AN INITIAL ASSESSMENT OF BENEFITS FOR NOISE-AWARE DECISION-SUPPORT TOOLS

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ABSTRACT

A current trend in Air Traffic Management research is the development of decision support tools to aid in the sequencing and scheduling of terminal area and en route traffic as a means of increasing overall capacity and efficiency of operation. What is emerging as an increasingly important factor for terminal operations, however, is the environmental impact – in particular that of noise exposure. Thus, "noise-aware" decision support tools are needed so that the decision process includes consideration of noise exposure levels, particularly for the population within the immediate vicinity of the airport. This paper describes two elements of our on-going work in this direction. We first present results from simulation of the effects of noise-aware decision support tools at four U.S. airports having drastically different features and constraints. These results indicate the potential for noise-aware decision support tools to significantly improve noise exposure profiles. We also discuss the means by which a newly developed noise-aware decision support tool, the Noise Avoidance Planner, is incorporating a noise figure of merit into real-time, dynamic determination of sequencing and routing information. This work complements the simulation study, and provides additional indications of the benefits of including noise-awareness in terminal area decision support tools.

INTRODUCTION

As the number of operations at the nation's largest hub airports continues to grow, and as future operational concepts (e.g., NASA's Small Airport Transportation System or SATS concept) allow more aircraft to use smaller, non-hub airports, the need for environmental consideration in shaping the terminal area operations is essential to minimize adverse impact to residents in the immediate vicinity of the airport (traditionally taken as those people inside the 65dB DNL contour).

Reduction of noise exposure levels around the airport requires intelligent modification of the arrival and departure trajectories. Promising concepts being investigated in this area include low-noise approaches such as the Continuous Descent Approach (in which idle thrust levels are utilized over the majority of the descent) [1], Curved Approaches (which can potentially minimize over-flight of noise-sensitive areas) [2], and Precision Navigation Instrument Departures [2]. Similar studies in the U.S. are being conducted at MIT [3]. One downside of these approaches at this stage of their development is their tendency to require significantly higher levels of separation as well as improved navigational precision. Similar efficiency-related concerns have arisen in the context of regional airspace re-design efforts in the Chicago, Washington, and New York areas.

Terminal area air traffic control (ATC) procedures contribute to noise issues (e.g., holding one flow below another flow), but their contributions have been difficult to quantify and even more difficult to remedy. This paper addresses both of these issues. First, we quantify the impact of postulated changes (such as consolidation of base-leg extensions and strict 24-hour adherence to noise abatement procedures) in terminal procedures at four U.S. airports [4]. Second, we present an architecture for a Noise Avoidance Planner (NAP) that integrates with the Center-TRACON Automation System (CTAS) for both departures and arrivals to show how noise-awareness can be combined with efficient scheduling and sequencing.

AIRSPACE DESIGN AND NOISE METRICS

Noise exposure is inherently tied to the nature of the flight paths flown over a given population distribution. Thus, assessing the impact of flow

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changes (geometry, traffic mix, runway use, etc.) requires a set of tools for first realizing such changes and then computing the impact of the changes on noise exposure.

Airspace Design

The primary tool used to emulate the effects of noise-aware decision support tools (DSTs) on traffic patterns was Metron Aviation's Airspace Design Tool (ADT). This tool provides the capability to import tracks from various sources (ETMS, ARTS, INM, NIRS, etc.), to display them in two and three dimensions, and to manipulate them graphically in 3-space. Supporting tools allow manipulation of non-spatial characteristics, such as aircraft types, event times, and runway assignments.

Noise Impact Modeling

The FAA's Noise Impact Routing System (NIRS) was used to compute noise exposure and to quantify the impact of postulated changes in operational procedures (assumed to be enabled by the availability of noise-aware DSTs). NIRS was chosen because it provides the same noise-calculation capability as the FAA's Integrated Noise Model (INM). It also includes several additional key features that are useful for the comparison of noise effects when aircraft have their flight characteristics influenced by the different DSTs. The two most important of these additional NIRS features are the ability to follow a specified flight profile and the ability to compare noise impacts in graphical and tabular formats for alternative cases (e.g., with or without DSTs).

The input data for the noise calculations consists of detailed track and event data. Each *track* is represented by a sequence of points (latitude, longitude, altitude) defining a flight path into or out of a given airport on a given runway. Associated with each track is a set of events that represent the specific flights that are to operate on this track. Each *event* contains a description of the aircraft type, the engine/airframe type, the time of the event, and the number of events of this particular type.

Noise computation involves tracing aircraft states along the spatial track and calculating the noise impact at each population location ("centroid") due to each flight. For this purpose, a flight path is generated for each track-event combination which models the thrust required for the aircraft to follow the prescribed trajectory. This process utilizes the altitude control codes specified in the track definition in order to "fly" the prescribed track in a fashion consistent with the modeled flight dynamics of each aircraft type.

The principal noise metrics are the Sound Energy Level (SEL) and the Day-night Noise Level (DNL). SEL quantifies perceived acoustic energy across events of different intensities and durations, while DNL quantifies total noise exposure due to multiple events at different times of day. In this work, we quantify the effectiveness of postulated modifications to operational procedures in terms of the change in the size of the total population receiving 50dB DNL or greater exposure. This is consistent with increasing pressure on the aviation community to substantially reduce noise exposures below the traditional 65 dB DNL.

