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ACOUSTIC SOURCE LOCALIZATION ON AIRCRAFT IN FLIGHT

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Abstract

Source localization techniques for the analysis of acoustic sources on aircraft and aircraft engines in flight have been developed and used since the 1970s. They have since evolved from a subject of scientific research into an established technique in the aircraft industry. Digital data acquisition hardware and microphones have dropped in price, making it possible and affordable to set up large microphone arrays with hundreds of microphones. The mathematical tools for the analysis of moving sound sources have been improved. In addition to the classical sum-and-delay beamforming in the time domain, which provides a robust, straight-forward solution when the movement of the source is taken into account, methods are now available that compensate the imaging properties of the microphone array and reconstruct the amplitudes of the moving sources. Fly-over measurements with microphone arrays have become a mature technology for industrial application that still inspires and requires the development of new analysis techniques.

1 INTRODUCTION

The main motivation for the development of acoustic source localization techniques is the need to reduce noise emissions. In order to reduce noise emissions, the locations of the sound sources and their relevance for the overall sound emission have to be known. This statement may sound trivial but it poses a serious problem for complex technical devices like aircraft and aircraft engines. Finding the exact location of the sources helps to identify the source mechanisms and a quantitative ranking of the different sound sources helps to identify the most promising candidates for noise reduction.

Acoustic imaging methods have been applied since aircraft noise has become a problem for the industry. This started in the late 1960s, when the number of jet-propelled aircraft became large enough to create community noise problems. In his book *Aircraft Noise*, Smith [51] describes the development that lead to the internal regulations for aircraft noise emissions that are defined by ICAO [23] and are continuously updated. Because airframers and engine manufacturers have to keep the emissions of their products below the noise limits, they perform experimental tests and numerical simulations in order to identify and understand the sound sources. However, one of the main problems for the analysis of noise sources on aircraft by means of wind tunnel tests or numerical simulations is the problem of model fidelity. It exists for both numerical simulations and for wind tunnel experiments. Many sound sources of aircraft are generated, or at least strongly influenced, by the flight speed. Small structures that are easily overlooked or hard to model can generate sound in flight and previously unknown sound sources cannot be modelled or included in numerical simulations.

Figure 1 shows how complex the situation on an aircraft is with all the different sources of airframe and turbomachinery noise. The dimensions of structures for aerodynamic sound sources range over several orders of magnitude which makes their modelling or meshing very challenging. This is a reason why fly-over measurements with full-size aircraft are and will continue to be performed, in spite of all the progress in numerical simulations and wind tunnel tests.

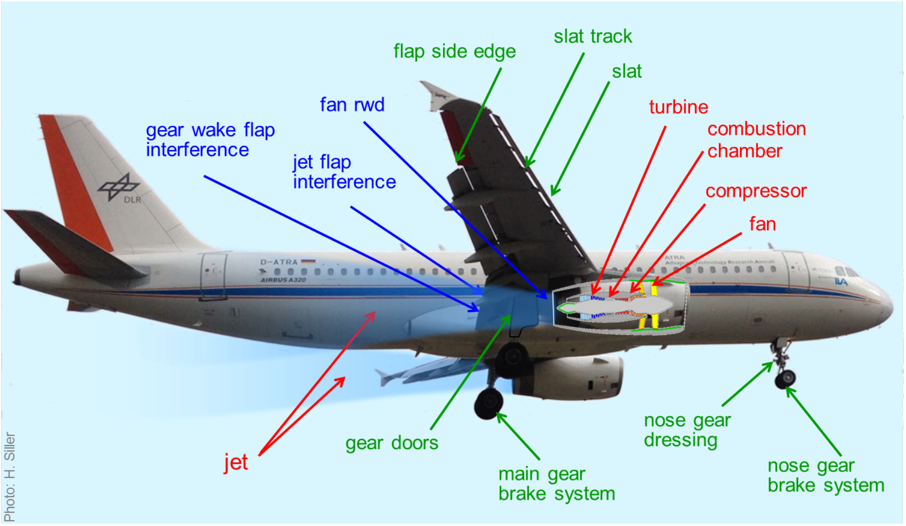

Figure 1: Sound sources on an Airbus A320, the DLR research aircraft ATRA (Image source: Delfs and Siller)

2 THE HISTORY OF ACOUSTIC BEAMFORMING ON AIRCRAFT IN FLIGHT

The general history of acoustic beamforming has been presented at the BeBec conference 2006 by Ulf Michel [31], who has been one of the key developers of the application of the microphone array technique for aircraft fly-over measurements (among many other things).

