

Trajectory Management for Aircraft Noise Mitigation

Towards Future ATM/CNS (EIWAC 2009)

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Abstract: This paper gives an overview of aircraft trajectory management aimed at producing noise abatement procedures. Area Navigation (RNAV) concepts play an important role in the design of flexible and, therefore, noise friendly depart or approach procedures. In addition, the lowest dispersion of RNAV tracks help to contain noise footprints in a smaller area if compared with footprints that are produced when conventional procedures are flown. However, RNAV turns still produce a significant amount of dispersion because of different aircraft performance and different Flight Management Systems (FMS) implementation. Noise exposure can be also mitigated if the aircraft trajectory is conveniently modified in the vertical plane. In this work, a brief overview of different lateral and vertical noise abatement strategies is given. Theoretical optimal trajectories are also assessed presenting some results of previous research done by the authors. The annoyance produced by aircraft noise in different noise sensitive locations is taken as minimization objective. This annoyance not only takes into account the measured acoustic values but also other important aspects that will affect the perceived annoyance by the population. The concept of equitable trajectories is also presented, where noise annoyance is minimized in the worst noise sensitive location and not as an average value for all locations.

Keywords: noise abatement procedures, trajectory management, RNAV navigation, noise annoyance, optimization.

1. INTRODUCTION

The noise produced by aircrafts during take-off and landing operations is a very serious ecological and social problem. The forecast in the demand for air transportation and the high levels of urbanization around airports make aircraft noise mitigation one of major drivers for the development of new airborne capabilities and flight procedures. Noise, is generally defined as an unwanted sound and its negative effects can be appreciated physiologically but also psychologically [1]. For an aircraft, two main sources of noise can be considered: aeronautical noise and engine noise. The aeronautical noise is the consequence of the friction of the air along the aircraft (wings, fuselage, landing gears, aerodynamic actuators, etc.) and the noise power can be considered to be proportional to the cube of the relative air-to-aircraft speed or True Airspeed (TAS). The powerplant noise is related to the four main components of the engines: compressors, turbines, combustion chamber and exhaust nozzle. Lighthill's *eighth power law* states that the acoustic power radiated by a jet engine is proportional to the eighth power of the jet speed and presents a directional distribution [2].

On departure procedures, high levels of thrust are used and, therefore, most of the noise comes from the powerplant. On the other hand, for arrivals and approaches, aircraft use much less thrust and aerodynamic noise becomes the main source, especially with high flaps/slats deflections or when the

landing gear is deployed. Although arriving aircraft are less noisy than departing ones, during an approach aircraft descend towards the runway on a shallow glide-slope (typically 3 degrees) and, therefore, they are closer to the ground for much more time if compared with a departure, where the aircrafts quickly gain altitude.

Modern aircraft with 4D-capable Flight Management Systems (FMS) will be able to plan fuel-efficient and noise optimized approaches or departures. This paper gives an overview of aircraft trajectory management aimed at producing noise abatement procedures. Section 2 deals with lateral trajectory management and, in particular, RNAV issues are addressed. Section 3, in turn, explains how noise can be mitigated by modifying the vertical profiles of the procedures. Finally, section 4 shows some work which has been done at research level for the optimization of noise abatement procedures where the annoyance is considered as the optimization criterion.

2. LATERAL TRAJECTORY MANAGEMENT

As it is well known, conventional navigation, which is based on overflying a set of radionavigation aids, has shown some limitations in last years due to the increase of air traffic. Area Navigation (RNAV) was first introduced, in Europe, by April 1998 and is considered as a vitally important contribution to the development of an optimal en-route operating environment in European airspace. Aircraft equipped with suitable systems can fly RNAV routes, which are

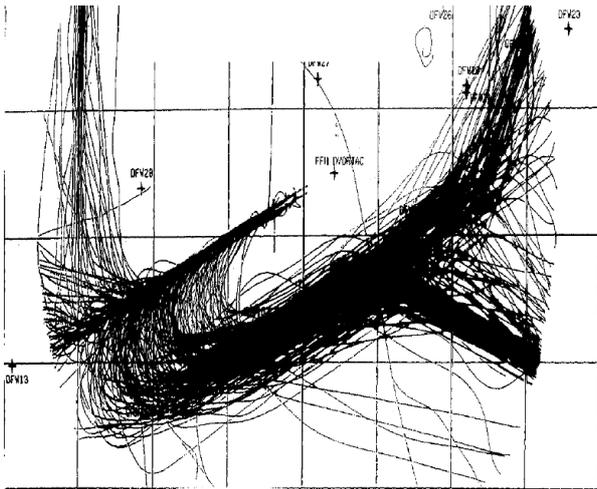


Figure 1: Radar tracks corresponding to conventional arrivals at Frankfurt airport. (Source: Sourdine II project [3])

