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REAL-WORLD STUDY CASES FOR AURALIZATION VALIDATION: SELECTION, MEASUREMENTS, AND METHODS

João Fatela[1*] **Luigi Maffei**[1] **Massimiliano Masullo**[1]
Michael Vorländer[2]
[1] Department of Architecture and Industrial Design, Luigi Vanvitelli University, Italy
[2] Institute for Hearing Technology and Acousitcs, RWTH Aachen University, Germany

ABSTRACT

Recent advances in the development of plausible environmental noise auralization tools are making way for their implementation in practical applications. In particular, increasingly realistic air traffic noise auralization frameworks are being developed. These could become powerful tools for assisting decision-making in architectural and urban planning projects, by allowing users to perceive and experiment with the impact of their design choices on noise mitigation. However, the auralization models must be validated before such solutions can be implemented. By comparing human impressions of the recorded spatial audio of a given real-world scenario versus a synthesized auralization of the same scenario, the quality of the models can be evaluated in terms of human perception. This paper presents a methodology to select and virtually model real-world urban scenarios for validation of air traffic auralization tools in an urban environment. First, the relevant principles behind a meaningful study case selection are proposed. Then, the necessary measurements for the definition of the virtual scenarios, and an optimized workflow for data gathering, are presented. The inner city of Naples, Italy, provides the setting for this study due to its proximity to Naples-Capodichino International airport (NAP).

Keywords: *auralization, case study, environmental noise, air traffic*

**Corresponding author*: *joao.garrettfatela@unicampania.it.*

1. INTRODUCTION

Urban environmental noise is known to greatly impact human health [1, 2]. This is a growing concern in urban environments. In particular, air traffic has become a major source of environmental noise in urban contexts [1]. Furthermore, Guski et al. [2] reports that aircraft noise is linked to the highest degree of long-term noise annoyance. The impact of this noise source in urban environments is expected to increase, with a predicted increase in air traffic operations in the future [3] .

It's up to decision makers, city planners, and architects to enact policies which mitigate the impact of such noise sources on the exposed populations. In this context, simulation tools can be extremely valuable. They allow users to make predictions on the characteristics of noise propagation in a given virtually modeled environment.

By modern standards, a characterization of noise from merely physical properties is deemed insufficient in order to assess its true health impact on a given population. The very definition of health as *a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity*, according to the World Health Organization (WHO), implies that factors such as annoyance are significant health indicators [1]. Such factors are even linked to other physical symptoms, in spite of not being physically measurable [1]. Annoyance, for example, is known to be influenced by not only audiovisual and sensorial characteristics of a given scenario, but also a subject's cultural context and personal views [4].

With this in mind, solutions such as auralization and Acoustic Virtual Reality present particularly powerful tools for testing the perception of noise. By making such tools more and more realistic, the human perception of the output is expected to match more and more the perception of real-world noise stimuli. In particular, the auralization of aircraft noise has found important advancements: recent sound propagation models are able to emulate the effect of an inhomogeneous atmosphere on the sound path geometry and consequently, the properties of the sound itself [5, 6]. Moreover, inverse modelling sound source synthesis [7], as well as state-of-the-art models for sound reflection, diffraction, and scattering [8] are promising advancements for perceptually accurate noise auralizations in urban environments.

All in all, the state-of-the-art noise auralization technologies may be at a point where different auralization tools can be combined into a framework fit for practical applications. However, the resulting framework must first be validated for the intended use. While each tool is typically validated independently, an ensemble and perception-centered validation is yet to be defined and performed.

In this paper, a methodology for perceptual validation of air traffic noise auralization tools in an urban environment is proposed. A step-by-step definition and discussion of the methodology is presented in the following sections. First, we broadly define the experiment design for the validation. The main idea is to compare real-world scenarios with the output of virtual reproductions of the same scenarios. Then, the selection of study cases for comparison is discussed. Afterwards, the methodologies for the necessary data gathering steps are presented: Real-world spatial audio recordings; real-world visual environment recordings; 3D modelling of the study case sites; documentation of the study case scenario characteristics. Finally, a potential location for study cases is discussed.