In 2012, Pieter Sijtsma presented the theory and practical applications in the report *Acoustic beamforming for the ranking of aircraft noise* [42]. In the same year, the paper *Localisation of sound sources on aircraft in flight* was presented at the BeBeC [44]. The review paper on acoustic imaging methods using phased microphone arrays by Merino-Martinez et al. [29], published in 2019, shows more recent applications and developments in the section on aircraft flyover measurements.

2.1 Early applications of linear microphone measurements with classical beamforming

The microphone array technique has been developed and first applied to the analysis of the sound sources of aircraft engines by Billingsley and Kinns [2, 3]. They named their method the *acoustic telescope* and applied it to the acoustic analysis of the Olympus engines for the Concorde hypersonic passenger aircraft. A group working on railway noise at DFVLR in Berlin, the organization that later became DLR, applied vertically mounted linear microphone arrays for pass-by measurements on high-speed trains (see Figure 2), using the analysis method described by Billingsley and Kinns [25] (more references can be found in the BeBeC 2006 paper by Michel [31]).

Figure 2: A linear microphone array for pass-by measurements with trains (photo: Bernd Barsikow).

Microphone array measurements with aircraft in flight have first been reported in 1986 by Howell et al. [22], who used a small linear microphone array and the method developed by Billingsley and Kinns. Ulf Michel and colleagues from DFVLR in Berlin transferred the microphone array technique from measurements on trains to aircraft in flight, using the classical beamforming algorithm in the time domain for moving sources. In May 1997, at the 3rd AIAA/CEAS Aeroacoustics Conference in Atlanta, Georgia, Ulf Michel presented the paper *Investigation of airframe and jet noise in high-speed flight with a microphone array* [32] and reported the results of fly-over measurements with Tornado fighter aircraft over a linear microphone array.

The next step was to develop and set up a two-dimensional microphone array with about 100 microphones, which had become possible due to the progress in the development of data acquition systems that could synchronously record larger numbers of microphone channels. This system was used to record data from aircraft landing at the Fraport Airport Frankfurt [33] and Ulf Michel and Weiyang Quiao presented their paper *Directivity of landing-gear noise based on flyover experiments* at the 5th AIAA/CEAS Aeroacoustics Conference [35].

2.2 Cooperation of ONERA and DLR in European projects

In France, ONERA developed a microphone array technique that was based on cross- or x-shaped arrays [37] for wind tunnel measurements with an evaluation algorithm that made use of the symmetry of the microphone array. ONERA adapted their method to measurements of aircraft fly-overs and als also started to use DGPS tracking in order to accurately determine the aircraft flight path. From 1998 on, ONERA and DLR performed measurements at the Airbus flight test site in Tarbes France with A340 and A320 aircraft [39]. ONERA set up a large cross-shaped array for the analysis in the frequency bands from 200 Hz to 5000 Hz and DLR a multiple-arm spiral array for frequencies between 2500 Hz and 8000 Hz. Figure 4 presents the schematic set-up: the ONERA cross-shaped array and the DLR multi-arm spiral array were mounted on a common wooden platform, with the DLR array in the center. An array of laser range finders and two line cameras were used to measure the ground and sink speeds of the aircraft and record trigger signals when the aircraft passed over the sensors. This set-up was changed later for the AWIATOR tests, when DLR set up their array on a concrete platform and ONERA mounted their microphones on plates that were fixed to steel cables stretched horizontally, see Figure 5. A concrete or tarmac base for the array has since then been used by DLR when the conditions permit, because it offers a defined acoustic boundary condition on solid ground and does not heat up in the sunlight as fast as dark wooden boards do. Figure 3 shows an aerial view of the most recent microphone array installation of DLR at the National Experimental Test Center for Unmanned Aircraft Systems of DLR in Cochstedt, Germany in 2025 .

