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INTEGRATED U-SPACE SOCIETAL ACCEPTANCE ASSESSMENT: ENERGY-BASED AND PERCEPTION-BASED ACOUSTIC METRICS

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ABSTRACT

Innovative Air Mobility (IAM) systems are progressing within the European U-space framework to promote efficient and environmentally friendly air transport. The ImAFUSA project contributes by developing an integrated U-space assessment tool to evaluate environmental, societal, and safety impacts.

This paper focuses on acoustic metrics for assessing environmental noise and annoyance caused by unmanned aerial systems (UAS). It explores both energy-based and perception-based indicators to evaluate UAS noise. These metrics allow the U-space noise assessment accounting for the interaction between UAS and existing soundscapes and number of events.

The IAM noise assessment tool utilises acoustic pressure time-series at listener positions, which can be generated from measurements or auralised signals. In the latter case, the integration of aircraft noise synthesis, flight-control data, and sound propagation along the flight path is potentially feasible as input for the assessment tool. This flexibility highlights the usability of the proposed metrics across diverse input types, laying the groundwork for future extensions that incorporate a broader range of data, including varied operating conditions and advanced predictive models.

Therefore, the calculated metrics would provide insightful estimations for the societal and capacity impact of U-space, potentially contributing to the strategic noise management of the UAM operations.

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1. INTRODUCTION

Innovative Air Mobility (IAM) solutions are anticipated to become a transformative element in the skies close to populated areas. In addition to the benefits IAM can offer to commerce, industry, and communication activities, their presence introduces a disruptive element to urban skies, potentially impacting various societal aspects, such as affordability and accessibility of the services and vertiports.

Such developments requires the use of multidisciplinary and innovative tools for precise U-space assessment. In this context, the **ImAFUSA** [1] project, funded by the Horizon Europe Programme, is developing an integrated assessment tool aimed at evaluating the impacts of Urban Air Mobility (UAM) within U-space. The project outputs comprise innovative tools to evaluate environmental, socio-economic, and safety aspects of IAM operations, as well as to analyse their effects on U-space capacity levels.

For the U-space environmental impact assessment, noise, visual and air pollution have been considered within the ImAFUSA framework. However, the focus on noise assessment in this paper reflects the specific scope of the current work, which is dedicated to the integration and application of noise metrics. While other societal and environmental factors are also relevant for IAM integration, noise was reported as a primary concern for EU citizens, as highlighted by the EASA report in 2021 [1]. This integrated Noise assessment tool will enable easy integration in decision-making processes and interdependency studies by taking into account the interaction between the source

[1] https://www.imafusa-sesar.eu

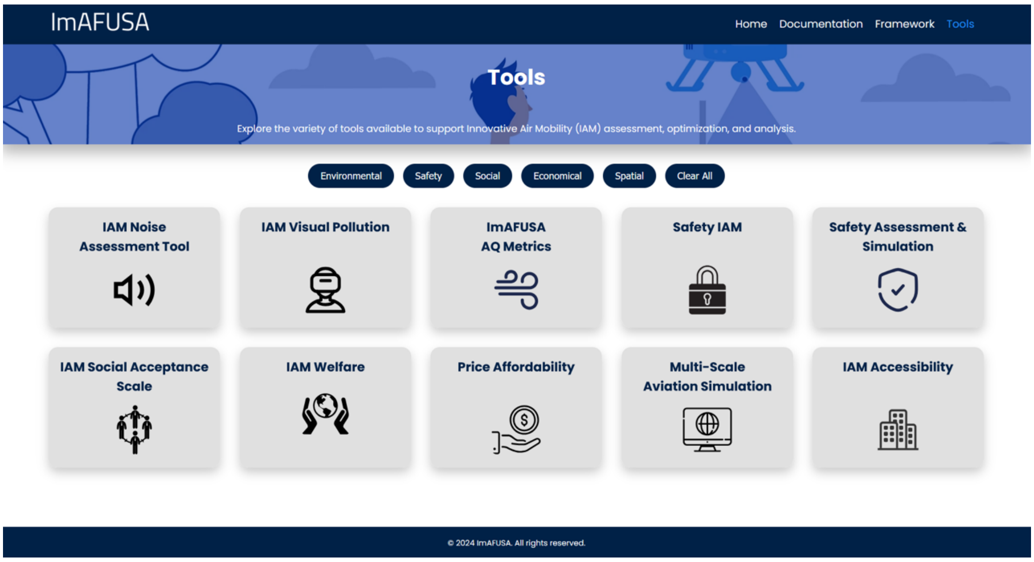

Figure 1. ImAFUSA integrated tools.

