Performance of Several Air Acoustic Vector-Sensor Configurations for DoA Estimation in the Reverberant Environment

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Introduction:

- Acoustic intensity is the product of pressure and particle velocity. The direction of acoustic intensity gives the signal's direction-of-arrival (DoA).
- Acoustic intensity is calculated using pressure-sensors with different geometrical arrangements (Acoustic vector-sensor configurations)
- The performance of these AVSs for DoA estimation have been evaluated without considering reverberant environment [1].
- The reverberant/noisy environment based DoA have been tested only for a single AVS configuration (delta configuration) [2, 3].
- We have evaluated and compared several AVS configurations for estimating the DoA of a single sound source under diffused reverberation environment.

Acoustic Intensity Based on Pressure Gradient:

Particle velocity along x-axis: $\mathbf{v_x(t)} = -\int_{-\infty}^{t} \frac{1}{\rho_0}\left[\frac{\partial p}{\partial x}\right] d\tau \approx -\int_{-\infty}^{t} \frac{1}{\rho_0}\left[\frac{p_2(\tau)-p_1(\tau)}{d}\right] d\tau$

Average acoustic intensity along x-axis: $\mathbf{I_x} = -\frac{1}{\rho_0 d}\int_0^{\infty} \frac{\mathrm{Imag}\left(\Gamma_{p_1 p_2}(\omega)\right)}{\omega} d\omega$

DoA w.r.t. to y-axis: $\hat{\theta} = \arctan\left(\frac{I_x}{I_y}\right)$ where, I_y is the average intensity along y-axis. If the pressure sensors are not along the horizontal and vertical axes, then the projection of the intensity on the orthogonal axes is used to calculate the horizontal and vertical intensity components.

Experimental Environment using COMSOL:

- AVS consisting of identical omni-directional pressure-sensors of zero sizes is kept at the centre of the room as shown Fig. 1.

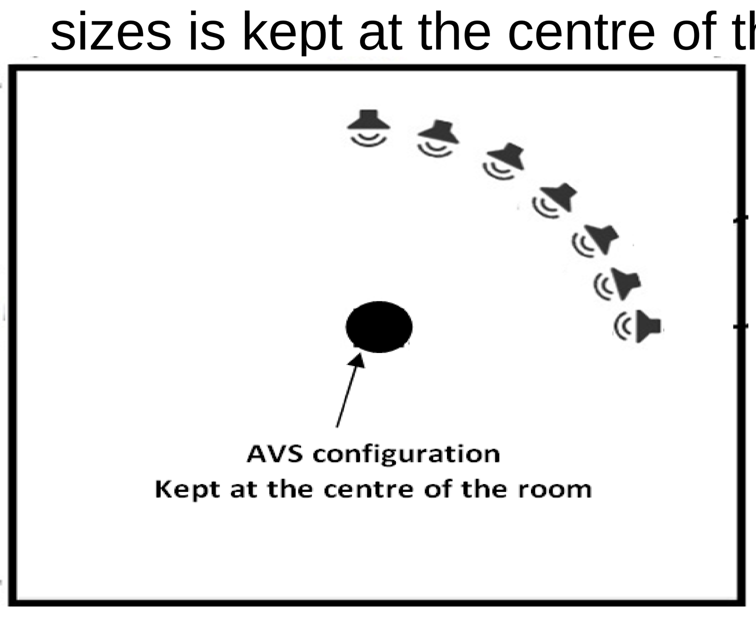


Fig. 1 AVS placed at the centre of 5 x 5 m[2] room, and sound source is located at a range of 1 meter and moved with an increment of 15º in a quadrant, walls of the room are considered to be reflecting. The floor and ceiling of the room are considered to be perfectly absorbing i.e. no reflection [3].

- The six different AVS configurations are tested for DoA estimation in the reverberant environment. These AVS configurations are named as delta, AVS1, AVS2, AVS3, AVS4 and AVS5 as shown in Fig. 2.