2. VALIDATION DESIGN

The validation of the auralization tools discussed in this paper depends on whether the perception of their output is matches the perception of air traffic noise in the real world to a given degree. The degree to which the perceptions should match for the tools to be considered valid is not adressed in this paper, and reserved for future discussion.

The validation relies on a comparison between an environment where the air traffic noise is synthesized (*auralization environment*), and an environment where the noise from a real-world aircraft flyover is implemented (*reference environment*). This section aims to define a meaningful framework for the comparison of these two environments, the validation. Let us define stimuli related strictly to the air traffic noise as *validation stimuli*, and stimuli *unrelated* to air traffic noise as *parallel stimuli* (e.g. other auditory stimuli, haptic, vestibular, visual, thermal stimuli).

In order to validate only the auralization, the source of air traffic noise stimulus must be the only difference between environments. Furthermore, the auralization must take as input the exact conditions of the real-world scenario.

The perception of sound is unique to any given listener. Hence, meaningful conclusions on this matter can only be drawn with a statistical interpretation of the impressions of multiple listeners. Thus, the comparison of the environments must be done with resort to large-scale listening experiments.

As motivated in the Introduction, the environments should be as immersive as possible. This way, we address the influence of parallel stimuli on the perception of the stimuli of interest. While placing the test subjects physically in real-world environments would guarantee the most immersive conditions, it does not ensure replicability of conditions between listening tests and test subjects. Thus, the real-world conditions must be recorded, documented, and imported into a multisensorial virtual reality (VR) environment. This is the reference environment. Analogously, the auralization environment is created by replacing the real world air traffic noise audio with the auralization of the same scenario.

This process does not necessarily aim to ensure that the auralization environment is indistinguishable from the real world. Rather, the goal is to certify that the auralization environment features a meaningful degree of ecological validity [9]. I.e. the auralization is deemed valid depending on whether the perception (evaluated namely by annoyance) of the auralization environment matches the perception of the real world. A possible issue is the perception of the reference environment (in VR), since it may not perfectly match a real-world scenario. Hence, evaluating the realism of the VR environments is still an important aspect, in order to support the validation process.

3. STUDY CASE SELECTION CRITERIA

The selection of the study cases must be done in a way that diversifies the perception of the environment. Namely, the presence or absence of other sound sources (noise or otherwise) can motivate the selection of given spaces. Furthermore, varied study case conditions are fundamental to evaluate the capabilities of the auralization framework. For example, spaces with different spatial characteristics will transform the air traffic noise in different ways as the sound travels through space. Hence, the selection of a given study case must be informed by the characteristics of other study cases selected. This ensures a diverse set of conditions, which test the capabilities of the auralization ensemble.

Modern auralization tools involved in air traffic noise synthesis encompass three main challenges:

1. the synthesis of the source signal;
2. the propagation of the sound in an inhomogeneous atmosphere;
3. the sound propagation around physical obstacles.

In order to validate the operation of such tools, the scenario selection should consider the diversity of:

- aircraft models and operating conditions – adressing the sound source synthesis;
- atmospheric conditions – adressing the sound propagation in the atmosphere;
- study case location geometries – adressing different obstacles to sound propagation;
- trajectories – affecting all three aspects.

Additionally, the selection of such case study scenarios can be made considering the relevance of a given location. The activities developed at a given study case site have no impact in the validation of the auralization tool. However, the authors believe it best to focus on spaces where aircraft noise is an obstacle to said activities (e.g. hospitals, education facilities). The reasoning, is that some results of this study could be immediately used to address the problem of aircraft noise in these locations.

4. REAL-WORLD ENVIRONMENT

4.1 Real-world spatial audio

The recording of real-world spatial audio is important for two main reasons: First, recording the air traffic noise of the reference environment. Second, recording the background noise for the auralization environment.