(unmanned aircraft), the environment (background noise — soundscape), and the listener (perception).

2. ASSESSMENT FRAMEWORK

ImAFUSA integrates state-of-the-art mathematical formulations and algorithms into an **Im**pact and capacity **A**ssesssment **F**ramework for **U**-space **S**ocietal **A**cceptance.

ImAFUSA focuses on assessing environmental factors such as noise, visual pollution, and air quality; safety considerations; and socioeconomic aspects including affordability, accessibility, economic development, public space utilisation, and connectivity (See. Fig. 1). By quantifying these elements through innovative performance indicators, the tool seeks to aid stakeholders in making informed and sustainable decisions, thereby promoting societal acceptance and positioning Europe as a leader in sustainable aviation.

In particular, the IAM noise assessment tool enables the evaluation of the acoustic impact of U-space use by incorporating both energy-based noise metrics and perception-based (psychoacoustic) metrics.

Expanding the analysis beyond traditional acoustic energy measures to include human perception is expected to enhance the environmental noise assessment of IAM operations. This approach allows for a more comprehensive understanding of community impact, capturing not only the additive effects of sound energy but also how noise is experienced by people in areas targeted for future IAM deployment [2].

These metrics have been extensively applied to single-aircraft and single-event operation scenarios. However, as periodicity or repetitiveness of UAM operations are expected for the potential definition of drone corridors or regular flight paths, a group of metrics should be further generated to quantify the effect of the number of flyover events and the number of people exposed along the flight paths [3]. In addition, high-order interactions between the target noise (aircraft), and masker noise (background noise), previously presented in the literature have also been integrated in the assessment framework [4].

3. NOISE ASSESSMENT METRICS

The set of metrics integrated into the IAM noise assessment tool, currently relies on acoustic pressure time-series data defined at a specific listener position. These signals can originate from various sources, including drone noise recording databases or auralised signals. From recordings, the tool can incorporate data for multiple UAS with varying sizes, take-off masses, numbers of rotors/blades, and operational variables such as altitude and speed (e.g., DroneNoise [5]). In cases where auralised signals are used, the integration of aircraft noise synthesis, operational flight control data, and sound propagation along the

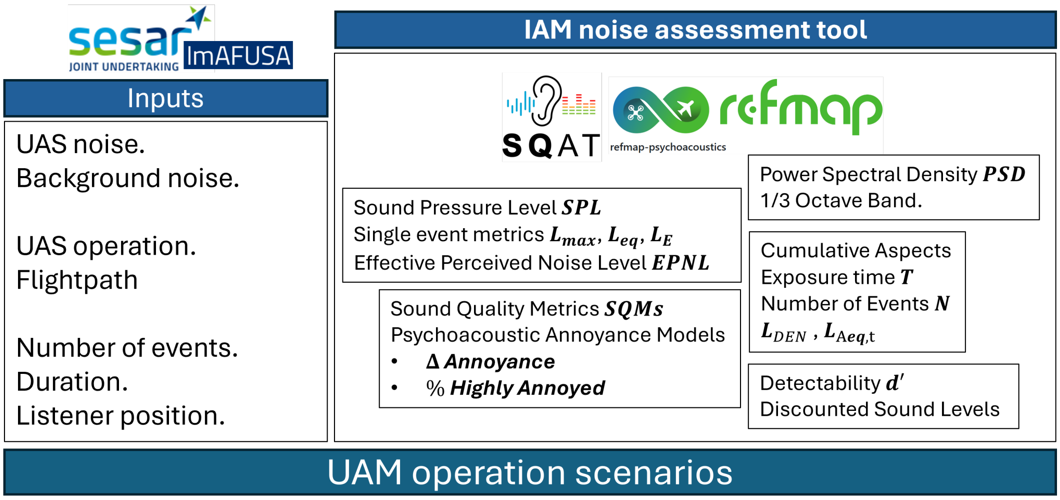

Figure 2. IAM noise assessment tool

flight path is feasible. This flexibility paves the way for future tool extensions that integrate even more comprehensive data sources, enhancing the versatility and applicability of the tool.

