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IMPACT OF WEATHER UNCERTAINTIES ON NOISE CONTOURS AND NOISE ABATEMENT DESCENT TRAJECTORIES

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Abstract

Aircraft noise pollution has become a serious issue at many hub airports worldwide. This research focuses on operational improvements for noise abatement, in particular descent trajectory optimization considering the meteorological effects on noise propagation. Japan Aerospace Exploration Agency (JAXA) has developed a noise prediction model taking into account the effect of wind direction and magnitude, humidity and air temperature on noise propagation. The impact of wind uncertainties on noise footprints is investigated by comparing the optimal footprints obtained under different weather conditions. Our preliminary results show that optimal trajectories can possibly be somewhat robust to wind deviations when only noise is considered, but the flight time analysis reveal the need for further investigation regarding fuel burn considerations and an extensive aircraft performance model verification, as well as increased number of weather scenarios to verify the preliminary propositions obtained here.

1 Introduction

At hub airports, aircraft noise has become a factor hindering air traffic and capacity growth. Numerous approaches have been considered and implemented, ranging from designing and building quieter aircraft to limiting operational hours of an airport. The authors have focused on operational improvements using technological advances which allow flexible descent path planning and execution.

This section presents the background of the current research, discussed what is necessary to plan and execute optimal dynamic descent trajectories which minimize noise pollution and defines the objectives of the current paper.

1.1 Background

Sustainable air traffic growth has called for the development and implementation of new technologies which allow tailored continuous descents for optimal aircraft performance and reduced environmental impact [1]. The very same flexible routing, however, can also cause high noise disturbances in airport vicinity, especially in areas which have experienced no such noise issues before [2]. Usually, the government provides subsidies to residents who live in areas experiencing cumulative noise levels higher than a certain threshold, so that the residents can soundproof their homes and this reduce the nuisance caused by aircraft noise. Such airport noise “control zones” are determined based on noise measurements and predictions, and once set they are difficult to change, as their expansion would require further public acceptance and more funds. For example, airport noise control zones of Narita International Airport, includes areas subject to cumulative noise levels of 62 dB or higher [3], so in order to avoid negative effects on citizens’ welfare and increase in the soundproof budget, new descent procedures should be designed to keep the noise footprint within the current zones.

1.2 Prerequisites for Noise Abatement Descent Trajectories

In order to be able to properly plan and execute descent trajectories for noise abatement, the following components are necessary: (a) an accurate noise model; (b) a trajectory optimization tool; (c) the ability to accurately follow the designed flight path. Regarding (a), JAXA has already developed an accurate noise prediction model considering the meteorological effects [4], as part of its DREAMS project which ended in 2015. Working on (b), we have developed an approach path optimization tool to keep the current noise levels even in the event of traffic increase [5], [6]. As for (c), at this stage of the research we assume modern aircraft capabilities and navigation techniques such as Ground Based Augmentation Systems (GBAS) which allow aircraft to follow precisely their planned flight path. Our simulations have shown that trajectory control can contribute significantly to noise abatement [6]. The optimal trajectories depend on the meteorological conditions, as weather has a twofold effect: first, it affects noise propagation and second, it affects the aircraft flight profile, thus thrust and trajectory, which in turn changes the noise source magnitude, direction and distance from the ground.

Previous work does not consider weather uncertainties, however. To the best of our knowledge, there has been no reported research on how weather uncertainties should be reflected in optimal path planning for noise abatement.

1.3 Research Goal and Current Paper Scope

This research goal is to reveal the effect of weather uncertainties on descent trajectories for noise abatement in the airport vicinity. We investigate how the noise footprint changes according to various weather conditions, in particular wind profiles, in order to develop an optimal descent trajectory tool robust to weather uncertainties. This paper presents preliminary simulation results which aim reveal potential directions for further investigations. The simulations implement an accurate noise prediction model and are based on real meteorological data.

This paper starts with a brief overview of JAXA's noise prediction model used in our research (Section 2). The simulation assumptions are shown in Section 3. Some preliminary results and analysis are presented in Section 4. Section 5 concludes the paper and gives a brief overview of the planned future works.

