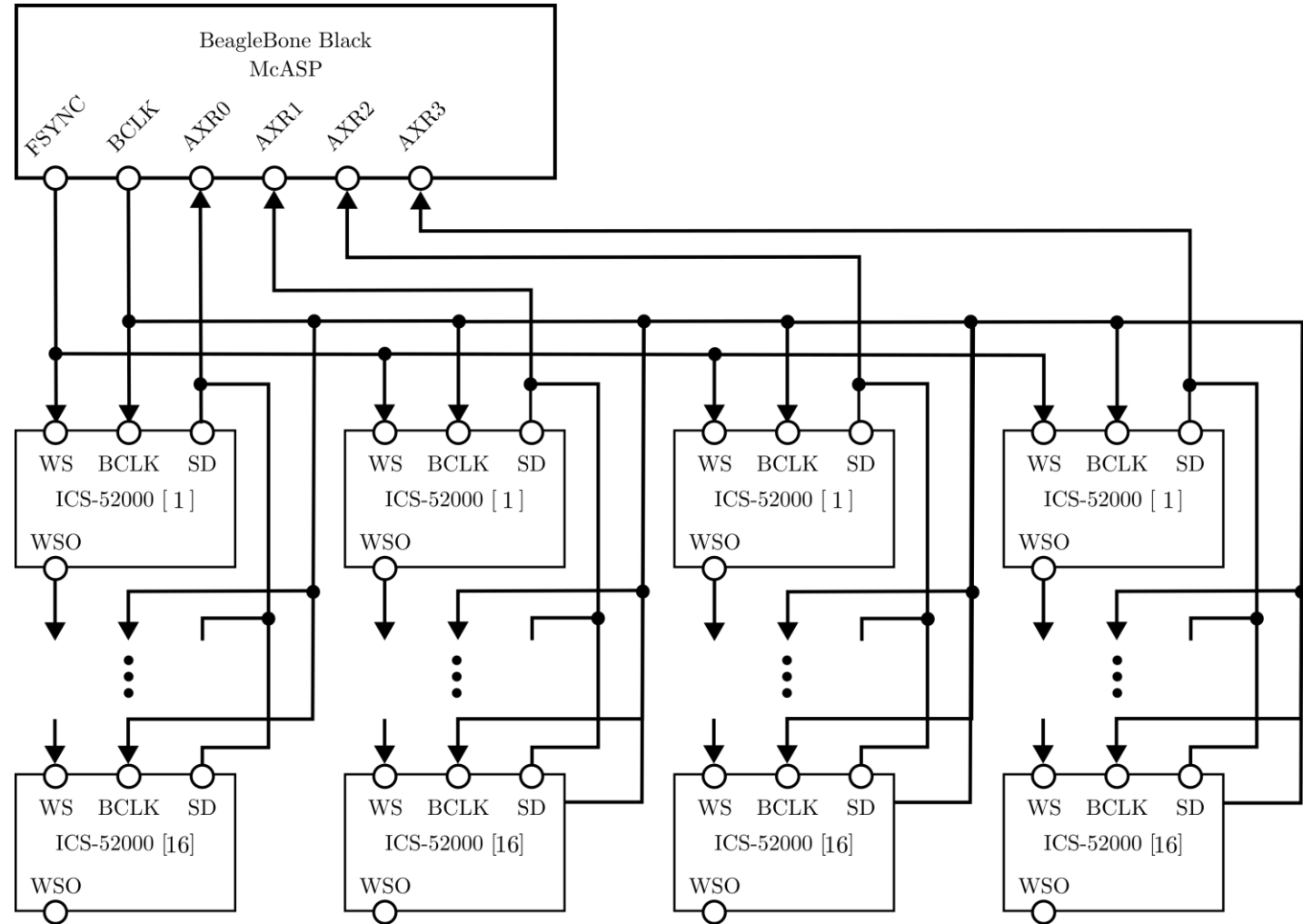
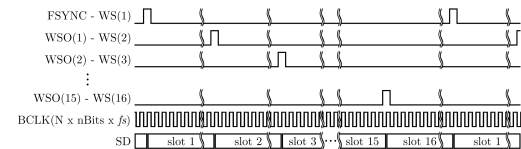
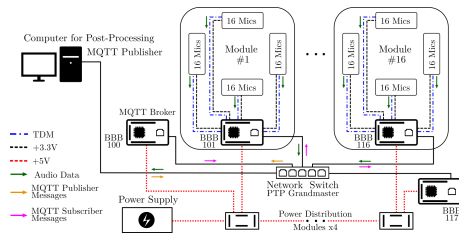
MxArray Architecture



