# AN INTERDISCIPLINARY APPROACH FOR A VIRTUAL AIR-TRAFFIC SYSTEM SIMULATION FOR SUBJECTIVE ASSESSMENT IN VR ENVIRONMENTS

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## Abstract

*An interdisciplinary approach is presented for achieving a Virtual Reality (VR) simulation of air-traffic for a more subjective assessment of aircraft noise impact on the ground. The motivation for this VR air-traffic simulation is derived from the fact that noise expressed in numbers alone can prove lacking in expressing the annoyance caused by the aircraft noise to the observer and simply indicates the energy of the noise. By both hearing and seeing an aircraft fly by however, an immediate impression is obtained regarding both loudness and annoyance of the noise. Via the collaboration of five different institutes of RWTH Aachen University, this VR simulation is achieved, producing both a 3D visualization as well as auralization capability of complete aircraft movements. The noise modeling methodology of the Institute of Aerospace Systems (ILR) shall be explained in detail along with results for operational plus environmental modeling of standard approach and departure procedures. The methodology for auralization and visualization of this data is explained and sample results of 3D visualization are also presented. Auralized audio files are made available on the official website of the VATSS project http://vatss.ilr.rwth-aachen.de.*

## 1 Introduction

The impact of aircraft noise on the ground up until now has mostly been displayed via a quantification of the energy of the noise i.e. the various decibel (dB) scales. These can however prove lacking in conveying the exact annoyance caused by the aircraft noise. 100 dB is of course louder than 90 dB, but the 90 dB noise may contain certain elements (tones, fluctuations etc.) which make it more annoying to the residents. For this reason, a method of more subjective assessment of aircraft noise is required and an approach to achieving this is presented here. The Virtual Air Traffic System Simulation (VATSS) project is an interdisciplinary project of RWTH Aachen University which attempts to both visualize aircraft noise impact on the ground via a 3D visualization of aircraft movement and time-dependent noise contours in a VR environment but also intends to couple this with an auralization i.e. aural simulation of aircraft noise produced by the corresponding movement. This way an observer can both see an aircraft fly by and also hear it at the same time, thereby gaining an immediate impression of both the loudness as well as the annoyance. The collaboration of the various institutes for the VATSS project is shown in Fig. 2.

The time-dependent operational plus environmental data modeling methodology of the ILR for complete aircraft movements is explained first, followed by the interdisciplinary collaboration for auralization with the Institute of Technical Acoustics (ITA) and with the Virtual Reality Group (VRG) for 3D visualization of the operational plus environmental dataset. While results for operational and noise modeling will be shown and explained in more detail, results of the visualization will be presented via sample screenshots of the visualized movements and those of auralization are made available online as synthesized audio files.

## 2 4D flight operational plus environmental dataset modeling

At the ILR in recent years, incorporation of the environmental impact of aircraft movements into preliminary aircraft design was initiated. This was done to append the ILR's Mission Analysis tool, which could model complete aircraft movements and determine the fuel used, power offtakes, emissions such as $NO_x$ and $CO_2$ produced over the entire mission among other parameters. A semi-empirical noise prediction code based on NASA's Aircraft Noise Prediction Program (ANOPP) [4] was used to model the noise for any aircraft and engine combination via the ILR's Noise Prediction tool, which together with the Mission Analysis tool allows simulation of noise impact on the ground due to any standard or noise abatement approach and departure procedure.

### 2.1 Flight path modeling and noise input parameter generation

Aircraft noise simulation requires detailed time-dependant flight path information, i.e. the aircraft position as well as the Euler angles and information on aerodynamic configuration, flow parameters and thermodynamic state variables for the semi-empirical noise source models.

In order to provide these data for the noise modeling, the ILR's Mission Analysis tool, which is a detailed mass-point flight performance model, outlined in more detail in [5], has been enhanced by a full thermodynamic model of the engine. This allows for modeling all needed thermodynamic state variables along the flight path.

Another specific need of noise simulation input data is that equidistant time steps are required. The typical sampling time of aircraft noise simulations and measurements is 0.5 seconds. Thus the flight performance data has to be resampled to equidistant time steps.

The flight path data along with the thermodynamic noise source model input is stored in an XML-flightpath file format which is then used for the noise modeling, auralization and visualization of the flight path.

### 2.2 Time-dependent noise modeling for modeled flight paths

Once the operational parameters such as aircraft altitude, Mach number, current range covered, thrust and flap setting etc. as well as the engine's thermodynamic parameters such as temperature, pressure and mass flows at each stage of the engine have been determined, the noise produced by the aircraft movements can be calculated. Major aircraft noise sources such as the fan (Heidmann [1]), jet (Stone [2]) and airframe (Fink [3]) have been modeled and noise both at the source (sphere of radius 1 meter around the aircraft) as well as at the observer on the ground is modeled by the ILR's noise prediction tool.

