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# Visualization Techniques to Identify and Quantify Sources and Paths of Exterior Noise Radiated from Stationary and Nonstationary Vehicles

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# Visualization techniques to identify and quantify sources and paths of exterior noise radiated from stationary and nonstationary vehicles


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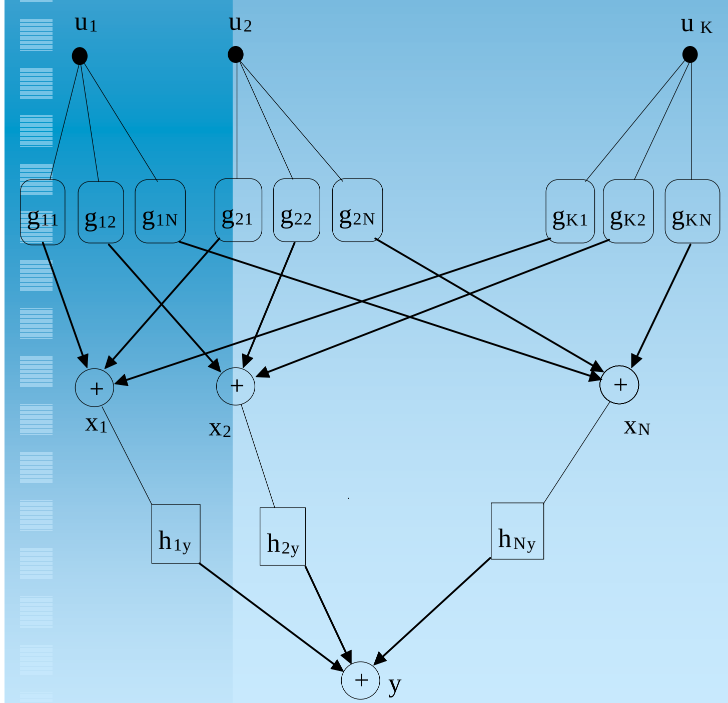
# Visualization Technique of Stationary Vehicles

- **Location** of "hidden" sources.
- **Source ranking** of "hidden" sources.
- **Transmission path** of "hidden" sources.
- **Contribution** of "hidden" sources.

**Currently no method exist which can provide these information easily.**

# Location of “Hidden” Sources

- MISO system




**Selection procedures which have been developed to-date are of two kinds:**

- **Exhaustive search by using SVD**
- **Sequential search by using Partial coherence analysis**

**However these procedures can not be used to localize sources.**

**Two new kind of algorithm is developed.**

- **Partial SVD method (PSVD).**

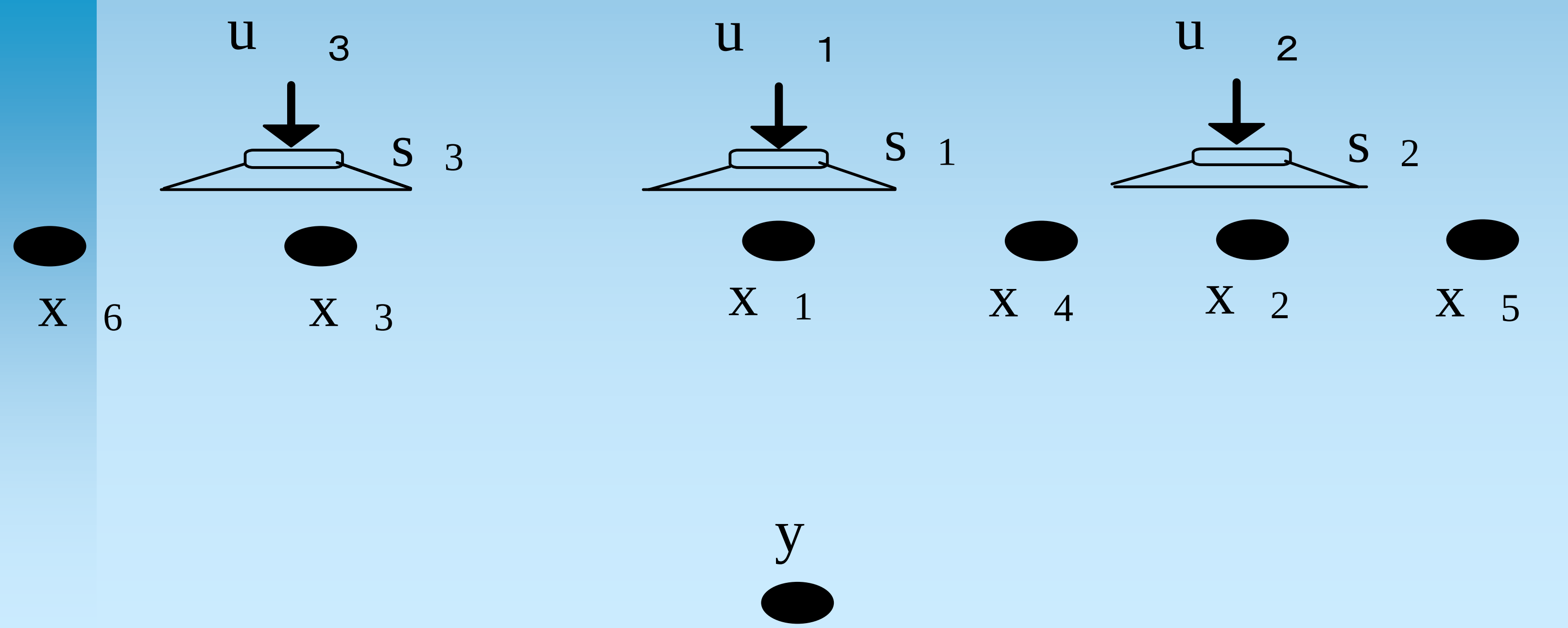
# Partial SVD method (PSVD)

- Remove one signal from the other signals by using a partial coherence procedure.
- The singular values of the conditioned cross spectral matrix are less than or equal to those of original matrix.

  $\lambda'_1 \leqq \lambda_1$ ; $\lambda'_2 \leqq \lambda_2$ ; …; $\lambda'_{n-1} \leqq \lambda_{n-1}$.
- The more significant the signal that is removed, the more the singular values of the conditioned cross spectral matrix will be reduced.

# Experimental Setup

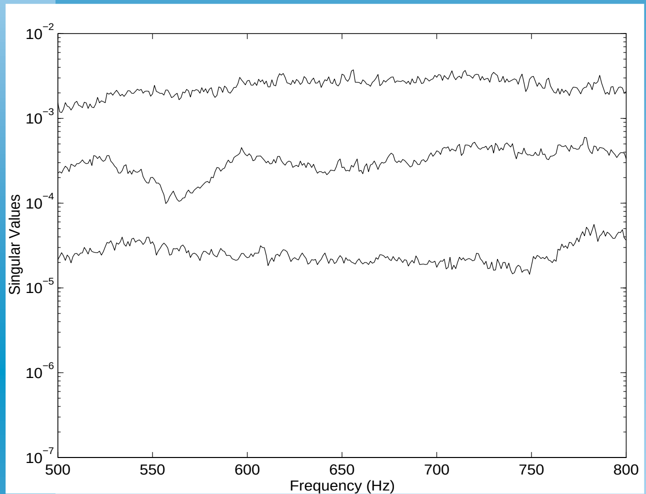
- 6 input microphones
- 1 output microphone
- 3 incoherent sources (loudspeakers)



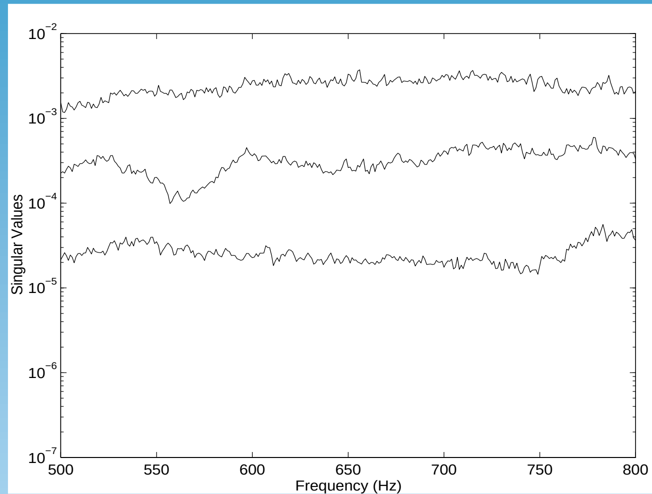
# Experimental Results

- **The singular values of cross spectral matrices of:**

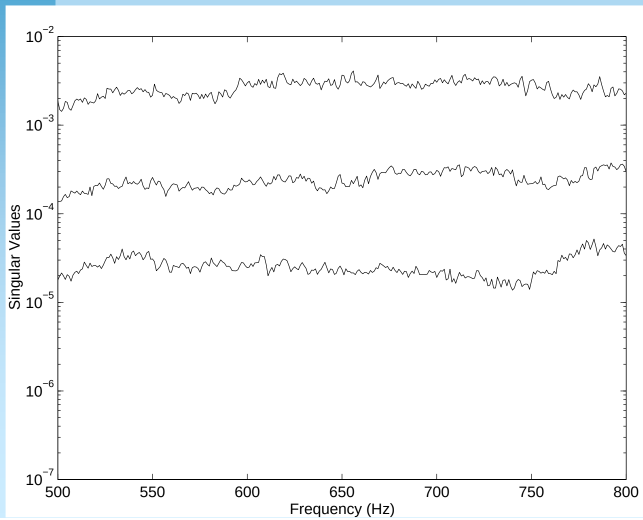
**(a) All 6 transducers**



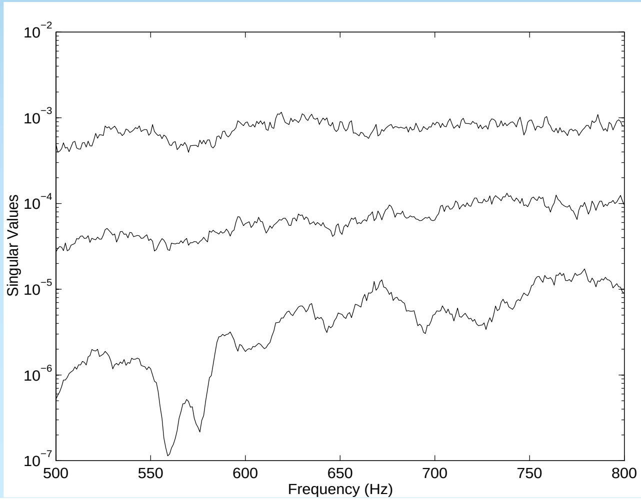

**(b) Transducer group (x1, x2, x3)**




**(c) Transducer group (x1, x2, x6)**




**(d) Transducer group (x2, x4, x5)**



# Integrated Nearfield Acoustical Holography (INAH)

- Source ranking of “hidden” sources
- Transmission path of “hidden” sources
- Contribution of “hidden” sources

