JOURNAL OF AIRCRAFT
Vol. 45, No. 4, July–August 2008

Environmentally Optimized Resolutions of In-Trail Separation Conflicts for Arrival Flights

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DOI: 10.2514/1.34090

This paper describes the development of a novel tool that calculates environmentally optimized conflict resolutions for two consecutive arrival flights that feature an in-trail separation conflict. This dual-event tool is an extension of a single-event version of the tool that was developed earlier for the analysis and design of noise-abatement procedures around airports. The new tool combines a noise model, an emissions inventory model, a geographic information system, and a dynamic trajectory optimization algorithm. The optimization algorithm generates routings and flight paths that minimize the environmental impact in the residential communities surrounding the airport while satisfying all imposed operational and safety constraints. The environmentally optimized conflict resolutions calculated with the dual-event version of the tool are illustrated in an example scenario based on an approach to one of the runways of Amsterdam Airport Schiphol in The Netherlands. The results indicate that the optimal resolution strategy heavily depends on the considered aircraft types.

I. Introduction

THE noise resulting from flight operations at major airports is a continuing source of annoyance in nearby residential communities. To mitigate the impact of aircraft noise, a range of strategic and operational measures has been implemented at airports located close to sensitive communities. One of the most effective measures to reduce the noise impact is to reshape the arrival and departure trajectories into and out of an airport. For this purpose, noise-abatement routes and procedures have been designed and implemented. To date, a number of different noise-abatement procedures are in use. In The Netherlands, for example, noise-abatement procedures are applied during the nighttime for approaches to Amsterdam Airport Schiphol. The applied procedures, enabled by modern guidance and navigation technology such as area navigation and flight management systems, allow aircraft to descend continuously from high altitude without any level-flight segment at low altitude. The higher flight path combined with lower engine thrust helps to reduce noise exposure in the communities surrounding the airport.

A downside of the application of noise-abatement procedures is that in present-day operations, they typically require significantly higher levels of separation in the arrival sequence and improved navigational precision. Because of differences in, for example, aircraft performance characteristics or flight-management-system behavior, variations in speed profiles among aircraft may occur that hamper the controller when making accurate trajectory predictions. Consequently, fairly large separation intervals in the arrival sequence are required, with obvious implications for runway throughput capacity. As a result, the application of noise-abatement arrival procedures is, at present, often limited to low-demand hours only.

Currently, significant research is being conducted to develop methodologies that permit more tightly spaced final-approach queues without the need for controller intervention. In [1], a near-term operational concept is proposed that can be used to determine, to a desired probability, the target spacing at a selected metering point that will allow a pair of aircraft to complete area-navigation arrivals without controller interference. Several recent studies into the long-term future of air traffic management foresee a paradigm shift in the form of a transition from current flight-plan-based navigation toward trajectory-based operations [2,3]. This transition is expected to increase the level of accuracy and detail of the aircraft trajectory by means of an accurate specification of future aircraft position (latitude, longitude, and altitude) and time at selected points along the flight paths. The resulting four-dimensional (4-D) trajectories will give the air traffic controllers a far more accurate projection of which aircraft will be where, at what time. As a result, they will be able to check trajectories for potential conflicts and provide coordinated planning of air traffic movements for periods further ahead than just a few minutes, without the current problem of sharply degrading prediction accuracy. By assigning optimally spaced landing times without the need to apply excess spacing buffers, the overall throughput efficiency can be improved. Airborne separation-assurance system operations have been proposed to maintain spacing with other aircraft, given that the initial spacing is reasonably well established [4].

A more accurate positioning combined with a more planning-oriented way of working will greatly improve the possibility for air traffic controllers to manage the environmental effects of individual flight movements. Indeed, a transition toward trajectory-based navigation will provide a unique opportunity to couple noise-abatement considerations to the traditional responsibilities of air traffic control by enabling aircraft to fly individually customized and optimized trajectories. As an initial step in this direction, a sophisticated tool for the design of flexible-geometry noise-abatement procedures called NOISHHH (a combination of the words *noise* and *shhh*, the sound that people make when they place their index finger to their lips in a gesture to quiet someone) has been developed [5–8]. The NOISHHH tool facilitates the development of advanced environmental procedures that dynamically adapt to changing needs and that maximize benefits based on an integrated assessment of multiple relevant factors, including noise, fuel burn, emissions, and transit time. To accomplish this, NOISHHH combines a noise model, a noise dose-response relationship, an emission inventory model, a geographic information system, and a dynamic trajectory optimization algorithm.

In its original form, the NOISHHH tool only permits the optimization of a single flight movement, without taking into account the interaction with other aircraft. This paper describes a recent extension of NOISHHH from a single-event tool to a dual-event tool, with the aim to obtain the capability to study the effect of conflict-resolution decisions on noise impact. In essence, the dual-event

Presented as Paper 7721 at the 7th AIAA Aviation Technology, Integration, and Operations Conference, Belfast, Northern Ireland, U.K., 18–20 September 2007; received 17 August 2007; revision received 4 January 2008; accepted for publication 4 January 2008.