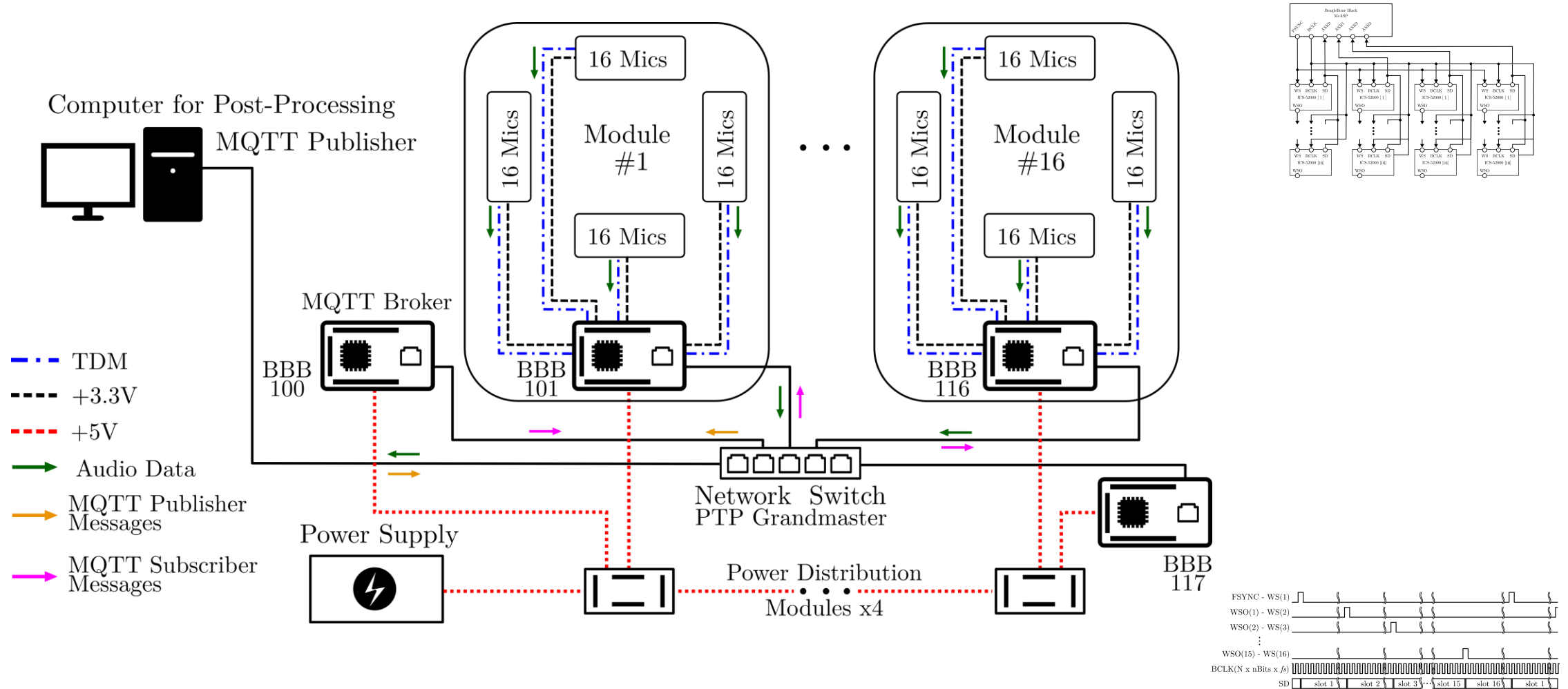
MxArray Architecture



MxArray Architecture

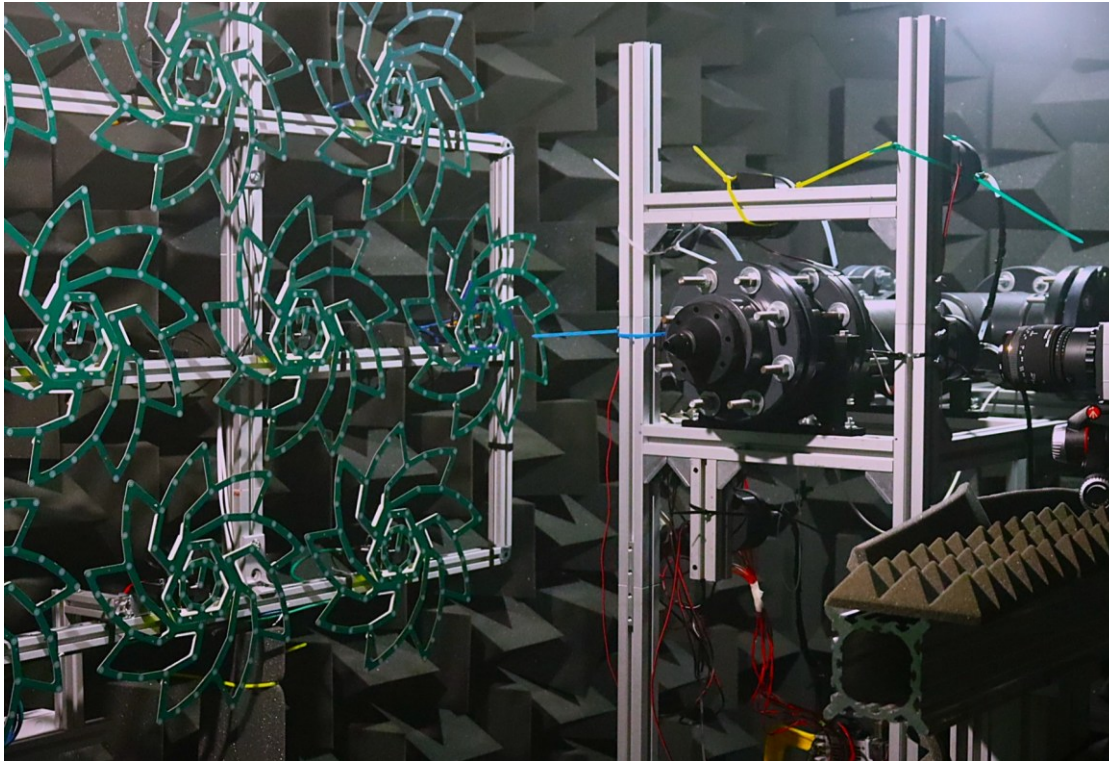


MxArray Architecture



**We aim to use the MxArray
to identify flow structures
that generate noise**

Measurement Setup



- (TuJeFa) Turbulent Jet-Facility for Aeroacoustics
- Scaled **subsonic jet**