**By using**

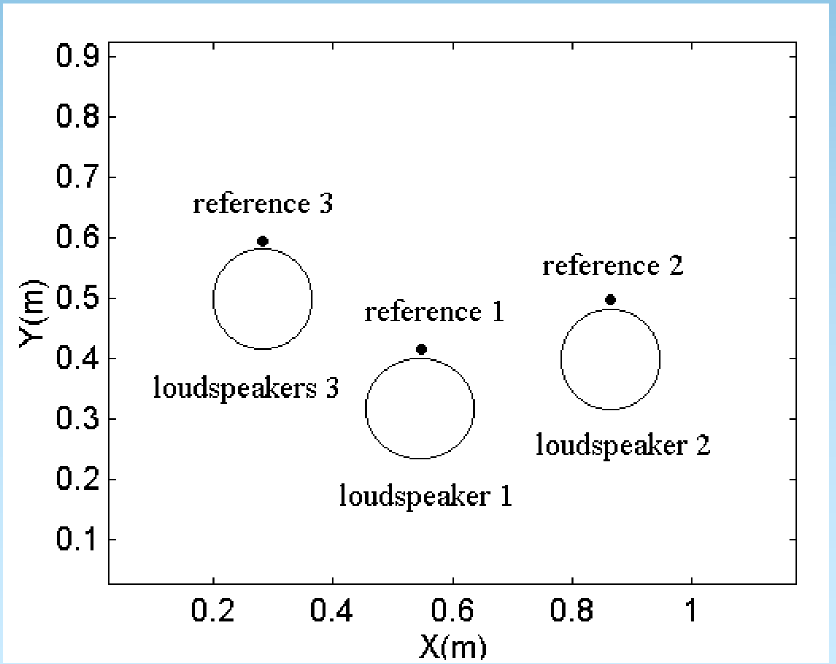
- NAH and partial field decomposition

# Decomposition of the Sound Field

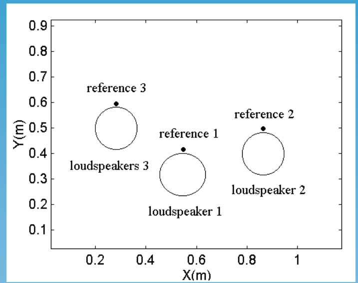
The partial field determination problem has been approached in two ways:

