The Porsche Wind Tunnel Microphone Array System

Jörg Ocker[1], Swen Tilgner[2]

[1] *Dr. Ing. h.c.F. Porsche AG, 71287 Weissach, Germany, Email: joerg.ocker@porsche.de*
[2] *gfai tech GmbH, 12489 Berlin, Germany, Email: tilgner@gfaitech.de*

Abstract

The new Porsche aero-acoustic wind tunnel opens great options for the automotive development process at Porsche. A very low background noise and the homogeneous flow characteristics allow the use of various measurement techniques and lead to an excellent quality and degree of reproducibility of acoustic measurements.

Especially in the early development stages a quick and reliable rating of aero-acoustic sound sources is important to fulfil the challenging requirements. For a localisation and detailed investigation of these aero-acoustic sources, a complex measurement system consisting of three single microphone arrays, was developed and installed.

All arrays are fixed at a framework positioned out-of-flow, with the smallest possible distance to the test object. In order to prevent negative effects during aerodynamic testing, the whole system can be moved back to a parking position out of the test section area.

The basic evaluation of the recorded microphone data is known as "acoustic camera principle" where acoustic source maps computed by special beamforming algorithms are mapped to an optical image (2D) or the car surface (3D).

The quality of these basic source maps ("dirty maps") - given by the dynamic of the localized sound levels and the spatial source resolution - is mainly defined by 4 hardware parameters:

- Array dimensions 5 m x 3 m each
- Number of microphones 192 microphones each
- Microphone layout irregular with an optimized layout
- Measurement distance automated positioning to 4 m

By the use of advanced post-processing techniques, e.g. algorithms like CLEAN SC [12], it is possible to improve the results significantly. However, the better the basic result the greater the success using these enhanced software tools.

Therefore great attention was paid to excellent properties of the mechanical installation as well as to a comfortable and fast data acquisition achieving an outstanding basic acoustic performance. Hence, further activities have been started and various investigations were scheduled to advance the data analysis.

The paper focuses on the first and terminated project phase: The development, design and installation of the system. Based on the results of several simulations and a study with real sound sources (loudspeakers with and without flow); the capability of the system is verified and the quality of first results is shown by means of a typical example.

Introduction

For a car manufacturer like Porsche, an outstanding sportive design and a great performance combined with a favourable passenger comfort and high efficiency are fundamentals to be regarded at all times. Therefore, the new Porsche wind tunnel is a very important tool in the aerodynamical and aero-acoustic optimization process, allowing evaluation of design- and material concepts as well as styling-driven shape decisions. The new Porsche wind tunnel was designed over several years and realized from 2011 to 2014 [14].

Now, aero-acoustic development can be performed over the full velocity range up to 300 km/h, and due to very low background noise levels, the localisation and precise investigations of sound sources are possible using microphone arrays. The Porsche wind tunnel microphone array system was developed and built in cooperation with GFaI, Berlin and installed in January 2015.

Basic Array Hardware

The system consists of 4 data recorders, 3 microphone arrays, each equipped with 192 electret microphones and an integrated Full HD camera. Additionally 24 measuring channels are provided to record reference signals and the test conditions. A high performance working station is dedicated to the data acquisition and analysis, operated by special controller software, adapted to the Porsche wind tunnel.

To achieve a high localisation accuracy of the acoustic sources, a signal sampling frequency up to 192 kHz is realized for each differential transmitted channel and a positional accuracy of ± 1 mm is ensured for all microphones. This precision is reached up to maximum speed by a high stability and a low weight of the arrays resulting from a special sandwich construction integrated in a lightweight reinforcing frame.

Beamforming in a Wind Tunnel

The result generated by an array system is called acoustic source map; superposed to an optical image or a 3D geometry of the considered object. The calculation of the source map is carried out using beamforming algorithms.

A picture (2D) or model (3D), divided into a grid of points, is used to represent the object under investigation. For 2D applications, the grid is arranged in the scan plane with a known distance to the microphones in the array plane (Figure). The evaluation of the runtime differences and amplitude decays of assumed sound sources between every grid point of the scan plane and every microphone of the array plane leads to the basic source map ("dirty map"). This elementary beamforming algorithm can be applied in the time or frequency domain whereat the time domain "delay and sum" algorithm is well known in acoustic signal processing for many years now.

In recent years more advanced frequency domain algorithms have been developed to improve the quality of the maps. In the frequency domain most algorithms base on the calculation of the cross spectral matrix (CSM). The CSM contains all cross spectra data of the microphone signals and therefore all level and phase information representing the runtime differences of the acoustic waves. By applying a so called steering vector to the CSM - to include the geometric information and distances - it is possible to calculate the source map. By the formulation of the steering vector, the focus of the evaluation can be directed to calculate exact levels or to a good source localisation in the source maps.

The main diagonal of the CSM contains the auto spectra data of the microphone signals which are often dominated by the background noise. Thus it is possible to improve the dynamic range of the source maps by removing the elements of the main diagonal from the CSM. However the energy content and thereby the absolute levels of the source maps are not correct in that case.

There are many publications in which the different methods and algorithms with their pros and cons are discussed in detail [2], [6], [7], [9], [13].

In a wind tunnel a shear layer appears between the flow region and the area in the plenum without a major flow where the arrays are positioned. The flow around the test object generates sound sources radiating acoustic waves. These waves get strongly affected when passing the shear layer (Figure). The shear layer causes diffractions of the acoustic waves and lead thereby to displacements and distortions in the source maps. For the application of beamforming in wind tunnels to aero-acoustic sources, it is indispensable to consider this shear layer effect, e.g. by a correction according to Amiet [12].

Amiet introduces a model where the diffraction effects are taken into account with good accuracy by reducing the shear layer to a flat and infinite thin extent specified by its angle and distance to the array and scan plane (Figure).

Unaccounted in this model are additional scattering effects due to the turbulence in the shear layer which lead to correlation losses of the signals with a degrading effect evaluating the phase shifts.