OPERATIONAL IMPACT OF NOISE-AWARE DECISION SUPPORT TOOLS

To quantify the potential benefits of adding noise-awareness to terminal area DSTs, we developed a number of techniques for manipulating data describing arrival and departure operations at four U.S. airports – Chicago O'Hare (ORD) and Midway (MDW), Boston Logan (BOS), and San Francisco (SFO) [4]. These airports were chosen as a cross-section of the 20 airports originally investigated in Reference [5] on the basis of data availability and the existence of potential noise-mitigation opportunities. Each of these airports provided important insights into the operational and noise-mitigation issues that will be faced by development and deployment of noise-aware DSTs. The source of the operational data used for each airport in this study is given in Table 1. Data representing an annualized average day of traffic was used in each case.

The approach used in developing changes to operational procedures was to visually study the arrival and departure traffic flows and identify potential changes in terminal area ATC procedures that might yield noise benefits (see Figure 1).

Table 1. Summary of Track and Event Data Sources for Quantification Study

Study Airport	Original Data Source	Original Data Format
ORD & MDW	Chicago TRACON Analysis Project data for 2000	NIRS tracks and events for the five configurations most often used on an annual basis
BOS	MassPort 2001 data and Metron 1997 data	Pre-INM tracks and INM tracks/events for average annual day
SFO	SFO Noise Office 2001 data	INM tracks/events for average annual day

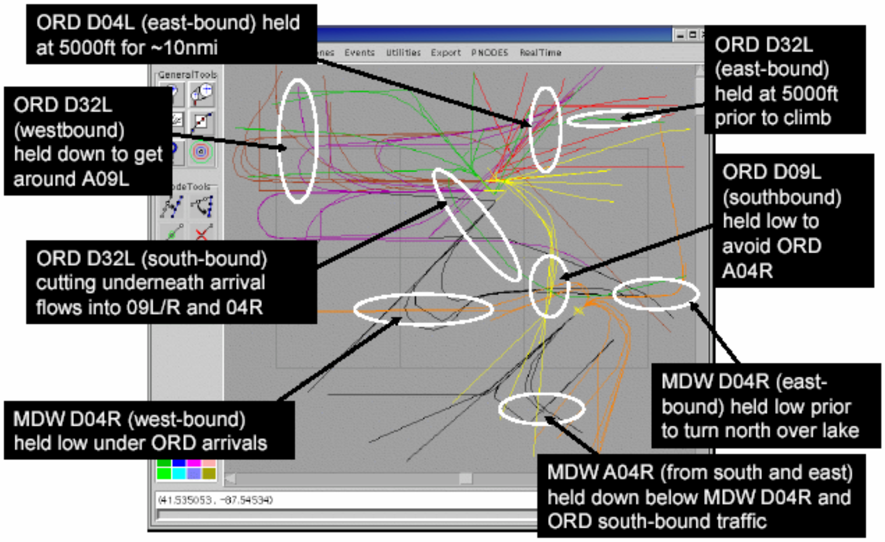


Figure 1. Identification of potentially noise-sensitive ATC procedural separation at ORD and MDW

This process included searching for interactions between arriving and departing flows and defining ways to mix these flows apart from the traditional method of procedural separation.

The primary source for the noise mitigation opportunities identified in this study was a survey of 20 airports [5] based upon contacts with local noise offices (including Fly Quiet Programs where applicable) and controllers. The result of this assessment was an enumeration of (a) the current operational features which could be improved through design of suitable noise-abatement procedures, and (b) limitations in executing current noise abatement procedures. These limitations include navigational errors, controller instruction errors (e.g., speed/heading directives), and the fact that the majority of such procedures are generally only carried out under low-demand situations (due to increase separation requirements, etc.).

Population data for the regions surrounding each airport was extracted from U.S. Census Bureau data for the year 2000. This population data extended well beyond the areas in which noise exposures would change due to effects of DSTs, so all such changes were captured in the noise calculations described below.

Types of Opportunities Simulated

The impact of new procedures and improved navigational capabilities was approximated by modifying the original operational data in different ways. Table 2 summarizes the general types of noise mitigation opportunities explored during this study, along with the relevant data characteristic modified in order to simulate the opportunity. The noise mitigation opportunities that were evaluated included "Avoid Dive and Drive", "Direct Climb to Cruise", the construction of additional runways, and the movement of "noisy" aircraft to noise-preferred runways.

Table 2. Summary of mitigation opportunities

Noise Mitigation Opportunity	Data Characteristics Modified
Noise-sensitive ATM approach procedures	
▪ Avoid dive and drive	▪ Altitude profile
▪ Avoid base leg extension into noise sensitive areas	▪ Track location
▪ Side-step approaches	▪ Track location
Route tracking (stay in precise route corridor)	
▪ Follow routes over low population areas	▪ Track location
▪ Avoid shortcutting	▪ Track location
Runway/route selection	
▪ Fanning across region	▪ Track location
▪ Route older aircraft to less noise-sensitive runways	▪ Track location, equipment type
▪ Greater usage of noise-preferred runways	▪ Runway assignment
Airport interactions within a TRACON	
▪ Modify existing procedures to consider noise	▪ Track location, altitude profiles
Nighttime operations	
▪ Extend procedures to higher traffic levels	▪ Event time
▪ Improve efficiency so that night time operations can be initiated on time	▪ Event time
Noise-sensitive ATM departures	
▪ Direct climb-to-cruise	▪ Altitude/speed profiles

As can be seen in Table 2, a large number of the simulations involved the modification of track (lat/lon) location. However, mitigation strategies requiring altitude profile modifications, such as “Avoid Dive and Drive” and "Direct Climb-to-Cruise", were also addressed. Each opportunity’s evaluation consisted of: assessing the current traffic situation (as described by operational data, aeronautical charts, etc.) and proposing new procedures or capabilities (e.g., greater adherence to noise-preferred trajectories via RNAV type capability).