The recorded audio must represent the real-world acoustic environments as closely as possible. For example, by recording the audio in ambisonics formats the acoustic environment is encoded with important spatial cues. This is essential for user immersion. The ambisonics audio can be later decoded for reproduction in a variety of formats or systems. Another option is to record the environment binaurally. While it provides in theory more precise results, the reproduction would be limited to a fixed user orientation. In order to increase the user's immersion in the VR scenario, the binaural output can be decoded from the ambisonics audio relative to listener's orientation. This can be done offline (using audio plugins in a Digital Audio Workstation (DAW), e.g. IEM SPARTA binauralizer or COMPASS binaural plugins [10]) or possibly in real time (e.g. using plugins such as Steam Audio [11] incorporated in a VR engine). The real-time decoding of the ambisonics recording to binaural audio is likely the more immersive option. This is because the listener's head movements are especially important for sound localization [12, 13].

The recording of background noise for the auralization environment comes with specific challenges. In the defined validation design, the background noise should match the reference environment's background noise during flyover. This is not possible, since there is no way of isolating the air traffic noise from the background without compromising audio quality. Furthermore, some sound sources (e.g. humans speaking) may change their emmission in the presence of a loud environment.

In order to record plausible background noise, recordings should be made as close as possible to the time interval of the real-world flyover. This raises an additional issue: Defining the beginning and end of the flyover event in terms of acoustic perception. Some approaches have been defined in order to correlate air traffic noise events with flight trajectory data [14, 15]. Nevertheless, these approaches do not consider the perception of the flyover, since the noise measurements in such studies follow the ISO 20906:2009 standard [16]. The approach for now is making long recordings in order to feature the aircraft flyover noise and the "pure" background noise in limited time intervals. The task of detaching the flyover and pure background noise audio segments is investigated in the future.

4.2 Visual environment

In order to visually immerse the user in the scenario, 360º video can be used. If synchronized with the audio, the visual cues will match the perceived auditory stimuli. This is thought to be important for the user immersion in the VR environment, since visual cues are known to improve the localization of sound sources [12]. However, the visual cue of the aircraft itself will be absent from the auralization environment.

Professional 360º video cameras allow for recording of 3D video, which is a further step in the immersion of the user: Stereoscopic image reproduction is a standard requirement for VR simulations. Furthermore, modern cameras are capable of capturing images with High Dynamic Range (HDR) techniques, which can be calibrated to match the human perception better than alternative image acquisition technologies [17].

It's worth mentioning that recording the scenario in this way does not allow the user to translate within the VR environment. While the orientation can be changed, and the 3D video introduces important stereoscopic cues, this format cannot account for visual parallax. This is an important 3-dimensional visual cue caused by the movement of the eyes relative to the observed 3D environment. Such an effect can be introduced by replacing the video with a textured virtual 3D model (see Section 5.1 for a potentially useful technique).

However, modelling visual cues for the parallel auditory stimuli (e.g. moving vehicles) is very challenging to achieve in an immersive fashion. Furthermore, large user movements would lead to mismatches between visual and auditory stimuli, since the audio is recorded at a fixed position. If the user is positioned in the scenario at a distance from surrounding bodies, the lack of parallax effect could become less noticeable. Hence, using 360º video is thought to be a good compromise in order to provide visual immersion of the user in the VR environments.

5. PREPARING THE AURALIZATION

5.1 3D spatial model

In order to simulate the effect of the physical features of a given space in the sound propagation, a virtual 3D model of the study case's physical space must be developed. From this model, the auralization modules responsible for simulating the sound propagations (with reflection, diffraction, and scattering effects) can be derived and implemented in the auralization workflow. Besides spatial characteristics, it's essential to categorize the materials and usage of the surrounding space in terms of acoustic properties. This information can be used to further improve the sound propagation characteristics of the auralization.

The development of the 3D model can be done in a variety of ways. The use of photogrammetric surveys to characterize an acoustic space has become a recently explored avenue [18, 19]. This technique is thought to respect important conditions for correct acoustic simulations. Furthermore, visual texture information from the photogrammetric process can be used to optimize the surface material assignment [19].