- Partial coherence analysis
- Singular value decomposition

## Experimental Setup

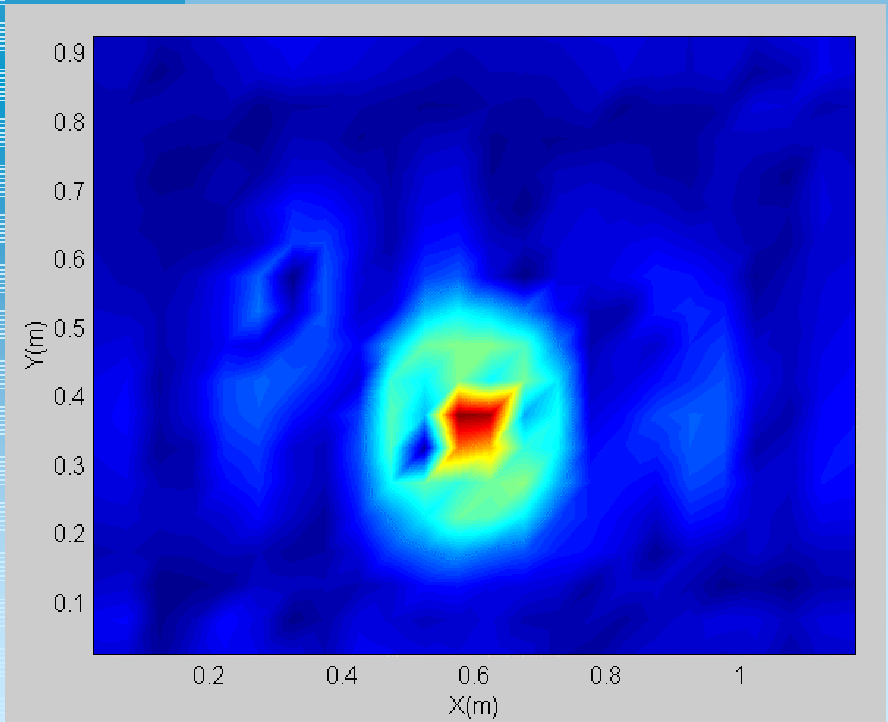


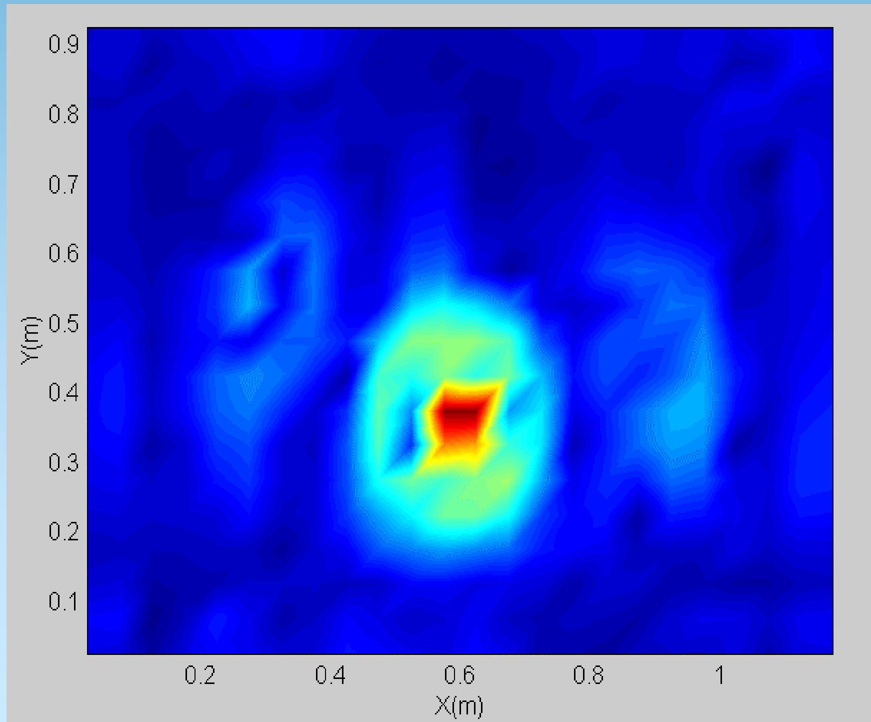
# Results: Partial field 1



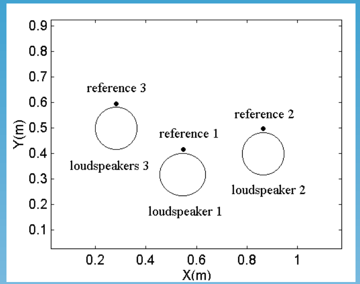

**Partial coherence**

**SVD procedure**

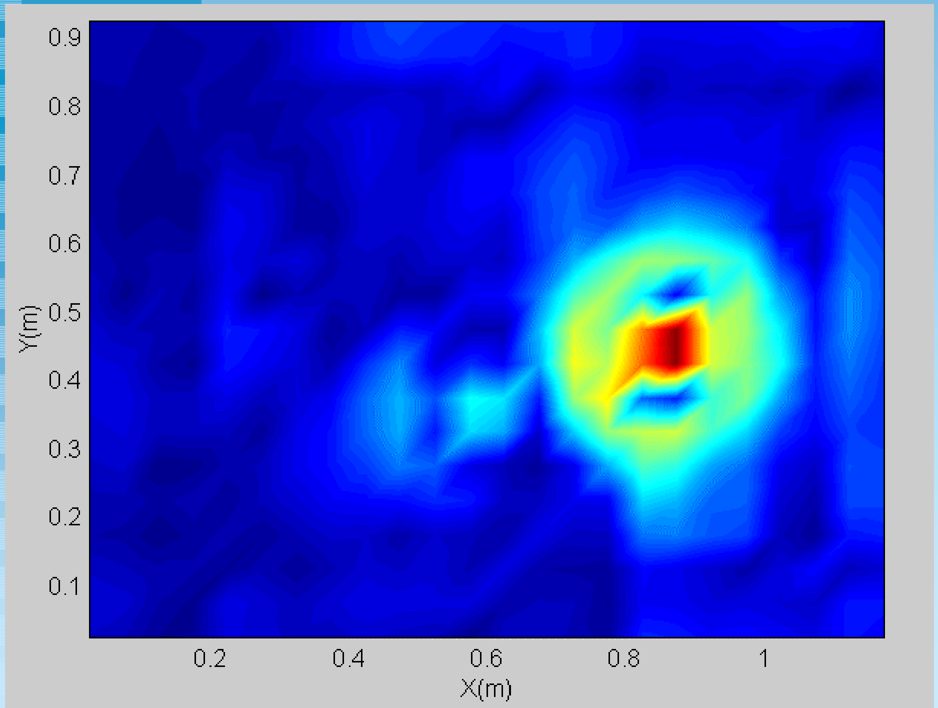


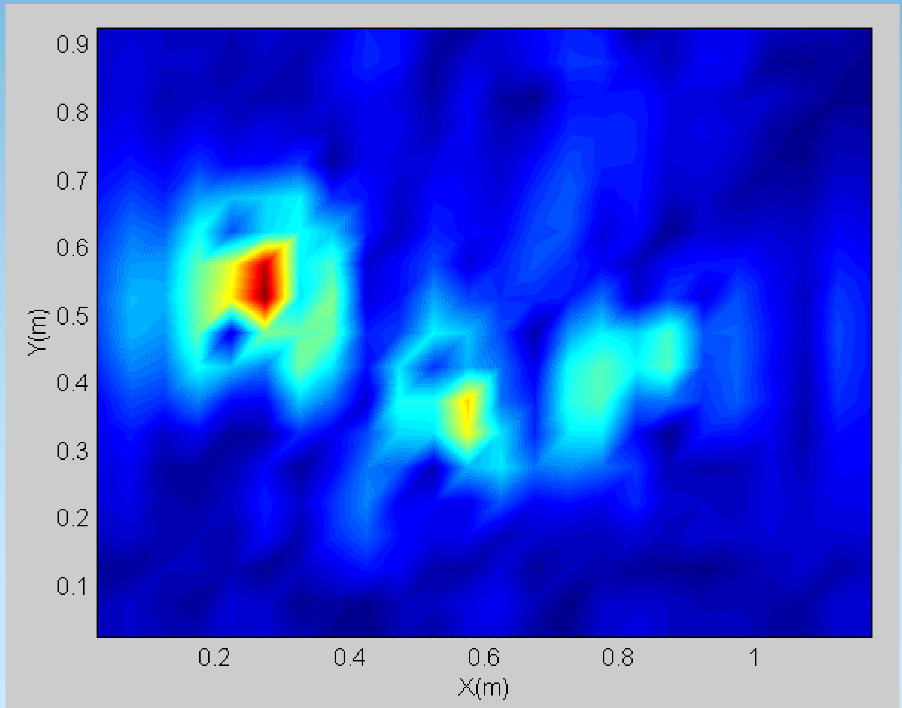
# **Results:** Partial field 2



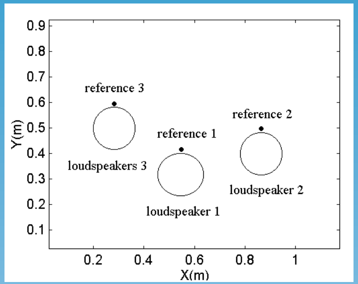

## Partial coherence



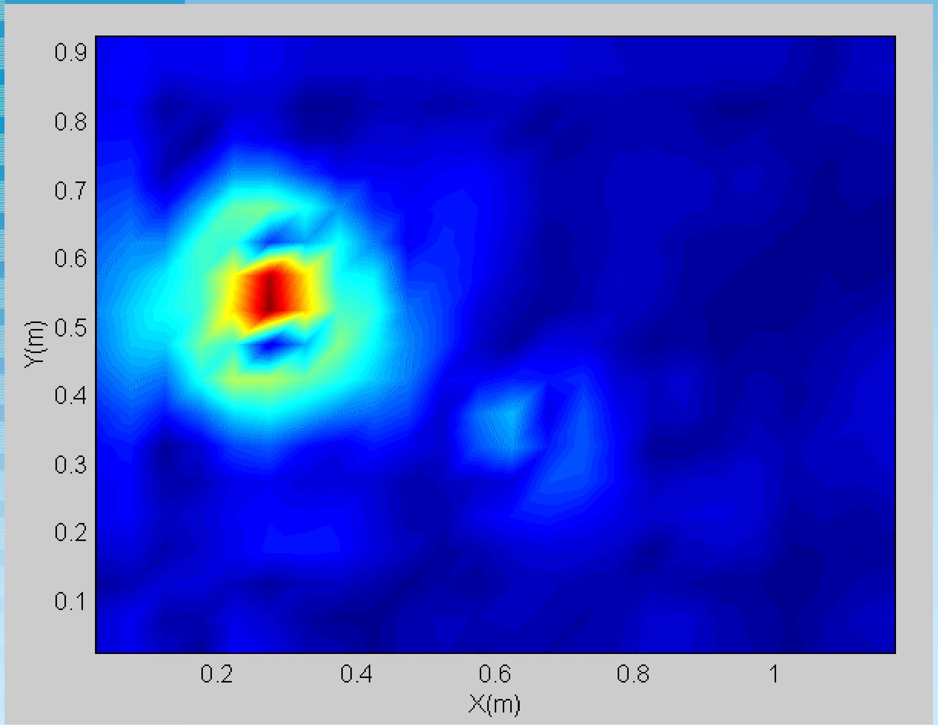

## SVD procedure



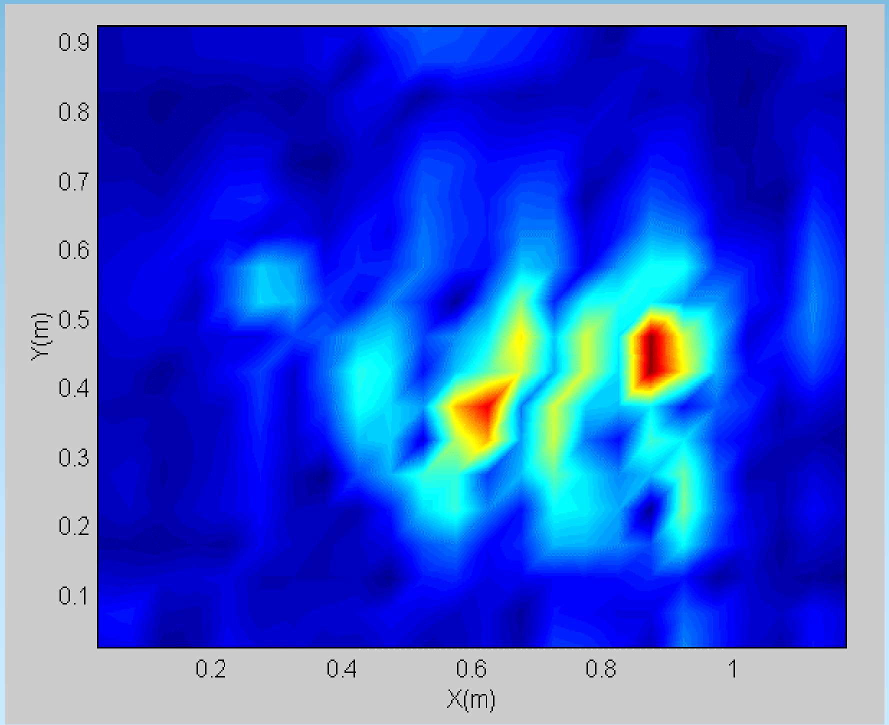
# Results: Partial field 3




## Partial coherence

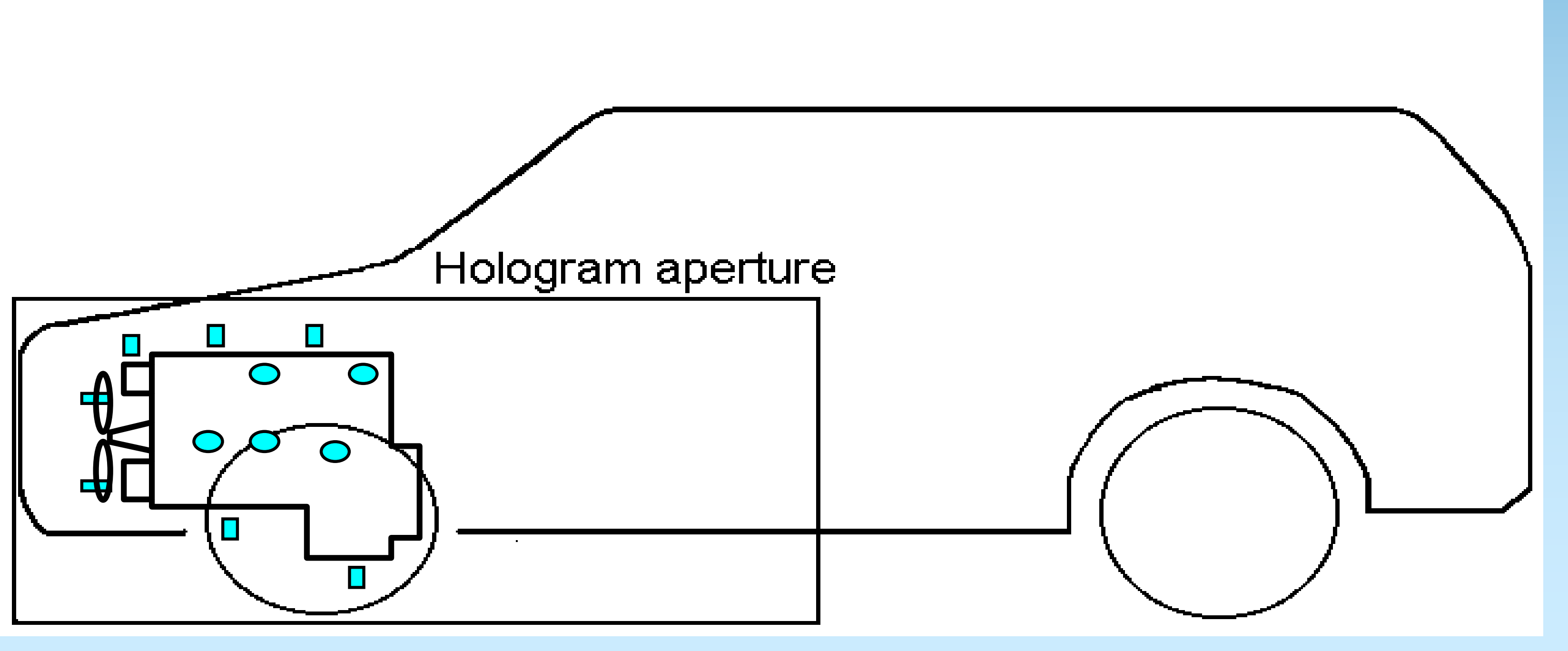



## SVD procedure



# Exterior Noise Field of a Vehicle - Experimental Setup

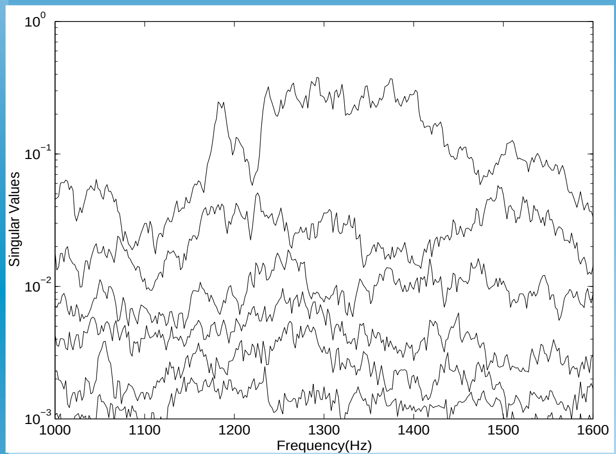
- Twelve candidate microphones.
- Sound pressures were measured on a plane 5cm away from the left side panel on a 48 x 19 grid, with a inter-microphone spacing of 5cm, by using a 4 x 19 planar microphone array.