 $Re \approx O(10^4)$
- Far-field acoustics captured by the **MxArray**
- **Synchronized**, non-time-resolved 2D Particle Image Velocimetry (**PIV**) snapshots tracking near-field velocity fluctuations.

Measurement Setup

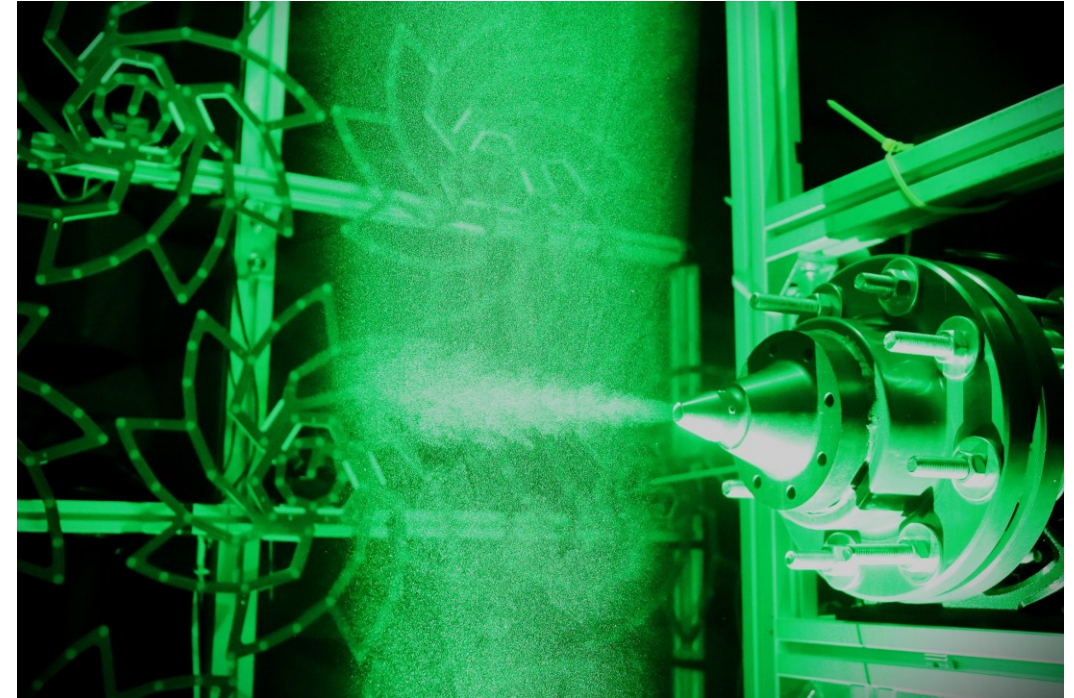
Acoustic (MxArray)

$$f_s = 8\text{kHz}$$



PIV (Video Camera)