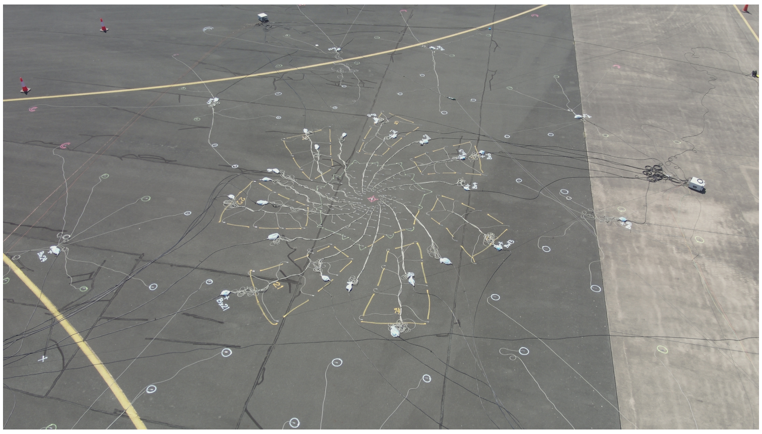

Figure 3: Aerial view of the DLR microphone array that has been set up for fly-over tests at the experimental airport in Cochstedt in 2025.

Results of the A340 flight test campaign in the EU project RAIN are reported in the paper

Localization of the acoustic sources of the A340 with a large phased microphone array during flight tests by Piet et al. [38]. Results from the flight tests in the EU project Silence(r) can be found in *Flight Test Investigation of Add-On Treatments to Reduce Aircraft Airframe Noise* by Piet et al. [36]. Fleury and Malbequi [12] published results on slat noise based on the measurements performed by ONERA and DLR in the framework of the European project AWIATOR.

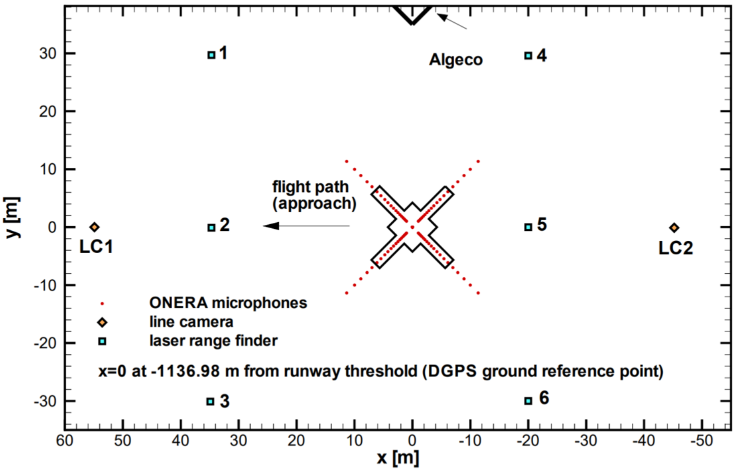

Figure 4: Set-up of the platform for the ONERA cross-shaped and the DLR spiral arrays at the airport of Tarbes in France for the Silence(r) and the first AWIATOR flight tests in 2001 and 2003.

Figure 5: Modified set-up of the DLR spiral array with the ONERA cross-shaped aray in the backbround and at the airport of Tarbes during the AWIATOR flight test in 2006.

2.3 Fly-over measurements of DLR in German national projects

The next phase of flight testing at DLR was motivated by the development of noise abatement modifications on existing aircraft. DLR performed extensive array measurements with

Airbus A319, McDonnell Douglas MD11, and Boeing 747 aircraft in the framework of German national projects in cooperation with Lufthansa, who provided and operated the aircraft [14, 15, 45, 46, 48]. Figure 6 shows deconvolution source maps of a Boeing 747 in landing and take-off configurations.