defined between arbitrary waypoints that do not necessarily have to be placed over radionavigation aids as it happens with conventional navigation procedures. This concept is possible thanks to the on-board Flight Management Systems (FMS) that continuously calculate the position of the aircraft using data from one or several sensors. RNAV positioning can be done with VOR-DME positioning, DME-DME positioning, by using Inertial Reference Systems (IRS) or even with Global Navigation Satellite Systems (GNSS).

RNAV navigation provides not only flexibility in the procedure design but also the flown tracks turn to be more accurate, giving a much lower dispersion around the nominal track than in conventional navigation. For example, figures 1 and 2 show the flight tracks corresponding to a Standard Terminal Arrival Route (STAR) at Frankfurt airport, in Germany. In Figure 1 the flight tracks corresponding to a STAR based on conventional navigation are shown, while in Figure 2 the tracks correspond to same procedure when flown by using RNAV equipped aircraft.

It is obvious that RNAV navigation is one of the main key enablers for new noise-friendly aircraft procedures. However, despite RNAV procedures are being implemented gradually worldwide not all the aircraft are equally equipped and, for compatibility issues conventional procedures are still widely used in some major airports. In addition, RNAV implementation is not as easy as the concept turns to be. As procedures were implemented at different locations it was identified almost immediately that aircraft equipped with different FMS were not all flying the same ground paths and nor do they turn or descend at the same point in space. The result is that aircraft tracks are not as predictable as many initially believed they would be. There are four primary elements that contribute to variations in the aircraft RNAV ground track: FMS equipment installed on the aircraft, procedure coding into FMS databases, aircraft to FMS interfaces and associated aircraft performance capabilities, and flight crew procedures [4].

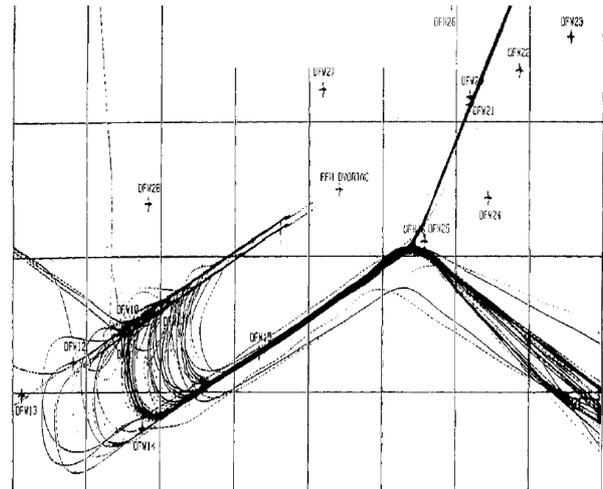


Figure 2: Radar tracks corresponding to RNAV arrivals at Frankfurt airport. (Source: Sourdine II project [3])

2.1 RNAV implementation

As explained before, a RNAV system receives data inputs from various sensors and also databases, computes aircraft position, interprets a flight plan, calculates what is required to achieve the desired flight path and then sends pitch or vertical speed/path and roll to the Flight Control Computers, which, in turn, will command the flight surfaces directing the aircraft on a particular path generated by the FMS.

The interpretation of a published procedure into a format that the aircraft FMS can interpret is a critical issue, because in RNAV navigation the pilot is not longer flying “a chart” but it is the FMS which is flying “a database”. To facilitate this interpretation there is a database standard published by Aeronautical Radio, Inc. (ARINC): the ARINC 424 standard [5]. This document details how navigation databases for FMSs are to be coded. One of the most important elements of this coding is that of *Path Terminators*, which provide the means to translate terminal area procedures, such as SIDs, STARS and approach procedures, into FMS readable coding. Each Path Terminator is made up of a two letter code that defines a specific flight path and a specific type of termination for that flight path. It is important to note that there are 18 different published versions or supplements of the ARINC 424 standard and, therefore, not all existing FMSs have been implemented in the same way and in the same period. In practice, this leads to some track dispersion around the RNAV nominal path, especially during turns, but it means also that not all Path Terminators can be flown by all RNAV equipped aircraft.