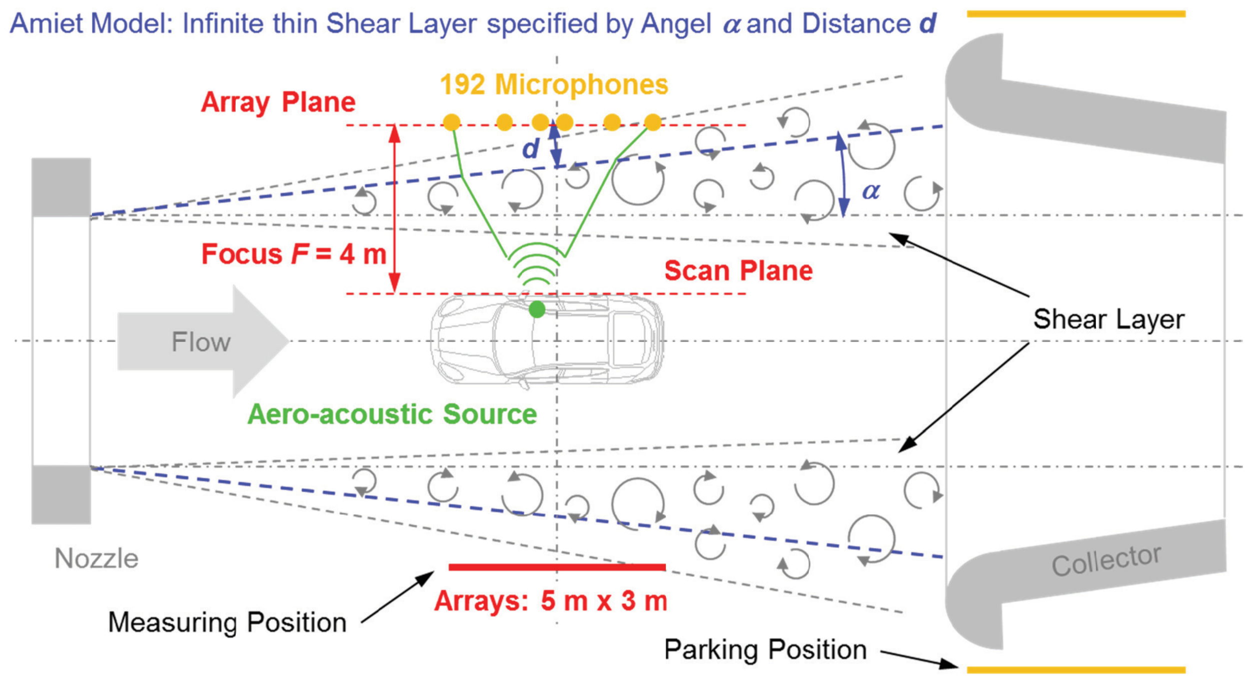


Figure 1: Sketch of wind tunnel shear layer and parameters of the Amiet model.

With the Porsche Array System, most of the analyses are carried out in the frequency domain based on the CSM with diagonal removal. An Amiet shear layer correction modified by Puhle [8] and a steering vector formulation concentrating on an exact source location is used. The implemented basic algorithms were validated in great detail in the context of an intensive cooperation between GFaI, DLR Göttingen, Volkswagen group research and Porsche.

To rate the performance of an array, the Point Spread Function (PSF) can be used. The PSF is the frequency-dependent array response to an omnidirectional point source with a defined location, typically calculated by a simulation. The result is also called beam pattern.

In Figure 2 a typical PSF of the Porsche arrays is plotted for the third-octave band of 2500 Hz. The main lobe represents the real source, whereas the side lobes are artefacts generated by the beamforming algorithms. The dynamic range (DR) is defined by the difference between the level of the main lobe and the highest side lobe.

The beamwidth (BW) defines the width of the main lobe at 3 dB level decrease. Dynamic range and beamwidth are the basic indicators for the quality of sound source location and thus for the capability of an array. Both parameters depend strongly on the hardware parameters: the array dimension, the number and layout of microphones and the measurement distance (focus).

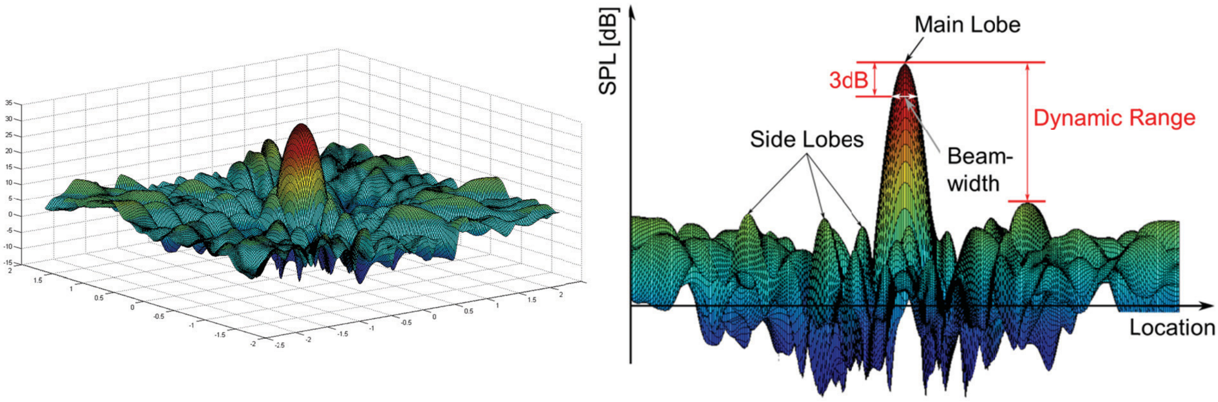


Figure 2: **Simulated Point Spread Function (PSF), f = 2500 Hz, F = 4 m, DR = 21dB.**

Array Dimension

The required size of an array first of all depends on the lowest frequency to be considered. The lower the frequency and thus the bigger the wavelength, the larger the array dimensions to capture enough information of the acoustic wave. That means to measure enough runtime difference or respectively phase shifts in the frequency domain for the observed wavelength.

To minimize the beamwidth over the whole frequency range, basically maximum array dimensions with a minimal focus are aspired. Under flow conditions in a wind tunnel, however, higher frequencies correlation losses increases together with the array dimension and the flow speed. This effect results in phase errors for distant microphones.

Taking into account all these effects and adjusting the arrays to the size of the cars to be analysed, the overall dimensions of the Porsche arrays were defined to 5 x 3 m. As shown in Figure 3 in addition, the central part of the arrays (3 x 2 m) has been designed especially for the investigation of higher frequencies in a preferred measurement window of 1.5 x 1 m. To obtain comparable results, all arrays (left, right and on top) were constructed with the same dimensions.

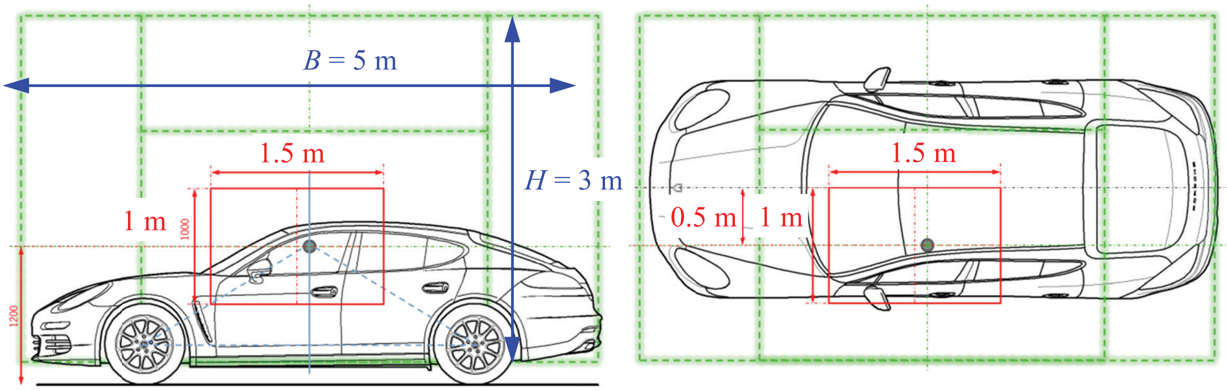


Figure 3: **Overall array dimension: 5 x 3 m, centre array: 3 x 2 m, extension: 3 x1 m, preferred measurement window: 1.5 x 1 m.**

Number and Layout of Microphones

The number of microphones and thereby the number of measurement channels needed by the data acquisition system defines a major part of the hardware costs of an array system limited by the project budget. Otherwise, to reach an excellent dynamic range of the source maps, as much microphones as possible should be applied. As a compromise, each Porsche array was equipped with 192 microphones.

Another important point, especially regarding the dynamic range, is the layout of the microphones. A lot of effort was provided to find the best arrangement of the microphones. Therefore, a completely new optimisation strategy was developed and applied by Dr. Hartmann from Volkswagen group research.