Since nighttime operations are weighted so heavily by the Day-Night Sound Level (DNL) metric, a substantial effort was also made to reduce the spillage of evening-night shoulder events into the night hours and to increase the usage of noise-preferred runways for night operations. Simulation of mitigation opportunities involving wind, speed profiles, and noise-power distribution (NPD) curves were not addressed.

Figure 2 through Figure 4 illustrate several of the mitigation opportunities simulated in this manner.

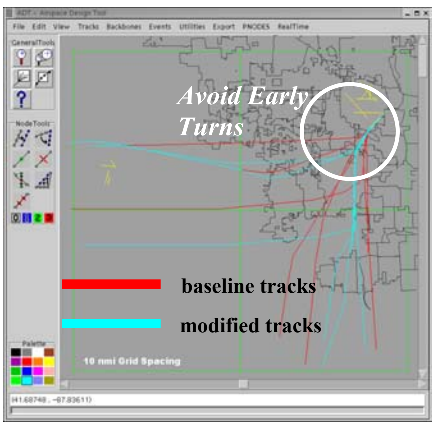


Figure 2. Improved Flight Corridor Adherence for ORD Runway 22L Departures

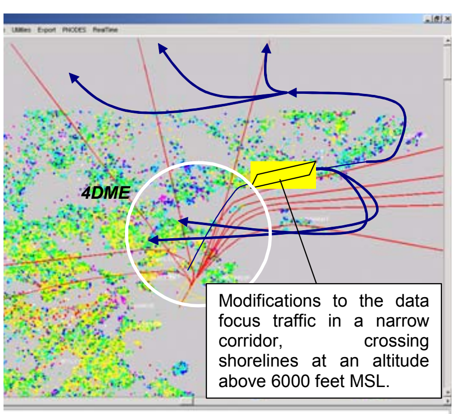


Figure 3. Increased Flight Corridor Adherence for BOS Runway 04R Departures

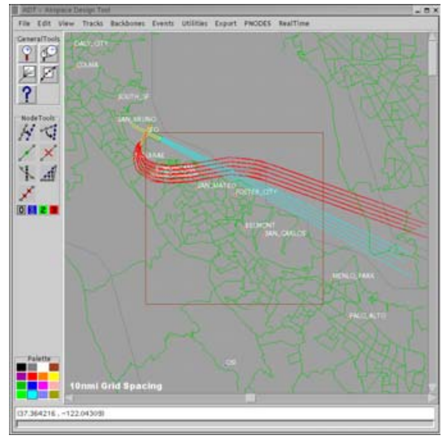


Figure 4. SFO Noisy Aircraft Departures (19L/19R) Reassigned to 10L (red = original; cyan = modified)

In each of these figures, the original tracks are shown in red, with the corresponding modified tracks indicated in cyan or blue. Figure 2 highlights a mitigation strategy for ORD which involves tighter adherence to departure corridors specified by the Chicago Fly Quiet Program – in this case, keeping departure tracks over highways for an extended period during the climb out prior to initiating their turns. Figure 3 shows a similar situation at BOS in which departing aircraft off runway 04R are postulated to have precise enough navigation to enable them to be tightly funneled over a low population area rather than being dispersed over more highly populated regions. In the case of Figure 4, the departure events from runways 19L/R were reassigned to existing tracks departing over the water on runway 10L.

Results Obtained

After modifying the track and event data to simulate the effects of one or more noise-aware DSTs – consistent with the specific elements of the traffic patterns at each airport and the population distributions encountered in the vicinity of these patterns – a noise impact analysis was carried out using NIRS.

Noise exposure was computed for the baseline (without DST) and alternative (with DST) cases, and differences between the cases were calculated. NIRS provides the capability to generate noise impact tables, graphs, and maps. The impact table and impact graph provide categorization of population centroids in noise bins of interest, and quantify the "before DST" and "after DST" effects on population centroids within each bin. The impact map provides a graphical depiction of the population centroids whose noise exposure categories are different between the baseline and alternative cases.

Impacts for future years (2006 and 2011) were obtained from the baseline and modified 2001 data by

(1) applying traffic-scaling factors that raised the 2001 traffic levels to those future levels estimated for ORD/MDW, BOS, and SFO and (2) re-calculating noise impacts at all population locations based on the new traffic levels. The chosen net measure of this noise mitigation benefit was the total number of people receiving annual DNL at 50 dB or greater.

For our initial analysis, we assumed that the proposed mitigation strategies would be implemented for 100% of the affected flights. Thus, the noise mitigation results represent the impact of 100% compliance to the noise-mitigation traffic patterns. Later, we also assessed the sensitivity of these results to partial implementation of the proposed traffic modifications where possible. This assessment was done in recognition that operational limitations related to safety and capacity might constrain the application of the suggested noise-sensitive procedures. In other words, the postulated mitigation strategies may not be 100% effective. Thus, for each noise mitigation strategy, we enumerated the potential operational limitations that might inhibit their use. We then performed a simple analysis to provide a rough estimate of the impact of partial implementation on noise exposure benefits.