Propagation effects of spherical spreading, atmospheric damping and ground reflection are applied to the source noise and a noise value at the ground is obtained. At the source, the noise results of ILR's noise prediction tool are presented as 1/3 octave band spectra for frequencies of 50 to 10000 Hz in polar angles of 0 to 180 degrees for engine noise sources as well as azimuthal angles of 0 to 360 degrees for airframe noise components. For airframe noise, the noise produced by flaps deflection, slat deployment, landing gear etc. can be simulated, which can become significant during approach. Sample noise spectra produced by the engine and airframe noise components are shown in Fig. 3.

On the ground, the noise results are presented via noise contours, either for the overall flight path at the end of the mission via maximum SPL values at each point on the ground or time-dependent noise contours for each time-step where current SPL values at each point on the ground are displayed. For noise contour construction, the path from the aircraft to observer is divided into a number of segments and the noise at the source is propagated to each segment's end until it reaches the ground with a reduced intensity. Due to atmospheric damping and its intensity depending on air temperature and relative humidity, the higher frequency components of noise are damped stronger than the lower frequency components and the high-frequency fan tones for instance are damped much more than the low-frequency broadband jet noise. Along with the Doppler effect and wind turbulence, the jet noise when heard therefore remains longer and more persistently than the fan tonal noise, which peaks at much higher frequencies (depending on the Blade Passing Frequency (BPF), the fundamental tone occurs at 600-1200 Hz). When the propagation effects are applied to a number of observer points on the ground after segmenting it into a grid, noise contours can be obtained for both the overall aircraft movement as well as time-dependent noise contours for each time-step and mission point.

### 2.2.1 Overall mission noise modeling

For overall mission contours, an algorithm is applied which searches for the shortest distance between the current ground point and all the mission points in the considered mission. The noise to that ground point is then only propagated for mission points which are within a selected range of the closest mission point. This is based on the knowledge that the noise intensity peaks when the aircraft is closest to the ground and ends up saving considerable computational time, producing noise contours for complete aircraft movements in the range of seconds. An overall mission noise contour produced using ILR's Noise Prediction tool for an A320 aircraft take-off segment up to a range of 4000 meters for both engine and airframe noise components is shown in Fig. 1.

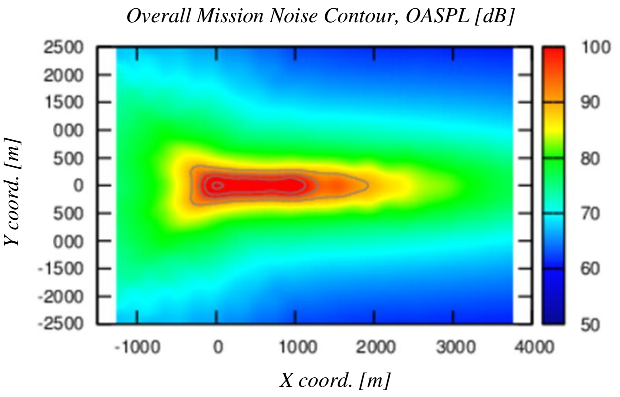

Figure 1: Noise contour for engine plus airframe noise during take-off produced using ILR's Noise Prediction tool

### 2.2.2 Time-dependent mission-step noise modeling

For time-dependent noise contours for each mission-step, the time-delay between the emission time $t_e$ when noise is emitted and reception time $t_{reception}$ when the noise reaches the ground has to be considered. The reception time on the ground and emission time from the aircraft are separated by a time-delay $t_{delay}$, which is simply the ratio of the current aircraft to observer distance $s_{source-observer}$ divided by the speed of sound at the source altitude. In order to realize time-dependent contours, the reception times on the ground are taken as the known value and emission times are calculated at which the noise would have been produced in order to reach the ground at the current reception time. These emission times are referred to as retarded emission times.

A vector (array of adjustable size in C++) of reception times from start to end of considered mission is run for each ground point and the retarded emission times are calculated for the each of the reception times. If the retarded emission time value is negative, then the noise for this value is set to a minimum value (e.g. 0 dB) there is no noise produced before the first emission time. For the retarded emission times that are positive, an interpolation is made between neighboring emission times for which the noise is known. The noise at the source found in this way is then propagated to the ground by applying the three aforementioned propagation effects and a noise value on the ground is obtained for the current reception time at the current ground point. This process is then repeated for all the points on the ground grid and time-dependent noise contours for each mission-step are hence obtained. These time-dependent noise contours are then visualized by the VRG for the 3D visualization, as is explained in section 3.2. ILR's Noise Prediction tool together with the Mission Analysis tool can model the noise impact for both standard departure and approach procedures as well as noise abatement procedures.