2.2 RNAV turns

One of the most relevant issue is how the turns are conducted when using RNAV navigation. There are two types of RNAV waypoints: fly-over waypoints and fly-by waypoints. In a fly-over waypoint (see Figure 3) the aircraft must overfly it before directing to the next flight plan leg. In Figure 4 a fly-by turn is shown.

Here the aircraft is allowed to anticipate the turn in order to perform it smoothly and efficiently. The Distance Turn Anticipation (DTA) is the distance preceding a fly-by waypoint at which an aircraft is expected to start a turn to intercept the course of the next segment. DTA values are based on the true airspeed at which a turn is carried out, wind speed and direction, bank angle limitations and degrees of track change required for the turn.

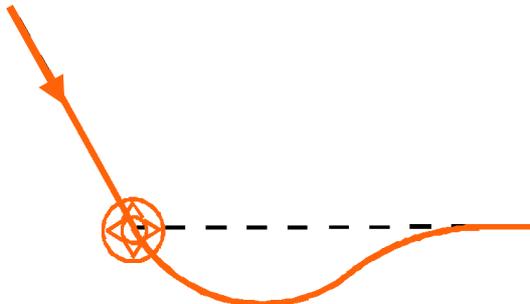


Figure 3: RNAV fly-over waypoint

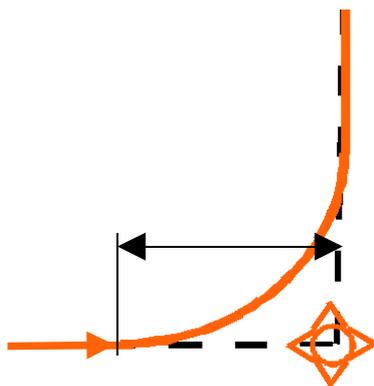


Figure 4: RNAV fly-by waypoint.

The way the aircraft proceeds from one leg to another will depend on the coded Path Terminators. For example, after a fly-over waypoint one can proceed *Direct* to the next *Fix* (DF Path Terminator) or the aircraft may join the *Track* between the two *Fixes* (TF Path Terminator). The ARINC 424 standard specifies 23 different path terminators despite FMSs usually can execute a small set of them. The basic and recommended Path Terminator for procedure designers is the Track between Fixes (TF) because all FMS implementations can perform it. However, as explained before, different aircraft, equipped with different FMS, flying at different speeds with different wind conditions will compute different DTA values for the same turn in a given fly-by waypoint. This will produce a certain ground track dispersion that may turn ineffective a noise abatement procedure.

There is another Path Terminator that specifies a constant radius turn between two waypoints: RF (*Radius to a Fix*). This Path Terminator is still a

recommended function for P-RNAV equipments and is not implemented in all FMS. During a RF leg, much higher accuracy throughout the turn is achieved because the aircraft is continuously adjusting the bank angle in order to perform the turn with a constant radius.

Figure 5 shows the radar tracks corresponding to the beginning of the SPIJKERBOOR (SPY) departure from runway 24 at Schiphol airport in The Netherlands. At 4NM after take-off, the aircraft may perform a right turn of almost 180° course change. For aircraft equipped with RNAV systems this turn corresponds to a Track between Fixes (TF) leg after a turning fly-by waypoint. For conventional equipped aircraft the turn is performed after reaching 4NM after take-off.

The nominal path of this procedure passes in between two populated areas: Nieu Vennepe and Hoofddorp. However, due to aircraft flying with conventional radionavigation means and due to the different turn anticipation distances for aircraft flying with RNAV equipment, the dispersion of ground tracks during the right turn is quite significant having a bad impact on the noise footprint over the population areas. On the other hand Figure 6 shows the same procedure when the right turn has been coded as a RF leg instead of TF leg. These experimental results were conducted by KLM in a pilot project aimed at showing the benefits of the RF Path Terminator for noise abatement procedures. As it can be seen in the figure, the dispersion of the aircraft flying this leg type is significantly smaller.