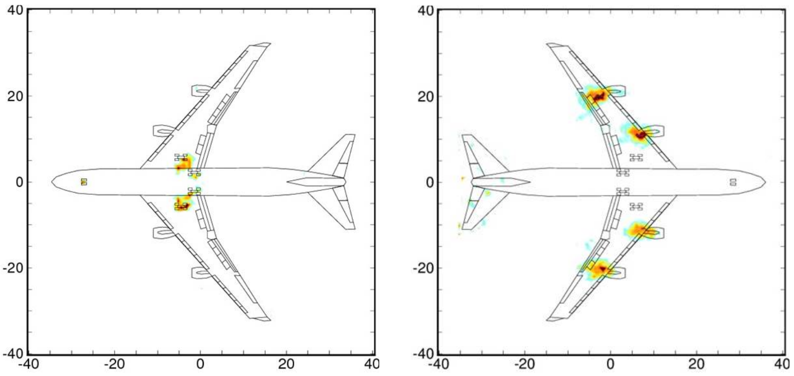

Figure 6: Devonvolution maps for a Boeing 747 in landing configuration in the 800 Hz *band in the forward arc (left) and in take-off configuration in the* 3150 Hz *band seen from below.*

Michel and Guérin investigated the noise emissions of the Airbus A319 with a phased microphone array at Parchim Airport in 2004 in the framework of German national research projects. The aircraft were operated by Lufthansa and flown by airline pilots who volunteered for the job and performed excellently in flying the aircraft along the prescribed trajectories. From this data set, Michel and Guérin developed a model for Aircraft noise prediction and presented a database compiled from 37 fly-overs in take-off and 82 in approach configuration with variations of thrust, airspeed and the settings of the high-lift devices and the landing gear [14]. Based on the coherence of the microphone signals in the different frequency bands, a weighting scheme was applied that led to considerable improvements in the localization results.

2.4 Tonal sources at the wings of the Airbus A319 and A320 aircraft

A lasting legacy of these flight tests is that DLR identified the sources of two very dominant tones from the Airbus A319 and A320 models and developed a vortex generator to stop the noise in cooperation with Lufthansa. Figure 7 shows the frequency spectrum and the source positions at the underwing openings of the over-pressure valves of the tanks. These tones used to be present in approach, but disappeared when the high-lift devices were deployed for the final landing configuration. DLR proposed to place vortex generators upstream to inhibit the sound generation mechanism that Lufthansa started to mount on its Airbus A319 and A320 by the end of 2013. Airbus developed a similar device that is mounted on all A320 built after 2014 and has been successively retrofitted by all major airliners.

2.5 Wake vortex measurements

A rather exotic application of microphone arrays in flight tests was based on Ulf Michel's idea that wake vortices, because they are audible, can be localized and tracked using microphone

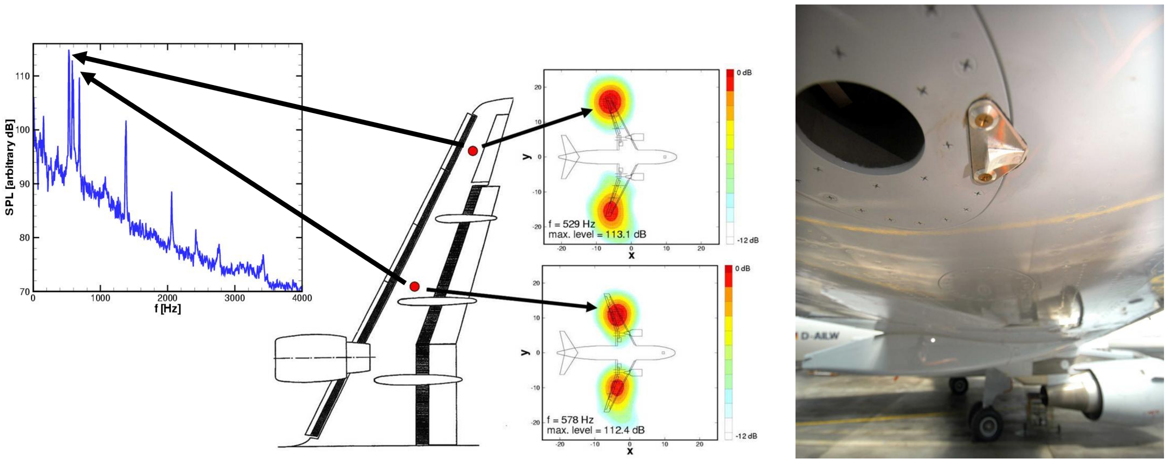

Figure 7: Left: Sound sources at the fuel tank over-pressure valve openings of the A319/20 models at the time, which generated strong tones with 530 Hz *and* 580 Hz*. Right: Prototype of a vortex generator that inhibits the noise generation mechanism.*