## 2.3 Applications of the operational plus environmental dataset

The consistent operational plus environmental dataset produced by the ILR's Mission Analysis and noise prediction tools provides a range of possibilities for research and application. Some of these can be listed as: Preliminary aircraft design for minimum environmental impact after integration of ILR's noise prediction tool into ILR's preliminary aircraft design platform – MICADO *(Multidisciplinary Integrated Conceptual Aircraft Design and Optimization environment)* [6]; research and application to flight trajectory definition based on noise impact produced and effect on air capacity; airport planning and design as well as eco-efficient airline operations; demonstration of the impact of air traffic in administrative procedures to non-experts e.g. in hearings on noise and emissions, air pollution, effect of a new planned runway etc. by means of auralization and visualization of the operational and environmental dataset via the VATSS project.

## 3 Interdisciplinary collaboration for subjective assessment of air-traffic noise in VR environments

In order to apply the operational and environmental dataset for subjective assessment in VR environments in the most efficient way, the approach at RWTH Aachen University was to use the expertise of individual institutes of the university specialized in the respective fields required for the VR simulation. As described earlier in section 1, five institutes contribute to realize the air-traffic simulation with auralization and visualization in the CAVE facility of RWTH Aachen. The focus here shall be on the approach of the ITA for auralization and that of VRG for visualization of ILR's operational and environmental dataset, followed by a brief description of the data-sharing methodology of the various institutes for efficient collaboration.

## 3.1 Real-time auralization of aircraft noise for modeled flight paths

Auralization of aircraft noise can be defined as the conversion of a predicted spectrum into an audible sound [7]. With regards to the interdisciplinary collaboration for the VATSS project, this is done in three steps of noise source modeling, noise propagation and sound reproduction, see Fig. 4.

Firstly, the noise spectra for each time-step produced by the ILR's noise prediction tool are converted to 3D directional audio datasets using the ITA's open source data format – Open Directional Audio File Format (OpenDAFF). This involves a conversion of the 1/3 octave band noise spectrum for each source in each direction (polar angle 0-180 degrees) into a single directional audio dataset where the noise intensity in each direction is determined by the respective model (Heidmann, Stone, Fink etc.) incorporated into ILR's noise prediction tool. Sample DAFF datasets for fan and jet sources are shown in Fig. 5 and Fig. 6.

For simplicity, only the fan tones and jet broadband noise are presently auralized. For the auralization of fan tonal noise, modal synthesis is used where modulated sinusoidal signals of the form of (1) are computed for the fundamental frequency and its harmonics.

$$s_i(t) = a_i \sin(\varphi_i(t) + \phi_i) \qquad (1)$$

The initial phase $\Phi_i$ is set as random to obtain a more chaotic, less synthetic sound and the instantaneous phase $\varphi_i$ is obtained from the harmonic being considered via (2).

$$f_i(t) = \frac{1}{2\pi}\frac{d\varphi_i(t)}{dt} \Rightarrow \varphi_i(t) = 2\pi\int_0^{\tau} f_i(\tau)d\tau \qquad (2)$$

The fundamental tone is determined by the Blade Passing Frequency (BPF), which is the product of the fan rotational speed N1 and the number of fan blades, B. The amplitudes $a_i$ are all set to unity so as to obtain a flat harmonic spectrum, to which the directivity pattern contained in the fan DAFF dataset is applied via a 1/3 octave filter bank. For auralization of broadband jet noise, a white noise signal is filtered with the 1/3 octave spectral directivities obtained using the method of Stone from ILR's noise prediction tool.

To the tonal and broadband sound signals, the Doppler effect is applied via a Variable Delay Line (VDL), which delays the incoming stream of samples by an adjustable amount and with the time-delay, a shift in frequencies is obtained, giving an impression that the aircraft is coming closer and going further away before and after the closest position to the observer. The propagation effects of spherical spreading and atmospheric damping are then applied to the sound signal to reproduce sound at the observer position.

The monaural audio signal obtained thus far is converted to a binaural signal to present the auralized sound from the correct spatial direction to the observer. This is done by convolving the monaural signal with a corresponding Head Response Transfer Function (HRTF) based on the aircraft position with respect to the observer and the HRTF filter is updated instantaneously for any movement of the observer for a realistic sound experience. The auralization procedure for complete take-off and landing movements has been outlined in further detail by the authors in [8]. Via this auralization capability of aircraft noise, a means is obtained to express the annoyance which aircraft noise may cause alongside the loudness.