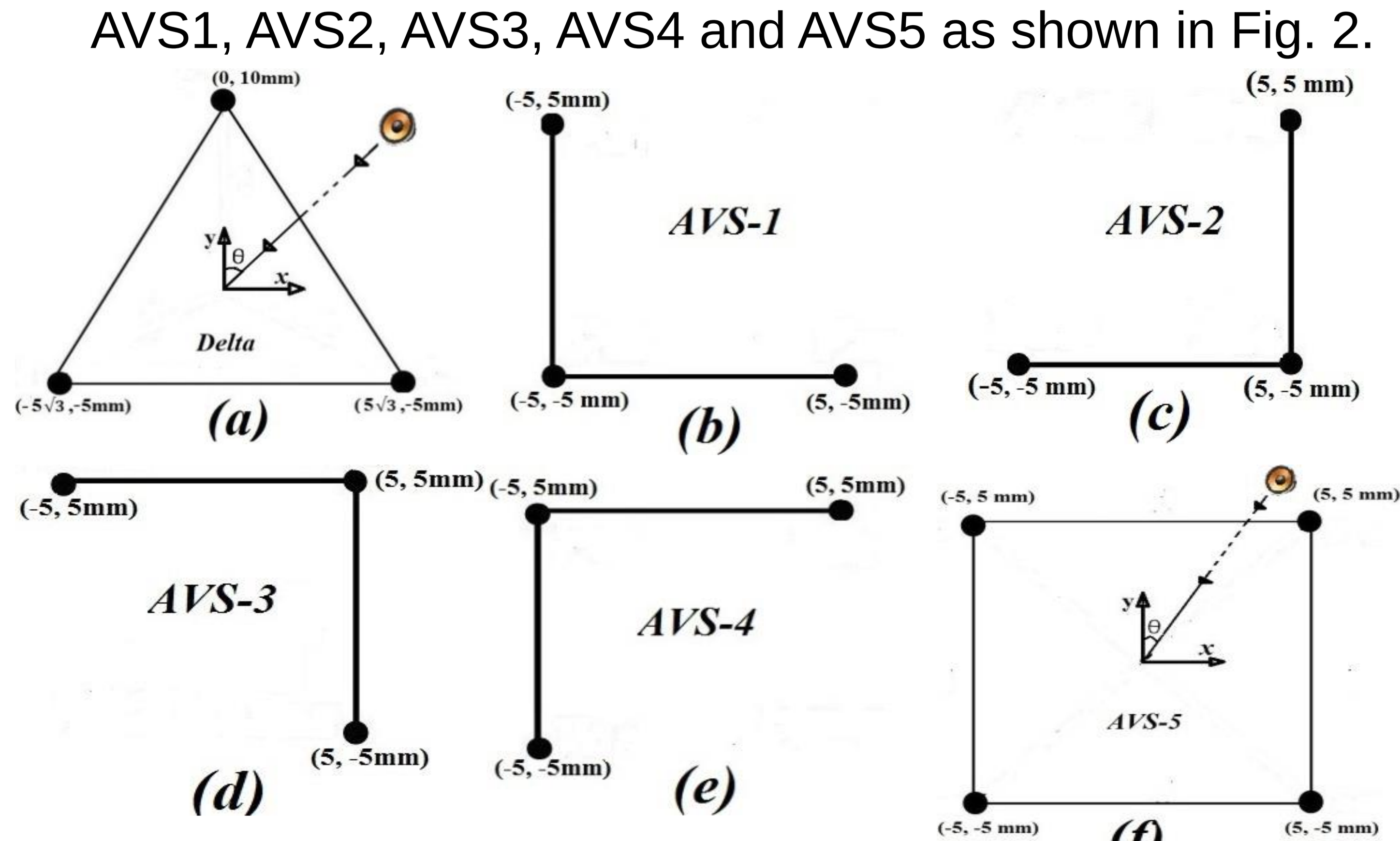


Fig. 2 AVS configurations (a) Delta, (b) AVS1, (c) AVS2, (d) AVS3, (e) AVS4 and (f) AVS5 (Filled circle are representing omni-directional pressure sensors) [1].