- Idle (stationary).



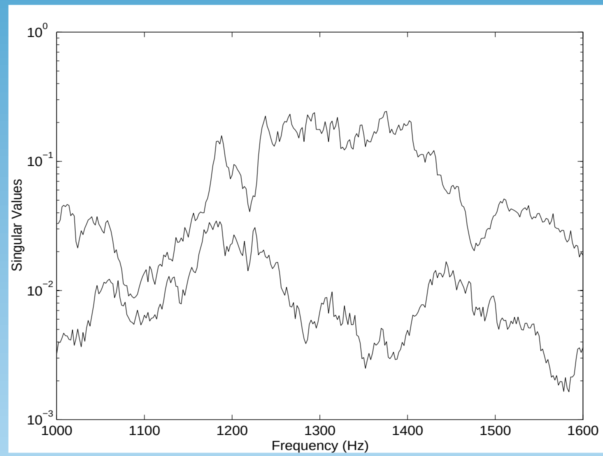
# Results: Localize sources

**Singular values of input signal cross spectral matrix based on:**

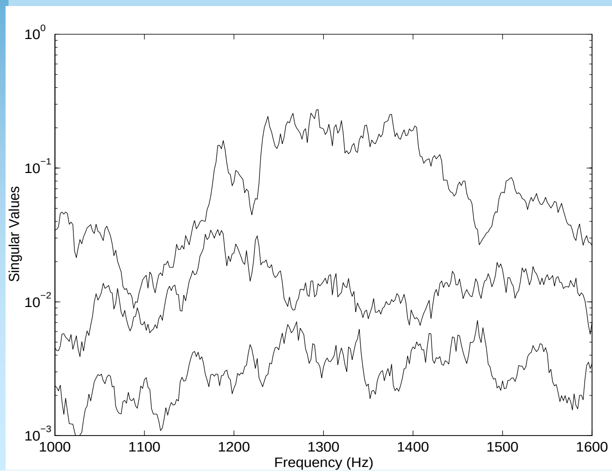
**(a) All 12 microphones**



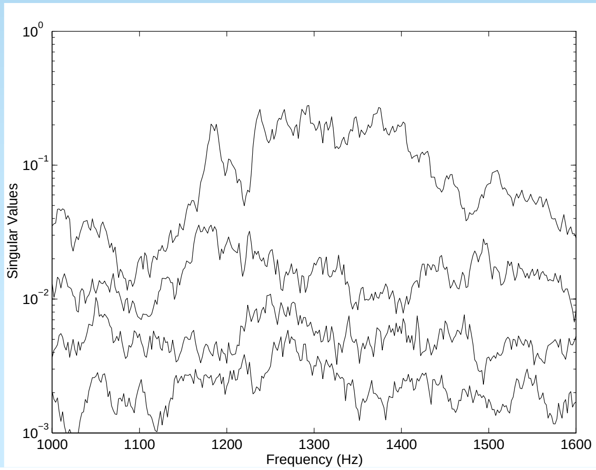

**(b) Microphone group (12, 11)**




**(c) Microphone group (12, 11, 8)**

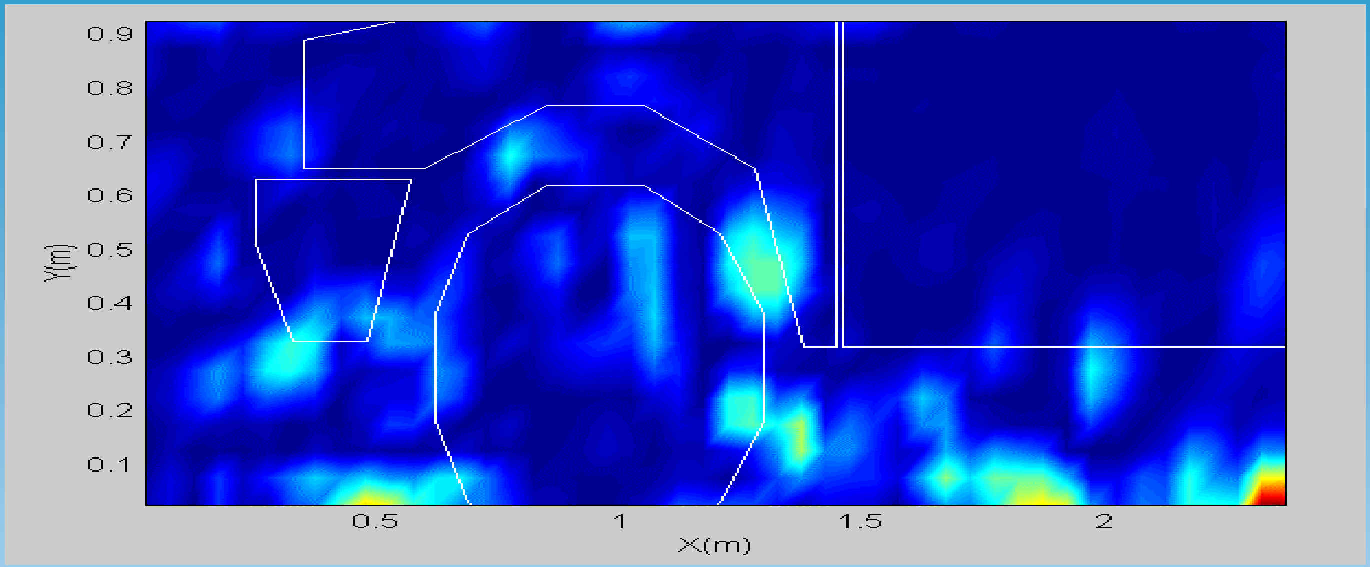



**(d) Microphone group (12, 11, 8, 9)**

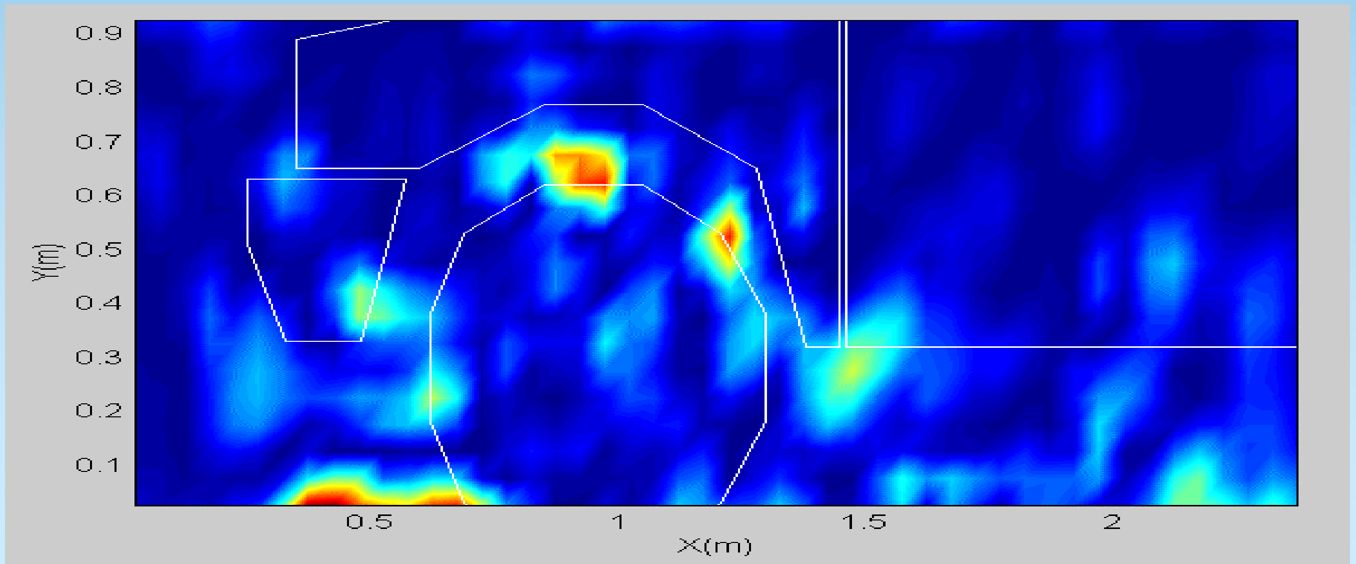


# Results: Transmission path

Partial sound field associated with **reference 1**




Partial sound field associated with **reference 2**



# Results: Ranking, Contribution

**Two mutually incoherent sources at 1317 Hz:**

- **Source location and ranking by integrating AI over the hologram plane**

  **1. Engine head (77 % of total sound power)**

  **2. Oil pan (23 % of total sound power)**

- **Source contribution at the center point 1m from the side panel by reconstruction of AI at the observation point**