As a first approximation, we have chosen to define a measure of DST effectiveness, called the DST Effectiveness Factor, which is meant to capture an estimate of the realizability of a given DST. We define this factor independently for each mitigation opportunity, since operational constraints vary across airports depending on the nature of their traffic flows. This DST Effectiveness Factor is used to scale the noise impact (measured in terms of the net change in the population experiencing noise of 50 dB or higher) to produce a more realistic estimate of the potential noise benefits. In order to compare the effectiveness of different mitigation strategies, we define a measure called the *Expected Noise Benefit* (ENB), as the product of the percentage decrease in the total population above 50dB DNL and the DST Effectiveness Factor. The ENB gives the total expected noise benefit associated with each mitigation opportunity. We provide an overall rating for each mitigation opportunity on the basis of the ENB to identify those with the highest potential value should the identified strategy be implemented.

In this portion of our work, we manipulated tracks solely to quantify noise benefits measured in terms of reduced average exposure via the DNL metric. Estimating the impact that these manipulations would have on operations was beyond the scope of this effort, but every effort was made to perform the manipulations in a manner that would not have significant operational impact.

Table 3. Categorizing Expected Noise Benefits

Category	Percent Improvement Required
High	>=10% reduction in population above 50 dB
Moderate	from 2% to 10% decrease
Low	less than 2% decrease

The summary of quantitative results in Table 4 indicates that Expected Noise Benefits vary across a broad range, from less than 0.1% to over 20%. This is due to the enormously varied traffic patterns, mitigation-opportunity characteristics, and population distributions across the airports studied. In particular:

- At ORD and MDW, 2 of the 7 mitigation opportunities studied were rated high or moderate impact. Achievement of the 2 high and moderate mitigation objectives at ORD and MDW (Preferred Flight Track Conformance and Direct Climb to Cruise) at the estimated levels of DST effectiveness represents a 15% decrease in the population above 50 dB, or over 460,000 people.
- At BOS, all 4 of the mitigation opportunities studied rated high or moderate impact. Achievement of the 4 high and moderate mitigation objectives at BOS (Arrival and Departure Corridor Adherence, Noisy Aircraft on Preferred Runways, and Night Operations on Preferred Runways) at the estimated levels of DST effectiveness represents a 47% decrease in the population above 50 dB, or over 105,000 people
- At SFO, 4 of the 7 mitigation opportunities studied rate high or moderate impact. Achievement of the 4 moderate mitigation objectives at SFO (Shoreline and Dumbarton Departures, Quiet Bridge Approaches, and Noisy Aircraft on Preferred Runways) at the estimated levels of DST effectiveness represents a 13% decrease in the population above 50 dB, or over 31,000 people

These quantitative results lead to several general conclusions: (1) DSTs can provide substantial benefits at airports that have noise-mitigation opportunities similar to those analyzed in detail here for ORD, MDW, BOS, and SFO; (2) the benefits will probably lie in the range of 10% to 50% of the population exposed at 50 dB DNL or above; and (3) such benefits are likely to be extremely attractive to airports that desire to improve public acceptance of aircraft noise, especially in light of conflicting pressures for decreases in noise impact and increases in capacity.

Table 4. Summary of Noise Mitigation Effectiveness Including DST Efficiency

Airport	Mitigation Opportunity	Net Population Noise Impact (100% effective) >50dB (2001)	>50dB (2006)	>50dB (2011)	DST Effic. Factor	ENB (>50dB) (2006)	Overall Rating
ORDMDW	**(baseline population > 50 dB DNL)**	**2,822,203**	**3,110,062**	**3,307,614**			
	Preferred Flight Track Conformance	12.4	12.4	12.0	1.00	12.40	H
	Avoid Dive&Drive	1.4	1.1	1.2	0.50	0.55	L
	Direct Climb to Cruise	8.1	6.8	6.3	0.50	3.40	M
	Noisy Aircraft to Noise-Preferred Rwys	0.2	0.5	1.0	0.75	0.38	L
	Avoid Night Spillage	5.2	5.2	5.2	0.25	1.30	L
	Shoulder Hours Ops	1.4	0.7	0.4	0.50	0.35	L
	Base Leg Extensions	0.13	0.1	0.1	0.75	0.08	L
BOS	**(baseline population > 50 dB DNL)**	**199,971**	**222,808**	**227,605**			
	Arrival Corridor Adherence	1.8	4.5	4.9	0.75	3.38	M
	Departure Corridor Adherence	16.8	17.7	18.0	0.25	4.43	M
	Noisy Aircraft to Noise-Preferred Rwys	27.0	28.9	28.9	0.75	21.68	H
	Night Ops to Noise-Preferred Rwys	35.8	36.9	36.2	0.50	18.45	H
SFO	**(baseline population > 50 dB DNL)**	**226,487**	**242,105**	**246,169**			
	Shoreline Departure	10.4	10.6	10.0	0.25	2.65	M
	Dumbarton Departure	6.9	8.1	7.7	0.50	4.05	M
	Oceanic Departure	1.0	1.2	0.74	0.25	0.30	L
	Quiet Bridge Approach	0.44	0.9	0.3	0.75	6.75	M
	Tipp Toe Approach	0.1	0.4	0.1	0.75	0.30	L
	Noisy Aircraft to Noise-Preferred Rwys	2.8	3.3	2.2	1.00	3.30	M
	Increase Head-to-Head Operations	2.5	1.7	3.5	1.00	1.70	L

NOISE AVOIDANCE PLANNER

The aforementioned study of mitigation opportunites consisted of essentially "static" changes to operational procedures. Although these changes showed potential for benefits from a noise perspective, there was no means of judging the impact of such changes on the operational efficiency of the airport. As a means of overcoming this limitation, we describe the initial development of the Noise Avoidance Planner (NAP). NAP, being developed under a Phase II SBIR with NASA Ames Research Center, is a noise-aware version of the CTAS Final Approach Spacing Tool (FAST) and Expedite Departure Path (EDP) DSTs. NAP is intended to operate dynamically in real-time to enable the FAST/EDP scheduling logic ([6]) to utilize a noise figure-of-merit (FOM) in determining path stretching and speed modifications for resolution of spacing constraints.