## 3.2 3D visualization of aircraft movements and ground noise impact

Auralization of noise produced by aircraft movements provides a great means of subjective assessment of aircraft noise annoyance. But when a 3D visualization is added to the auralization, then the observer can truly feel immersed in a VR environment and relate the sound to the visual, gaining an immediate idea of distance and orientation of the aircraft. The 3D visualization for the VATSS project is carried out in the CAVE facility of VRG, see Fig. 7. For this purpose, the open source 3D visualization and computer graphics software – the Visualization Toolkit (VTK) [9] is used, which is applied for visualization in the CAVE via the VR toolkit ViSTA developed at the VRG [10]. Using the VTK data format, the operational and environmental dataset provided by the ILR can also be visualized on a local computer.

For the visualization, a scene is created consisting of one or more *scenarios* (such as standard or noise abatement procedures), which represent a self-contained and complete configuration of the scene in consideration. One scenario consists of one terrain dataset for visualizing the ground and one or more aircraft datasets. The aircraft dataset consists of the flight path and noise impact on ground data, besides the geometric model of the aircraft itself. One scenario is played out at one time.

For the visualization of noise impact on the ground using VTK, a *structured points* dataset format is used, chosen for its simplicity over an unstructured grid VTK dataset format. The structured points format also proves to be analogous to the ILR's noise impact on ground calculation over segmented ground grids. The *scalars* dataset attribute is used with values read from a lookup table containing the dBA intensities provided as doubles by ILR's noise prediction tool and the points are spread over a certain range (x,y,z) in meters from the origin of the scenario defined in global coordinates. The origin here is chosen to be the point of brake-release on the runway at the considered airport. The total number of points used is determined by the extent of the flight path for the individual scenario. For the simulations so far, points spacing has been set to 100m x 100m.

## 3.3 Data-sharing approach for the interdisciplinary collaboration

For the interdisciplinary collaboration, two types of basic data are primarily used – path data, which describe the position of the aircraft and the operational parameters for each time-step; and volume or surface data. Path data are stored in XML format and are produced as output from the Mission Analysis tool of ILR, which are then read by ILR's Noise Prediction tool for noise calculation and by the VRG for aircraft path visualization. All volume and surface data are stored and read in the VTK data format by the various partners. The ground data are constructed as a surface mesh while atmospheric data including the temperature, pressure, relative humidity etc. are stored as volume data. Besides these two data types (path and volume or surface), also geometry data and sound data are used (containing the auralization information, which is synchronized with the path data for the visualization).

## 4 Results

The operational and environmental modeling of the ILR is shown in Fig. 10 and 11 for an Airbus A330-200 aircraft designed using MICADO. A final approach segment for a standard approach procedure is modeled using the Mission Analysis tool of ILR and the operational parameter plus noise relevant thermodynamic parameter variation over the course of the approach procedure is shown in Fig. 10. Airframe noise was not included in this modeling to focus on engine noise auralization. The standard approach procedure is carried out in steps of altitude reduction and the aircraft Mach number is reduced from 0.4 to 0.23 when the aircraft touches down on the runway after covering a horizontal distance of 22000 meters over the approach segment. As the final approach is initiated at 4000 meters, the fan rotation speed N1 (and hence thrust setting) is increased from 25 to 40 revolutions per second and is then reduced gradually in steps to approximately 33 revolutions per second. The thermodynamic parameters of fan and jet mass flow and primary jet velocity are seen to vary accordingly with the thrust variation. Fig. 11 shows the noise on ground impact of the final approach segment via the overall mission noise contour produced using ILR's Noise Prediction tool. The time-dependent noise impact on ground for each mission step of 0.5 seconds is provided by the ILR to the VRG in the VTK format for visualization either on a local computer or via ViSTA in the CAVE facility. A visualization screenshot of the standard approach procedure is shown in Fig. 8. A similar visualization screenshot of the noise abatement HeNAP procedure [11] is shown in Fig. 9. Auralized audio files for a flyover with constant aircraft settings and a standard take-off procedure can be found on the official website of the VATSS project: http://vatss.ilr.rwth-aachen.de. Further auralized audio files for standard and noise abatement procedures are to be added to the presently auralized audio files.

## 5 Conclusions and aims for future

An interdisciplinary approach has been presented for realizing a 3D simulation of air-traffic where aircraft noise impact for observers on the ground is made perceptible both aurally as well as visually. For this purpose, the consistent operational plus environmental dataset produced by the ILR for each time-step of aircraft movement is auralized via an interdisciplinary collaboration with the ITA and visualized by an interdisciplinary collaboration with the VRG. This results in a fast and efficient way of realizing a complex simulation in a VR environment, which would be much more time-consuming and would not reach the required complexity for realistic implementation without the utilization of the individual specializations of the various institutes. The VR simulation, when experienced in the CAVE facility of RWTH Aachen University, provides the observer an immersive VR experience of air-traffic in the airport vicinity where he can both see and hear aircraft as they approach and depart allowing a method for subjective assessment of air-traffic.