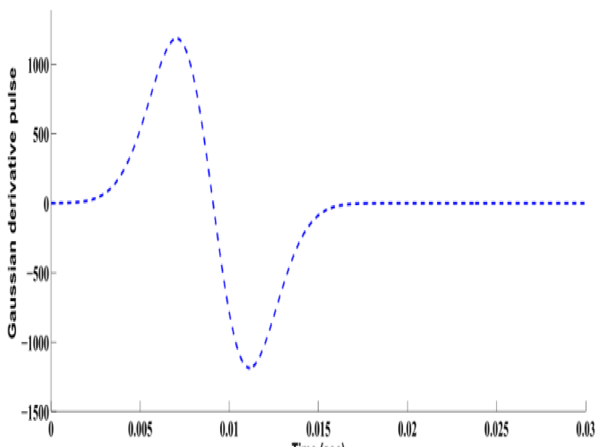


Fig. 3 Gaussian derivative pulse, emitted by the sound source at range of 1 meter.

- Durations of received signal (sampling rate is 8 kHz) are 0.4, 0.6 and 0.8 seconds. Reverberation time (RT_{60}) are 0.3, 0.45 and 0.6 seconds.

Evaluation Parameter:

The accuracy of DoA estimation has been evaluated in terms of absolute angular error (AAE) defined as, $\mathbf{AAE} = \left|2\sin^{-1}\left(\frac{\|\mathbf{u}-\hat{\mathbf{u}}\|}{2}\right)\right|$, where$\|*\|$ is the l_2 norm,$\boldsymbol{u}$ and $\hat{\boldsymbol{u}}$ are the unit vectors pointing to the true direction of the sound source and its estimated direction respectively. When averages of AAE are taken over all seven angular locations in a quadrant then the symbol $\overline{\mathrm{AAE}}_{0^o:15^o:90^o}$is used:

$$\overline{\mathbf{AAE}}_{0^o:15^o:90^o} = \frac{1}{7}\sum_{k=1}^{7} \mathbf{AAE}(\theta_k),$$

where $AAE(\theta_k)$ represents AAE for a sound source at an angle of θ_k.

Results and Discussion:

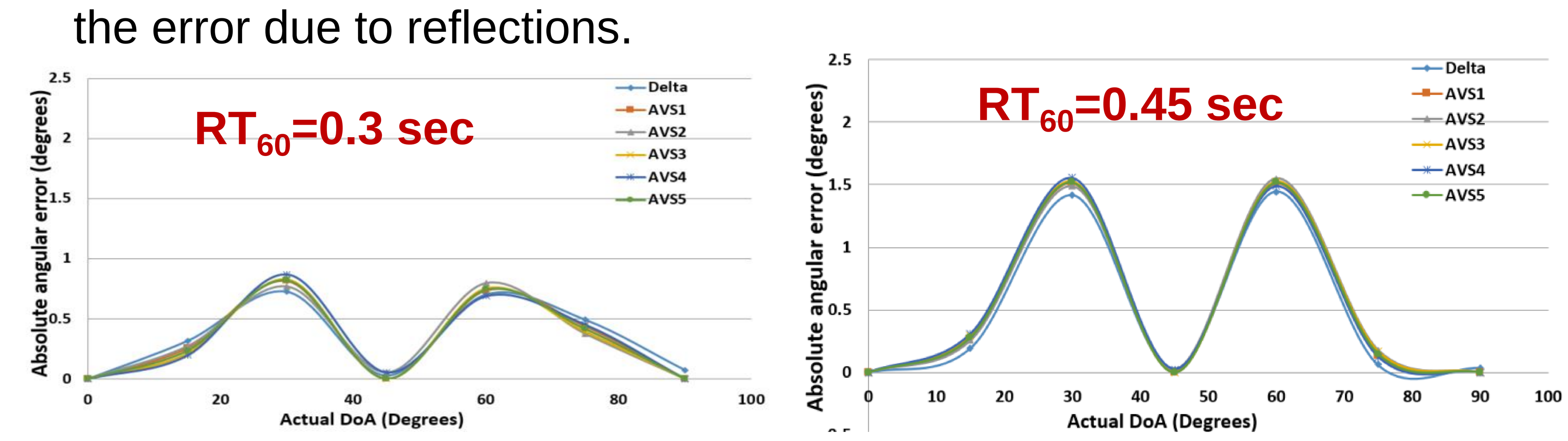
RT_{60} (sec)	$\overline{AAE}_{0^o:15^o:90^o}$ (degrees) Received signal duration is 0.4 sec					
	Delta	AVS1	AVS2	AVS3	AVS4	AVS5
0	0.131	0.036	0.145	0.042	0.148	0.003
0.3	0.292	0.269	0.277	0.258	0.278	0.264
0.45	0.336	0.317	0.325	0.307	0.325	0.312
0.6	0.369	0.347	0.354	0.337	0.354	0.342