  **1. Engine head (95 %)**

  **2. Oil pan (5 %)**

# Visualization Techniques of Nonstationary Vehicles

- Standard Vehicle Passby Tests
- De-Dopplerization (*propagation distance calculation*)
  - **backward propagation procedure**
  - **forward propagation procedure**
- Amplitude Correction (*compensating for spherical spreading*)
  - **intuitive method**
  - **maximum likelihood estimation**
- Array Design
- Experimental Results

# Kinematics of Moving Noise Sources

**Source signals :**

$$p_s(t) = A\exp\left(j\omega t\right)$$

**Received signals :**

$$y_m(t) = \frac{A}{R_m^0}\exp\left[j\omega\left(t - \frac{R_m^0}{c}\right)\right]$$

(Mach number effects on amplitude neglected)

**Delay-and-sum beamformer :**

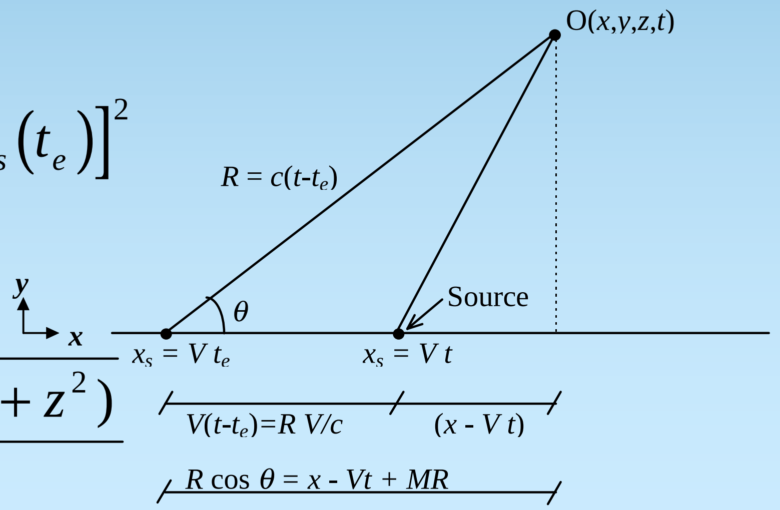
$$z(t) \equiv \sum_{m=0}^{M-1} w_m y_m(t-\Delta_m)$$

$$\Delta_m = -R_m / c$$

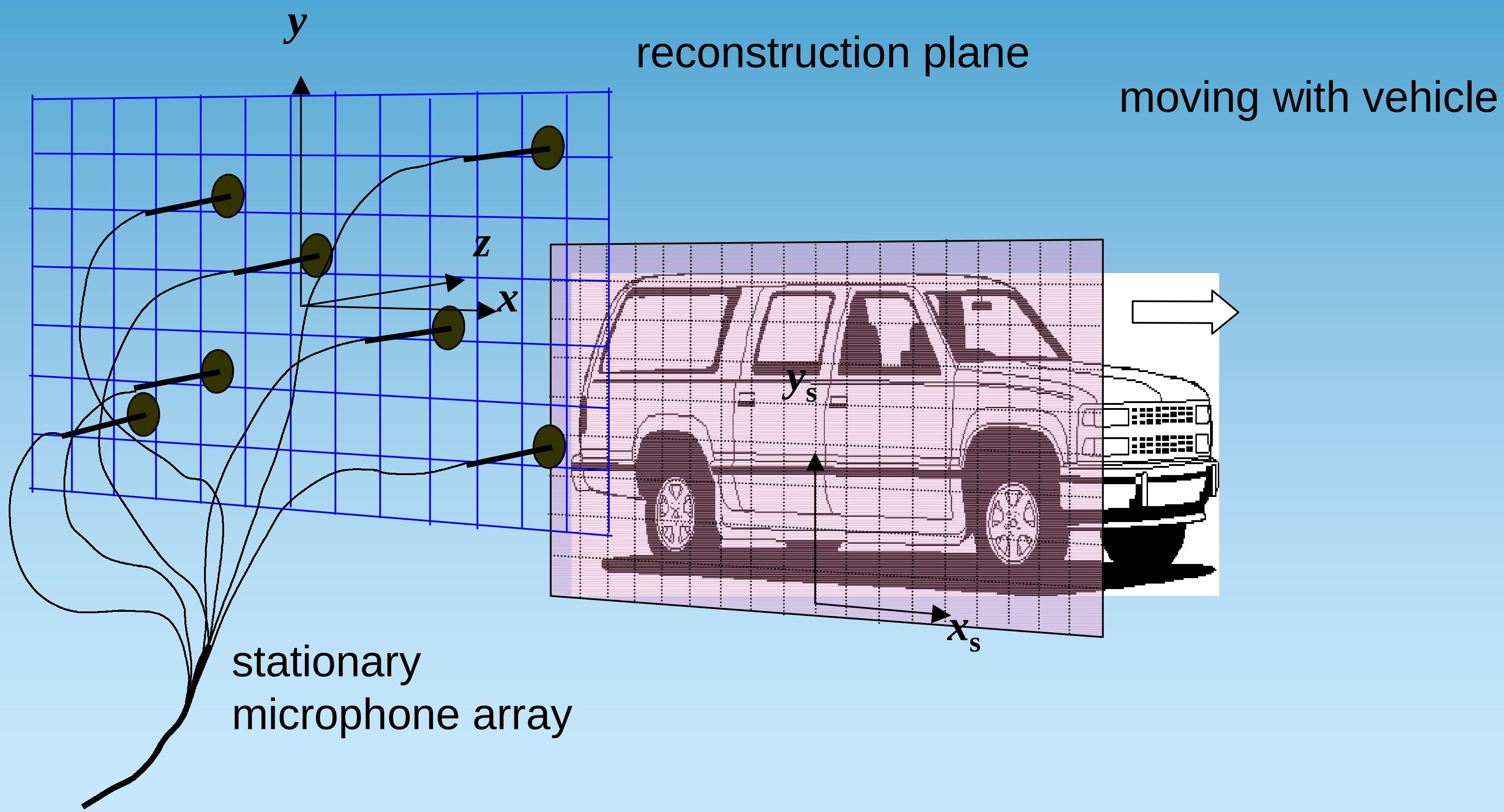
$$R^2 = \left[x - x_s(t_e)\right]^2 + \left[y - y_s(t_e)\right]^2 + \left[z - z_s(t_e)\right]^2$$

*(for constant velocity V)*

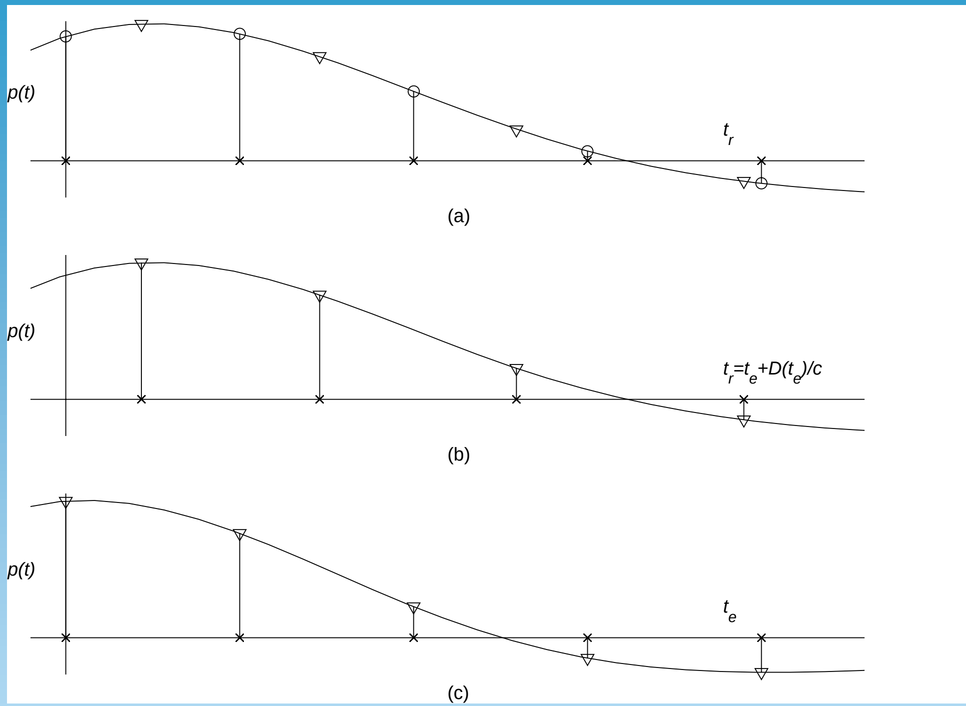
$$R = \frac{M(x-Vt) + \sqrt{(x-Vt)^2 + (1-M^2)(y^2+z^2)}}{1-M^2}$$