The optimisation performed by a generic algorithm in combination with a gradient based search of local minima operates directly to all microphone coordinates – not just to some layout parameters. Thus, for 192 microphones with adjustable x- and z-positions 384 degrees of freedom have to be optimised.

The target function for the optimisation was generated by a rating of weighted sums for each criterion below:

- beamwidth
- distance of the main lobe to the highest side lobe
- level of the highest side maximum
- average of the side lobe levels in the preferred measurement window

Further restrictions were introduced to concentrate microphones in the centre array. This could be important for the high frequency region if the use of a shading procedure to the outer microphones could reduce negative correlation loss effects as discussed before. In this case only few microphones would be affected by shading. Future work is scheduled regarding this topic.

The result of the optimization is an irregular microphone layout as depicted in Figure 4, where simulated source maps are compared to the best symmetric standard layout considered.

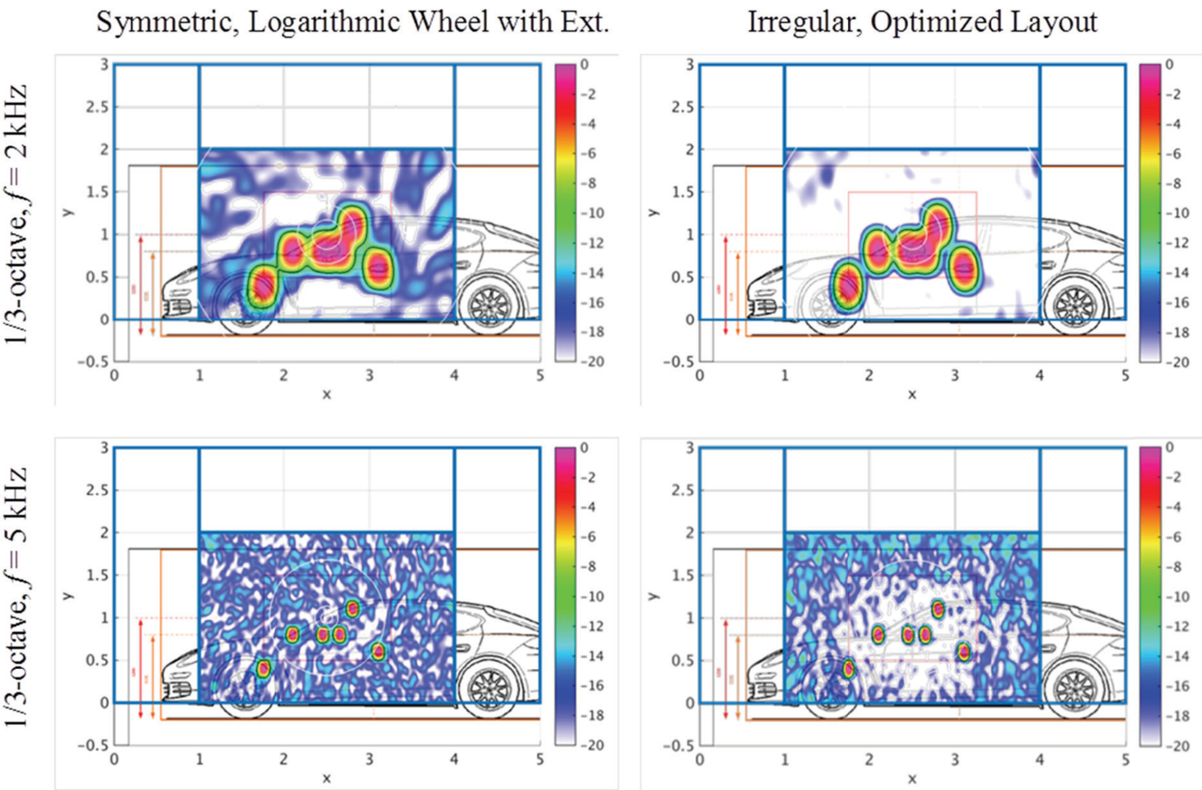


Figure 4: Simulated source maps, 6 sources with same level, F = 4 m, 192 microphones.

To compare on the same basis, the number of microphones was extended to 192 for the logarithmic wheel standard layout. The improvement of the dynamic range achieved by the optimized layout is clearly visible for all frequencies and particularly clear in the preferred measurement window.

The only disadvantage observed regarding the asymmetric dimension and layout is a slightly asymmetric representation of the sources in the source maps.

According to the array dimension, the number and layout of microphones was defined to be equal for all arrays installed to get comparable results.

Measurement Distance or Focus

For the integration of the arrays in the wind tunnel, a purpose-built framework was installed on a special rail system to be moveable in flow direction. The fixing to a defined position is realized by several pneumatic cylinders bracing the whole framework to the wind tunnel walls. High system rigidity is achieved by this mechanism.

Due to the given conditions, a measuring distance of 7 m to the wind tunnel centre would have been reached by a direct installation of the arrays to the framework. This corresponds to a focus of approx. 6 m to the scan plan assumed at the side of a car with a typical width. But, as a preferably short measuring distance (focus) is important for excellent results, shorter distances were investigated in a study carried out with 5 microphones mounted at the edges and in the centre of a frame with the array dimensions of 5 x 3 m (Figure 5).

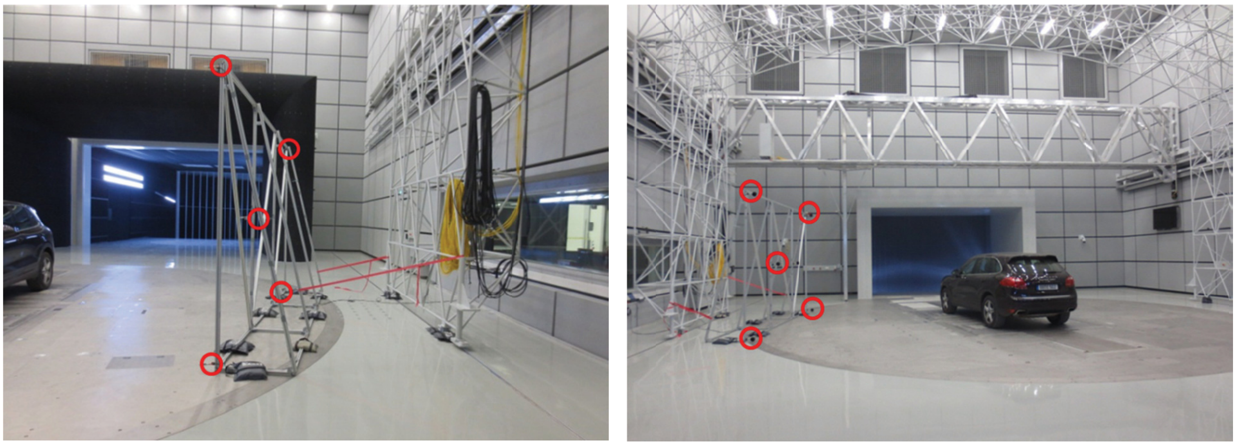


Figure 5: Test set-up to determine the optimal measurement distance.

The evaluation of the study leads to the result that a minimal measuring distance of 5 m to the wind tunnel centre and thus a focus of approx. 4 m to the assumed scan plane can be realised. By a further reduction, the microphones near to the collector would be strongly affected by the shear layer. However, for a focus reduction, an additional mechanical construction is needed. Due to the expectable improvements in result quality, the implementation of an array positioning system was decided.