Currently, FAST and EDP operate on the basis of analysis categories – a set of unique states into which aircraft arriving or departing the terminal area are partitioned for the purpose of route generation, sequencing and conflict resolution. The DFW site adaptation database currently has approximately 520 unique analysis categories. For example, the category *DFW_18R_BAMBE_ JET_BEFORE_FEEDER_GATE* applies to a jet assigned to DFW Runway 18R while the aircraft is outside of the Bambe arrival metering fix. These analysis categories define the initial route for the aircraft as well as its confliction resolution sets. Associated with each analysis category is also a set of degrees-of-freedom (DOFs) that FAST and EDP utilize to realize the required path stretching and speed control for achieving the desired inter-aircraft spacing. A DOF is defined to have both FAST and SLOW limit values (e.g., the minimum and maximum extent of fanning from a particular waypoint). These FAST and SLOW limit values define the lower and upper bounds for the time required to fly along a portion of the trajectory. These bounds form the basis for spatial constraint resolution. This resolution is time-based in nature. Specifically, combinations of DOFs are sought which provide the necessary amount of delay to properly space leading and trailing aircraft at various segments along the trajectory. At present, the FAST/EDP constraint resolution process terminates once a single satisficing solution has been found. The search through the possible space of DOF combinations is currently deterministic in nature and follows a pre-defined recipe (including a fixed set of mixing ratios for the various DOFs).

From the perspective of generating noise-preferred advisories with FAST/EDP, however, this search methodology is unacceptable. What is needed is a *set* of satisficing solutions (those that satisfy all constraints) from which the best noise solution can be selected. Figure 5 illustrates this idea, showing a search through a sequence of points in DOF combination space (A_i) where multiple satisficing solutions (e.g., the green X's) are collected and compared relative to one another using a noise figure-of-merit.

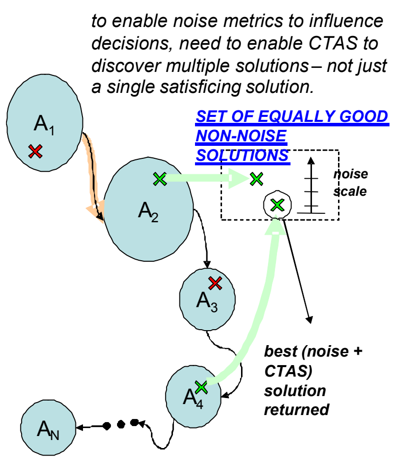


Figure 5. Change in FAST/EDP Logic Needed for Noise Avoidance Planning

Architecture

As an initial step toward introducing noise awareness into the FAST/EDP scheduling logic, we focus on the noise sensitivity of the vector (e.g., spatial) DOFs of each analysis category. As such, we define the trajectory space for a given category to be bounded spatially by the FAST and SLOW limits of its vector DOFs, assuming all other DOFs (e.g. speed DOFs) are set to their FAST limits (see Figure 6). This trajectory space defines a time band ranging from Δ_{min} (which represents no delay from the vector DOF) to Δ_{max} (which represents the most delay achievable with the vector DOF). In general, each vector DOF will have a different range of possible delay absorption values.

We can define the noise exposure for the bounds on the trajectory space by computing the SEL experienced by the population underlying the FAST and SLOW trajectories, respectively. To determine the noise exposure for trajectories between these bounds we have two options. We could choose to linearly interpolate in the noise metric (SEL) space – assuming that the noise exposure level is monotonic between the two end points. Alternatively, we can choose to interpolate in the trajectory space first, and then subsequently compute the noise exposure values for each of the interpolated trajectories. This latter approach does a better job of capturing local fluctuations in noise exposure level due to the distribution of the underlying population.

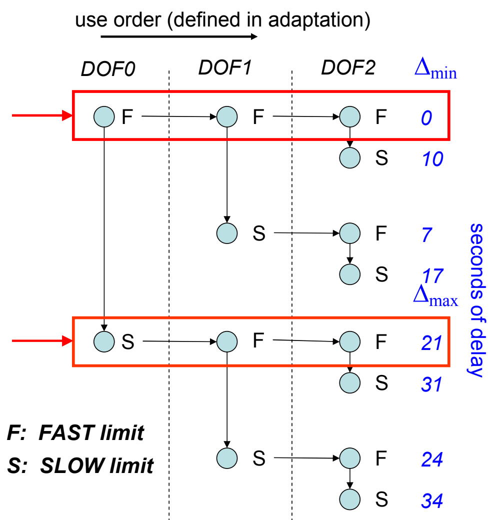


Figure 6. Defining the Endpoints of the Trajectory Space for Noise Avoidance Planning

At present, the Noise Avoidance Planner consists of two distinct off-line processing steps combined with real-time data handling. The first step stimulates the FAST/EDP scheduling logic to generate the interpolated set of trajectories for each analysis category. The second step then processes these trajectory sets with NIRS to compute a noise sensitivity for each analysis category (and its associated vector DOF). These sensitivities take the form of noise exposure curves as a function of DOF value (i.e., as a function of delay absorption). Note that since the off-line steps are solely a function of the site adaptation and population distribution, they only need to be performed once in their entirety. Results of this off-line processing are stored in a database for access during run-time. Localized changes to the site adaptation can be accommodated simply by reprocessing any new or revised analysis categories. Changes in population distribution due to new census data will require reprocessing of all analysis categories.