2 JAXA's Aircraft Noise Prediction Model

2.1 Aircraft Noise Metrics- General Overview

Noise is usually defined as unwanted sound, and can physically be described as pressure variations (waves) of various frequencies. A common noise metric is the instantaneous sound pressure level, which describes the pressure variations at a certain location (i.e. distance from the source) at a single time. Assuming a noise source at a given distance *r* from the observer, the instantaneous sound pressure level for a frequency f is denoted as $L_p^f(r)$. Often, it is convenient express the noise as one single value, rather than dealing with separate values for each frequency. This is done by introducing the so-called A-weighting. A-weighted sound levels $L_A$cover the audible frequencies between 20 Hz and 20 kHz and put different weights on frequencies to compensate for human hearing sensitivity. A-weighted sound pressure level L_A is generally accepted for community noise measurement, although there has been dispute over the appropriateness and accuracy of such a universal application [7]. Once the weighted sound level L_A is determined, the maximum sound level L_{Amax} can be found. The metrics presented so far are instantaneous, i.e. they do not consider the duration of the noise. In order to account for noise duration, sound exposure level $L_{AE}$is used. L_{AE} is calculated as the time integral in which L_A is within 10 dB of L_{Amax}, over the squared weighted sound level (please refer to the shaded zone in Fig. 1. L_{AE} reflects both the noise loudness as well as its duration, and is therefore a measurement of the entire noise event.

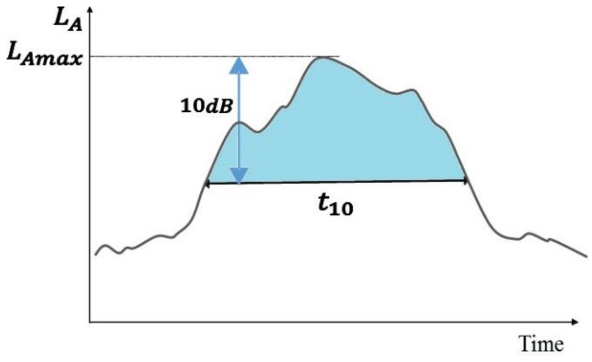

Fig. 1. Maximum sound level and sound exposure

The cumulative noise of multiple aircraft L_{den} used in Japan is determined as follows:

$$L_{\mathrm{den}} = 10\log_{10}\left(\frac{1}{86400}\left(\sum_{\mathrm{i=1}}^{\mathrm{N_1}} 10^{\frac{L_{AE}}{10}} + \sum_{\mathrm{j=1}}^{\mathrm{N_2}} 10^{\frac{L_{AE}+5}{10}} + \sum_{\mathrm{k=1}}^{\mathrm{N_3}} 10^{\frac{L_{AE}+10}{10}}\right)\right) \quad (1)$$

where $\mathrm{N_1}$, $\mathrm{N_2}$ and $\mathrm{N_3}$ are the number of aircraft during the day, evening and night, respectively. L_{den} is the value used to determine the noise contours around the airport and thus the areas which are eligible for financial support under government noise insulation programs. Therefore, L_{den} is the major metric used throughout this research.

2.2 Overview of JAXA's Model

JAXA's aircraft noise model follows the steps described above. It first calculates time series of instantaneous noise levels on arbitrary positions $L_p^f(r)$.The noise at the observer depends on the aircraft type, the distance to the aircraft, its heading (noise propagation is directional, so the direction of the engines matters) and engine power settings, for example. It should be noted that JAXA's model does not distinguish among specific aircraft noise sources such as airframe noise and engine noise, but considers the aircraft as a whole.

Experiments conducted by JAXA [8], as well as past research in the area of acoustics [9] have shown that weather affects sound propagation. The weather parameters considered in JAXA's noise model are wind direction and velocity, as well as atmospheric temperature and humidity. Ground effects need to be considered as well.

JAXA's noise model calculates the instantaneous sound pressure level as follows:

$$L_p^f(r) = L_w^f + \Delta L_{\mathrm{dir}}^f - 11 - 20\log_{10}(r) + \Delta L_{\mathrm{grnd\&met}}^f + \Delta L_{\mathrm{atm}}^f \quad (2)$$

In the above equation, f is octave band center frequency [Hz], r is distance between the source and the observer [m], $L_p^f(r)$ is an octave band sound pressure level at the observer [dB], L_w^f is sound power level of the source [dB], $\Delta L_{\mathrm{dir}}^f$ is adjustment for the three-dimensional directivity of the source [dB], $\Delta L_{\mathrm{grnd\&met}}^f$ is adjustment for ground effects and meteorological conditions [dB] particular considering vertical atmospheric temperature gradient and vertical gradient of wind speed, and $\Delta L_{\mathrm{atm}}^f$ is adjustment for atmospheric absorption [dB].