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version of NOISHHH facilitates the assessment of the combined single-event noise impacts of two in-trail arrival trajectories that feature a separation conflict. The trajectories can be optimized with respect to a defined environmental criterion, either with or without resolving the in-trail separation conflict. A comparison of the results not only allows quantifying the noise impact of a conflict resolution, but also allows identifying the essential characteristics of the optimal resolution strategy.

The solution behavior observed in optimal dual-event solutions gave rise to the idea that optimal conflict resolution might be approximated by combining two optimal single-event trajectories, each computed with a fixed transit time. For this reason an additional issue addressed in this study is whether impending in-trail conflicts can be resolved in a near-optimal fashion by introducing time constraints in individually optimized flight trajectories. This issue is particularly important for the development of the future trajectory-based operational concept that we envision, in which the ground-based air-traffic-management system maintains a database comprising a set of alternative 4-D trajectories for each arrival.

The environmentally optimized conflict resolutions calculated with the dual-event version of the NOISHHH tool are illustrated in an example scenario based on an approach from the north to runway 06 of Amsterdam Airport Schiphol in The Netherlands. This is followed by a numerical example in which two optimal single-event 4-D trajectories, each computed with an appropriately specified fixed transit time, are combined. The presented examples rely on models of two distinctly different aircraft types, in terms of gross weight and single-event environmental impact: the Boeing 747-400 and Fokker F100 jet transports. The dual-event-tool description and associated numerical examples are preceded by a brief outline of the single-event tool, along with an illustrative numerical example involving an approach of a Boeing 737-300 aircraft.

II. Single-Event Optimization

A. Multi-Objective Environmental Optimization Framework

To facilitate informed decision-making on environmental tradeoffs (e.g., between noise and emissions) in the synthesis of advanced noise-abatement trajectories, the NOISHHH-tool concept has been principally based upon a multi-objective optimization framework. The NOISHHH tool features a variety of environmental performance criteria, including gaseous emissions, fuel burn, transit time, and noise exposure. Typically, these different criteria are not compatible; the decision variables that optimize one objective may be far from optimal for the others. Improvement with respect to one particular criterion is often achieved at the expense of one or more of the other environmental criteria. To permit a tradeoff, NOISHHH considers a composite performance index that essentially consists of a weighted combination of the various criteria.

The emissions inventory implemented in NOISHHH is based on the engine-exhaust-emissions data bank [9]. At present, the emissions inventory model comprises three pollutants: nitrogen oxides, carbon monoxide, and unburned hydrocarbons. Moreover, there are several pollutants that are directly proportional to fuel burn, including sulfur oxides. The local emission performance criteria implemented in NOISHHH correspond to the mass of each of these pollutants emitted below 3000-ft above ground level. Aircraft emissions above that altitude are considered to have no discernible effect at ground level near the airport [9].

The NOISHHH trajectory-synthesis tool features a range of noise performance criteria. Some of these noise criteria are generic in nature (e.g., a criterion that is based on the total area enclosed within a specified noise-level contour) and others are site-specific, in the sense that they depend on the density and distribution of the population in the vicinity of a particular airport [8]. A typical example of a site-specific noise criterion is the population count within a specified noise-level contour. In the numerical examples presented herein, the noise-impact assessment remains restricted to the site-specific criterion awakenings, which represent the number of people within the exposed community that are expected to awake due to a single-event nighttime flyover.

A performance criterion that is consistently included as a secondary criterion in every noise optimization study conducted with NOISHHH is fuel: the fuel consumed during an arrival or departure trajectory. Including fuel consumed in the composite performance index is of particular importance to mitigate the occurrence of "exotic" horizontal arrival or departure routings and extremely large transit times that may result from bypassing noise-sensitive areas.

The transit time for a departure or an arrival flight can be included as a criterion in the composite performance index. However, it is also possible to explicitly include transit-time constraints in the trajectory optimization formulation. This latter feature is particularly important in the context of the development of 4-D noise-abatement procedures.

To provide a clear illustration of the trajectory optimization capability of NOISHHH, the numerical examples of the nighttime noise-abatement trajectories presented in this study are based on a composite performance index that comprises a weighted combination of two criteria only, fuel (a generic criterion) and awakenings (a site-specific criterion):

$$J = \text{fuel} + K \cdot \text{awakenings} \tag{1}$$

where $K(\geq 0)$ is a user-selected weighting factor. Note that the unit-of-measure value of the composite performance index is in kilograms; the weighting factor K is specified in terms of kilograms per awakening.

The specification of an awakenings-related performance index requires knowledge of the relationship between aircraft-noise exposure and sleep disturbance. In NOISHHH, the dose-response relationship has been implemented as proposed by the Federal Interagency Committee on Aviation Noise in 1997 [10] (see Fig. 1). Figure 1 summarizes the results of the experimental study reported in [10], in which aircraft noise was measured in people's bedrooms while their "behavioral awakening" was simultaneously monitored. The solid line in Fig. 1 is the dose-response relationship, which represents a worst-case bound on the percentage of people likely to awake (percent awakening) due to a single flyover and does not take into account the person-to-person variability. The indoor sound level at a particular location is obtained by lowering the outdoor sound level computed for that location by 20.5 dB. The 20.5 dB value represents the average transmission loss for a typical home [10]. The methodology for calculating the outdoor noise exposure from each individual aircraft flyover that has been adopted in NOISHHH is based on the well-known integrated noise model (INM) [11]. Outdoor sound-exposure levels are calculated at specified observer locations that are arranged in the form of a rectangular grid. The grid area size that was adopted in the single-event example study is $27 \times 31\ \text{km}^2$, with a grid cell size of $1 \times 1\ \text{km}^2$.