# Beamforming on a Reconstruction Plane Attached to and Moving with the Vehicle



# Backward Propagation



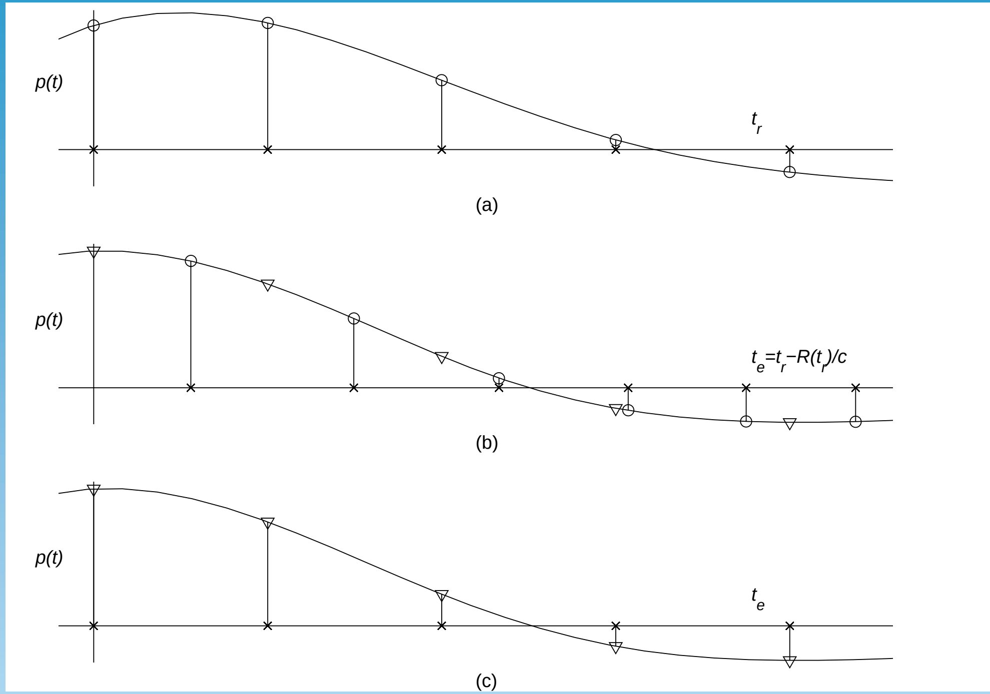

(a) *Calculate the propagation distance, $R(t_r)$, for the samples received at $t_r$ (receiver time)*

(b) *Generate the emission time vector corresponding to the receiver times*

$t_e = t_r - R(t_r)/c$

(c) *The resulting non-equi-spaced time history is resampled to obtain an equally-spaced time history in the source (i.e., emission) time frame*

# Forward Propagation




(a) *Calculate the instantaneous distance, $D(t_e)$, between the assumed source position and the microphone for an assumed signal emitted at $t_e$*

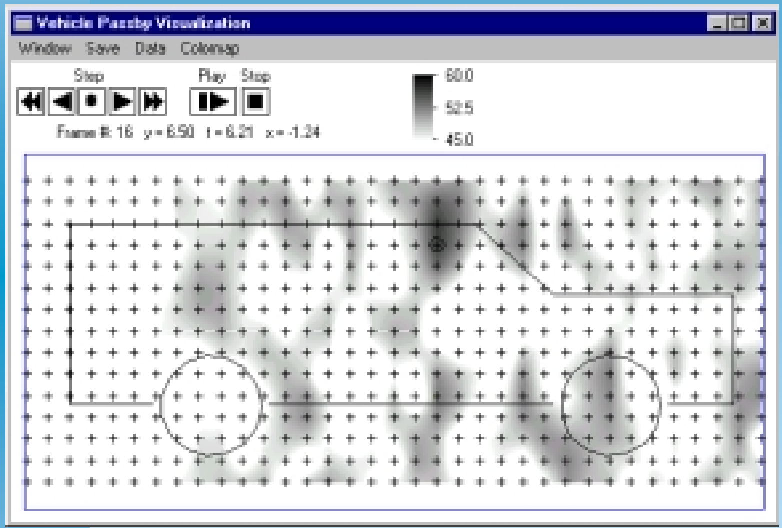
(b) *Generate the corresponding receiver time vector by using the formula,*

$t_r = t_e + D(t_e)/c$

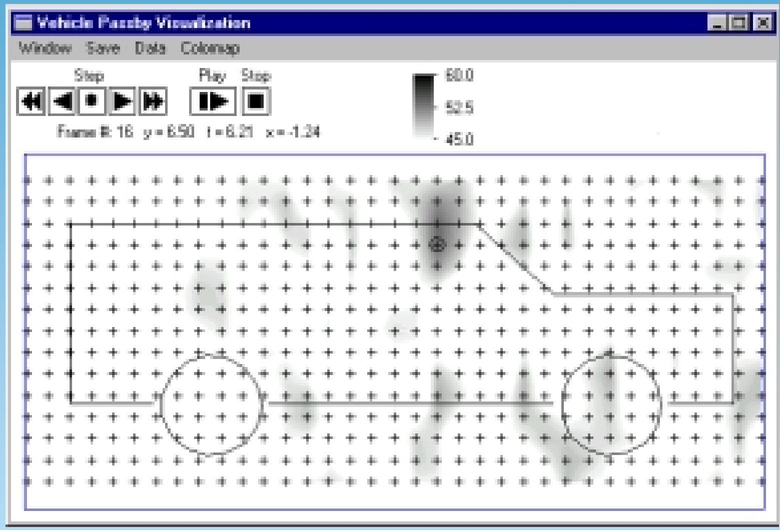
(c) *The measured microphone outputs sampled at equally-spaced sample times in the receiver time frame are resampled using the unevenly-spaced receiver time vector obtained in (b)*

# Forward vs. Backward Calculations

simulated results for 35 km/h cruise test. ⊕ denotes simulated loudspeaker location; loudspeaker at 2950 Hz, front hub at *x* = -1.24 m, 50 Hz analysis bandwidth.




results from backward propagation procedure




results from forward propagation procedure

- The calculation time was reduced by a factor of three <u>by using the forward propagation procedure</u> when compared to the backward propagation procedure.

# Amplitude Estimation

*Spherical spreading in near field*

$$y_m(t) = \frac{A}{R_m^0} \exp\left[ j\omega\left( t - \frac{R_m^0}{c} \right)\right]$$

*Weighting factor* ***$R_m/M$*** (intuitive weighting factor)

$$z(t) \equiv \sum_{m=0}^{M-1} w_m y_m(t - \Delta_m)$$

$$= \sum_{m=0}^{M-1} w_m \frac{A}{R_m^0} \exp\left[ j\omega\left( t - \frac{R_m^0}{c} + \frac{R_m}{c} \right)\right]$$

$$= A\exp(j\omega t)$$

( *with* $R_m = R_m^0$ *and* $w_m = R_m / M$ )

# Maximum Likelihood Estimation

assumptions : source waveform unknown, source position known

source signals : $a(t)$ noise : $n_m(t)$

time shifted measured signals : $y_m(t+R_m/c)=\frac{1}{R_m^0}a\left(t-\frac{R_m^0}{c}+\frac{R_m}{c}\right)+n_m\left(t+\frac{R_m}{c}\right)$

in vector form : $\mathbf{y}=a(t)\mathbf{s}+\mathbf{n}$

where

$$\mathbf{y}=\{y_0(t+R_0/c),y_1(t+R_1/c),\ldots,y_{M-1}(t+R_{M-1}/c)\}^T$$

$$\mathbf{s}=\left\{\frac{1}{R_0^0},\frac{1}{R_1^0},\ldots,\frac{1}{R_{M-1}^0}\right\}^T$$

$$\mathbf{n}=\{n_0,n_1,\ldots,n_{M-1}\}^T$$

# Maximum Likelihood Estimation (cont.)

$p_{y|a(t)}$ denotes the joint *probability density function* of the vector $y$ being observed when the signal source amplitude was *a(t)* at time $t$

$$\ln p_{\mathbf{y}|a(t)} = -\frac{1}{2}\ln\det\left[2\pi\mathbf{K}_{\mathbf{n}}\right] - \frac{1}{2}\left[\mathbf{y} - a\mathbf{s}\right]'\mathbf{K}_{\mathbf{n}}^{-1}\left[\mathbf{y} - a\mathbf{s}\right]$$

where $\mathbf{K}_{\mathbf{n}}$ noise covariance matrix

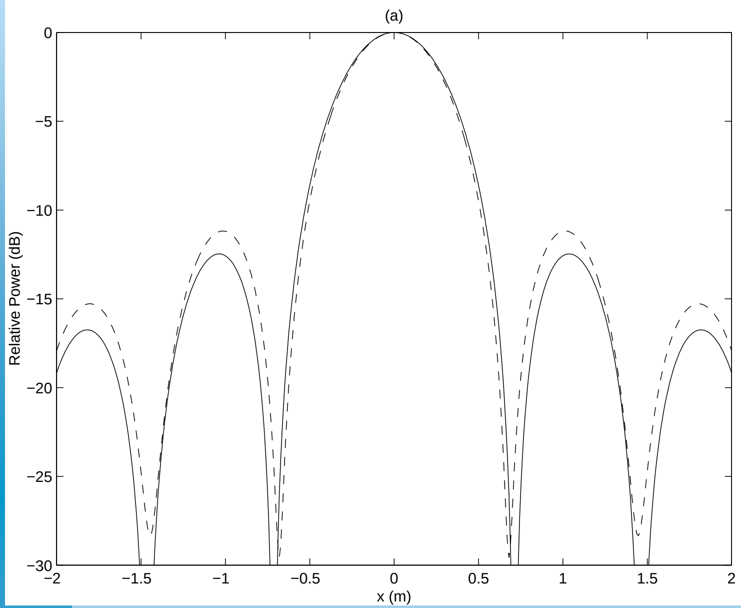
Then $\hat{a}_{ML} = \dfrac{\mathbf{s}'\mathbf{K}_{\mathbf{n}}^{-1}\mathbf{y}}{\mathbf{s}'\mathbf{K}_{\mathbf{n}}^{-1}\mathbf{s}}$ maximizes the *pdf* $p_{y|a(t)}$