In addition to the aircraft noise signals, the tool also provides access to several examples of ambient sounds (e.g., EigenScape [6]). These capabilities enable a better assessment of IAM operation flight scenarios under different simulated operational conditions.

Firstly, energy-based metrics measure the acoustic intensity of the incident noise at a specific receiver point. This group of metrics has been used extensively for conventional aircraft noise assessment [7]. Secondly, the perception-based metrics evaluate the psychoacoustic effects of the sound signal on a human listener. This group of metrics considers the sound quality [8], which becomes important as the operation of IAM solutions is expected to be carried out at lower altitudes, closer to people than conventional aircraft systems [9].

The assessment tool also account for the masking effect of background environmental noise by using a discounting index. This index adjusts the acoustic metrics based on the detectability of the assessed noise source in relation to surrounding sounds. This approach includes in the analysis how much the annoyance response differs due to the non-constant prominence of the noise source in the presence of a masking sound, such as residual background noise along a flight path [4].

This ongoing project also aims to predict virtual scenarios in which more than one vehicle operates in the same urban area, and recurrent operations are expected to be carried out on an established drone path. In this regard, cumulative aspects such as exposure time and number of operations are required. Models incorporating the effects of multiple UAS events are being investigated as part of the ImAFUSA sister project, RefMap [2] [10].

To assess a UAM operation scenario, Fig. 2 illustrates the input parameters required by the IAM noise assessment tool. The inputs are the time-series data of acoustic pressure signals containing the operating source (target or UAS noise) and the soundscape where the source is expected to be operating (masker or background noise). Additional information on overflight operations will assist in the assessment of cumulative effects such as the number of operations and the number of aircraft in the flight corridor.

3.1 Energy-based metrics

3.1.1 Time-series

Sound Pressure Level SPL quantifies the wide variation in acoustic pressure from UAM operations and urban noise on a logarithmic scale in [dB]. SPL is calculated using the root-mean-square (RMS) of the pressure signal relative to a reference pressure (20 μPa). Since hu-

[2] https://www.refmap.eu The ImAFUSA and RefMap projects form the Aviation Twin Transition Cluster.

man hearing sensitivity differs from measurement devices, an A-weighting filter would be applied to better reflect perceived loudness, producing A-weighted SPL in [dBA]. As sound levels vary with source operation, time-window framing is used with exponential weighting to show SPL evolution (e.g., fast weighting: 0.125 s or slow weighting: 1 s).

Power Spectral Density PSD. represents the acoustic power distribution over frequency [11]. Spectral amplitudes are normalised by frequency resolution and expressed in [Pa^2/Hz]. Calculating power over successive time frames creates a 3D spectrogram (frequency vs. time vs. power), while averaging power over time yields a 2D plot spectrum (frequency vs. power), which also be expressed on a logarithmic scale as [dB/Hz]. PSD analysis across the full frequency range can be represented using frequency bands centred at standard frequencies f_c. Each band encompasses energy between a lower and upper cut-off frequency, with the ratio defined as $f_u = 2^n \times f_l$. An octave band corresponds to $n = 1$, where the upper-to-lower frequency ratio is 2. For greater detail, the analysis can use 1/3-octave bands, where $n = 1/3$ [12, 13].

3.1.2 Single-values

For aircraft noise emission, L_{max}, L_{eq}, and L_{E} are used to summarize the SPL evolution over time in a single value. When these metrics consider the sensitivity of the human ear, they are denoted with an A-weighting (e.g., L_{Amax}, L_{Aeq}, L_{AE}).

Maximum Sound Pressure Level L_{Amax} measures the maximum level of acoustic energy at the listener's position due to the operation of the UAM. For a flyover, it is expected to occur at the slant distance where the UAM is closest to the assessed point.

Continuous Equivalent Sound Pressure Level L_{Aeq} characterizes the time-varying acoustic event of duration T as a constant-amplitude sound, representing the averaged sound energy over the same time period.

The Sound Exposure Level L_{AE} allows for the comparison of different time-length signals by uniformly compressing their energy into a reference time T_{ref}. The total sound energy of a UAM operation is typically normalised to $T_{\text{ref}} = 1$ s. For aircraft flyovers, L_{AE} is accurately estimated by including only those sounds that lie within 10 dB of L_{Amax}. The L_{AE} increases by 3 dB if the duration is doubled while keeping the L_{Amax} value, because the energy is doubled [14].