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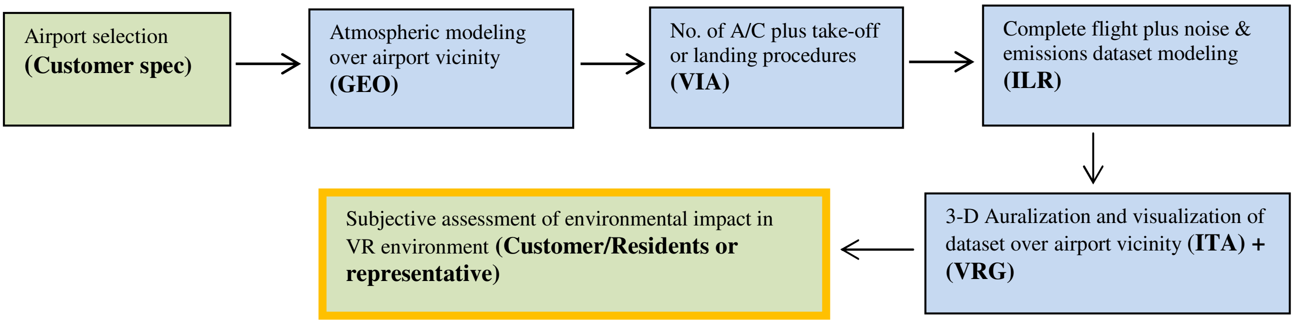

Figure 2: The work flow for achieving the VR simulation of air-traffic at RWTH Aachen University

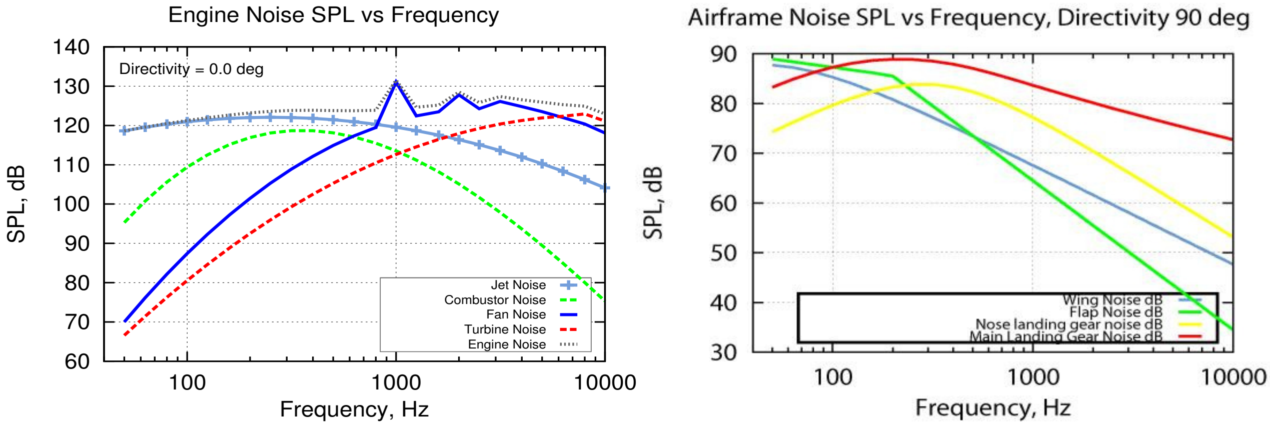

Figure 3: Engine noise spectrum (left) and airframe noise spectrum produced using ILR's Noise prediction tool