Finally, by combining the percent-awakening results of a flyover with the actual population-density distribution in the noise-exposed residential communities, the absolute number of people likely to

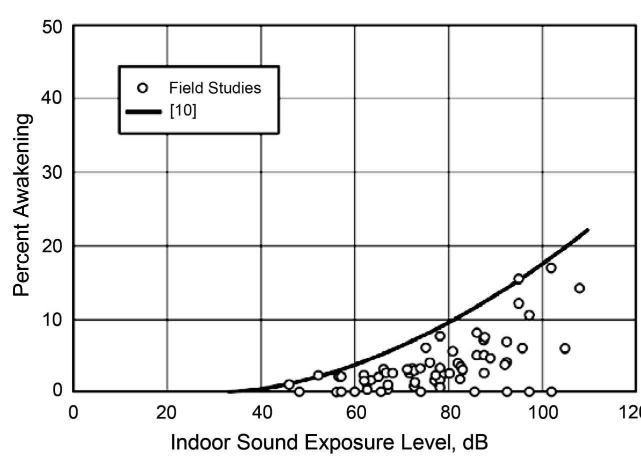


Fig. 1 Sleep-disturbance dose-response relationship as proposed by the Federal Interagency Committee on Aviation Noise.

awake due to the flyover can be determined. Additional details concerning the environmental models implemented in NOISHHH can be found in [5–8].

B. Aircraft Performance Modeling

The NOISHHH tool does not rely on the flight-path computation methodology implemented in the INM package, but makes use of a slightly simplified point-mass model instead. More specifically, the optimal trajectory calculations are based on the so-called intermediate point-mass model [5]. The underlying assumption for the intermediate point-mass model is the equilibrium of forces normal to the flight path. In the intermediate point-mass model, the control variables are thrust setting, roll angle, and flight-path angle. The state variables are the three position coordinates (downrange, crossrange, and altitude), airspeed, and heading angle.

To date, the aircraft characteristics pertaining to three different aircraft types have been implemented in the NOISHHH tool: the Fokker F100 (gross weight $W = 400$ kN), the Boeing 737-300 ($W = 550$ kN), and the Boeing 747-400 ($W = 2450$ kN). The employed data sets comprise separate drag polars for each flap setting. Also, performance data sets are available for aircraft configurations with the undercarriage extended [5].

At present, all calculations are performed using the assumption of standard atmospheric conditions with no wind present. However, weather (notably, wind and temperature variations) has a significant effect on aircraft performance and noise propagation and, consequently, on the noise impact of aircraft operations. For this reason future, research will be directed toward capturing the effect of wind or other atmospheric conditions on aircraft performance and noise propagation in the NOISHHH models.

C. Trajectory Constraints

To obtain realistic results, a variety of constraints need to be imposed in the problem formulation. These constraints do not only arise as a result of existing operational requirements, but also to ensure that the trajectories generated by the optimization tools remain practically feasible and more or less resemble the flight paths that are currently flown. The usual constraints include a limit on the allowable roll angle (assumed to be 25 deg in this study) and an initial air speed (IAS) limit of 250 kt, imposed by air traffic control. In addition, constraints were included that prevent the occurrence of (local) speed and altitude increases during an arrival flight. An extensive overview of all operational constraints implemented in NOISHHH is given in [5–8].

D. Optimal Control Problem Statement

The optimal control problem to be solved can now be formally stated as follows. Find the optimal controls (consisting here of thrust setting, roll angle, and flight-path angle) that transfer the point-mass modeled aircraft from its specified initial state to the specified final state, subject to the constraints outlined in Sec. II.C, while minimizing the performance index given by Eq. (1).

E. Numerical Optimization Method

The numerical trajectory optimization method implemented in NOISHHH is the direct optimization technique of collocation with nonlinear programming (NLP). The collocation method essentially transforms an optimal control problem into a NLP formulation by discretizing the trajectory dynamics [5]. To this end, the time interval of an optimal trajectory solution is divided into a number of subintervals. The individual time points delimiting the subintervals are called nodes. The values of the states and the controls at the nodes are then treated as a set of NLP variables. The system differential equations are discretized and transformed into algebraic equations (implicit integration). The path and control constraints imposed in the original optimal control problem are treated as algebraic inequalities in the NLP formulation. To solve the described optimal control problem, a software package called EZopt [12] was used. The collocation approach adopted in EZopt results in piecewise-constant control histories and piecewise-linear state histories. This renders EZopt fully compatible with the discretization (segmentation) approach taken in the INM.