$$f_s = 8\text{Hz}$$



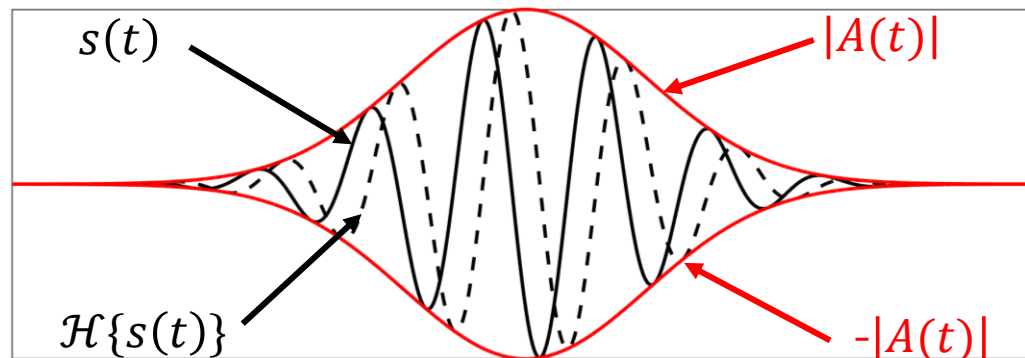
Data Compression (HPOD)

Hilbert Transform

Analytic signals

$$\hat{s}(t) = s(t) + j\mathcal{H}\{s(t)\}$$
$$\hat{s}(t) = A(t)e^{j\varphi(t)}$$

Eliminates redundant negative frequency components



Hilbert Proper Orthogonal Decomposition

Truncates the sum to r modes

$$\hat{s}(x, t) = \sum_{i=1}^r \hat{\psi}_i(t) \sigma_i \hat{\phi}_i(x)$$

Complex "Time" Mode Real Singular Value Complex "Space" Mode

Captures traveling waves in a complex mode

Optimal for non-stationary acoustic signals and PIV wavepackets

M. Raiola and J. Kriegseis. Hilbert proper orthogonal decomposition: A tool for educing advective wave packets from flow field data. Physical Review Fluids, 11(4):044905, 2026.

Data Compression

Acoustic

Temporal Transform

H Transform

$$\hat{s}_{ac}(k, n, \mu) = p(k, n, \mu) + j\mathcal{H}_n\{p(k, n, \mu)\}$$

HPOD

$$\hat{s}_{ac}(k, n, \mu) = \sum_{i=1}^{32} \sigma_i \psi_i(k, n) [A_{i,\mu}(\mu) e^{j\phi_{i,\mu}(\mu)}]$$

$$\psi_i(k, n) = A_{i,k,n}(k, n) e^{j\phi_{i,k,n}(k, n)}$$

PIV

Streamwise Spatial Transform

H Transform

$$\hat{s}_{PIV}(k, x, y) = u(k, x, y) + jH_x\{u(k, x, y)\}$$

HPOD

$$\hat{s}_{PIV}(k, x, y) = \sum_{i=1}^8 \sigma_i \psi_i(k) [A_{i,x,y}(x, y) e^{j\phi_{i,x,y}(x, y)}]$$

k = slow-time **snapshot** index (**8 Hz**)

n = fast-time **sample** index (512 per snapshot @ **8kHz**)