Considering sound propagation in urban environments, not only immediately neighboring physical features affect the sound propagation, but also potentially the geometry of features not visible from the listener's position. Particularly, the top edges of buildings may impact the diffraction effects on the noise propagation. Hence, an efficient way of acquiring quality photogrammetric data of out-of-reach locations (e.g. tops of buildings, balconies, terrasses) is necessary. An approach is to use openly available satellite data. However, the resolution of such products may not be high as necessary for this application, and the camera positions are limited. As a result, important geometric properties may be lost. A possibility is using Unmanned Aircraft Systems (UASs) for this purpose. Their use in photogrammetric surveying is widespread and known to provide good results [20].

Photogrammetry techniques, though powerful, come with considerable challenges. For one, the quality of the sample data is highly dependent on factors such as camera characteristics, light conditions, number of photos taken. In general, the dense point cloud resulting from the raw photogrammetry data is far too dense for virtual acoustic applications [19]. Furthermore, implicit uncertainties of the sample point coordinates make it so that important characteristics of the space are lost. For example, the mesh nodes on a given flat surface may not be coplanar, or perpendicular surfaces may not be constructed from perpendicular polygons. Mesh decimating algorithms can be applied to partially address these issues [19,21]. However, strict mesh reduction requirements may compromise important details of the geometry. Another option is to develop a Computer-Aided Design (CAD) model by hand, informed by the photogrammetric data [18]. The post-processing of the raw photogrammetry data for virtual acoustics applications is a wide topic in itself, being investigated to this day.

The resulting point cloud and texture maps can be used for the visual cues of the VR environment. Some advantages and disadvantages of such an approach are summarized in Section 4.2. The texture data can also potentially be used to categorize the 3D model's surfaces in terms of acoustic properties [19].

5.2 Sound source characterization

Characterizing the sound source and its behaviour in the scenario comes down to two major aspects: recording the movement of the source during the scenario, and defining the type of source.

Much of this data is available with use of Automatic Dependent Surveillance - Broadcast (ADS-B) technology. Many modern aircraft are equipped with ADS-B transmitters [22]. The ADS-B transmissions include data about the aircraft (e.g. aircraft model, International Civil Aviation Organization code). More importantly, the transmissions include the position, elevation, and heading of the aircraft at regular time intervals. These are provided by the own aircraft's navigation system, which relies on Global Navigation Satellite System (GNSS).

The access to this data, as well as a history of past ADS-B transmissions is publicly available. Web-based interfaces use a network of ADS-B receivers distributed around the world to provide users with real-time and historic air traffic data [22, 23].

Given the navigation data transmissions over time, it is possible to extract the aircraft trajectory and orientation data relative to the position of the receiver. The positioning data complies with standard navigation system precision, which is considered suitable for the objectives laid out in this paper.

The access to the operating conditions of the aircraft recorded in the scenarios is more challenging. Factors such as engine speed and thrust, flap usage, and deployment of landing gear, are known to influence the acoustic characteristics of the source in a significant way [24]. Such information is difficult to access, since it is typically kept by airline operators. Some approximations could be made by developing inverse models to estimate some of the operation conditions from the real-world audio [25]. However, such a methods might require further measurements and experiments. Moreover, it may lead to inaccurate results.

5.3 Weather conditions

The ability to emulate the effects of the atmospheric conditions on the sound propagation properties is one of the major auralization developments under scrutiny. Hence, a way of defining the atmospheric profile for each study case scenario is required.