The run-time usage of the noise sensitivity data is anticipated to consist of a simple table lookup into the database to return the tradeoff between noise exposure and delay. The noise-aware version of the FAST/EDP scheduling logic will be modified to incorporate this sensitivity data to search for a combination of DOFs which minimizes the noise exposure level whenever possible. For this purpose, we assume noise preferred values of the vector DOFs will be selected and values of the speed DOFs will be chosen to achieve the remaining amount of delay needed for traffic separation. Figure 7 illustrates the basic components of the FAST/EDP architecture used to develop the initial NAP functionality.

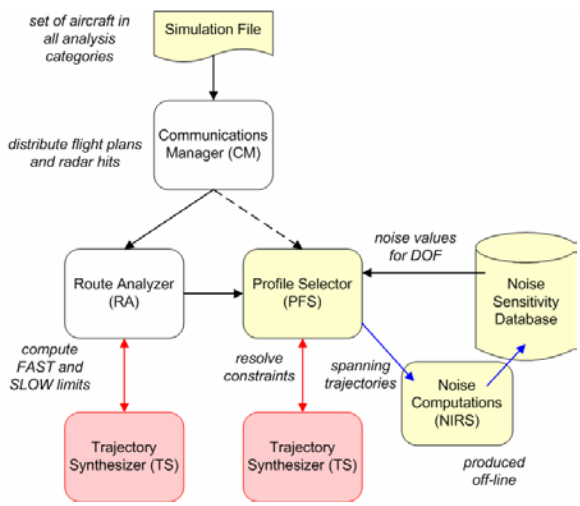


Figure 7. Basic Noise Avoidance Planning Architecture (NAP-specific components yellow)

Off-Line Noise Computation

As shown in Figure 7, the noise sensitivity generation process is driven by a Simulation File containing a set of aircraft radar hits which correspond one-to-one with the set of analysis categories for a particular site adaptation database. Our process for creating the Noise Sensitivity Database leverages off of the existing FAST/EDP flight processing logic. In the current architecture, the Communications Manager (CM) is used to distribute the flight plans to both the Route Analyzer (RA) and Profile Selector (PFS) processes. The CM then distributes the radar hits to the RA which classifies the aircraft into a particular analysis category. The RA uses the category's binary analysis tree (specifying the order in which its N DOFs are to be used in absorbing delay) to define the set of 2^N unique combinations of DOF limits. These combinations correspond, for example, to each of the paths to the right-most leaves of the tree in Figure 6. For each of these combinations of FAST and SLOW DOF values, the Trajectory Synthesizer returns the corresponding 4-dimensional trajectory. From this trajectory, the aircraft's time of arrival to the meter fix and/or runway can be computed.

The set of arrival times is then passed to the Profile Selector (PFS) which uses its own TS to define the initial trajectories for all flights. Note that, unlike the RA which is event-driven in nature, the PFS scheduling process is initiated every six seconds. As such, the scheduling process is applied to all flights which accumulate between updates. Since we have established (in the Simulation File) only a single aircraft in each analysis category at any given time, there are nominally no conflicts for the PFS to resolve. Thus, no iteration through the DOF analysis tree is initiated.

Since our approach hinges on the exploration of the vector DOFs, we have modified the PFS logic to initiate a *pseudo resolution cycle* in which we set the amount of delay to be absorbed incrementally between the FAST (zero seconds delay) and SLOW (Δ_{max}) limits. Each time through this cycle, the TS returns a resolution trajectory which is then recorded to a file. The set of stored trajectories is then post-processed using NIRS to develop the corresponding noise exposure values. In this fashion, we are able to span the trajectory space for each analysis category and define the noise sensitivity curve as a function of the category's vector DOFs. Examples of the exercising of the vector DOFs are given in Figure 8 and Figure 9 for DFW arrivals on 18R over BAMBE (*FAN FROM WAYPOINT*) and FEVER (*BASELEG EXTENSION*) respectively.

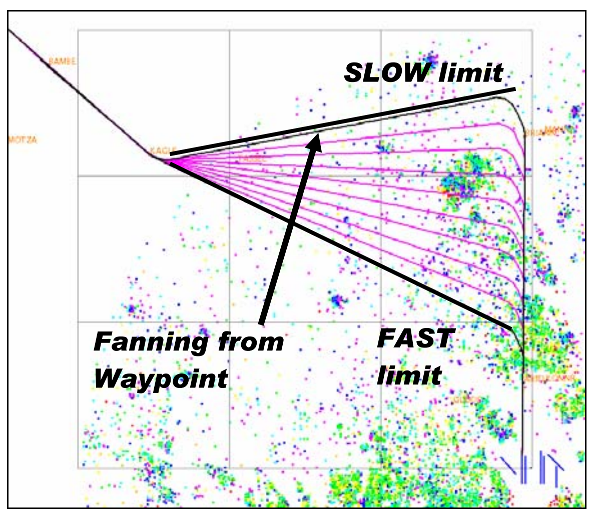
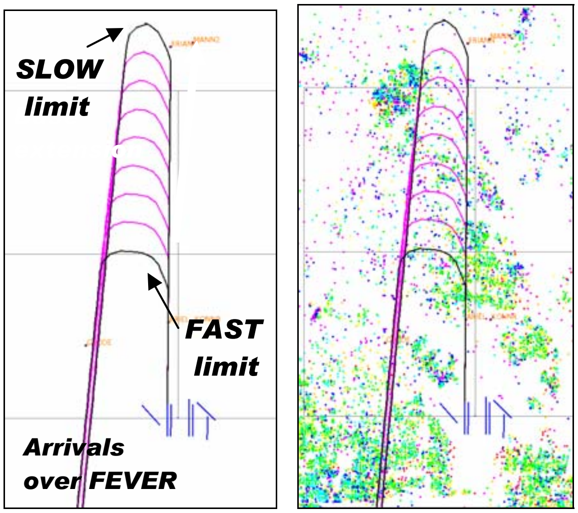


Figure 8. The trajectory space spanned by the *FAN FROM WAYPOINT* DOF for arrivals over BAMBE



(a) (b)

Figure 9. *BASE EXTENSION* DOF for jet arrivals into runway 18R at DFW over FEVER (a) without and (b) with underlying population shown.