As explained before, RF legs are not widely available in all FMS systems flying nowadays. Therefore, there are still few airports that enforce this kind of functionality to their operators. An example of current RF procedures for noise abatement purposes (as well as for not overflying restricted airspace) are these published at Ronald Reagan National Airport, in Washington DC (USA). Figure 7 shows the approach to runway 19. As it can be seen, a set of RF legs are published after SETOC waypoint in a configuration that the aircraft overflies as much as possible the Potomac River.

3. VERTICAL TRAJECTORY MANAGEMENT

Acting in the vertical plane of a trajectory is also a very efficient method to mitigate aircraft noise if, for example, lateral adjustments are not possible and the trajectory must overfly certain populated regions. There are several ways to improve the noise footprint if the vertical profile is optimized. Unlike lateral trajectory modifications, a given vertical trajectory profile will closely relate thrust settings with flight path angles and aircraft speed during the procedure.

Some vertical trajectory improvements have been used extensively in the past, while other techniques are still

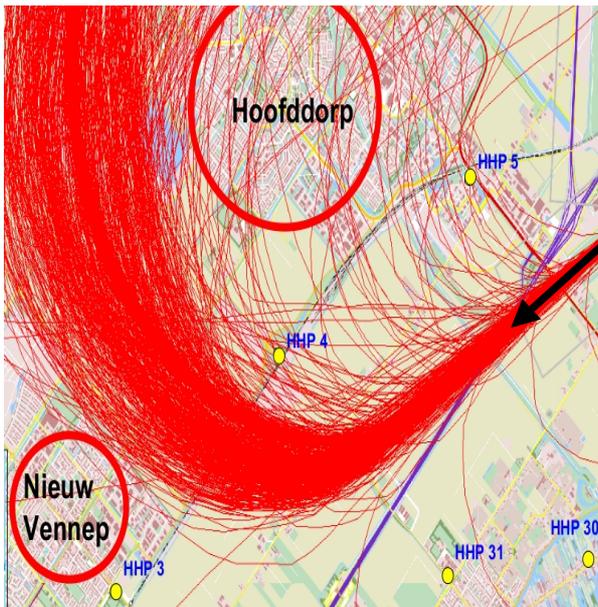


Figure 5: Radar tracks corresponding to the initial turn of the Spijkerboor departure from runway 24 at Schiphol airport. Set of aircraft using conventional and RNAV navigation with no RF leg capability (Courtesy of Theo van de Ven, KLM).

under testing or validation phases and, sometimes, waiting for new technology improvements in aircraft and ATM systems. Next, a summary of existing and forthcoming Noise Abatement Procedures (NAP) is provided for both depart and arrival/approach phases.

3.1 Approach and arrival NAPs

3.1.1 Increase the ILS interception altitude

ILS glide-slopes are usually intercepted after a flat segment (the intermediate approach segment) at altitudes ranging from 2000 to 3000 ft. Increasing this interception altitude will keep a higher vertical distance from the ground during these flat segments, where higher thrust is normally required. This technique is already being applied in many airports and does not impact, in general, on the airspace capacity besides ATC should give attention to monitor traffic on longer final approaches [6].

3.1.2 Higher ILS glide-slope angle

The standard ILS interception angle is 3° and, according to the ICAO PANS-OPS document [7] the maximum angle is 3.5° for CAT I approaches and remains 3° for CAT II-III approaches. In exceptional cases this angle can be increased, like for example in London City Airport [8]. The main reason for these higher angles is, in general, obstacle clearance issues in the final approach segment being the potential noise reduction a collateral benefit from these procedures. However, this technique has important drawbacks as, for instance, special crew trainings and aircraft certification issues.