Generally, the accuracy of the numerical solution of the problem improves with an increasing number of subintervals or, equivalently, the number of nodes. On the other hand, increasing the number of nodes requires a larger computational effort, hence forcing a compromise between desired accuracy and computational burden. In the NOISHHH context, the adopted flight-path segmentation is primarily based on the requirements associated with the computational methodology employed in the INM. The INM includes logic for delimiting the length of path segments. For example, INM subdivides a user-specified path segment if its length multiplied by the change in speed is greater than $100,000$ ft $\cdot$ kt. The segmentation logic implemented in INM also ensures that a line segment replaces not more than 30 deg of turn angle. Although the INM segmentation logic has not been implemented in NOISHHH, each solution obtained using NOISHHH is tested for compatibility with the INM segmentation logic.

In the dual-event study presented herein, the overall time interval is nominally divided into 19 nonequidistant subintervals, yielding an NLP problem of 264 NLP variables and 266 nonlinear constraints. In the initial flight phase, in which no significant changes in heading angle or speed occur, the selected time interval is fairly large (about 30 s). In the final flight stage, in which the aircraft decelerate rapidly and significant turning takes place, the time interval is reduced to about 10 s.

F. Single-Event-Approach Example

The potential single-event noise benefits of arrival trajectories synthesized with NOISHHH are illustrated in an example scenario based on a (hypothetical) nighttime approach from the north to runway 06 of Amsterdam Airport Schiphol in The Netherlands. Figures 2 and 3, respectively, illustrate approach trajectories that are optimized using NOISHHH with the emphasis on fuel consumption and a noise-related criterion (the expected number of awakenings). In establishing the fuel-optimal trajectory, the underlying population is not taken into account, and as a result, it may occur that densely populated communities are directly overflown. In contrast to the

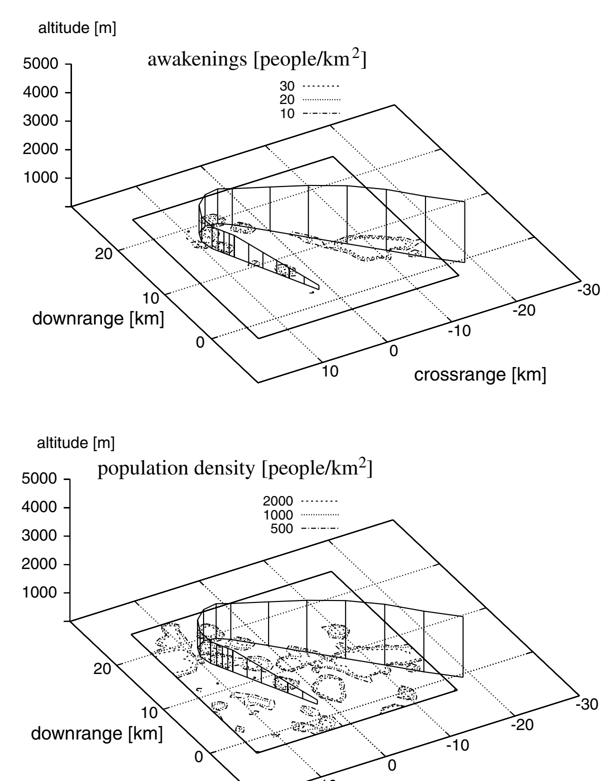


Fig. 2 Fuel-optimized approach.

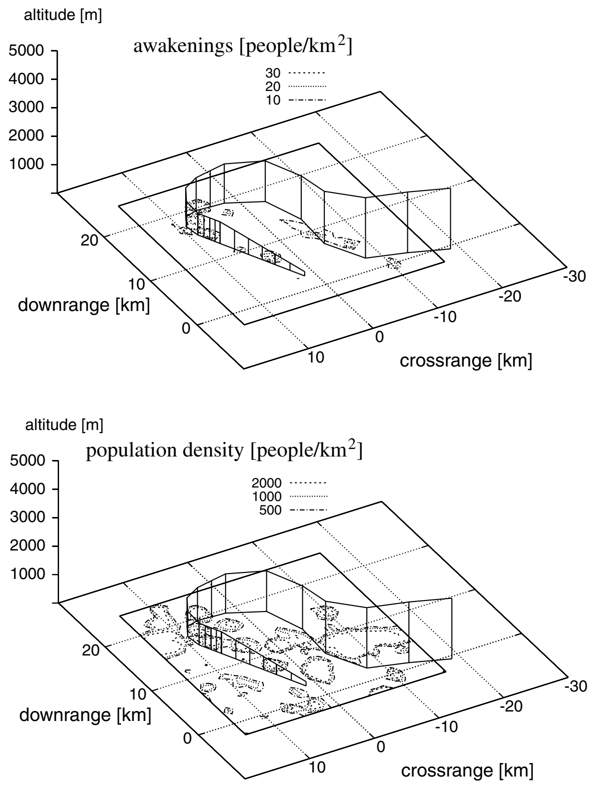


Fig. 3 Noise-optimized approach.

fuel-optimized trajectory, the noise-optimized trajectory circumnavigates residential areas. The flight characteristics in the vertical plane (altitude, speed, and thrust profiles) are modified as well. In particular, the thrust setting is set to flight idle when the aircraft flies close to the outskirts of the population centers. In the noise-optimized solution, the number of expected awakenings reduces from 3166 for the fuel-optimal trajectory to 1495 for the noise-optimal trajectory, an improvement of more than 50%. With respect to fuel consumption, the differences between the minimum-fuel and the minimum-noise trajectories are rather modest. The noise-optimal trajectory requires only about 30 kg (or about 15%) more fuel.