Array Positioning System

The array positioning system has been specially designed for the new Porsche wind tunnel. It consists of several control arms connecting the arrays rotatable to the framework, an electric winch system operated by a control unit and a pneumatic locking system to fix the arrays in the parking position reliably (Figure 6 and Figure 7).

All arrays can be moved automatically to the measuring or parking position in less than 3 minutes. Various sensors are installed to prevent operating errors.

Figure 6: Framework and arrays in measuring position.

Figure 7: Framework in measuring position Arrays in parking position.

To avoid any taping of loose cables and to be ready performing measurements within a few minutes, the entire wiring of the array system is routed through a cable track. Because the whole system is moveable on the rail system, the preferable measurement window can be easily aligned to every interesting part of the test object and a parking position can be reached quickly to prevent any negative effect to aerodynamic testing (Figure 8).

Figure 8: Framework and arrays in parking position.

A nearly perfect fixing of the framework to the wind tunnel wall structure, combined with a high rigidity of the positioning system and the framework, leads to a very good reproducibility for the array positioning and low displacements and vibrations during the wind tunnel operation, even at maximum speed. This is essential, especially for optimal source localisation on a 3D model.

By the use of a FARO Laser Tracker with a measurement accuracy of 0.03 mm at 18 m distance, the deviations of the array positioning, regarded at multiple operations and the array displacements during wind tunnel operation were measured.

	Max. Deviation
Side Arrays	0.06 mm
Top Array	0.33 mm

Table 1: Array positioning accuracy.

Flow Speed	Max. Displacement
140 km/h	0.22 mm
300 km/h	1.32 mm

Table 2: Array displacement during operation.

Performance Tests

Setup

For the determination of the basic array properties, extensive performance tests were carried out with a 1:1 model of a test vehicle (Figure 9). To be as flexible as possible for analysing the system, the study was conducted with generic sound sources, generated by loudspeakers (LSP). When selecting the loudspeakers, a lot of attention was paid to fulfil the following requirements:

- Providing enough power to generate source levels representing real aero-acoustic sources typically analysed at a speed range between 100 and 200 km/h.
- *LSP* membranes as small as possible for a precise analysis of the source localisation accuracy.
- No generation of additional sound due to the shape of the *LSP* themselves.
- Providing a preferably linear frequency response over a wide frequency range.

Two types of LSP, shown in Figure 10, were found fulfilling these requirements. Type 1 with a membrane diameter of 36 mm provides enough power and a nearly linear frequency spectrum between 1 and 10 kHz. LSP of type 2 extends the lower frequency limit to 500 Hz providing nearly the same characteristics with a membrane diameter of 50 mm.

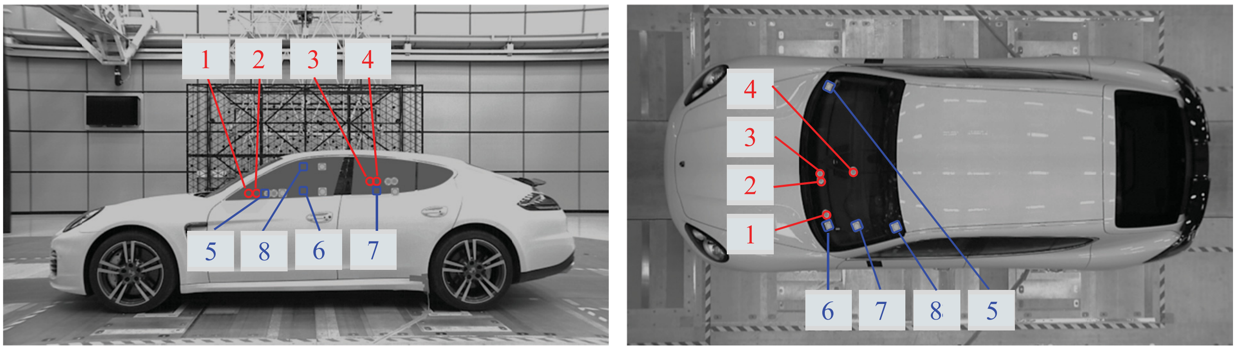


Figure 9: Setup of performance test, conducted with 8 loudspeakers.

Loudspeaker Type 1
Nubert DX19NC05-06

Louspeaker Type 2
Nubert BMR 46XE

Position	Type 1	Type 2
1	x	
2	x	
3	x	
4	x	
5		x
6		x
7		x
8		x

Figure 10: Loudspeaker used for the performance tests.

By the use of a suitable signal conditioner and amplifier combined with a new developed Matlab script, it is possible to run 8 LSP time synchronously with signals independent from each other. The signal levels and frequency characteristics are thereby adjustable by a set of parameters for each LSP separately. The phase relation between the sources can also be varied.

In total, 16 LSP positions were defined on the side window and the windscreen based on intensive discussions between the project partners. For a preferably good sound radiation, all LSP are mounted absolutely flat to the surrounding surface, realized using a special 1:1 test vehicle model where the whole glazing is made of foam material instead of glass. However, due to confidentially reasons, all results reported here are mapped to an image of a current production line vehicle. The LSPs are thereby pictured at the exact same positions. To focus the attention on the LSP sources the rear view mirrors, one of the dominant aero-acoustic sources has been removed from the vehicle model.

For comparable and reliable results, sources emitting the same sound levels and frequency content are essential. Therefore, all LSP were calibrated to radiate the same sound level in one meter distance. In addition, the frequency spectra were adjusted to the background noise of the wind tunnel to analyse with a similar signal to background noise ratio for all frequencies. All investigations are performed based on uncorrelated sources and a modified white noise signal.

Source Localisation

The source localisation accuracy was regarded first conducting the performance tests. Great importance was thereby attached to the comparison of the results without flow and with a flow present, while applying the shear layer correction.

Figure 11 shows the quality of source localisation for the left and the top array with 8 LSP switched on, respectively emitting sound signals with the same level and frequency content.

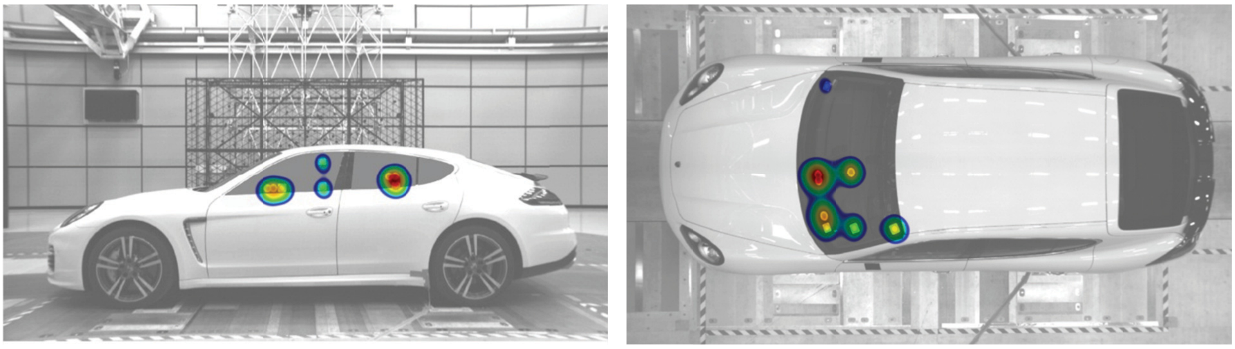


Figure 11: Localisation of 8 uncorrelated sources with the same level at u = 140 km/h, 1/3-octave, f = 4000 Hz, DR = 10 dB.