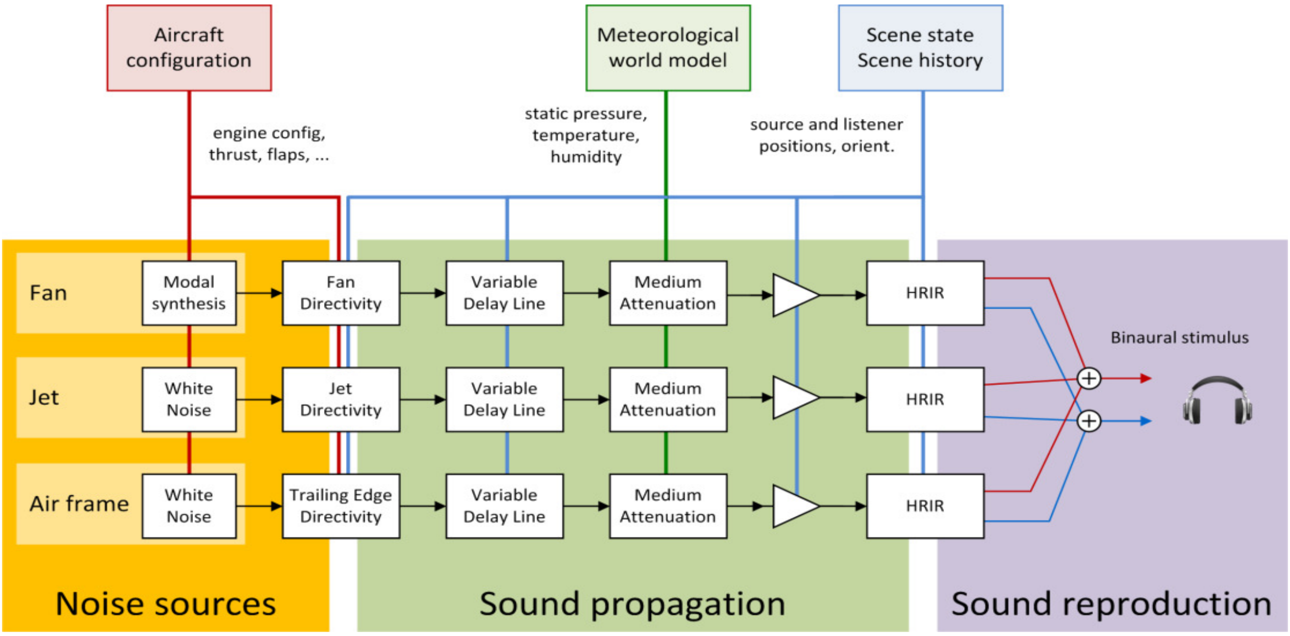

Figure 4: Auralization methodology carried out by the ITA of RWTH Aachen University

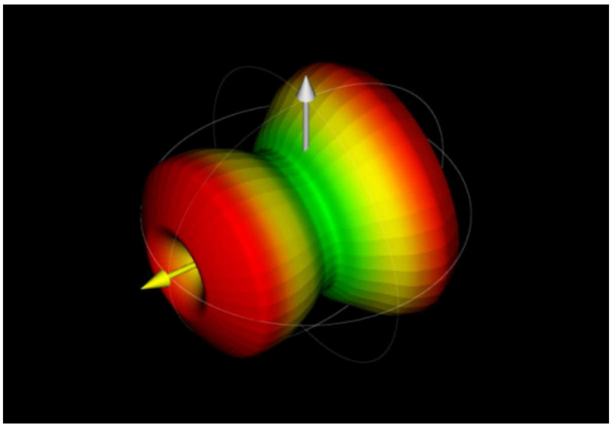

Figure 5: DAFF directivity dataset for fan noise with linear scaling at a frequency of 1000 Hz for one engine setting at one time-step

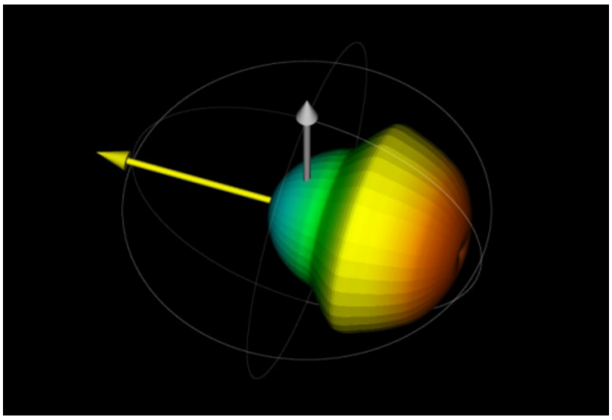

Figure 6: DAFF directivity dataset for jet noise with linear scaling at a frequency of 50 Hz for one engine setting at one time-step