The single-event optimization of approach trajectories includes the entire glideslope phase. In the glideslope phase, the flight-path angle was a priori set to −3 deg and the roll angle was set to zero, so that only thrust setting remains as a control variable. During the glideslope phase, multiple aircraft configuration changes such as flap or gear extension take place. To accommodate such changes, NOISHHH makes use of a so-called multistage optimization formulation, which allows the implementation of a different set of constraints and/or a different dynamic model (drag polar) in each flight stage. Along the glideslope approach, flaps are lowered according to a specified flap-speed schedule [7].

Some care has to be taken in the problem formulation to ensure a realistic behavior during the glideslope approach. Indeed, it is not too hard to conceive that without the introduction of appropriate path constraints, the optimization process is likely to result in a completely unpowered glide to a landing. To obtain a more or less conventional instrument-landing-system approach, a constraint is introduced that ensures that the glideslope is captured at or above a specified minimum altitude. In the present example, the minimum altitude at which the glideslope is captured was (fairly arbitrarily) set at 2500 ft above mean sea level (AMSL); note that the elevation of runway–06 at Schiphol airport is −11 ft AMSL. In the final stage of the glideslope approach, which commences when the assumed stabilization height of 1200 ft AMSL has been reached, thrust is stabilized to maintain the target approach speed along the remainder of the final-approach path [7]. Further noise-abatement benefits can be expected when more sophisticated glideslope approaches are permitted, such as the 3-deg decelerating approach [13,14].

In the present study, it is assumed that a flight terminates at an altitude of 500 ft AMSL. The remaining (stabilized) part of the glideslope approach and the ground run during which the aircraft decelerates to a complete stop have not been considered. If so desired, the noise contribution of these particular segments can be computed offline and added to the overall noise impact. Because the influence of these final segments remains primarily limited to the (unpopulated) vicinity of the runway, these particular corrections have not been incorporated here.

The high nonlinearity of the problem and the possibility of nonconvexity of the performance index may lead to local minima. For complex problems such as the present one, the existence of multiple local minima is typically investigated through numerical trials. To this end, the optimization algorithm is executed to obtain converged solutions, starting from widely varying initial guesses for the trajectory solution. For the scenarios considered in this study, different initial guesses always lead to consistent optimal solutions.

III. Dual-Event Optimization

A. Dual-Event-Tool Description

To assess the impact of in-trail conflict-resolution decisions on noise impact, a dual-event version of NOISHHH was developed. The dual-event version of NOISHHH allows the simultaneous optimization of two (coupled) trajectories for common initial and terminal points in the three-dimensional (3-D) space. The acoustic and performance models implemented in the dual-event version are exactly the same as those employed in the single-event version of NOISHHH. From an acoustic point of view, the two in-trail arrival flights are treated in NOISHHH as completely independent events. This seems to be a reasonable assumption, given the required spacing between two consecutive arrivals. For reasons of computational efficiency, the glideslope phase has not been included in the dual-event version. Indeed, retaining the glideslope in the dual-event problem formulation results in a NLP problem of more than twice the size of that of the original single-event problem. The terminal point adopted in the dual-event optimization relates to the point of glideslope interception. The performance index employed in the dual-event formulation is simply based on the summation of the single-event criteria in Eq. (1) for the two aircraft involved. If so desired, a different value of the performance-index weighting factor K can be selected for each aircraft.

A slight weakness of the summation approach with respect to the awakenings component of the performance index is that it considers the two consecutive arrivals as isolated events. A conceivable modification to the awakenings component of the performance index is to allow for the fact that the chance of sleeping through the two consecutive nighttime flyovers is the combined chance of sleeping through the first one and sleeping through the second one. Mathematically, this represents a joint probability. Obviously, the chance of sleeping through an event is one minus the chance of being awakened by that event. The probability of awaking at least once from two consecutive flights is one minus the probability of sleeping through these two events and can thus be written as [15]

$$
\begin{aligned}
\%\,\text{awakening}_{1+2} &= \left(1 - \left(1 - \frac{\%\,\text{awakening}_1}{100}\right)\right. \\
&\quad \left.\cdot \left(1 - \frac{\%\,\text{awakening}_2}{100}\right)\right) \cdot 100 = \%\,\text{awakening}_1 \\
&\quad + \%\,\text{awakening}_2 - \frac{\%\,\text{awakening}_1 \cdot \%\,\text{awakening}_2}{100}
\end{aligned}
\tag{2}
$$

where the subscripts 1 and 2 denote the first and second flyover events, respectively. Because the single-event probabilities of awakening are relatively small (typically less than 4%), the impact of the performance-index modification is not expected to be very significant. Moreover, if the summated awakenings component of the performance index is replaced by the probability of awakening from repeated noise events [given by Eq. (2)], the ability to apply different values for the performance-index weighting factor K for different aircraft is lost.