However, for LSP with the shortest distances, the localisation is biased because no clear source separation is possible. Two sources appear as a single one with a source centre in between. This frequency dependent effect can be controlled by the beamwidth and the dynamic range and will be discussed below.

In Figure 12 the localisation quality is depicted for single LSP sources (sum levels). With the top array, the source localisation on the windscreen is excellent for the case without a flow and just as well with a flow of 140 km/h.

On the side window, slight deviations for the localisation with the left array can be observed. These deviations are most likely caused by small inaccuracies in matching the acoustical and optical calibration of the array because they are nearly identical without and with a flow present. Indeed, the results also confirm a perfect function of the implemented shear layer correction.

A frequency dependent evaluation of the source localisation, as shown in Figure 13 for LSP 1, indicates different distances of the located SPL maxima to the LSP membrane centre for each 1/3-octave-band. This effect results probably from a variable sound radiation by the LSP membrane, regarding the frequency range of interest. Therefore, LSPs are only suitable for the acoustic source localisation to a limited extend.

An optimized matching procedure for the acoustical and optical calibration, using a special sound source with a very local sound radiation is already scheduled. It will improve the source location quality. An accuracy of at least +/- 5 mm is expected.

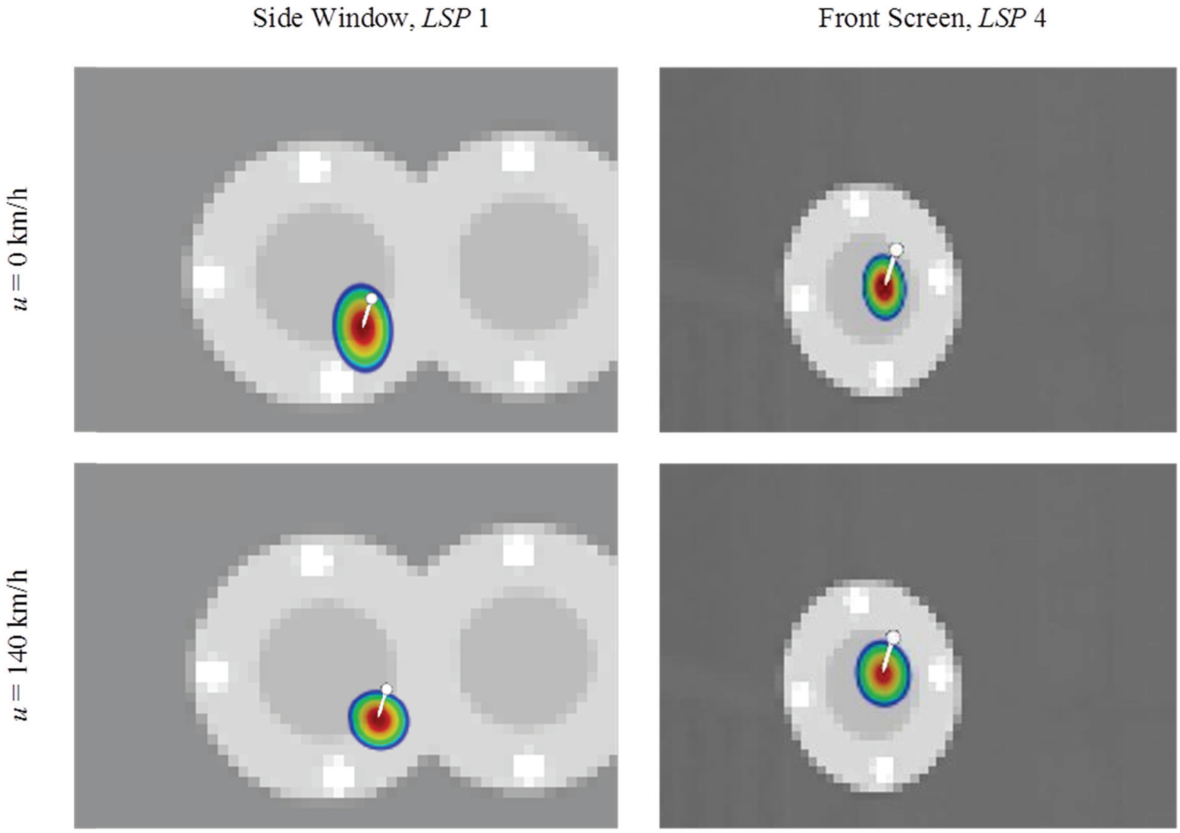


Figure 12: Localisation of a single source without and with a flow present, DR = 1 dB.

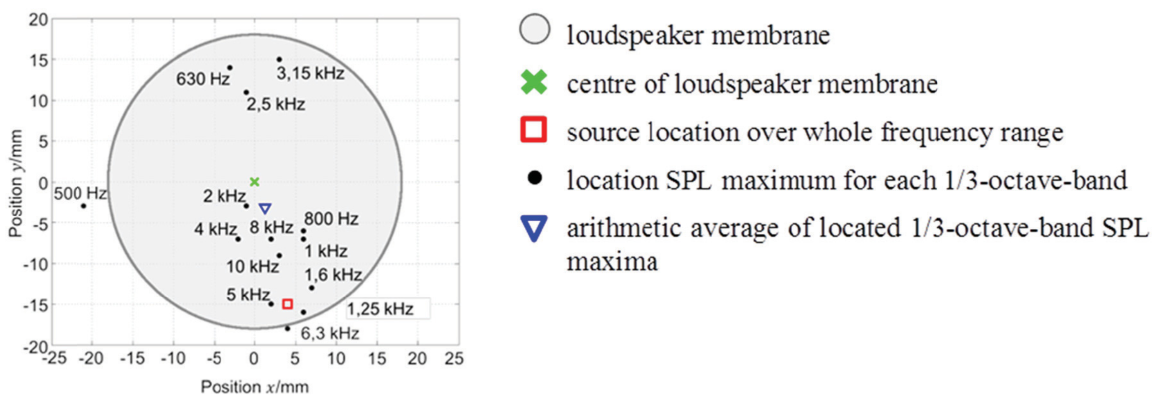


Figure 13: Frequency dependent source localisation of LSP 1 without flow (Scale 1:1, printed on DIN A4).

Beamwidth

The beamwidth is the basis for the source separation in a beamforming map. The smaller the beamwidth the sharper a source appears in the map and the better a separation is possible. An estimation of the beamwidth based on the basic array parameters, dimension and focus can be calculated according to Sijtsma [11] at a level decrease of 3 dB.

In Figure 14, a typical beamwidth is plotted for a frequency of 800 Hz to indicate the manner of the beamwidth determination in the beamforming map at a 3 dB level decrease. Due to the irregular design of the Porsche arrays, the horizontal beamwidth differs from the vertical one and therefore sources appear asymmetric in the maps.

A comparison of the estimated and measured beamwidth, pictured in Figure 15, reveals a very good agreement and a strong frequency dependency of the beamwidth. Figure 16 shows the beamwidth of the Porsche arrays measured at various flow speeds.