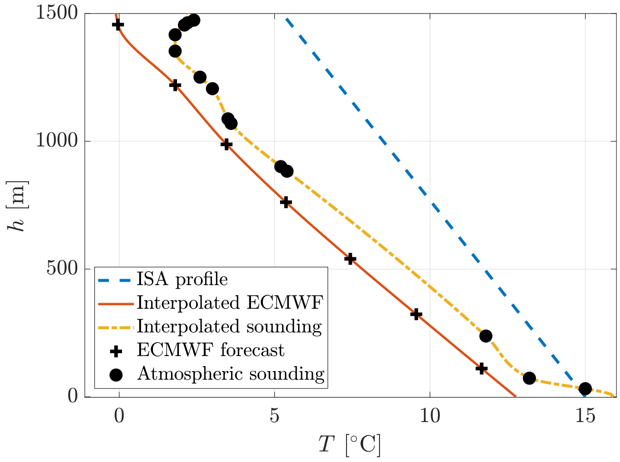
In theory, the more precise the definition of atmospheric conditions, the more realistic the auralization output. It is not known whether this is the case in practice. Furthermore, it is difficult to account for effects of the local topography and human-built environment on the lower layers of the atmosphere. Hence, an all-approaches-welcome attitude is taken at the moment, in order to characterize the atmosphere. Considerations on which approach is the most perceptually valid are left to future study. In this paper, we present three separate options for the definition of atmospheric conditions: Measurement-based, forecast-based, and model-based.

A simple measurement-based approach is to perform atmospheric soundings at each real-world scenario recording, thus profiling the atmospheric conditions at the required instants in time. This is not practical due to the resources and equipment required to perform such measurements (e.g. weather balloons, radiosondes, Doppler radar/lidar). Moreover, given the geographical proximity of the scenarios of interest to air traffic operations, some sounding techniques are likely impossible in practice. While not widely available, some atmospheric sounding data can be accessed in online repositories, e.g. the University of Wyoming's atmospheric sounding database [26]. While sounding data provides precise measurement of the atmospheric conditions, it also represents a frozen instant in time. That means that the data may be vulnerable to outliers resulting from the inherent turbulence of the atmospheric boundary layer. Furthermore, the available measurements are sparse, both spatially and in time.

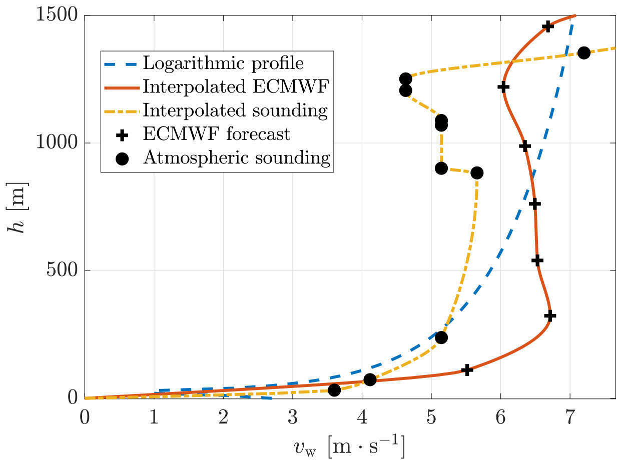
A forecast-based approach can be done by accessing open weather forecasting data. An option is the European Centre for Medium-range Weather Forecast's (ECMWF) Open Data [27] or other public datasets. Due to the nature of forecasting methods, this is a more statistical approach to the atmospheric profiling than the previous method. It does not represent the exact conditions of a given instant, rather the most likely conditions over a time interval. The forecast-based approach may improve the time and geographic resolution relative to a measurement-based approach. Further approximations can be done via interpolation. Considering that the profile is derived from a global weather forecast rather than measured data, large uncertainties may be at hand.

Model-based approaches are relatively easy to implement. A basic example is the assumption of International Standard Atmosphere (ISA) conditions [28]. However, real-world conditions may be drastically different. Nevertheless, the atmospheric boundary layer (up to $3000\,\mathrm{m}$ altitude) is a thoroughly explored topic in micrometeorology [29]. As a consequence, several models to define it have been proposed over the years. From these models, the atmospheric profile can be estimated considering surface weather conditions. The surface weather conditions are typically available in real-time from local weather observatories.

In Figure 1, different methods for atmospheric profile estimation are juxtaposed. The temperature profiles shown in Figure 1a behave similarly, despite different estimation approaches. The wind speed profiles in Figure 1b also share some similarity. In both plots, however, the absolute values of the temperature and wind speed distributions are significantly different. These plots showcase how differently the atmospheric conditions can be profiled. The differing profiles can lead to differently perceived audio [30].