RT_{60} (sec)	$\overline{AAE}_{0^o:15^o:90^o}$ (degrees) Received signal duration is 0.6 sec					
	Delta	AVS1	AVS2	AVS3	AVS4	AVS5
0	0.131	0.039	0.156	0.044	0.159	0.002
0.3	0.334	0.319	0.323	0.311	0.323	0.315
0.45	0.453	0.489	0.499	0.502	0.499	0.495
0.6	0.656	0.700	0.708	0.711	0.707	0.705

RT_{60} (sec)	$\overline{AAE}_{0^o:15^o:90^o}$ (degrees) Received signal duration is 0.8 sec					
	Delta	AVS1	AVS2	AVS3	AVS4	AVS5
0	0.138	0.041	0.167	0.049	0.170	0.003
0.3	0.651	0.677	0.688	0.685	0.688	0.680
0.45	1.825	1.910	1.905	1.902	1.908	1.904
0.6	2.801	2.942	2.94	2.926	2.939	2.934

Table 1. $\overline{\mathrm{AAE}}_{0^o:15^o:90^o}$ (degrees) for different AVS configurations with different reverberation time and of duration of the received signals at the pressure sensors.

- For the no reverberation case, the performance is different for different AVS configurations for the given duration of the received signals and the same is observed in [1]
- The best performance is for the AVS5 configuration among all the AVS configurations and worst performance is for the Delta configuration.
- With the increase in the reverberation time, the performance of all the AVS configurations for DoA estimation will degrade, as noticed for Delta configuration in [2].
- Also, it has been observed from the results in Table 1 that under reverberant environment, all the AVS configurations give almost same performance for the given value of RT_{60} and received signal duration.
- Without reverberation, the DoA error performance differences amongst the different AVS configurations are due to the different biases for different AVS configurations. This bias is insignificant when considering the error due to reflections.



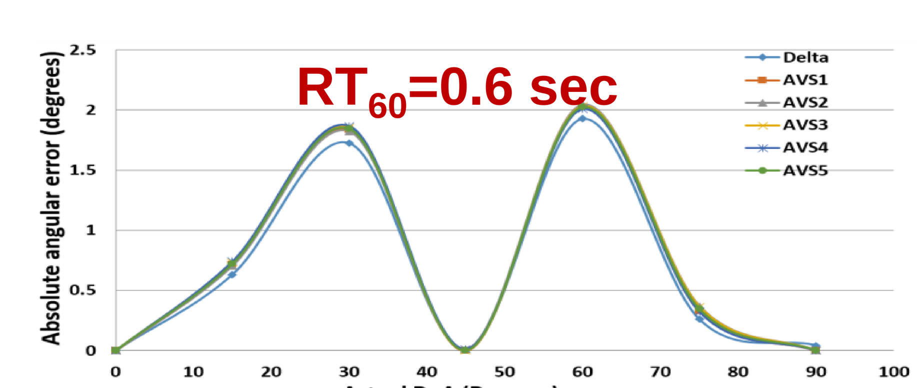


Fig.4 AAE versus actual DoA for different AVSs, when the AVS is placed at the centre of 5 x 5 m room, and sound source is located at a range of 1 meter with RT_{60}=0.3, 0.45 and 0.6 sec and received signal of 0.6 sec duration.

- From Fig. 4, it is seen that the angular error is minimum at 0^o, 45^o and 90^o of DoA for all AVS configurations. This is due to the symmetric reflecting boundaries. At $0^o$and $90^o$of DoA, the horizontal gradient and vertical pressure gradient are almost zero. At 45^o DoA, the horizontal and vertical pressure gradients error are identical due to the symmetric reflections and nullify the effect of each other in DoA estimation.

Conclusions: The DoA error pattern for various source directions is different for different AVS configurations, however in the reverberant environment it is similar for all the AVS configurations for the given received signal duration and reverberation time. The placement of the microphones in an AVS configuration plays insignificant role under the reverberant environment.

Key References:
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