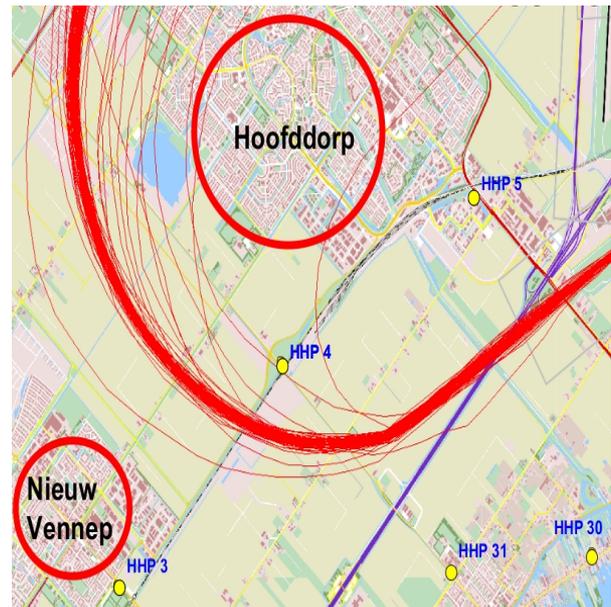


Figure 6: Radar tracks corresponding to the initial turn of the Spijkerboor departure from runway 24 at Schiphol airport. Subset of aircraft using RNAV navigation upgraded with RF legs capability. (Courtesy of Theo van de Ven, KLM)

3.1.3 Dual landing thresholds

Dual landing threshold allows the overall noise contour to be shifted towards the airport by enabling light and medium aircraft to perform approaches to a displaced threshold, thus reducing final approach spacing and runway occupancy time, thus increasing arrival capacity. However, dual landing threshold requires a dedicated implementation study for suitable runways [9]

3.1.4 Low Drag Low Power (LDLP) approach

This technique is currently widely used and drives the aircraft in clean configuration (i.e. with flaps and slats retracted) as long as possible as well as with the landing gear up. This reduces aerodynamic noise produced by these elements even if it requires to fly the aircraft at higher speeds increasing aerodynamic noise on the other hand. The extension of the landing gear is one of the biggest sources of drag and noise and drag has to be compensated by increasing engine thrust. This procedure has some minor disadvantages regarding capacity and ATC aspects. In fact, reduced flap settings during final approach leads to a higher final approach speed, which may result in a reduction of airport capacity by increasing runway occupancy time [3].

3.1.5 Continuous Descent Approaches

During a Continuous Descent Approach (CDA) the aircraft performs a thrust-idle flight until a point before ILS-Localizer interception, reducing considerably the noise footprint during the descent. With current flight guidance systems two main different types of CDA can be flown: fixing speed profiles (leaving free the vertical profile) or fixing the

values. The second most important contribution is that the annoyance minimization is performed in a way that the worst noise sensitive location is taken into account for the minimization algorithm.

4.1 Noise annoyance

The annoyance or perception of the acoustic noise describes the relation between a given acoustic situation and a given individual or set of persons affected by the noise and how cognitively or emotionally they evaluate this situation.

One of the acoustic metrics most widely used is the maximum sound level (L_{max}) of a single sound event (like a flyover). However, the time duration of the event (i.e. the exposure to noise) is also an important component to be measured. In this context, there are several different exposure based metrics such as the Sound Exposure Level (SEL), which measures the sound level of a one-second event equivalent in acoustic energy to the original event. This metric allows comparing events that vary in duration.

An other widely used metric is the LAEQ or equivalent sound level metric, which is an accumulative measure of the perceived sound exposure during a 24-hour period. The Day-Night average sound level metric (DNL) adds a 10 factor penalty multiplier to night noise events (occurring between 22h and 7h) taking into account their greater intrusiveness and eventual sleep disturbance. Other metrics deal with the time or percentage of time that the noise level is above a specified noise-level threshold, considering aircraft operations during a particular time period (usually 24h). For more noise metrics and their exact computations the reader could refer to [18].

As it can be seen, all metrics and weighing scales try to model the way the sound is perceived by humans. However, these metrics are not sufficient measurements defining completely the annoyance that a particular noise produces. In addition to acoustic elements such as the loudness, the intensity, the spectra and duration there is a list of non-acoustic elements that should be taken into account to define a global annoyance figure. For example one should consider the following factors:

- Types of affected zones (rural zone, residential zone, industrial zone, hospitals, schools, markets,...)
- Time interval during the noise event (day, evening, night)
- Period of time between two consecutive flights
- Personal elements (emotional, apprehension to the noise, personal health, age,...)
- Cultural aspects (young or aged people habits, activities, holiday,...)

Therefore, the annoyance is a subjective and a complex concept which can be studied as a qualitative

form using fuzzy logic sets, as previous similar works in this area have been shown [19-22].

Fuzzy set theory is a generalization of traditional set theory and provides a powerful means for the representation of imprecision and vagueness [23].