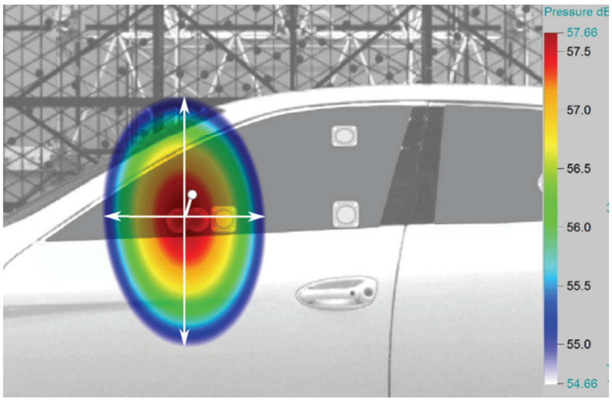


Figure 14: **Determination of the beamwidth, 1/3-octave, f = 800 Hz, DR = 3 dB.**

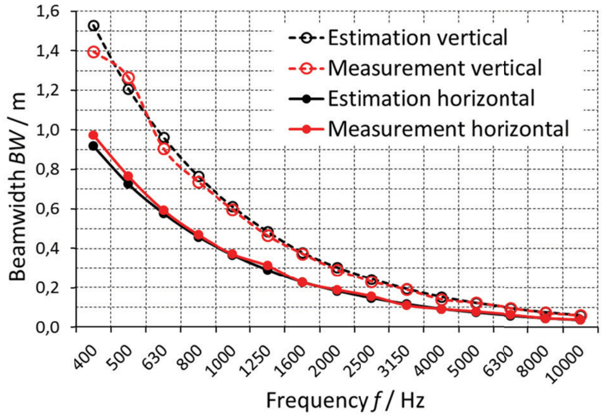


Figure 15: **Estimation and measurement of the horizontal and vertical beamwidth.**

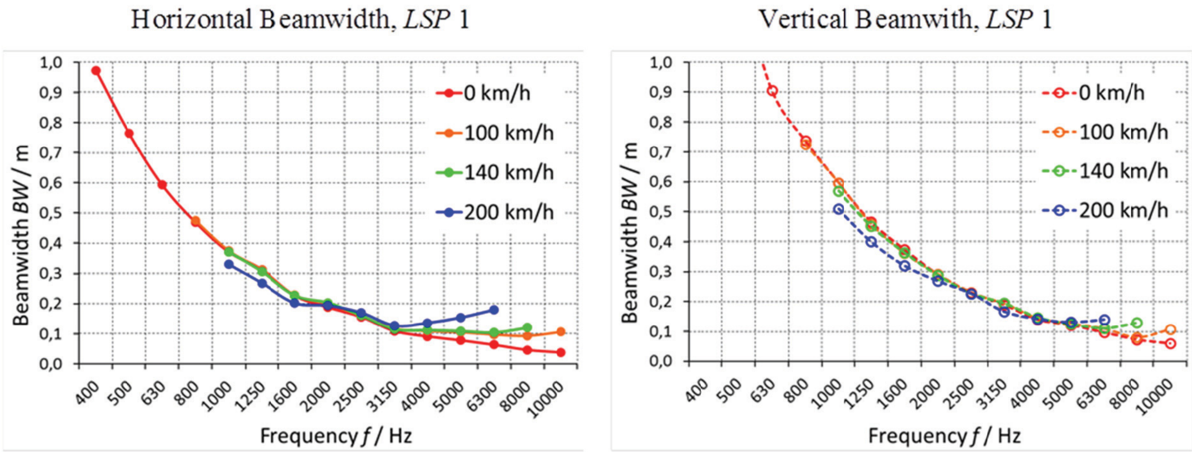
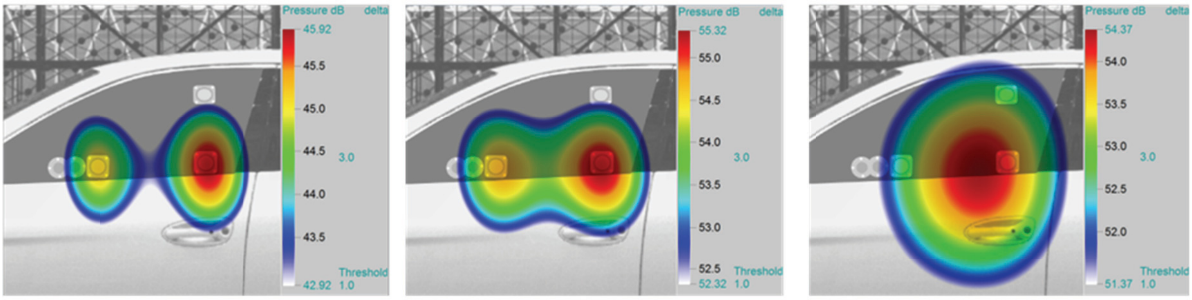


Figure 16: **Measured beamwidth of the Porsche arrays.**

So far, no clear explanation could be found for the slightly better beamwidth at 200 km/h in the mid frequency region. The observed higher values for the beamwidth at higher frequencies and flow speeds are probably caused by the correlation loss effects for distant microphones using a big array. These effects will be investigated in detail by an already scheduled study.

Source Separation

For an aero-acoustic analysis of a car, an individual and detailed evaluation of each single source is important. Therefore a good separation of the sources is required, basically depending on a preferably small beamwidth. Figure 17 depicts the way of determining the source separation, by a 3 dB criterion or a visual evaluation. The slight level differences between the two sources, emitting the same level are caused by the used steering vector formulation, chosen to give the best localisation accuracy.



3 dB separation, $f = 1600$ Hz   Visual separation, $f = 1250$ Hz   No separation, f = 800 Hz

Figure 17: Determination of the source separation for LSP 5 and LSP 6 without flow, 1/3-octave, DR = 3 dB.

Figure 18 shows the capability of the Porsche arrays to separate sources with the same level for analysis without a flow. By simulations, the limitations of separation were determined by a step by step reduction of the source distance for each 1/3-octave-band, evaluating the 3 dB criterion and the visual impression. These results are compared with the measurements, representing the realised discrete distances between the loudspeakers.

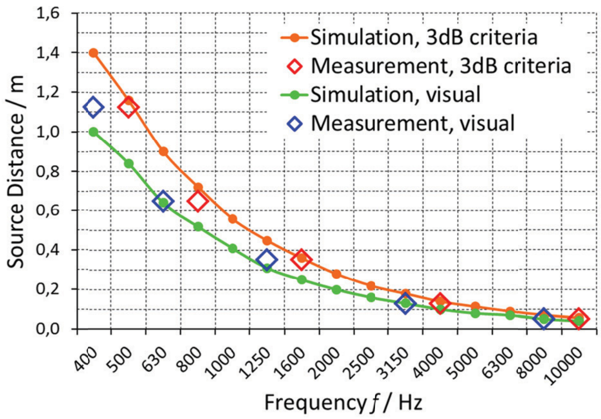


Figure 18: Separation of horizontal arranged sources on the side window without flow, 1/3-octave.

Without a flow, the agreement between simulations and measurements is very good and the visual source separation is thereby nearly identical to the horizontal beamwidth. With a flow present, the source separation at higher speeds and frequencies is also slightly disturbed by the already mentioned correlation loss effects.

The use of advanced post-processing techniques, e.g. algorithms like CLEAN SC [12], can improve the source separation significantly. Weaker sources may be masked by dominant sources and their side lobes. By a successive subtraction of the dominant sources and their correlated fractions from the dirty map, the originally masked sources can be revealed.

Dynamic Range

The dynamic range (DR) of an array is mainly defined by the number and the arrangement of the microphones. For the Porsche arrays, a remarkably high DR could be achieved by the use of 192 microphones, irregularly arranged in an optimized layout as described before.