$\hat{a}_{ML} = \dfrac{\mathbf{s}'\mathbf{y}}{\mathbf{s}'\mathbf{s}}$ (for spatially white background noise)

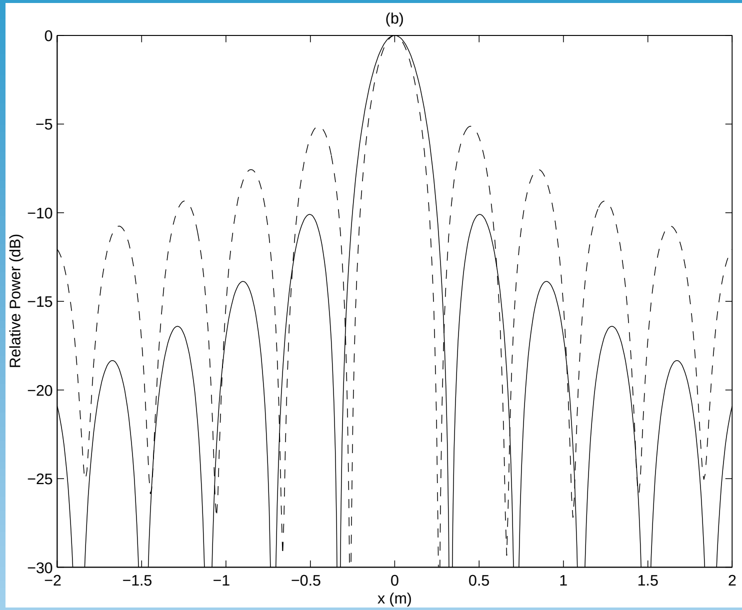
$$\Rightarrow \hat{a}_{ML}(t) = \frac{\sum_{m=0}^{M-1} y_m\left(t + R_m/c\right)/R_m}{\sum_{m=0}^{M-1} 1/R_m^{\ 2}} \qquad \Rightarrow w_m = \frac{1/R_m}{\sum_{m=0}^{M-1} 1/R_m^{\ 2}}$$

new weighting factor

# Results (1D-simulation, intersensor space 50 cm)




16-microphone array
($f$ = 500 Hz, $x_0$ = 0 m)



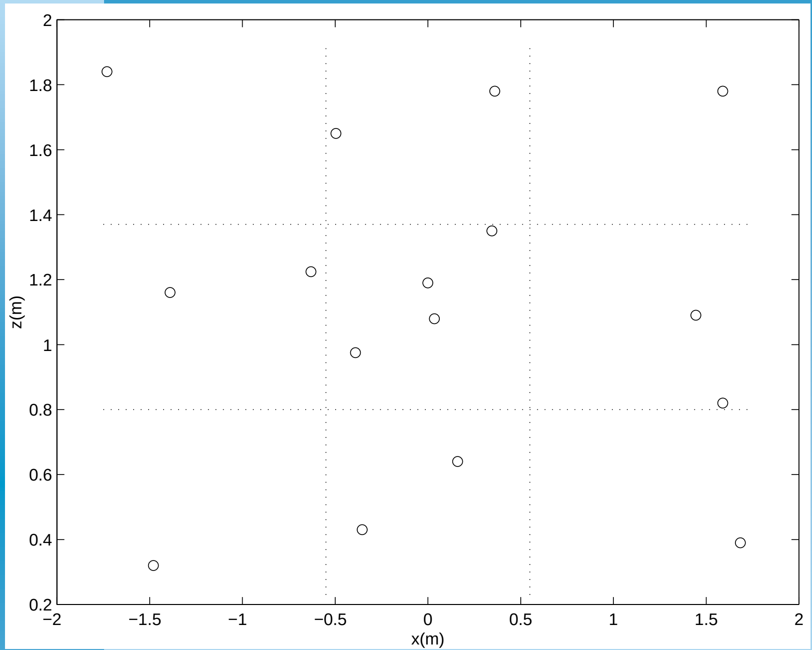

64-microphone array
($f$ = 500 Hz, $x_0$ = 0 m)

--------- $w_m = R_m / M$

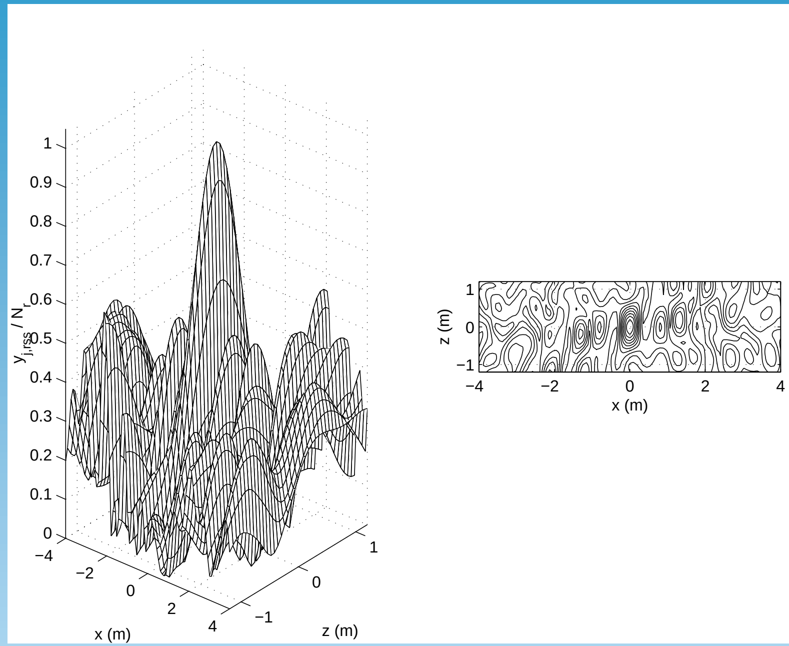
———— $$w_m = \frac{1/R_m}{\sum_{m=0}^{M-1} 1/R_m^{\,2}}$$

- Sidelobe levels decreased by more than 5dB as either the number of microphone or array aperture size is increased.