Results

As an initial demonstration of the value of providing a noise figure-of-merit to FAST/EDP, we present the variation in Sound Energy Level (SEL) exposure over the space of trajectories for the two analysis categories described in the previous section. The variation (for population centroids experiencing greater than 55dB of exposure) is shown in Figure 10. We present the results in terms of the percentage of the total population (within a 30 nautical mile radius of DFW, or 4710027 people) experiencing SEL values greater than 55dB. This figure shows that interpolating linearly (in noise space or SEL value) between the FAST and SLOW limits can provide a rather poor estimate of the actual noise impact for the intermediate trajectories.

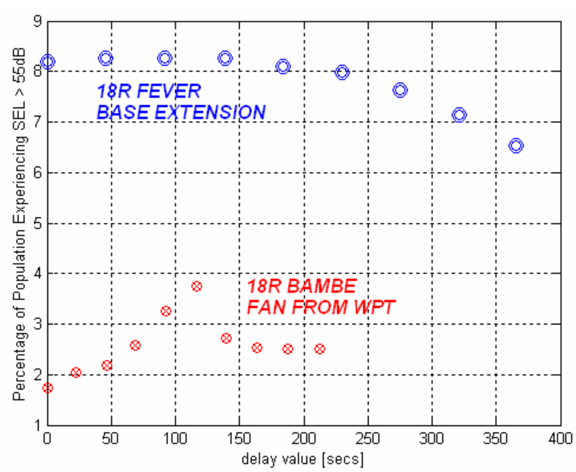


Figure 10. The variation of noise SEL with respect to delay absorption for several DOFs

Instead, by interpolating in DOF space (e.g., geometric trajectory space), we are able to capture the finer detail of the noise exposure/delay tradeoff surface. For example, simple linear interpolation in SEL space for the *18R BAMBE FAN FROM WAYPOINT* category would predict that 2 percent of the population would experience SEL greater than 55dB for 100 seconds of delay absorption. Interpolating in trajectory space, however, provides a better estimate of 3.5 percent. Currently we use a simple uniform sampling (in DOF/time) between the two limits (e.g. $\Delta_i = \Delta_{max}/10$). In general, one could define more sophisticated sampling schemes (for example an iterative bisecting scheme with a difference threshold) to maximize the capture of the details of the noise exposure surface between the DOF's FAST and SLOW limits.

One can also assess the variation in noise exposure for different delay values graphically by examining the noise footprint created by displaying the color-coded SEL values for each population centroid. Figure 11(a)-(c) show the noise footprint created by arrivals into DFW 18R over BAMBE using the FAST route (zero delay), 69 seconds of delay, and 212 seconds of delay, respectively. A considerable shift of the noise footprint can be observed in these figures. In particular, as the aircraft fans closer to the SLOW limit, it is actually at a higher altitude prior to initiating its turn onto the final approach course. Therefore, the noise footprint is reduced for populations away from the final approach course.

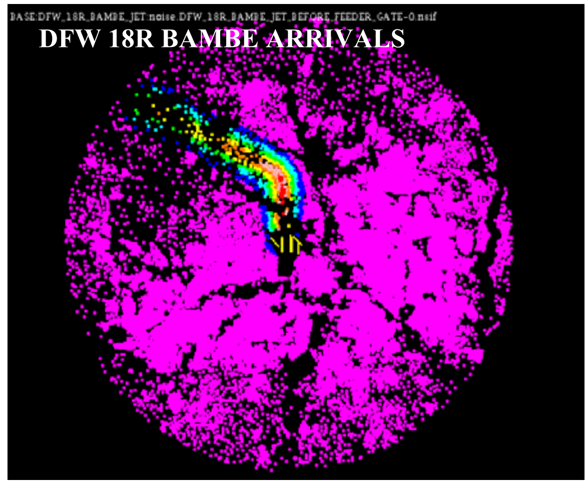
A MERGING OF PHILOSOPHIES

The previous section demonstrated the variability in noise exposure for a single aircraft flying each of the trajectories contained within the space bounded by the vector DOF's FAST and SLOW limits. These sensitivity curves are a first step towards the integration of noise-awareness into the decision support capabilities of ATM tools such as FAST/EDP. Such a capability can allow noise to influence localized routing decisions (e.g., trading path stretching for speed adjustment).