The cumulative noise L_{den} is determined following the steps described in Section 2.1. Once the time series of instantaneous noise levels at arbitrary positions are calculated, L_{Amax} , L_{AE} and L_{den} at each grid in the vicinity of the airport are calculated. Noise contours can then be determined based on L_{den}.

3 Simulation Assumptions

3.1 Aircraft Dynamics Model

The trajectory is defined by a number of waypoints, including the initial and final waypoints. The fourth-order Runge-Kutta method was applied to determine the state values between each waypoint (integral time $\Delta t = 5\ s$).

The aircraft dynamics are modeled based on Eurocontrol's BADA model [10]. This simplified point mass performance model balances the primary forces of lift, thrust, drag and weight. The equations governing the aircraft's motion are shown below:

$$\begin{aligned}
\dot{x} &= V_{TAS}\cos\gamma\sin\psi - v_{wx} \\
\dot{y} &= V_{TAS}\cos\gamma\cos\psi - v_{wy} \\
\dot{z} &= V_{TAS}\sin\gamma - v_{wz} \\
\dot{V}_{TAS} &= \frac{T-D}{m} - g\sin\gamma \\
\dot{\psi} &= \frac{L\sin\varphi}{mV_{TAS}\cos\gamma} \\
\dot{\varphi} &= \frac{\varphi_{cmd} - \varphi}{\Delta t}
\end{aligned} \quad (3)$$

where V is the true airspeed, γ is the flight path angle, ψ is the azimuth angle, m is the aircraft mass, φ is the bank angle, φ_{cmd} is the bank command angle at each waypoint, $v_{wx,y,z}$ are the wind speed components, L and D are lift and drag forces, respectively, and T is the thrust force.

$$L = \frac{1}{2}\rho \cdot {V_{TAS}}^2 \cdot CL \cdot S \qquad (4)$$

$$D = \frac{1}{2}\rho \cdot {V_{TAS}}^2 \cdot CD \cdot S$$

where

$$CD = CD_0 + CD_1 \cdot CL^2 \qquad (5)$$

$$CL = \frac{2mg}{\rho V_{TAS}^2 S\cos\varphi}$$

with parameters obtained from BADA [10] data for Boeing 777-200. The model is a simplification of the full 6 degree-of-freedom model [11], but it is sufficient for the purposes of trajectory planning and provides the necessary fast-time optimization performance. In this research we assume standard atmosphere.

All optimizations here assume that GBAS is available and aircraft can precisely follow their prescribed trajectory.

3.2 Optimization Assumptions

3.3.1 Objective Function

As mentioned earlier, the noise exposure level caused by a single aircraft L_{AE} is determined as an integration of sound level over the interval where the instantaneous noise level is more than (L_{Amax}-10 dB). The cumulative noise of multiple aircraft L_{den} is determined by "penalizing" evening and night flights (see Eq. (1)). In this research, for simplicity, we consider only day flights. Assuming only Boeing 777-200 which follow the same flight profile, cumulative noise for N aircraft $L_{\mathrm{den,N}}$ becomes

$$L_{\mathrm{den,N}} = 10log_{10}N + L_{\mathrm{den,1}} \qquad (6)$$

In this series of simulations we optimize single aircraft trajectories to determine $L_{\mathrm{den,1}}$, below referred to L_{den} only, but in order to develop simulation environment for multiple aircraft, we use the L_{den} metric. The threshold $L_{\mathrm{den\_X}}$ used in the numerical simulations for a single aircraft and analogous to the L_{den} used to define the noise control zone discussed in Section 1, is set to 26 dB. Assuming 400 aircraft landing daily, according the above equation this is equivalent to L_{den}=52 dB from arrival aircraft (note departure aircraft are subject to future work) include departure aircraft as well). All trajectories are optimized to minimize the "new" areas in respect to the baseline which experience cumulative noise levels higher than the threshold of 26 dB. The mathematical formulation of this objective is shown in Eq. 7 below.

$$\text{Minimize } fval = \sum_{\mathrm{i=1}}^{GRID\_NUM} if\left(L_{den\_ref\ i} \le L_{den\_X}, if\left(\underline{L_{den\_opt\ \ i} \ge L_{den\_X}}, 1, 0\right), if\left(\underline{L_{den\_opt\ \ i} \ge L_{den\_X}, 0.0001, 0}\right)\right) \qquad (7)$$

Here, GRID_NUM = $2.2\text{x}10^8$ is the number of grids used and the grid spacing is $2.5\text{x}10^{-5}$ deg, with longitude between 140.1 and -140.5 deg and latitude between 35.7 and 36.05 deg, i.e. an area centered around the simulated airport of about 36 km x 39 km.