(a) Temperature profiles.



(b) Wind speed profiles. Logarithmic profile based on surface weather conditions, zero plane displacement $d = 25\,\mathrm{m}$ elevation, surface roughness $z_0 = 2\,\mathrm{m}$.

Figure 1: Example atmospheric profile estimations for Naples city center on 29/3/2023 12:00UTC.

6. NAPLES CITY CENTER: PRELIMINARY STUDY CASE LOCATION

The inner city of Naples is seen as a adequate location to select study cases. The air traffic patterns of both arrivals and departures at the Capodichino International Airport (NAP) feature trajectories which fly directly above the urban area. Under certain atmospheric conditions, the aircraft fly directly over the city center and major residential areas. Figure 2 shows two example aircraft trajectories of landing (red dashed line) and takeoff (green dotted line) in the Naples International Airport. Notice the overlap with residential areas and vicinity to noise-sensitive locations, namely hospitals and education institutions. Moreover, because the airport is located near the city center, the elevation range in which the aircraft operate in this area is rather low (elevation $h < 1500\,\mathrm{m}$). The low elevation, added to the acceleration and deceleration of the aircraft in these operations may increase the noise impact of the air traffic in Naples.

The environmental noise in the city center (such as road traffic noise) means that the study case scenarios will feature complex and comprehensive background noise. As motivated in Section 2, this is seen as an important aspect of the validation process.

7. CONCLUSION

This paper lays out a set of data gathering tasks necessary for an auralization validation procedure. This procedure aims to validate perceptual characteristics of air traffic noise auralizations. The validation can be done by comparing real world audio with auralizations of selected aircraft flyover scenarios in VR environments. The selection criteria of the specific scenarios to represent (study cases) is essential for a meaningful evaluation of the auralization tools.

In order to develop the VR environments, it's necessary to thoroughly document the study case scenarios: Spatial audio and video recordings establish the baseline of the VR environments. The recordings represent the reference environment (real-world flyover audio) and help immerse the user in the auralization environment (syn-

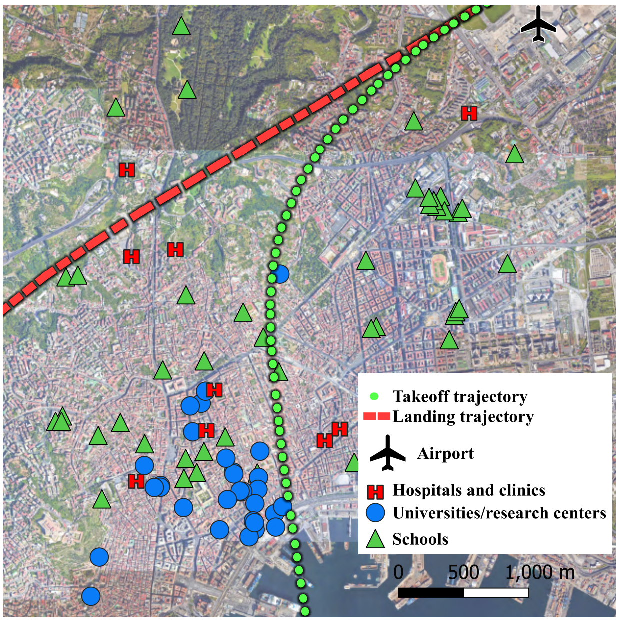


Figure 2: Example aircraft trajectories over the city of Naples (Sources: FlightRadar24 [22], Comune di Napoli Open Data [31]).

thesized flyover audio). Further data is necessary for the auralization input. A 3D model of the study case site is essential, as well as documentation of weather conditions, and aircraft type, operation mode and trajectory.

The main challenges of the data gathering approach are associated with the unpredictability of the real-world environments. For example, air traffic operations suffer frequent disruptions and delays. Many external factors can compromise the quality of the audio and video recordings. This can be problematic due to the large datasets that are generated at each scenario documentation. If the data gathering process is made inefficient, the post-processing of the data can face major challenges. The tuning of the 3D spatial model is also predicted to require significant effort.

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