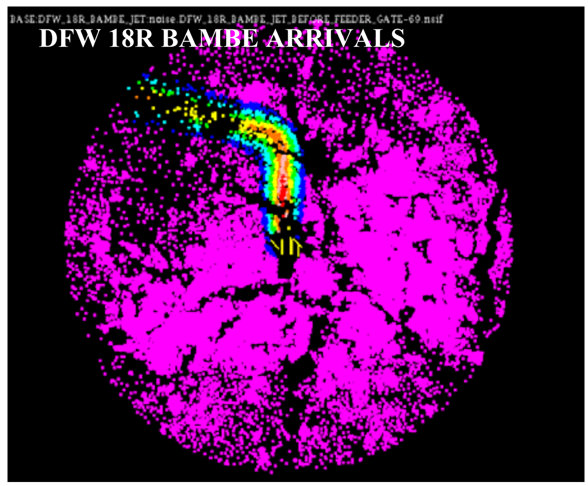
Will aggregation of noise-preferred trajectories (on the basis of SEL) over the course of a 24-hour period result in a net reduction in noise exposure (in terms of DNL)? Shaping the noise impact of routings on a given population distribution is a terminal area-wide airspace utilization problem. FAST/EDP, however, are designed as tactical, time-based sequencing tools. Therefore, it seems plausible that if one consistently modifies traffic flow on a given segment in a similar fashion (e.g., locally noise-preferred), one could inadvertently create a new noise problem under that modified flow. This leads one to the consideration of adding a "rolling window" type of noise exposure measure to the run-time FAST/EDP processing. In this manner, statistics regarding the distribution of noise exposure over the affected communities as a whole could be collected and used to either positively or negatively reinforce certain routing decisions in a time-varying manner.

The one-to-one correspondence between analysis category and DOF sensitivity we take advantage of at present is enabled by the fact that only a single vector DOF is currently defined (and used for resolution) for each analysis category. If one relaxes that restriction such that multiple vector DOFs are chained together, the resulting bounds of the reachable trajectory space increase in complexity. One then must consider various combinations of limit trajectories and take into account the spatial coupling of multiple vector DOFs. This reiterates the point that the noise exposure for a trajectory is defined by the combination of all segments, not necessarily a single segment. One possible approach to this problem, derived through analogy to graph search algorithms such as A* ([7]), is to develop a single heuristic estimate of the noise sensitivity downstream of a given decision point for each possible "branch" of the decision tree. This would allow a tool such as NAP to condition current routing decisions based on an estimate of future noise impact. The idea would be to avoid situations in which a locally optimal sequencing decision on one segment leads to a excessively high noise impact a later segment.

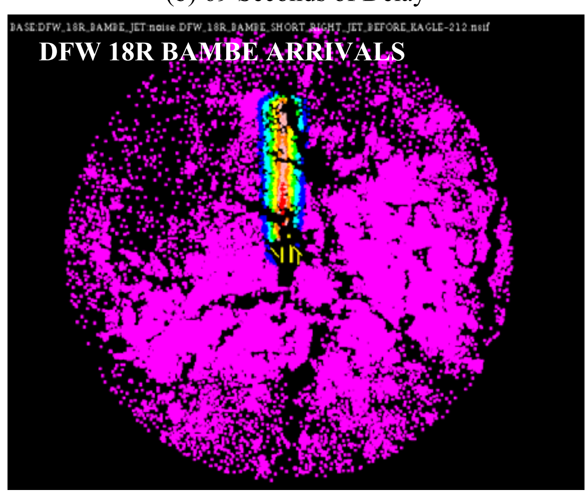
The current NAP architecture leverages the existing FAST/EDP infrastructure to explore the trajectory space. This was a natural choice given the manner in which FAST/EDP uses this space to resolve spatial conflicts. Another option, however, would be to essentially ignore the existing scheduling logic and instead, simply search for an "optimal" (e.g., in a "global" sense – with minimal procedural constraints) noise trajectory for a given aircraft/engine combination from each meter fix to the runway (or vice versa for departures). This trajectory could be represented as a "cloud" defining the relative sensitivity of noise values in its immediate neighborhood. In other words, any trajectory contained in the cloud would be essentially equal from a noise perspective. The burden would then fall on FAST/EDP to stay within this noise preferred region as much as possible given its sequencing and scheduling constraints. An obvious issue with this approach is if the noise-preferred cloud region does not overlap with the FAST/EDP trajectory space. In this case, the current technique of spanning the FAST/EDP trajectory space in some manner would be applicable.



(a) No delay (FAST) route



(b) 69 Seconds of Delay



(c) 212 Seconds of Delay

Figure 11. Frames (a)-(c) show noise footprints for arrivals into DFW 18R for different delay values.

CONCLUSIONS AND FUTURE WORK

We have described results obtained from a quantitative study which demonstrated the potential benefits of noise-aware DSTs by simulating modifications to terminal area air traffic control procedures. What this initial benefits study lacked was a means of addressing the throughput and efficiency impacts related to such procedures. We then presented some initial results obtained during the development of a noise-aware version of the FAST/EDP DSTs, called the Noise Avoidance Planner. We focused on vector degrees of freedom to develop their noise sensitivity with respect to delay absorption. These results seem to indicate that there is potential for tools such as FAST (arrivals) and EDP (departures) to factor noise into their sequencing and scheduling decisions. It was pointed out, however, that decisions that provide a noise benefit for certain population centroids can have a corresponding negative impact (e.g., increase in noise exposure) for other locations. Aggregate measures of benefit, potentially over extended time horizons, are thus generally preferred. The definition and evaluation of such metrics are the next steps in the development of the Noise Avoidance Planner. Future research will involve examination of the impact of the vertical degrees of freedom (thrust, altitude profile) and increased emphasis on departure scenarios.

Finally, it should be pointed out that noise exposure is a time-varying phenomenon that is a strong function of the terminal area weather conditions, including cloud coverage and winds. For this reason, a spatial trajectory that is noise-preferred on a calm, clear day may not be the same as that required on a windy day with low ceilings. Future research is needed to incorporate actual and forecast winds into the noise prediction process – with a need for real-time evaluation of the trajectory space given winds.

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