arrays [4–6, 34]. The idea has been successfully tested in fly-over measurements by DLR in the European project C-Wake and in the US, where DLR participated in a project of NASA and the US Department of Transportion with measurements at the airport of Denver, Colorado, USA in 2003, which are reported in Dougherty et al. [10].

2.6 Investigations of aeroengine noise

Investigations focused on engine noise sources have been reported in the paper *Aeroengine noise investigated from flight tests* by Guérin and Michel [15]. They show that tonal noise levels at the blade passing frequency (BPF) and its first harmonic increase very rapidly with the engine shaft speed N_1. The tonal amplitudes increase with N_1 with an exponent between 9 and 10, instead of only 5-6 as would be expected from the theory for cut-on waves. The sound pressure levels of the BPF tones reach a maximum near cut-back (when the fan is transonic), before they decrease for higher fan speeds. An investigation of buzz-saw noise emitted from turbofan engine during take-off based on fly-over measurements with an Airbus A320 aircraft is presented in the 2002 paper by Siller and Michel [47].

2.7 The Boeing QTD program

The development of microphone arrays for fly-over tests in the US can be touched here only briefly – the subject deserves a paper in itself by an author more familiar with the developments.

Boeing performed a series of large scale flight tests in the framework of the *Quiet Technology Demonstrator* (QTD) program. In the first phase, QTD1 in 2001, the focus lay on fan, jet and Airframe noise. The test vehicle was a Boeing 777-200ER with Rolls-Royce Trent 800 engines. Bartlett [1] describes the tests with a three-arm spiral array consisting of 187 microphones that covered an area of 15×15 m^2. For the QTD2 tests in the year 2005 [20, 21, 40] with a Boeing 777-300ER, the microphone array was increased in size to 90×75 m^2 and 614 microphones, which still could be the record for free-field microphone arrays. The paper of Elkoby et al. [11] presents the microphone array measurements a focus on airframe noise.

2.8 Fly-over measurements by JAXA in Japan

In Japan, Jaxa and Bruel&Kjær performed fly-over tests with a MU300 business jet from Mitsubishi Heavy Idustries, using a time-domain beamforming foolowed by a deconvolution in the frequency domain [19, 24]. In the FQUROH project for the demonstration of airframe noise reduction technologies, JAXA flight tested their research aircraft [54]. A large data set of 187 records from microphone array measurements with different aircraft landings has been measured by JAXA in 2019 at Narita International Airport in Japan. [53]. In the data analysis, they applied the CLEAN algorithm after an initial classical beamforming in the time domain.

2.9 Deconvolution methods for moving sources

With the availability of microphone array data from fly-over tests, there was an increasing demand to obtain more information on the sound sources from the data. The classical beamforming algorithm only provided good quantitative estimates on point sources, e.g. the engine inlets and exhausts or parts of the landing gear. The contribution of distributed sources, like those on the flaps and slats of the high-lift system on the wings, to the overall noise could not be evaluated adequatly.

In the netherlands, NLR performed microphone array measurements on aircraft landing at the Amsterdam Airport Schiphol. In their analysis of the data, Sijtsma and Stoker [43] applied their *source power integration* method. They also introduced many concepts that have since become standard tools, like the removal of the main diagonal of the cross-spectral matrix, applying frequency dependent weighting factors to the microphone signals and correcting the beamforming results with scaling factors obtained from simulations of monopole point sources.