The first component (underlined in yellow) minimizes the excess area outside the reference (baseline) footprint and the second component (underlined in grey) minimizes the area inside the reference one. The weight 0.0001 guarantees that any new areas outside the baseline noise footprint are much more penalized that any suppressions in the areas already included in the baseline footprint. This formulation allows us to represent the objective function as a single-value scalar. To aid the reader's understanding of the objective function, it is visualized in Fig.2.The optimization tries mainly to minimize the yellow area and keep the grey area as small as possible as well.

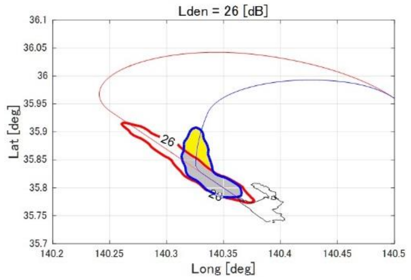

Fig. 2. Visualization of the objective function

Table 1. Optimization constraints

Description	Notation	Value
Initial coordinates	$[X_0,Y_0,Z_0]$	$[X_0,Y_0,Z_0]=[-11720,20690,1800]$[m,m,m] (local)
Final coordinates	$[X_f,Y_f,Z_f]$	$[X_f,Y_f,Z_f]=[0, 0, 0]$ [m,m,m] (local)
Initial bank angle	$\varphi_{cmd\ ,0}$	$\varphi_{cmd\ ,0}\ = 0$ [deg]
Initial glide angle	γ_0	$\gamma_0\ = 0$ [deg]
Initial true airspeed	$V_{TAS,0}$	$V_{TAS,0}=120$ [m/s]
Final true airspeed	$V_{TAS,f}$	$V_{TAS,f}=60$ [m/s]
Final segment speed change	$\dot{V}_{TAS\ ,WP6}$	$\dot{V}_{TAS\ ,WP6}\ = 0$ [m/s]
Speed decrease	V_{TAS}	$-0.5 \le \dot{V_{TAS}} \le 0$ [m/sec^2]
Azimuth angle	ψ_{WP4}	$-30 \le \psi_{WP4} \le 30$[deg] (local)
Azimuth angle	ψ_{WP5}	$\psi_{WP5}\ = 0$[deg] (local)
Azimuth angle	ψ_{WP6}	$\psi_{WP6}\ = 0$[deg] (local)
Altitude	Z_{WP6}	$Z_{WP6}= 152.4$ [m] (500 [ft])
Glide angle	γ	$-3 \le \gamma \le 0$ [deg]
Bank angle command	φ_{cmd}	$-20 \le \varphi_{cmd}\ \le 20$ [deg]
Thrust	T	$0 \le T \le 400000$ [N]
Lift coefficient	CL	$0 \le CL \le 2.5$ [-]

3.3.2 Trajectory Model and Constraints

Here, we simulate the approach to Runway A at Narita International Airport. Constraints on the airspace, waypoints location, altitude and runway alignment are imposed to reflect realistic operations. We assume a trajectory defined by 6 mid-waypoints. The waypoints definition is shown in Fig. 3. The aircraft performance constraints are shown in Table 1. Their values have been set considering a baseline descent trajectory of Boeing 777-200. The optimization method applied is interior-point method, with most coding being done in MATLAB®.

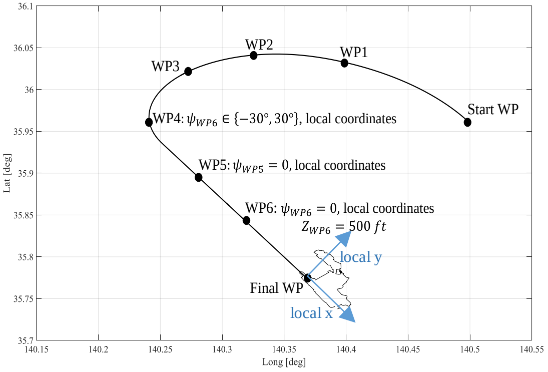

Fig. 3. Waypoints along the descent trajectory

3.3 Weather (Wind) Assumptions

As for the weather conditions, and wind in particular, we consider two cases: no wind (Wind 0), and wind data for 2009/08/10, 17 pm (Wind A), shown in blue in Fig. 4. The maximum wind magnitude is 23 kt. The data also includes temperature gradient and air humidity.