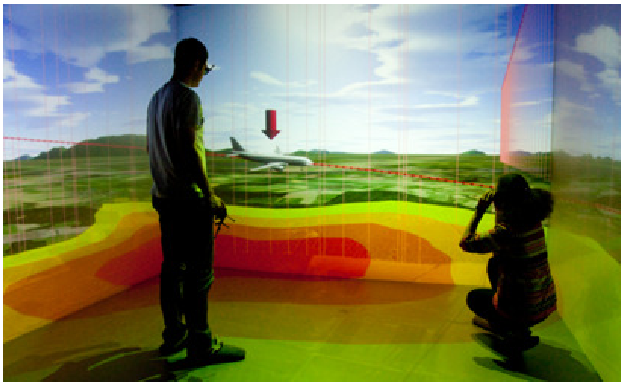

Figure 7: Visualization in the CAVE facility of RWTH Aachen University

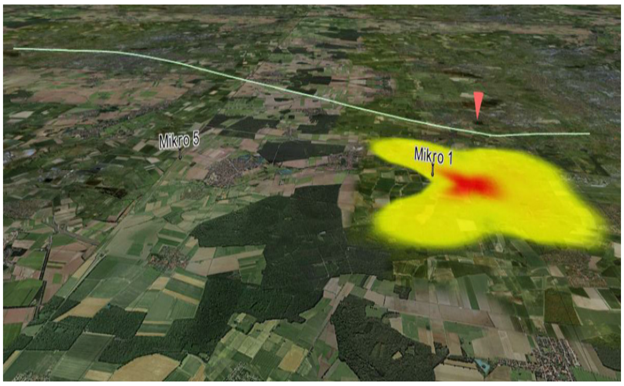

Figure 8: Visualization of standard approach procedure by the Virtual Reality Group

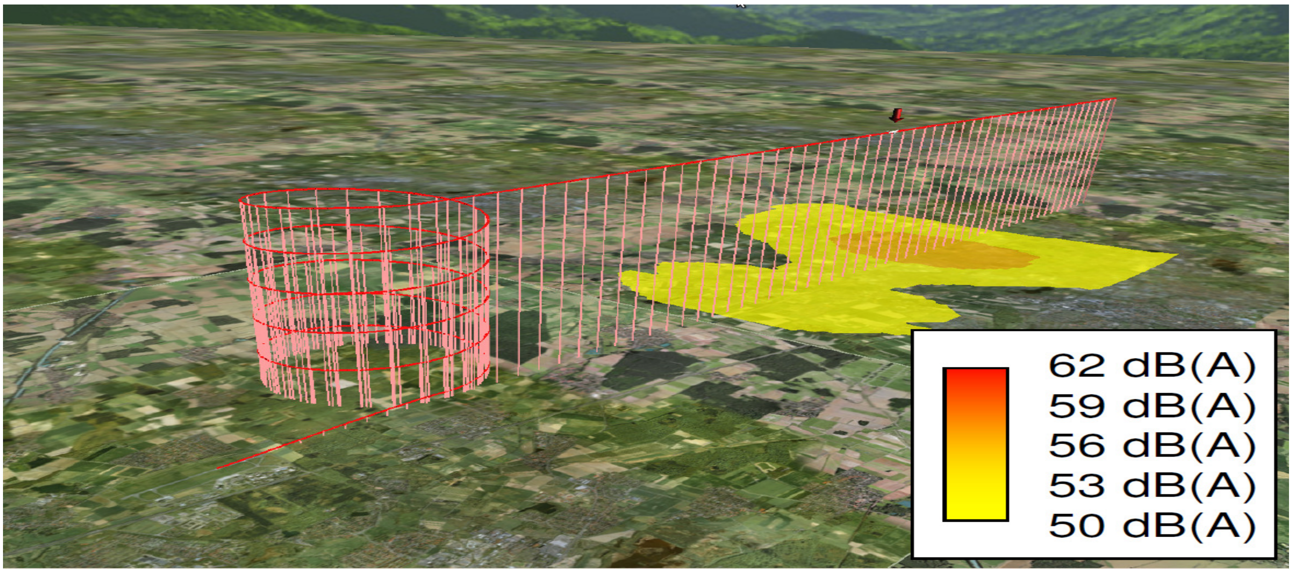

Figure 9: Visualization of a helical noise abatement approach procedure by the Virtual Reality Group