4.2 Equitable trajectories

The optimization of noise abatement procedures involves the optimization of several objectives at the same time, such as noise, (or annoyance) at different locations, as well as some airliner or ATM considerations (like fuel, time or aircraft emissions). Therefore, the goal of the optimization process is to find the best trajectory minimizing a given set of optimization criteria.

4.2.1 Multi-objective optimization

The word minimize means that all the objective functions may be minimized simultaneously. If there is no conflict between the objective functions, then a solution can be found where every objective function attains its optimum. In this case, no special methods are needed to solve this multi-objective problem, but unfortunately such trivial cases does not correspond with the problem tackled when optimizing NAPs. The objective functions are in general conflicting, meaning that a trajectory that produce acceptable values for a given criterion may lead to very poor results on other criteria. Because of the contradiction and possible incommensurability (i.e. merging objectives in different units) of the objective functions, it is not possible to find a single solution that would be optimal for all the objectives simultaneously. In addition, there is no natural ordering in the objective space because it is only partially ordered.

However, there are some of the objective vectors that can be extracted for examination. Such vectors are those where none of the components can be improved without deterioration to at least one of the other components. This definition is usually called *Pareto Optimality*, after the economist and sociologist Vilfredo Pareto, who developed it further.

Mathematically, every Pareto optimal solution is an equally acceptable solution of the multi-objective optimization problem. However, it is generally desirable to obtain one point as a solution. Selecting one out the set of Pareto optimal solutions calls for information that is not contained in the objective functions. This is why, compared to single objective optimization, a new element is added in the multi-objective optimization which is a *decision making process*.

4.2.2 Worst case minimization

In general, multi-objective optimization problems are solved by scalarisation. However, this methodology presents, in some cases, important drawbacks that can only be bypassed by using alternative multi-objective optimization techniques [24].

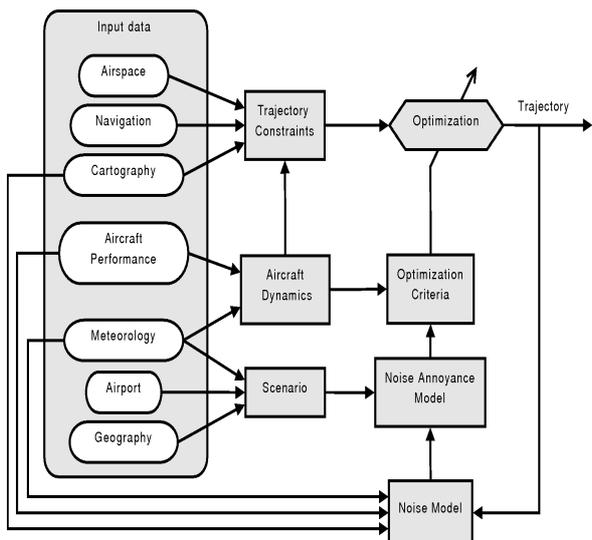


Figure 8: Noise annoyance optimization framework.

For NAPs, if we consider that all the population has the same importance, regarding their noise exposure, scalarisation techniques will assign the same weight to all noise sensitive locations, which represent different optimization criteria. In general, this will lead to a Pareto Optimal trajectory minimizing the *average noise exposure* of the overall population. In [17] the authors proposed an alternative multi-objective optimization technique that minimizes the annoyance in the *worst noise-sensitive location*. With this approach, the average noise annoyance is not minimal (as it is guaranteed when using weighting techniques). Nevertheless, when the average annoyance is minimized, it is quite probable that some locations may suffer from high values of annoyance while other locations may have low or null annoyance. In this way, the final annoyance average value may be satisfactory even if in some locations the annoyance is too high. Thus, depending of the sensitivity of the scenario, we could find that if the annoyance is slightly increased in some locations, other locations may enjoy significant noise annoyance reductions.

4.3 Numerical example

The authors [16], presented a framework to optimize departing or approaching trajectories which can be summarized in Figure 8. The involved airport, with its surrounding cartography, geography and meteorological data, will define a scenario which will be used to compute a given noise annoyance in function of the emitted aircraft noise along its trajectory. This value, together with some airliner economic considerations, will define one or several optimization criteria. Then, an optimization algorithm will compute the best departing or approaching trajectory minimizing these criteria and satisfying a set of trajectory constraints which, in turn, will depend on the dynamics of the aircraft, navigation constraints and specific airspace configurations.