μ = **microphone** index

x = streamwise coordinate

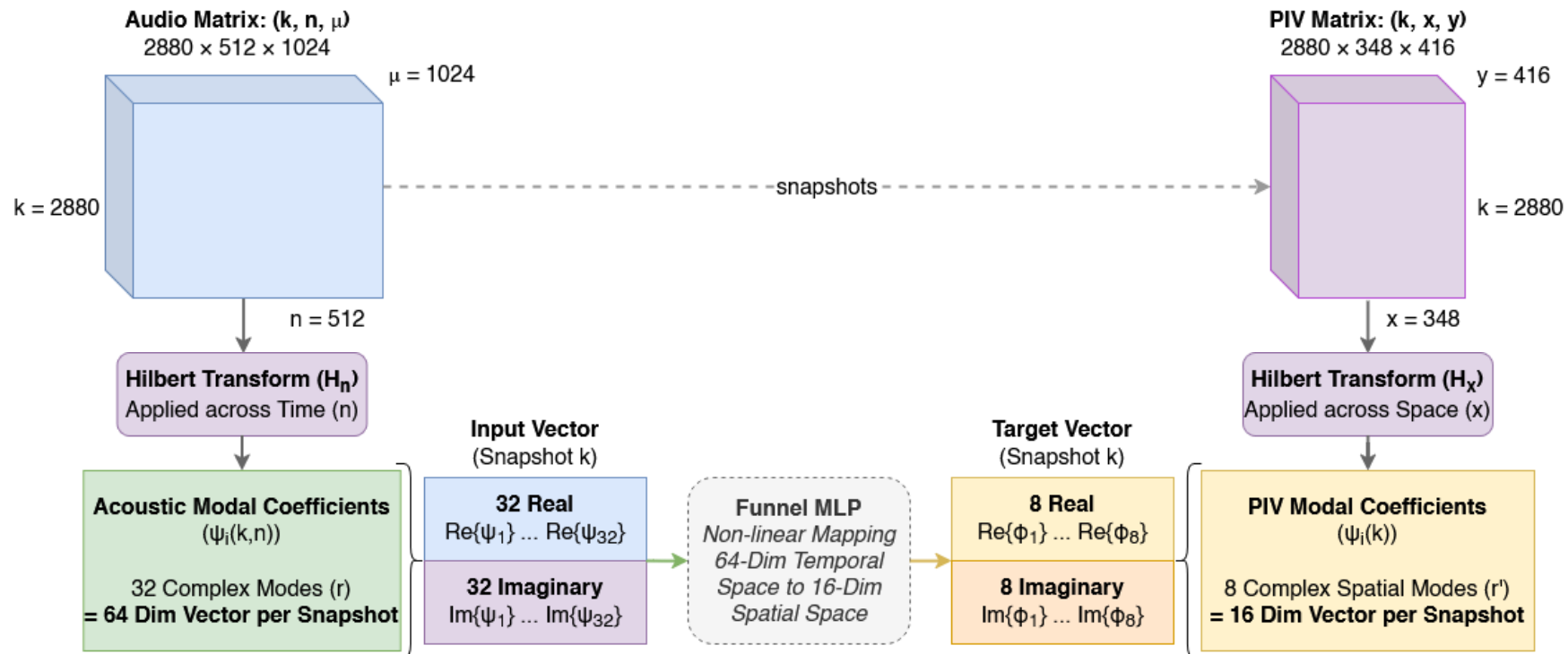
y = transverse coordinate

Data Compression

Acoustic

Temporal HPOD

$$\hat{s}_{ac}(k, n, \mu) = \sum_{i=1}^{32} \sigma_i \psi_i(k, n) [A_{i,\mu}(\mu) e^{j\phi_{i,\mu}(\mu)}]$$