Although the two trailing aircraft start their respective approach trajectories at the same initial point, they obviously initiate their trajectories at different points in time. In NOISHHH, the initial time separation between the two aircraft is a user-specified parameter. To facilitate the possibilities of different initial and final times for the two aircraft, the dual trajectory optimization problem was formulated as a multiphase problem. More specifically, the flight trajectories are split into three consecutive flight phases. In the first phase, only the lead aircraft enters the system and starts its approach. The first phase ends when the trailing aircraft enters the system at the user-specified time. The second phase, which considers the movements of both aircraft, ends when the leading aircraft reaches the terminal point. The third phase considers the movement of the trailing aircraft only and ends when the trailing aircraft reaches its final point.

The user has the option to simultaneously optimize the two trajectories, with or without conflict resolution. In the context of NOISHHH, a conflict occurs when the minimum horizontal distance between the two aircraft in time–space is less than the required minimum separation distance $R_{\min}$. Mathematically, conflict resolution is enforced by including the following inequality constraint in the optimization problem formulation:

$$(x_L(t) - x_T(t))^2 + (y_L(t) - y_T(t))^2 \geq R_{\min}^2 \tag{3}$$

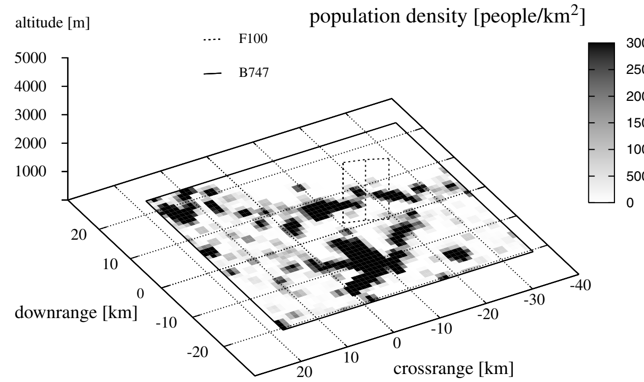
where the variables x and y represent the position coordinates of the aircraft, the subscript T denotes trailing, and the subscript L denotes leading.

B. Dual-Event-Approach Example

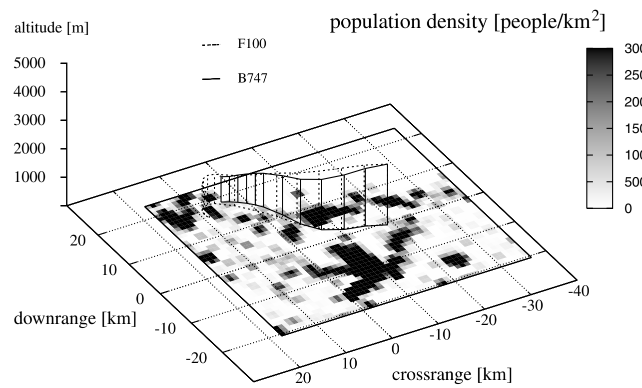
Figure 4 illustrates an example scenario in which the leading aircraft is a Fokker F100 and the trailing aircraft is a Boeing B747. The noise-grid area size that was selected in this particular example is 45×55 km^2. Figure 4 shows the results for the trajectories in the 3-D space at the end of phases 1, 2, and 3, respectively. Note that in this dual-event example, the B747 enters the system 1 min behind the F100. In the optimal solution presented in Fig. 4, the conflict was resolved by enforcing the aircraft to maintain a safe minimum separation $R_{\min} = 3$ n mile. The weighting parameter K in the performance index (1) is equal for both aircraft and was set at 0.05 kg per awakening. Both aircraft enter the system with the same initial airspeed of 250-kt IAS (the maximum permissible speed). The terminal speed for both aircraft is specified as 190-kt IAS. This value corresponds to the flap-5 scheduling speed for the B747. Both aircraft are assumed to fly in a clean configuration throughout the entire flight.

It is important to realize that in the present optimization formulation, safe separation between the two arrivals can only be assured until the end of phase 2. Beyond phase 2, aircraft will continue to decelerate, and because the B747 has a higher speed on approach than the F100, the spacing between the two aircraft will eventually fall below the 3-n-mile separation requirement. Obviously, this problem can, in principle, be rectified by including the ensuing glideslope phase and ground run in the dual-event formulation. However, as mentioned earlier, this is likely to seriously affect the tractability of the optimization problem. A simpler, but less precise, approach is to add a buffer to the 3-n-mile separation standard to allow for the trailing aircraft closing in on the lead aircraft, beyond phase 2. A good estimate of the required buffer size can be obtained from single-event optimal solutions.