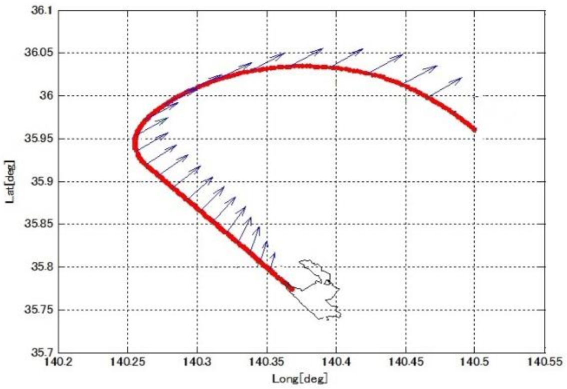

Fig. 4. Wind A- direction

3.4 Wind Uncertainty Model in This Paper

To model the wind prediction uncertainty, we take the following approach:

Step 1: The baseline noise footprint (L_{den}) is determined based on a conventional stepdown approach.

Step 2: Assuming "Wind *i*", where i=0 or A, determine the optimal descent trajectory "Traj *i*" so that the obtained noise footprint for L_{den_X} does not exceed the baseline noise footprint while maintaining as quiet descent as possible overall.

Step 3: Calculate the noise footprint for "Wind *i*"+"Traj *i*".

Step 4: Calculate the noise footprint for "Wind ≠*i*"+"Traj *i*" and compare to the results in Step 3.

In this paper, Step 4 models the wind uncertainty. The wind effect to noise trajectory optimization is twofold- first, the wind influences the aircraft motion and second it affects the noise propagation and therefore the noise footprint. In our simulation, we consider the wind effect in the aircraft motion by adjusting the ground speed only, i.e. the trajectories obtained in Step 3 and Step 4 will have the same geometry but due to the difference in the ground speed, the flight time will differ. The wind effects on propagation are accounted for as described earlier in Subsection 2.2.

4 Simulation Results and Analysis

Here, some preliminary results obtained so far are presented. We consider two specific weather conditions, as described in Subsection 3.3. The simulation results for the noise footprints and lateral projections of the trajectories are shown in Fig. 5 and Fig. 6 . The baseline (conventional step down approach) is shown in red. In practice, it can be substituted by any area, as it is only used as a reference. All trajectories are optimized to minimize the "new" areas in respect to the baseline which experience cumulative noise levels higher than the threshold of 26 dB, so all noise footprints fall within the red one.

Assume that accurate weather prediction can be made and the actual weather coincides with the weather for which the descent trajectory was optimized (Wind A + Traj A). The noise footprint and trajectory in this case are shown in black in Fig. 5. Due to the optimization, the area is smaller than the baseline. If the wind is not as predicted (here, we assume that the predicted wind was Wind A and the actual wind was zero, i.e. null wind conditions), the footprint would shrink even more. The noise footprint for trajectory A and null wind conditions is shown in amber in Fig. 5.