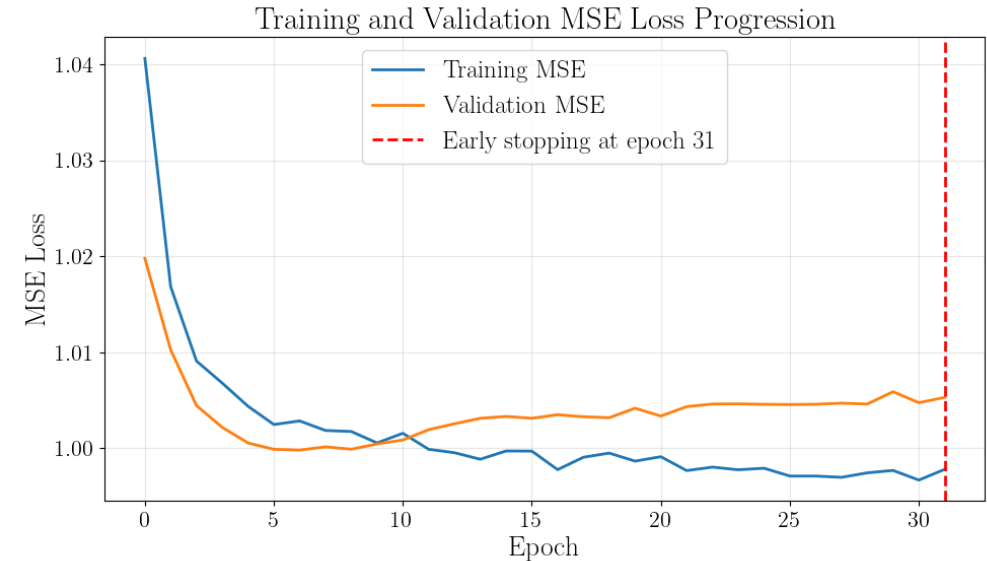
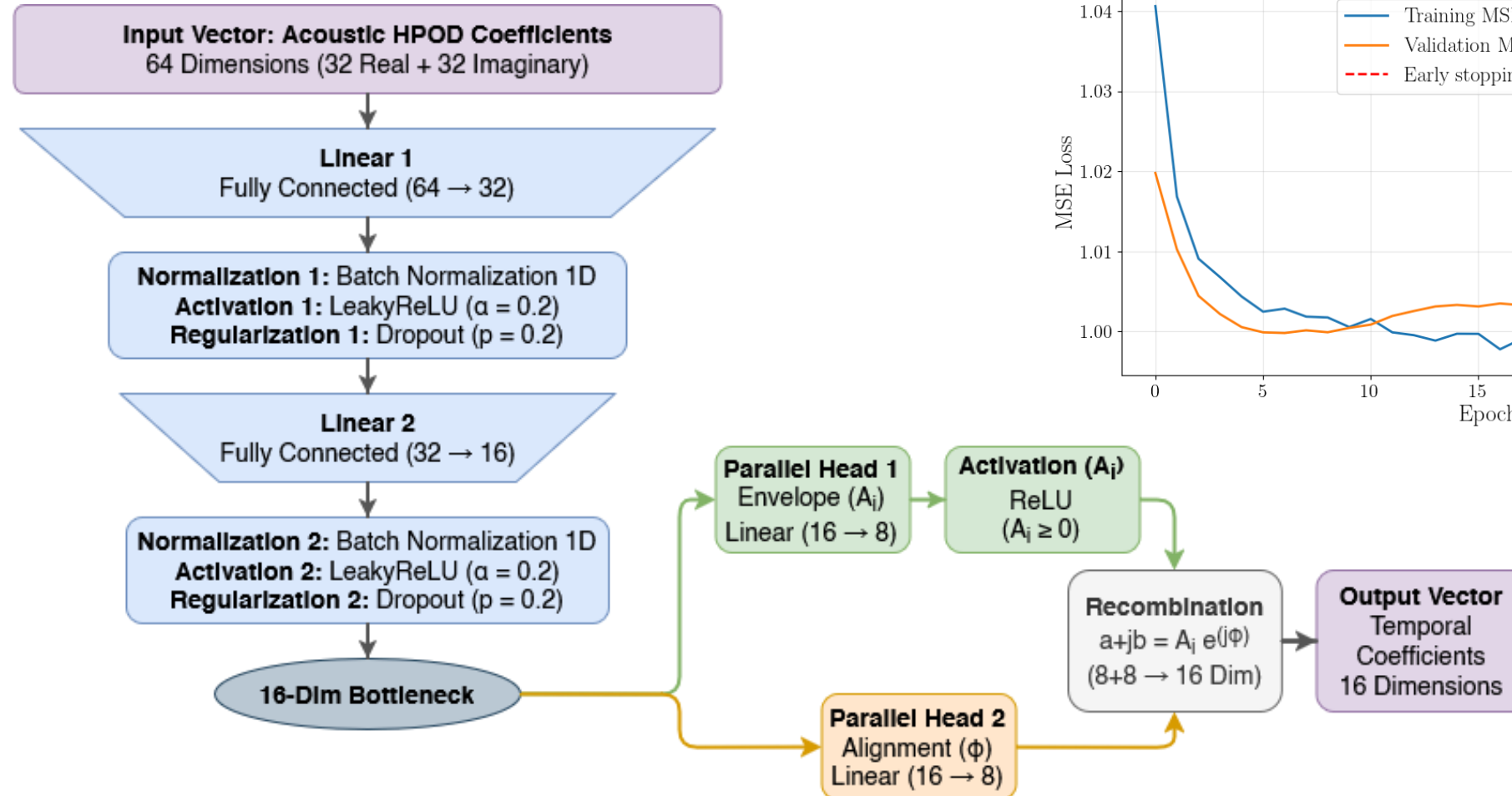


PIV

Spatial HPOD

$$\hat{s}_{PIV}(k, x, y) = \sum_{i=1}^8 \sigma_i \psi_i(k) [A_{i,x,y}(x, y) e^{j\phi_{i,x,y}(x, y)}]$$