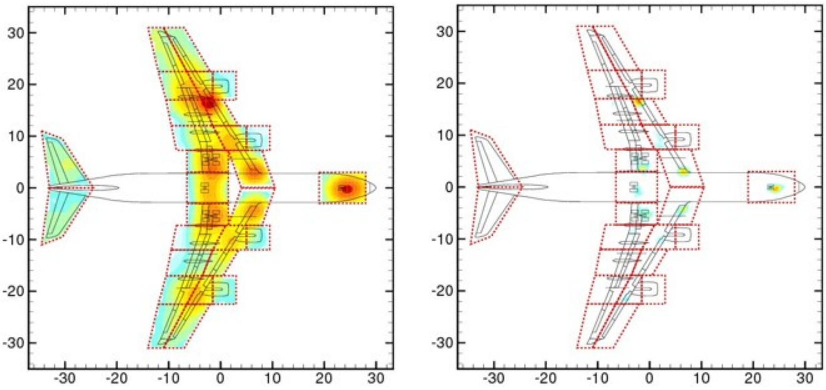

Figure 8: Classical beamforming map (left) and deconvolution map (right) for a fly-over of an Airbus A340 with the engines in flight-idle in the AWIATOR test campaign.

The next step important step to improve the quality of the acoustic maps was the development of a hybrid deconvolution approach, combining the classical beamforming in the time domain with the DAMAS algorithm for a deconvolution in the frequency domain. This approach has been initially presented by Guérin and Michel [18] at the Berlin Beamforming Conference

2006. Guérin and Weckmüller elaborated the method further and presented their progress at the BeBeC 2008 [17]. Guérin and Siller [16] present the application of the new approach to fly-over measurements with an Airbus A340 during the AWIATOR test. This was a breakthrough that allowed a quantitative analysis of distributed sources on aircraft. Figure 8 illustrates the improvement in spatial resolution and dynamic range that can be achieved by applying the deconvolution method. Figure 9 shows a deconvolution source map of an Airbus A320 and frequency spectra of the overall sound pressure levels in two different configurations in take-off and climb. The integration of the source powers in the source regions can be used to calculate a source ranking and a comparison of the contribution of individual components of the aircraft in different flight configurations.

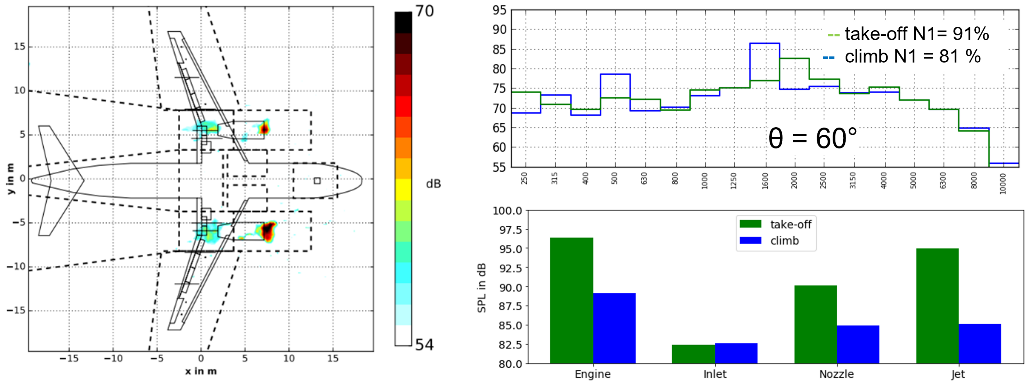

Figure 9: Source map of the ATRA in the 2 kHz *band with the definition of the integration zones (left), one-third-octave-band spectra of ATRA fly-overs in the take-off and climb configuration (center) and the source ranking obtained from the integration over the source regions in the deconvolution maps (right).*

In the paper *Extension of deconvolution algorithms for the mapping of moving acoustic sources* by Fleury and Bulté [13] propose a method to extend the DAMAS, DAMAS2, CLEAN, and CLEAN-SC methods to moving sources. The Universtiy of Delft has been very active in performing microphone array measurements with a small mobile microphone array and testing different beamforming and deconvolution algorithms [28, 30, 50, 52]. The group of MicrodB in France proposed an alternative deconvolution scheme, the SOOT algorithm in Lamotte et al. [26].