Figure 19 and Figure 20 show the measured DR regarding the sound radiation of LSP 6 for a large scan plane of approx. the size of the arrays (5 x 3 m) and for the optimized window of 1.5 x 1m. These results are compared to the DR of a simulated monopole sound source (Point Spread Function) located at the position of LSP 6. All analyses are carried out in the frequency domain based on the CSM with diagonal removal including a positive effect to the DR.

The differences observed are probably caused by the inhomogeneous local sound generation of the loudspeaker membrane and additionally by reflection and damping effects performing real measurements. Advanced algorithms like CLEAN SC [12] can be used to increase the DR.

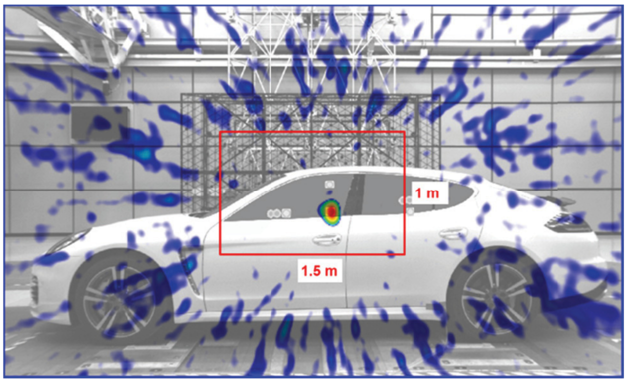


Figure 19: Beamforming map for LSP 6 without flow, 1/3-octave, f = 6300 Hz, DR = 25 dB.

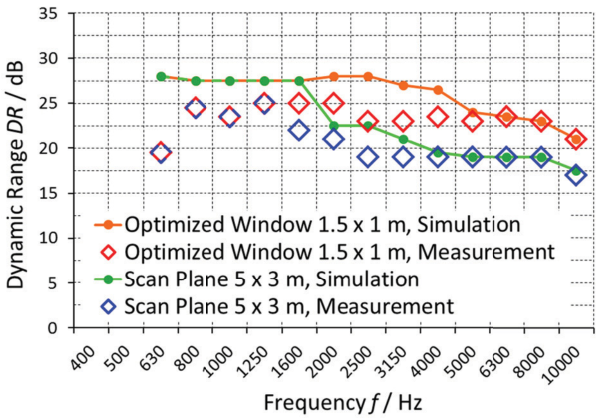


Figure 20: Dynamic range of the Porsche arrays without flow, 1/3-octave.

Typical Results

In Figure 21 and Figure 22 the valuation of a production line vehicle is pictured for the left side array and the top array. All expected sound sources and the improvements applying the CLEAN SC algorithm are clearly visible for all frequencies.

Small deviations of the source location in this overview plots result from a focus adjusted to only one scan plane defined in a certain distance to the particular array. Sources that are not located in this plane are therefore calculated with an incorrect focus leading to a slightly biased source representation in the beamforming map. Hence, to prevent this effect, the source mapping on a 3D model of the test object will be established as a standard method. Thereby the correct focus is considered for every single grid point, and thus for all sources with an assumed location on the test object surface.

Summary and Outlook

For the New Porsche wind-tunnel, a unique microphone array system was developed and installed. By a complex design and a perfect fixing to the wind tunnel walls, combined with very high system rigidity, an outstanding basic acoustic performance and a comfortable and fast data acquisition is achieved. Based on a study with LSP sources, the capability of the arrays was demonstrated and the limitations were determined.

To improve the data analysis significantly, further advanced evaluation techniques, like 3D-, differential- and correlation-beamforming [3], [10], have been implemented and an investigation of a frequency dependent shading procedure for distant microphones was started.