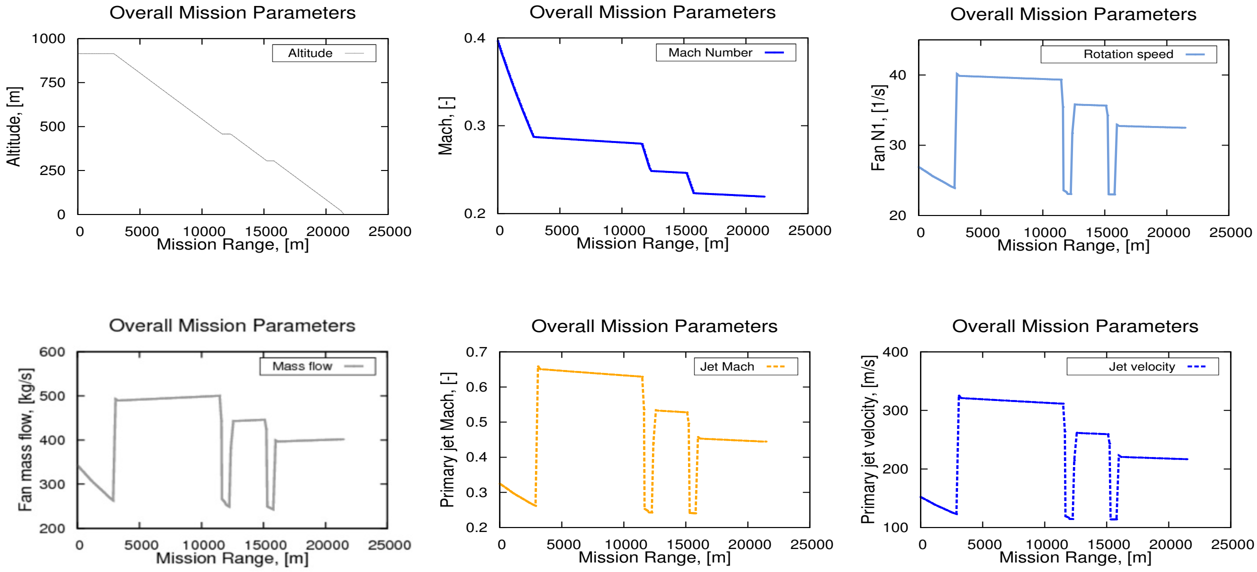

Figure 10: Variation of operational and noise relevant parameters over a standard approach procedure

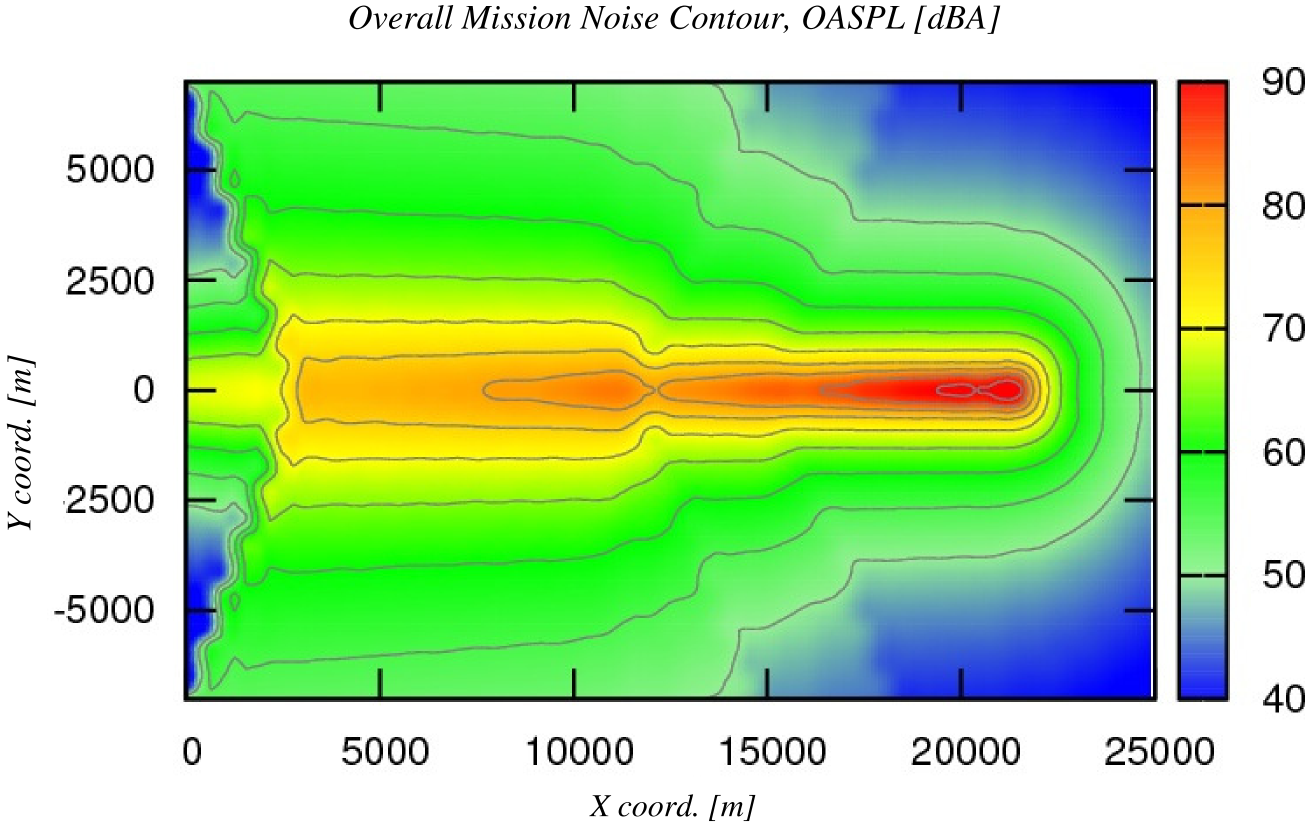

Figure 11: Noise contour for standard approach procedure produced using ILR’s Noise prediction tool