2.10 The LNATRA project of DLR

DLR performed extensive flight tests with the DLR research aircraft ATRA in the DLR internal project LNATRA for back-to-back tests of retrofit modifications of the landing gear, the high-lift devices, and the engine nozzles. Flight tests have been performed in 2016, 2019, and 2020 with the ATRA aircraft in its baseline configuration and with the retrofit modifications [49]. Figure 10 presents source maps of the ATRA aircraft for three emission angles $\theta = 60^\circ$, 90°, and 120° that have been calculated using the hybrid deconvolution method of DLR. The maps show sources at the engine inlets and exhausts in the forward arc. The jet plumes are well visible at all three emission angles.

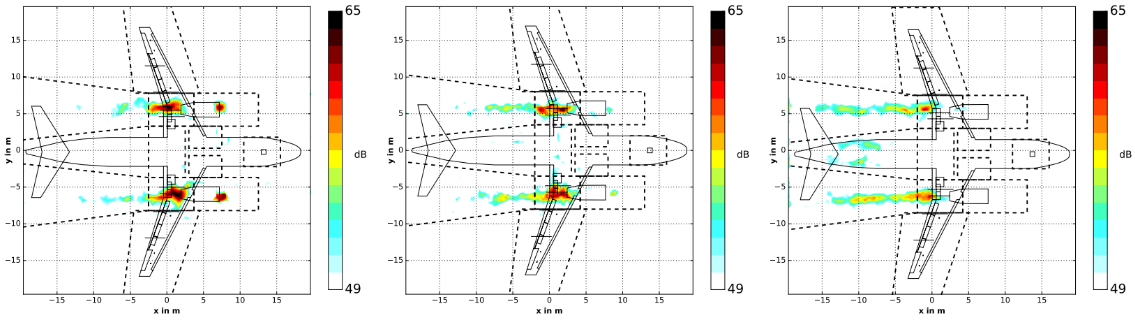

Figure 10: Deconvolution maps of the Airbus A320 ATRA at take-off in the 1 kHz *band in the forward arc (left), overhead (center) and in the rear arc (right).*

3 FURTHER DEVELOPMENTS OF ANALYSIS METHODS

The group at INSA in France has developed the CLEANT method to efficiently analyze moving sources in the time domain [7, 8, 27]. Schumacher at DLR modified the method by implementing a successive refinement of the source grid in regions where sources have been detected, which significantly speeds up the calculations [41].

The most recent report on fly-over measurements with acoustic arrays has been published by Dong et al. [9] and presents the measurement procedure and analysis for fly-over measurements with a microphone array on the COMAC C919 aircraft in China.

A relatively new approach is the use of microphone arrays on the aircraft fuselage for beamforming on the engines. This has been demonstrated successfully in the Boeing quiet technology demonstrator program and is taken one step further in current European projects, where MEMS arrays with very large sensor numbers are being developed by DLR that will be used on the new A380 research aircraft of Airbus to investigate the latest generation of ultra-high bypass engines and novel open rotor configurations in the context of the development of a new type of narrow body aircraft.

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5 CONCLUSIONS

The experimental and analysis techniques for microphone array measurements have been developed in the last decades of the 20th century. They have been applied to moving sources, initally trains, later aircraft, in order to localize and analyze the sound sources to gain an better understanding and ultimately develop sound abatement methods. With a reduction of prices and better availability of multichannel data acquisition systems, large microphone arrays with over 100 microphones became possible and have been used in extensive array measurement campaigns with large commercial aircraft in Europe with DLR and ONERA and in the US by NASA and Boeing. The results of these tests fed into the development of quieter aircraft and a better understanding and modeling of noise source mechanisms on aircraft in flight. The analysis methods have evolved in parallel, from the application of sum-and-delay beamforming in the time domain to hybrid deconvolution methods or CLEANT in the time domain. The experimental and the analysis techniques have reached a mature state and have become standard practise in the industry. A renewed interest in fly-over tests has been generated with the development of drones and air taxis, again driven by the need to understand and model the sources. The next generation of aircraft with new and unconventional propulsion systems, e.g. unducted single fans, or airframe configurations other than than the traditional tube and wing configuration will need to be investigated in fly-over tests with microphone arrays.

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