Multi-Layer Perceptron



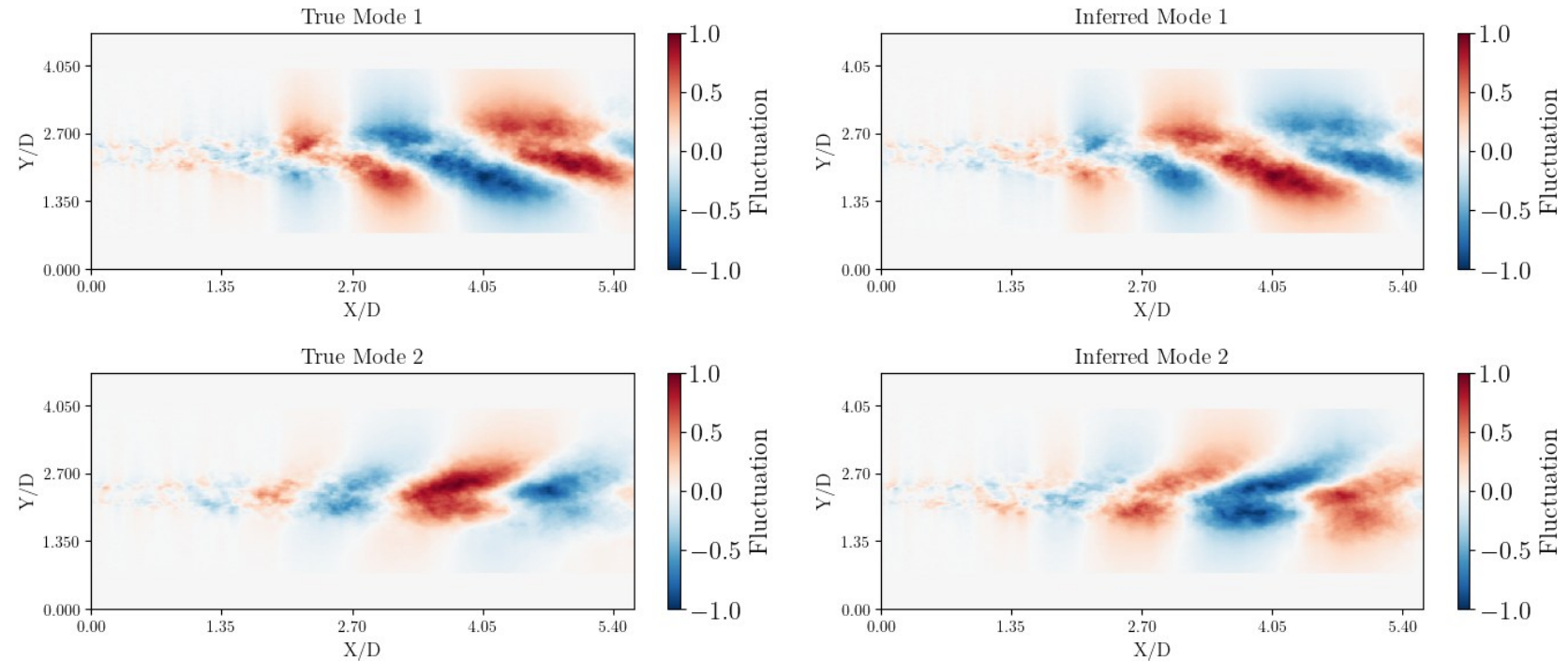
Results

The primary wavepackets reconstruction

$$v'_i(x, y) = \Re\{\phi_{y,i}(x, y) \cdot \psi_i\}$$

$$f_{mode} = \frac{St \cdot U_j}{D}$$

Mode	Strouhal Number	Frequency (Hz)
1	0.3	~2250
2	0.45	~3375



Representative snapshot from test partition dataset

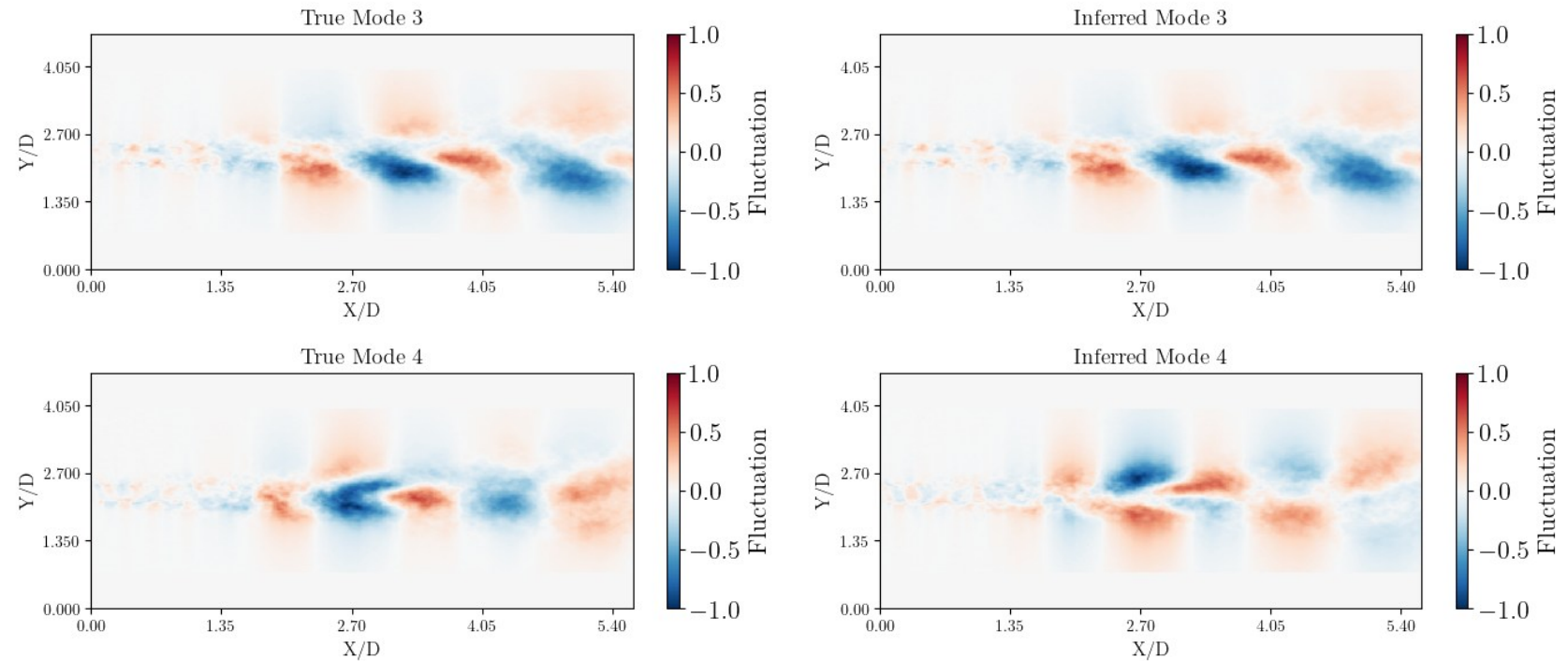
Results

The primary wavepackets reconstruction

$$v'_i(x, y) = \Re\{\phi_{y,i}(x, y) \cdot \psi_i\}$$

$$f_{mode} = \frac{St \cdot U_j}{D}$$

Mode	Strouhal Number	Frequency (Hz)
3	0.6	~4500
4	0.8	~6000



Representative snapshot from test partition dataset

Conclusions: Progress and Challenges

- Scalable **M**assive **M**icrophone **A**rray construction
 - **Preempt-RT** patch kernel compilation
 - **MxArray** control with Ethernet protocols
 - Modular **synchronization** and pulse injection to external devices
- Attempt to **infer flow characteristics** from acoustic signals:
 - Capturing **phase variation trends**
 - **Polar ambiguity** exists in early modes.
 - Higher-order modes are limited to Nyquist frequency.
- Additional assessment of the MLP pipeline with synthetic data.

Achievements

Conference proceedings

Moreno R., Franceschelli L., Azpicueta-Ruiz Luis A., García-Portugués E., Raiola M. Jet Coherent Structures Prediction Using the MxArray and Neural-Network-Based Mapping. **10th Berlin Beamforming Conference**, Berlin, Germany, 1-2 June 2026