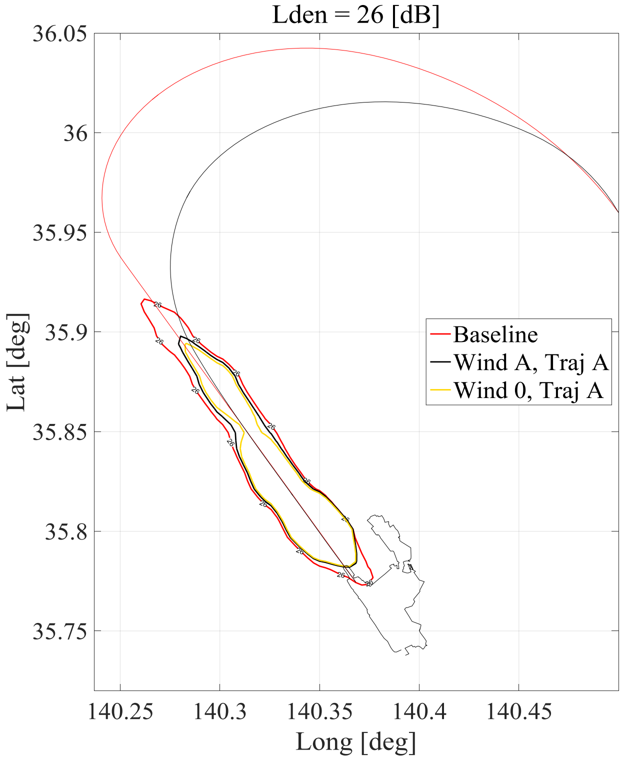

Fig. 5. Noise footprints for two wind conditions, trajectory A

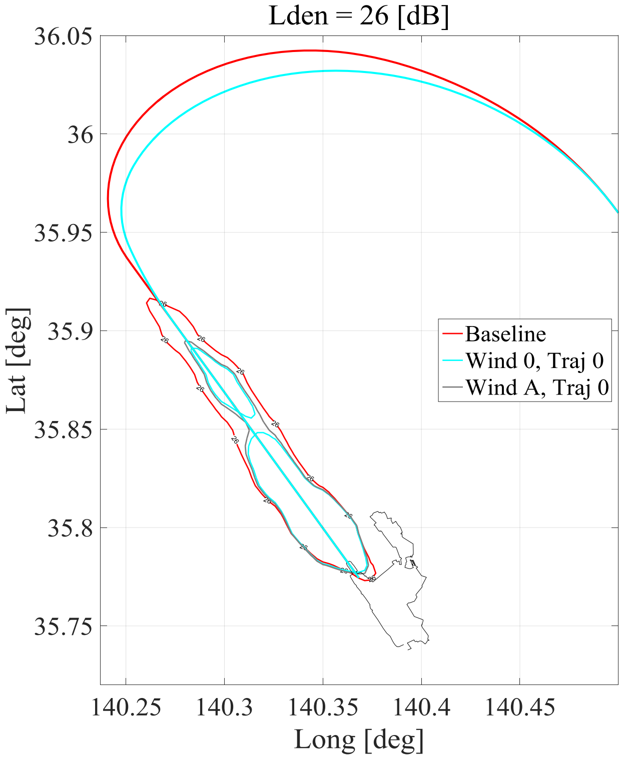

Fig. 6. Noise footprints for two wind conditions, trajectory 0

Assuming a calm day with no wind and optimizing the trajectory in this case can narrow down the noise disturbance area further, as long as the prediction for “no wind” is accurate (optimal trajectory and footprint shown in light blue in Fig. 6). However, if there is an error in the weather predictions and instead of the planned “no wind”, the wind conditions become Wind A, the noise foot print will expand to the grey area, when the aircraft follows the trajectory determined for “no wind” conditions.

A summary of the flight times and noise footprint areas is shown in Table 2. A seen from the table, in this particular wind conditions, trajectory 0 results in a smaller noise footprint for both Wind A and Wind 0 conditions. The flight time, however, differs greatly: 651 s for Wind A, Traj 0 versus 567 s for Wind A, Traj A. There are two possible reasons why the optimization for Wind A did not “find” trajectory 0 as being optimal. First, the “adjustments” in ground speed only might not be sufficient to represent an accurate and flyable flight profile, and second, the optimization is generally designed to look for trajectories with shorter flight time, as it is considered that the influence on flight time on the L_{AE} integral is substantial.

Table 2. Flight time and noise footprint areas

Wind	Traj	Time [sec]	Area [km^2]
A	A	567	32.2
0	A	519	27.9
0	0	618	27.3
A	0	651	30.9

The flight time difference also implies great difference in fuel burn. This simulation did particularly model fuel burn, but with 84 s difference in flight time it will be safe to say that trajectory 0 would consume more fuel than trajectory A in Wind A conditions. Besides, further increase in the wind scenarios is to be implemented in order to obtain more general results on the wind disturbance effects. Detailed analysis of these points will be a subject of future studies.

5 Concluding Remarks

This paper presented preliminary results on the impact of weather uncertainties on descent trajectories optimized for minimal noise disturbance in the airport vicinity. It was shown that the noise footprint changes significantly with wind conditions. Accurate wind prediction can lead to a descent trajectory with short flight time and small noise footprint. The preliminary results implied that noise footprints can be potentially robust to wind disturbances, but the flight time will change significantly. Simulation results revealed that a possible tradeoff between fuel burn and noise exists.

The current optimization technique searches for noise optimal trajectories among profiles with shorter flight time, but this might not necessarily be true in all conditions. In order to verify the preliminary results obtained here, the authors are planning further numerical simulations with a more detailed flight model and simulator tests to assess the flyability of the generated profiles. Investigation of fuel burn for the obtained trajectories is also a subject of future work.

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