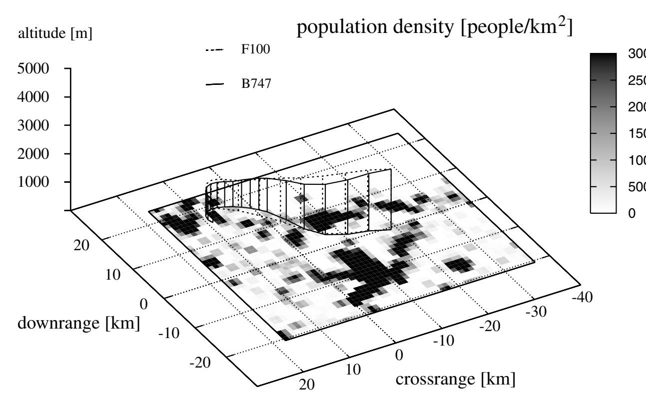
In Fig. 4, it can be observed that the trajectories of the two aircraft are quite different in behavior, both in lateral and vertical sense. Although both trajectories circumnavigate the most densely populated areas, the detour of the B747 is discernibly more pronounced. Figure 5 shows the optimal trajectory solutions that were obtained without resolving the conflict. Inspection of Fig. 5 makes clear that, in this case, the two solutions exhibit a very similar lateral behavior. To illustrate the impact of the conflict resolution in some more detail, Fig. 6 compares the conflicted and deconflicted trajectories for the F100 and B747 aircraft in the horizontal and



a) Solution at the end of phase 1



b) Solution at the end of phase 2



c) Solution at the end of phase 3

Fig. 4 Conflict-free optimal trajectories at three different stages, with underlying population shown.

vertical planes. To resolve the conflict, the leading aircraft (F100) is forced to fly slightly faster, whereas the trailing aircraft (B747) stretches its flight path. More specifically, for the F100, the transit time of the deconflicted trajectory is about 19 s less than with the conflicted solution, whereas the deconflicted B747 trajectory features an increase in transit time of about 3 s.

The main results for the conflicted and deconflicted solutions are summarized in Table 1. A close examination of the results presented in Table 1 shows that the impact the optimal conflict resolution on the fuel and noise performance remains very limited. The deconflicted solution even shows a slight improvement in the number of awakenings (on account of the B747). However, in the composite performance index, this improvement in awakenings is more than offset by an increase in fuel consumption for both aircraft. It is no surprise that the smaller F100 has to make a larger contribution to the conflict resolution than with the B747, simply because it contributes less to the composite performance index in terms of fuel, especially in terms of the expected number of awakenings.

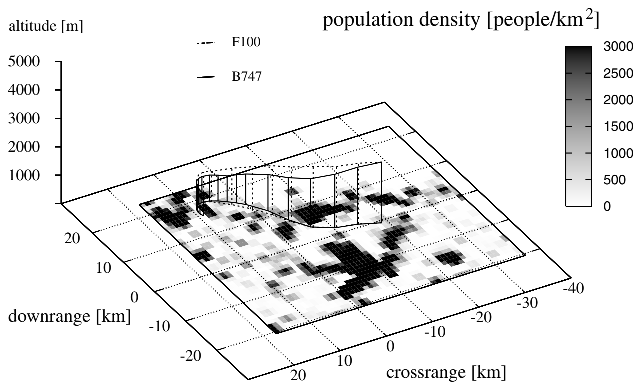
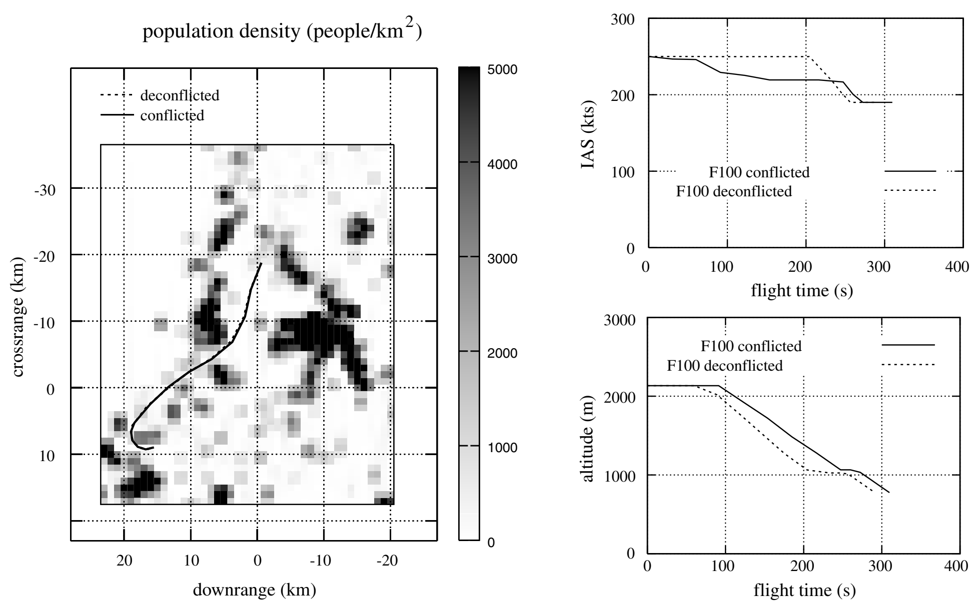