Moreno, J. R., Ortigoso-Narro, J., Raiola, M., De la Prida, D. & Azpicueta-Ruiz, L. A. Characterization of Planar Circular and Square MEMS Microphone Arrays for Low-Power Acoustic Applications. **Forum Acusticum Euronoise 2025, Malaga, Spain**, June 22-27th, 2025.

Article

Moreno R., Ortigoso-Narro J., de la Prida D., Azpicueta-Ruiz L.A., Genoves G.B., Raiola M., MxArray: A Modular, Multiplexed, and Massive MEMS-based Acoustic Array. Intelligent Sensors <https://doi.org/10.3390/s1010000>

Achievements

Learning activities

Data-Intensive Aerospace Engineering,
2025 October

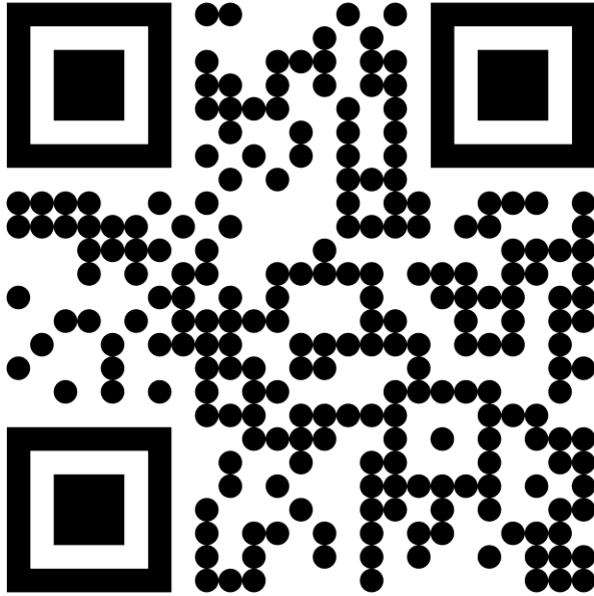
EAA Summer School, Malaga, Spain,
June 21-22nd, 2025

Outreach Activities

“De la onda al bit: explorando los micrófonos MEMS que digitalizan el mundo”, **Noche Europea de los Investigadores e Investigadoras de Madrid**, 2025, September 26th

“Localizando el sonido: tecnología acústica para ver lo que oímos”, **Semana de la Ciencia y la Innovación de Madrid**, 2025, November 15th

Q & A



Ricardo Moreno Benavides

jonmoren@ing.uc3m.es

Universidad Carlos III de Madrid

 (+34) 614324331

 Madrid, Spain



Experimental Aerodynamics
and Propulsion Lab



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