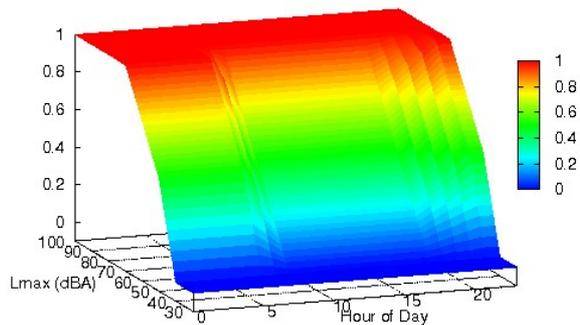


Figure 9: Normalized annoyance values for HOSPITALS

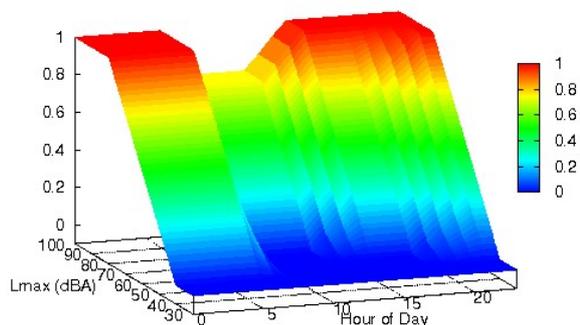


Figure 10: Normalized annoyance values for RESIDENTIAL AREAS

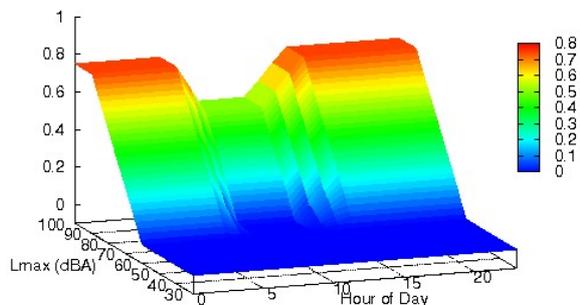


Figure 11: Normalized annoyance values for INDUSTRIAL AREAS

In this paper, the same methodology employed by the Integrated Noise Model (INM) program [25] is implemented when computing noise functions. On the other hand, the annoyance generated by the aircraft trajectories is represented by fuzzy logic sets from the fuzzyfication of the maximum sound level (L_{max}) and the hour of day where the trajectory is supposed to be flown.

Essentially, two membership set functions are defined. The first set introduces five linguistic terms to describe the magnitude of the maximum sound level (L_{max}):

- Very high noise
- High noise
- Medium noise
- Low noise
- Very low noise

A second set is related with the hour of the day, introducing the following linguistic terms:

- Morning
- Afternoon
- Night

Afterwards, a rule base is established to represent the annoyance of an event defined by the two fuzzy logic sets. This annoyance concept has been represented by the following five linguistic terms:

- Extreme Annoyance (EA)
- High Annoyance (HA)
- Moderated Annoyance (MA)
- Small Annoyance (SA)
- Null Annoyance (NA)

Finally, the fuzzy set of the annoyance is defined as a crisp set to obtain a normalized degree of annoyance. Extreme annoyance corresponds to a normalized value of 1, high annoyance takes 0.75 value, medium annoyance takes 0.5, small annoyance takes 0.25 and finally null annoyance corresponds to 0.

This fuzzy reasoning has been applied to three different noise sensitive locations that are often present around the airports:

- Hospitals
- Residential Zones
- Industrial Zones

Figures 9, 10 and 11 represent, respectively, the normalized annoyance value obtained at each different noise sensitive location in function of the maximum noise level and the hour of the day when this noise is perceived at that location. As it can be seen, the set of rule bases has been established to give an important amount of annoyance to the hospital, regardless the hour of the day, while in the residential zone a same amount of noise is less annoying during the morning that during the night or afternoon periods. Similarly the industrial zone receives more annoyance during the night or afternoon periods but being the ambient noise more important there the absolute values of annoyance are lower if compared with the residential zones.