These metrics have been extensively applied to conventional single-aircraft and single-event operation scenarios, and are still valid to evaluate IAM platforms. However, as periodicity or repetitiveness of IAM operations are expected for the potential definition of drone corridors or regular flight paths, a group of metrics should be further generated to quantify the effect of the number of flyover events and the number of people exposed along the flight paths [3].

If a series of non-consecutive overflights n_{eve}, each producing approximately the same SPL at the receiver location, occur over a given period, the cumulative sound pressure level can be estimated by accounting for the combined effect of these events. This scenario is plausible when periodic flights of the same aircraft follow the same path. The cumulative SPL$_{\text{eve}}$ is expressed as:

$$\text{SPL}_{\text{eve}} = \text{SPL} + 10\log_{10}(n_{\text{eve}}) \quad (1)$$

This formulation captures the cumulative acoustic impact of repeated events at equal SPLs.

3.2 Perception-based metrics

Effective Perceived Noise Level EPNL was developed for assessing the annoyance characteristic of aircraft noise. It evaluates noise perception resulting from the combination of sounds from different source components, mechanisms, frequency emissions, intensity ranges, and time-series profiles. This metric is an improved version of Perceived Noise Level [14]. EPNL is calculated by measuring a sequence of 1/3-octave band spectra at 0.5-second intervals during the noise event. Each interval spectrum is examined for the presence of tones, and a tone-correction is computed to give the tone-corrected perceived noise level (PNLT). To determine EPNL, the complete set of 0.5-second PNLT values is integrated to calculate the level of the long-term steady sound.

Sound Quality Metrics SQMs are used to assess how sound is perceived by the human hearing system, considering features like tonal components, modulation effects, amplitude, and frequency [8]. These metrics evaluate subjective human sensations of sound, with a linear scale meaning that doubling a SQMs corresponds to doubling the perceived sensation. The following SQMs have been included as predictors of psychoacoustic annoyance models for UAM [15].

Loudness N is a measure of subjective sound strength, evaluated through models that account for non-linear amplitude response and critical bands. It is often considered the strongest indicator of annoyance and is measured in [sone].