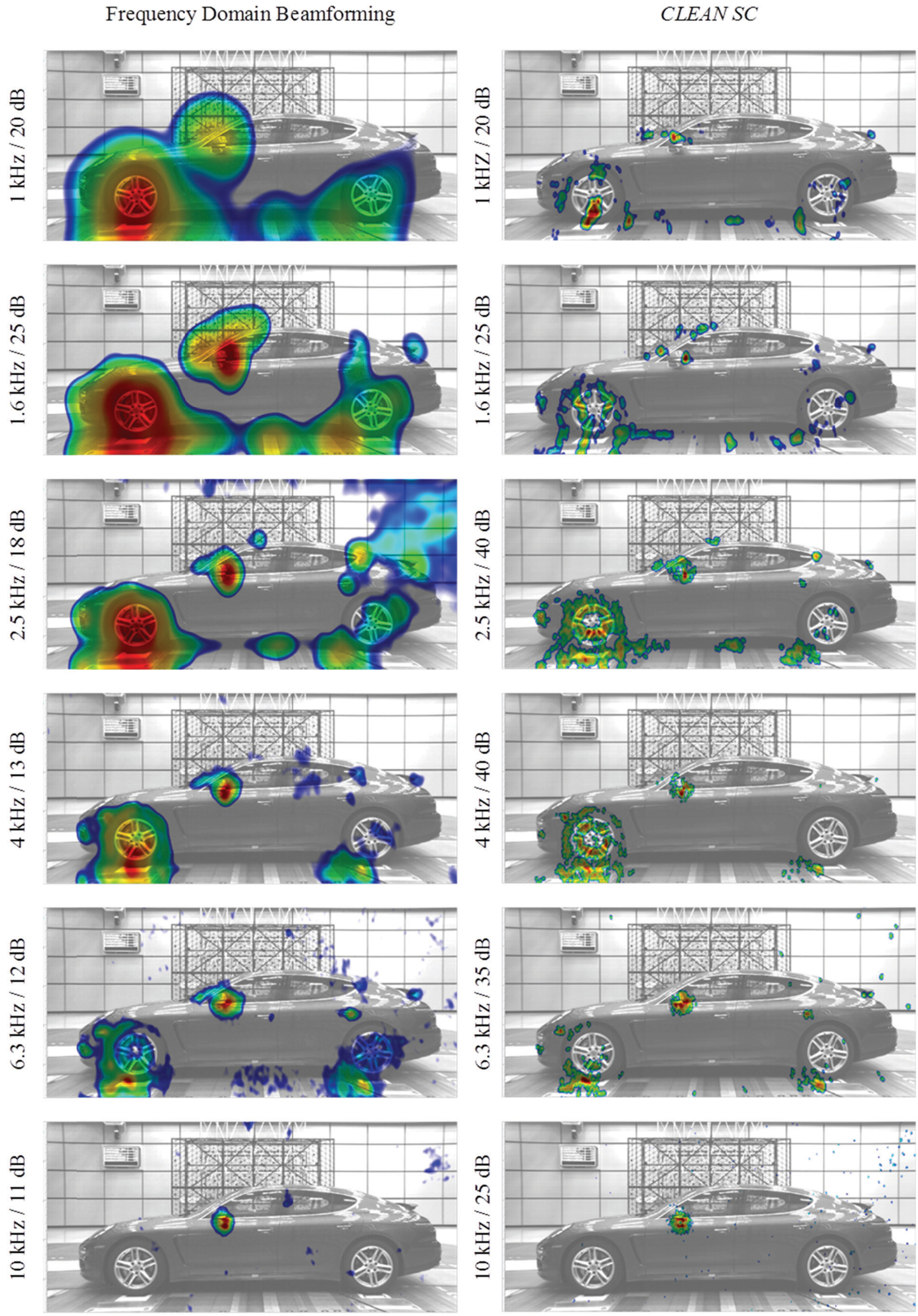


Figure 21: **Evaluation of a production line vehicle by the left side array.**

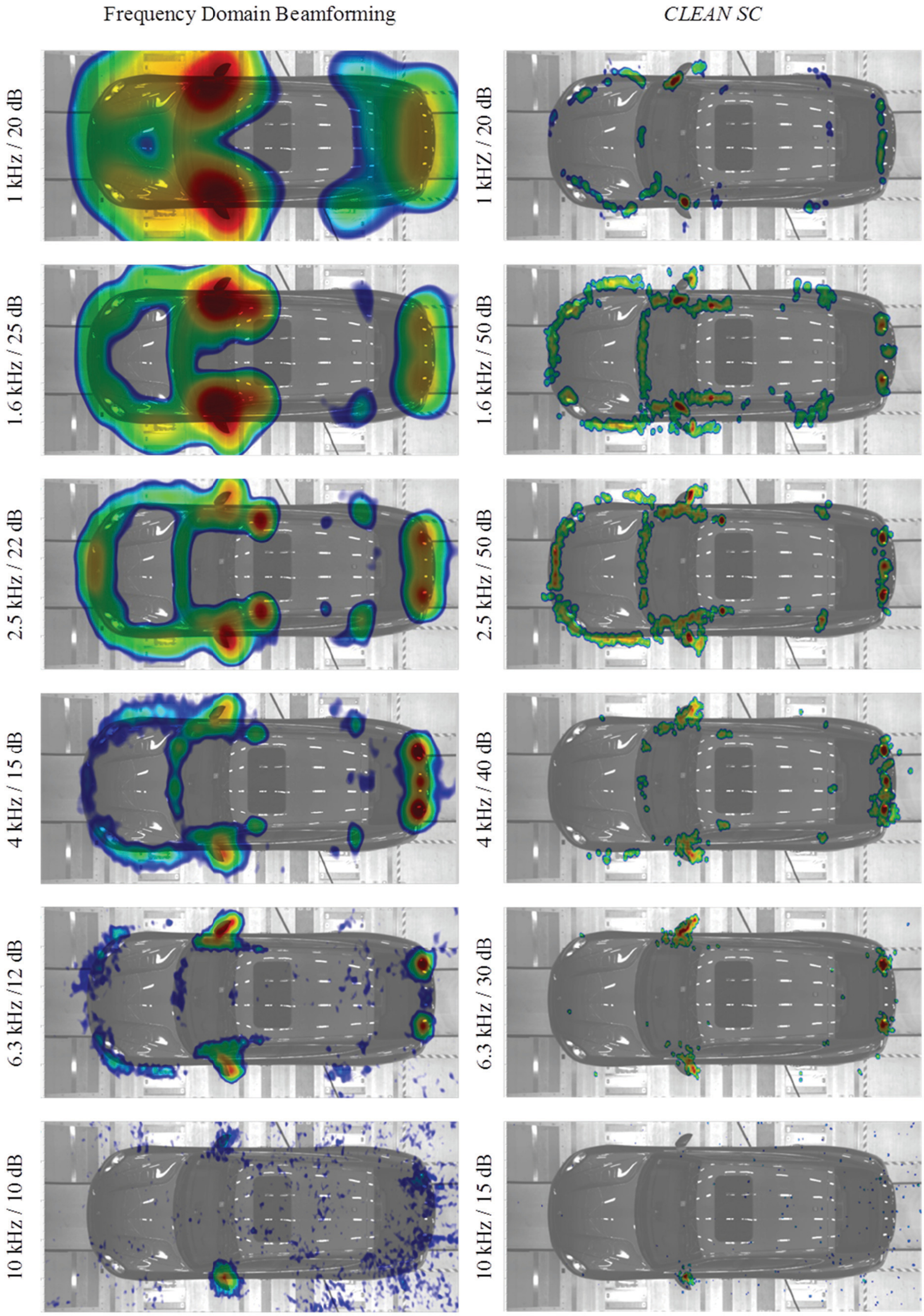


Figure 22: Evaluation of a production line vehicle by the top array.

Acknowledgement

Numerous people have generously given time, energy and encouragement to this project.

Perfect appreciation to all colleagues of gfai tech GmbH and GFaI e.V. involved in the project for the implementation of this great array system. Many thanks for the very good teamwork always focused on the best technical solution.

I am particular grateful to Michael Hartmann from Volkswagen group research for the performance of the complex and unique optimization work finding the best array layout and for his advice at any time.

My special thanks to Wim Lechner for his help conducting and evaluation the performance tests in the context of his bachelor thesis and to Dr. Siller (TU Berlin) supporting this thesis with great effort. Furthermore, I want to thank Carsten Spehr (DLR Göttingen) for the valuable consulting during the whole project and Günther Nubert (Nubert electronic GmbH) for his uncomplicated support selecting the most suitable loudspeakers for the performance tests.

Many thanks also to my colleagues of Porsche's acoustic department for their absolute support and to the project team of the New Porsche wind-tunnel for making the realization of the array system possible.

References

[1] Amiet, R. K.: "Refraction of Sound by a Shear Layer", Journal of Sound and Vibration, Vol. 58, No. 2, pp. 467-482, 1978.

[2] Ehrenfried, K., Koop, L.: "A comparison of iterative deconvolution algorithms for the mapping of acoustic sources", AIAA paper 2006-2711, 2006.

[3] Döbler, D., Puhle, Ch., Heilmann, G.: "Correlation of high channel count beamforming measurement of a car in a wind tunnel using CLEAN-SC", inter.noise conference, San Francisco, 2015

[4] Dougherty, R. P. "Extension of DAMAS and Benefits and Limitations of Deconvolution in Beamforming", AIAA Paper 2005-2961, 2005.

[5] Lechner, W.: "Evaluierung der Leistungsfähigkeit einer akustischen Kamera hinsichtlich Dynamik, Auflösung und Lokalisierungsgenauigkeit im neuen Porsche Windkanal", Bachelor Thesis, TU Berlin, 2015.

[6] Oerlemans, S., Broersma, L., Sijtsma, P.: "Quantification of airframe noise using microphone arrays in open and closed wind tunnels", NLR Report NLR-TP-2007-799, 2007.

[7] Oerlemans, S.: "Detection of aero-acoustic sound sources on aircrafts and wind turbines", PhD thesis, University of Twente, Enschede, 2009.

[8] Puhle, C.: "Über die Scherschichtkorrektur nach Amiet"; Technical Document GFaI, 2014.

[9] Sarradj, E.: "Three-Dimensional Acoustic Source Mapping with Different Beamforming Steering Vector Formulations", Advances in Acoustics and Vibration, Volume 2012.

[10] Schmidt, S., Döbler, D.: "Visualization of small design modifications using differential beamforming", inter.noise conference, San Francisco, 2015.

[11] Sijtsma; P.: "Experimental techniques for identification and characterisation of noise sources ", Advances in Aeroacoustic and Applications, VKI Lecture Series, 5:15-19, 2004.

[12] Sijtsma, P.: "CLEAN based on spatial source coherence", AIAA Paper 2007-3436, 2007.

[13] Sijtsma, P.: "Acoustic beamforming for the routing of aircraft noise"; NLR-Report, NLR-TP-2012-13, 2012.

[14] Stumpf, H., Röser, P., Wiegand, T., Pfäfflin, B., Ocker, J., Müller, R., Eckert, W., Kroß, H.-U., Wallmann, S.: "The new aerodynamic and aero-acoustic wind tunnel of the Porsche AG", 15. Internationales Stuttgarter Symposium, 2012.