# Array Design



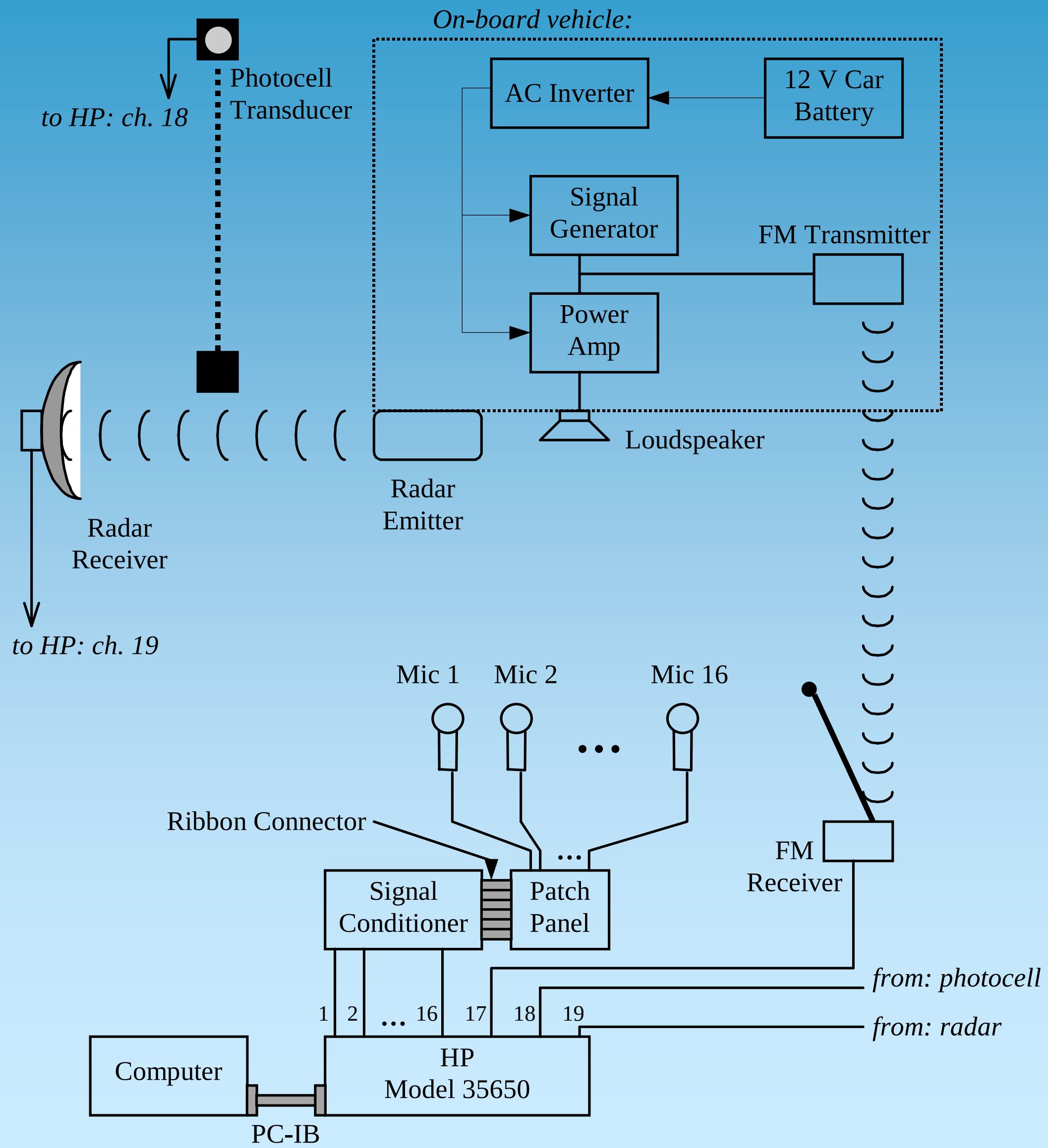

positions of microphones




array pattern at 2000 Hz

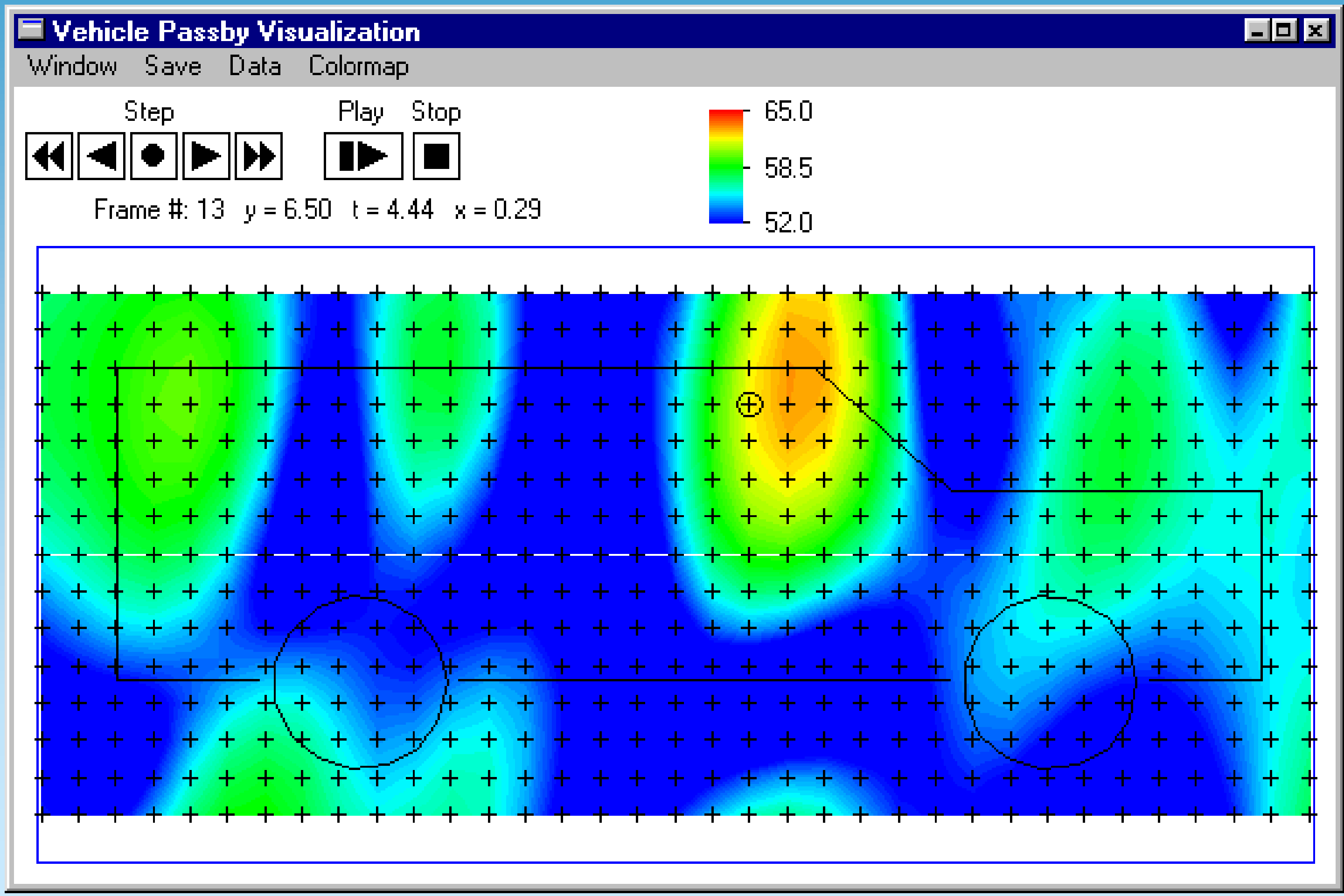
- Random array was randomly generated and snapped to an underlying grid.
- Random array reduces the number of redundancies in the co-array.

# Experimental Setup



# Experimental Results

Source localization results for 50 km/h cruise test, loudspeaker at 1005 Hz, $x$ = 0.29 m, 50 Hz band

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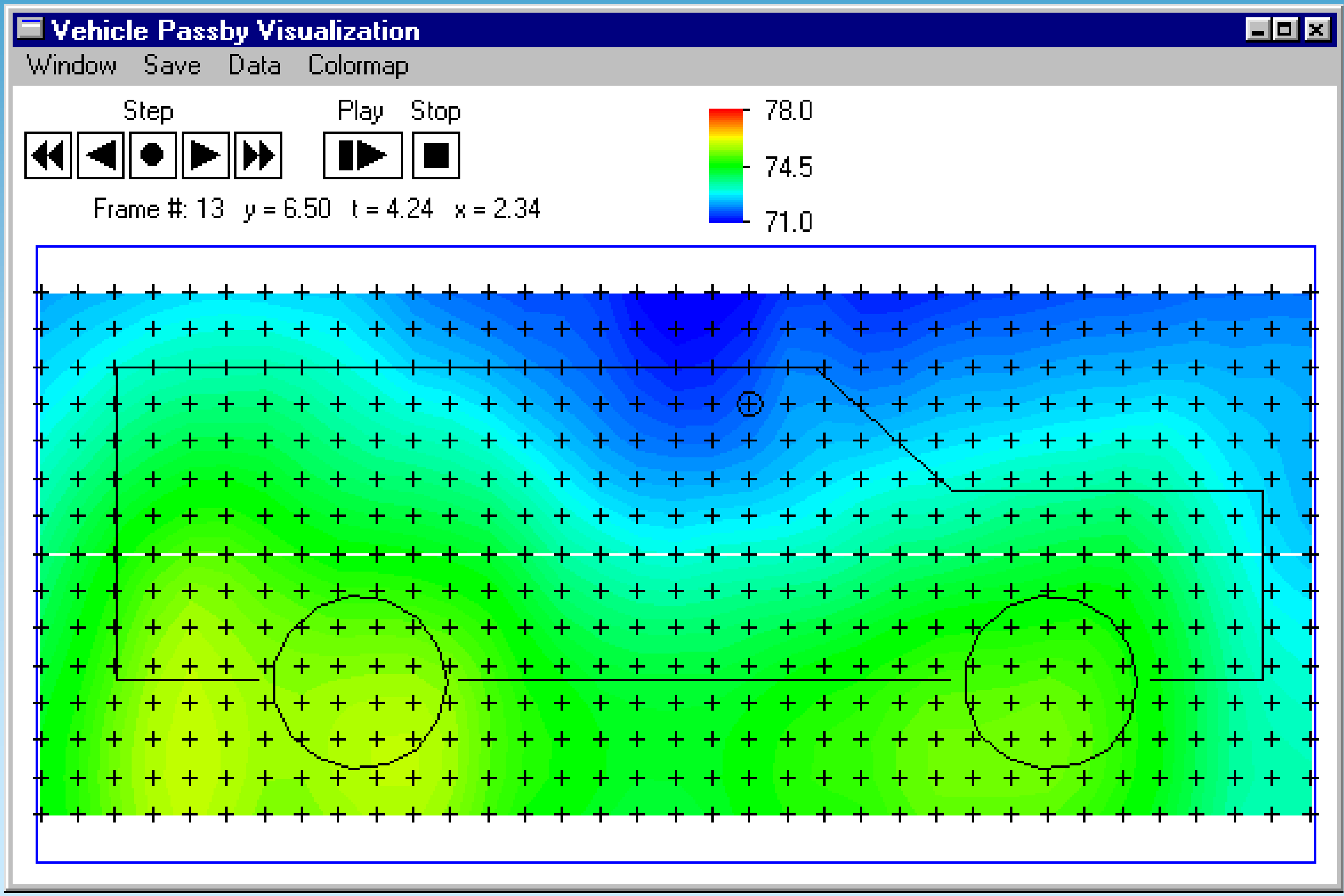
# Experimental Results (cont.)

Visualization results for acceleration test, loudspeaker at 1850 Hz, $x$ = 2.34 m



# Conclusions

- ***The partial SVD method associates the reference signals more directly with the physical sources than does the partial SVD method.***
- ***The partial coherence technique is applicable to the decomposition of the sound field from hidden sources.***
- ***Noise source visualization successful for non-constant velocity (capable of resolving loudspeaker and tire noise).***
- ***Improved computation time by using forward propagation procedure.***
- ***Reduced sidelobe levels by using maximum likelihood estimation for amplitude of the source strength.***