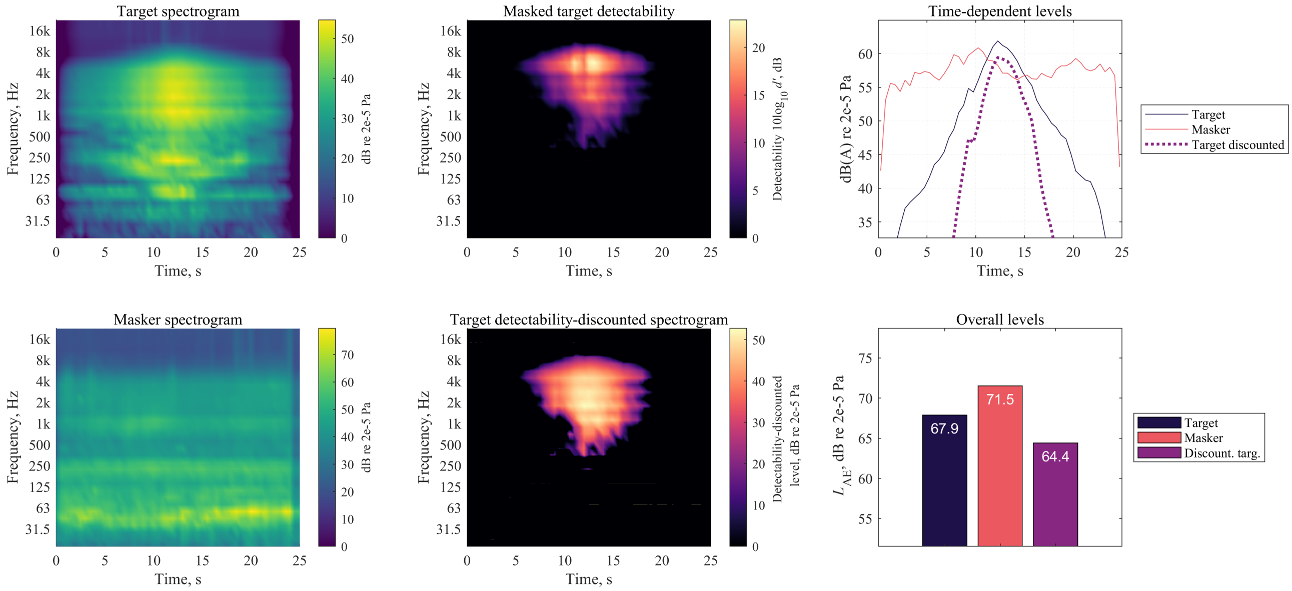

Figure 3. Example of detectability and discounting sound levels for UAS overflight (target) within urban street soundscape (masker).

Sharpness S quantifies the spectral character of a sound based on the balance between high- and low-frequency content. A sound with more high-frequency energy is perceived as sharper. It is measured in [acum].

Fluctuation Strength F assesses the perception of periodic variations in sound, comprising slow modulations (below 20 Hz, with a sensory peak ∼4 Hz) in amplitude or frequency, experienced as beating or pulsating. It is measured in [vacil].

Roughness R is similar to fluctuation strength, but it focuses on faster modulations (15-300 Hz with a sensory peak ∼ 70 Hz), causing the sound to be perceived as having a rough ‘texture’. It is measured in [asper].

Tonality T evaluates the presence of pure tones or narrow-band components in the sound. It tracks frequencies with salient amplitudes and is measured in tonality units [tu]. To evaluate these SQMs, computational tools have been implemented based on specific standards. The ImAFUSA toolkit integrates noise assessment algorithms developed in SQAT [16, 17] and RefMap [18].

Psychoacoustic Annoyance models use the aforementioned SQMs in non-linear models to assess annoyance. These models have shown good correlation with noise annoyance in jury tests. In one example [15], the 5% exceedance values (95th percentiles) are determined for each SQM. Other models have also been developed for UAS rotor sound [19]. These composite metrics have been found to be effective predictors for psychoacoustic annoyance assessment of UAM noise.

Detectability index d' incorporates ambient sound as a discounting factor for annoyance. Time series of 1/3-octave band power spectra are used to determine the time-dependent masking of the target source (the UAM vehicle) by the environment sound, affecting both audibility, and potentially, annoyance. To simplify the understanding of detectability, two scenarios can be considered. The first one occurs when the UAM signal is prominent over the ambient sound, i.e., it is clearly audible with no significant effect from the ambient sound on annoyance — for example, in a quiet environment. On the other hand, the second scenario involves a situation where the target sound is low compared to the ambient sound, rendering it partially masked, which may lead to a reduction in annoyance compared with the unmasked signal [4] — this scenario could occur environments with high levels of ambient sound.

The d' metric can be estimated from one-third octave band SPL data as a measure of the detectability of a signal. Then, discounted sound level metrics, which are determined from laboratory measurements of annoyance responses, can be derived from the target signal detectability [20]. Fig. 3 presents an example of detectability and discounted sound levels for a UAS overflight which is masked by a urban soundscape: the first column depicts the spectrograms of the target signal (a UAS overflight, upper left panel) and the masker signal (urban street soundscape, bottom left panel); the second column shows the detectability index d' of the UAS (upper centre) in presence of the masking soundscape and the UAS discounted spectrogram (bottom centre); the third column presents the A-weighted SPL time series, with/without detectability-discounting (upper right) and overall A-weighted sound exposure levels, with/without detectability-discounting (bottom right). In the example, the UAS L_{AE} of 68 dB within the ambient sound of 72 dB L_{AE} (in this case, 58 dB L_{Aeq}) is discounted by 3.5 dB.

4. CONCLUSIONS

This document presents the structure and metrics of the IAM noise assessment tool, developed within the framework of the ImAFUSA project. While this work primarily focuses on acoustic impact evaluation, it is designed to be part of a broader set of U-space assessment indicators, including societal acceptance, safety, and environmental impacts. By combining both energy-based and perception-based acoustic metrics, the IAM noise assessment tool aims to support more accurate predictions of community noise impact and contribute to comprehensive capacity assessments for future Urban Air Mobility (UAM) operations within U-space.

5. ACKNOWLEDGMENTS

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