4.3.1 Scenario description

The depart procedure from runway 02 of Girona International Airport (LEGE) is given as an example. Figure 12 shows a satellite view of the zone North of the airport, which is located in the bottom left of the picture. As it can be seen in the picture, there exist several noise sensitive zones. Residential zones are depicted with orange polygons while industrial zones

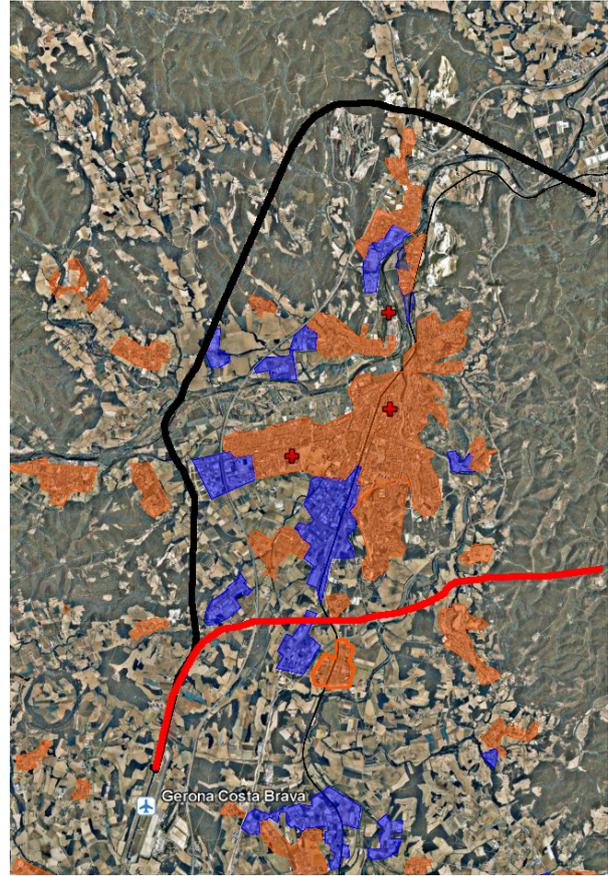


Figure 12: Noise sensitive locations affected by departures of runway 02 in Girona International Airport. In black the optimal trajectory at 10am, in red the optimal trajectory at 04am.

are represented in blue. There are also three different hospitals, represented by red crosses, that will be also taken into account in the optimization. The noise annoyance in the hospitals will be forced to be *Small Annoyance* (SA) or lower and these three locations will be considered in the optimization algorithm as constraints and not as optimization criteria. The rest of noise sensitive locations (residential and industrial zones) will be considered as optimization criteria.

4.3.2 Results

A departure of an Airbus A340-600 at its Maximum Take-off Mass of 368000 kg is optimized for the presented scenario. Take-off is supposed to be performed with CONF3 flaps/slats configuration and two different optimizations are carried out: a departure at 04 a.m. and an other departure at 10 a.m. Figure 12 shows the resulting optimal trajectories for these two hours. In red we have the optimal trajectory at 4 am. As it can be seen in the picture, after take-off, the aircraft performs a right turn passing in between some residential zones and leaving the three hospitals further north of the trajectory. On the other hand the optimal trajectory at 10 a.m. can continue northwards, approaching a little bit more the southern most hospital and avoiding industrial and residential areas with a couple of consecutive turns. Finally a right turn

is performed north of the urban area in order to join the departure point, located at the east of the figure. This trajectory could not be flown at 4 a.m. because the annoyance at this hospital would exceed the *Small Annoyance* restriction which has been imposed beforehand.

5.CONCLUSIONS

In this paper, an overview of aircraft trajectory management aimed at producing noise abatement procedures is given. One of the key enablers that will permit to design more green trajectories in the near future will be the progressive introduction of Area Navigation (RNAV) procedures in terminal airspaces. RNAV allows for flexible and noise-optimal trajectories and, in addition, keeps the dispersion of flown tracks much lower if compared with conventional navigation procedures. However, RNAV implementation is not an straightforward task and different issues arise, like for example the compatibility for certain equipments to fly advanced legs such as Radius to Fix (RF). Some results in theoretical optimal trajectories are also given in this paper. Noise annoyance produced by over-flying aircraft is modeled by using fuzzy logic in function of the received noise level during the trajectory, the sensibility of the areas being over-flown and the time of the day when the aircraft departure takes place. A non-linear multi-objective optimal control problem is solved in order to find the best trajectory for a given scenario, aircraft and hour of the day. An example is given for an A340-600 departure from runway 02 of Girona International Airport showing how this methodology would help airspace designers or airport authorities in order to implement noise-friendly procedures.

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