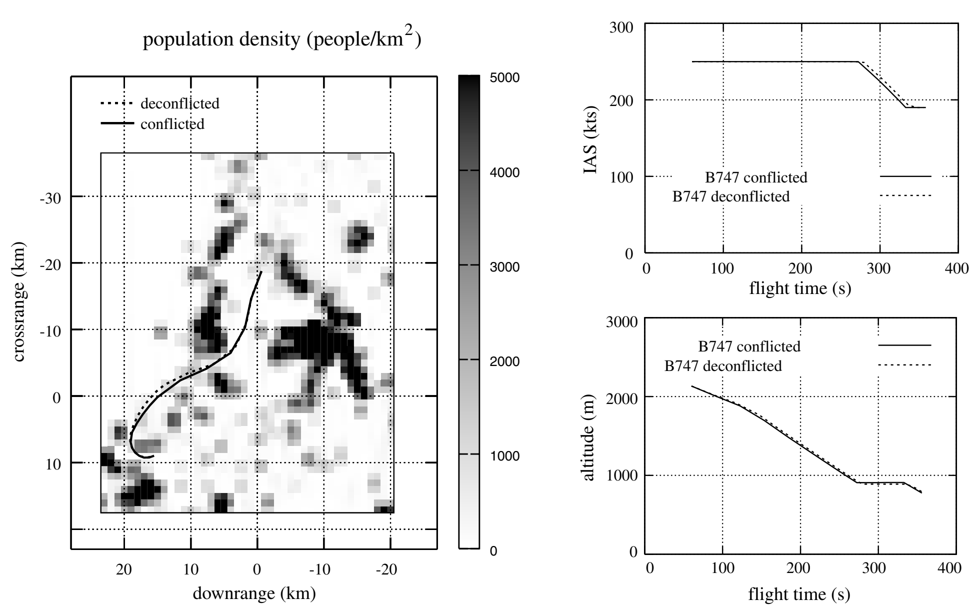
Fig. 5 Conflicted in-trail optimal trajectories, with underlying population shown.

The results shown in Fig. 6 make readily clear that the resolution strategy for the two considered aircraft is completely different. For the smaller F100, conflicts are primarily resolved by altering the flight characteristics in the vertical plane (altitude, speed, and thrust profiles) rather than through course changes. In contrast, in the B747 solution, the speed profile remains largely unaffected, and the conflict is primarily resolved through extension of the lateral flight path. It is important to note that in experiments in which a smaller aircraft type (F100 or B737) was selected as the trailing aircraft, it was found that the resolution strategy was to slow aircraft down by gradually reducing airspeed, leaving the lateral flight path essentially unchanged [16]. It is conjectured that the difference in behavior between the B747 and the smaller aircraft can be partly attributed to the fact that the best glide-angle speed (the airspeed that maximizes the lift-to-drag ratio) is significantly higher for the B747 than with the smaller aircraft. Flying at a speed close to the best glide-angle speed (which is close to the 250-kt speed limit for the B747) is beneficial from both fuel and noise perspectives. Another factor is that the awakenings' contribution to the composite performance index is, in relative terms, much larger for the B747 than with the F100. This implies that in the optimization process, the emphasis is directed more toward reducing awakenings in the case of the B747, whereas in the case of the F100, the attention is more focused on reducing fuel.

A final observation of interest pertaining to Fig. 6 is that all solutions feature a horizontal segment just before the turn to



a) **F100**



b) **B747**

Fig. 6 Comparison of conflicted and deconflicted optimal solutions.

Table 1 Summary of results for example scenario, with and without deconfliction

Trajectory	Deconflicted?	Transit time, s	Fuel, kg	No. awakenings	Composite index contribution, kg
F100	No	309.7	100.5	826	141.8
B747	No	295.8	234.8	6057	537.7
F100	Yes	291.0	101.5	845	143.8
B747	Yes	298.6	240.4	5972	539.0

final approach. This horizontal segment, which is flown at idle thrust, ensures that the aircraft rapidly decelerates to the imposed final speed (190 kt). Executing the turn at low speed helps to reduce the turn radius. The final speed is generally attained well before the turn is completed; the final part of the turn is a descent at constant speed. It is noted that the horizontal segments in the optimal solutions arise as a result of the flight-path-angle constraint that was imposed to prevent the occurrence of altitude increases during an arrival flight (see Sec. II.C). Without enforcing this constraint, the optimal trajectories would actually feature a climb to decelerate even more rapidly.

In Fig. 7, the time history of the separation distance between the two aircraft is plotted for both the conflicted and deconflicted solutions. Obviously, the results shown relate to phase 2 only, because in both phase 1 and phase 3, the movement of a single aircraft is considered. In the deconflicted solution, the minimum separation is attained exactly at the end of phase 2. In the case in which no conflict resolution is enforced, the trailing aircraft catches up with the leading aircraft during the turn to final approach, resulting in an infringement of the minimum separation constraint by about 1.5 km.

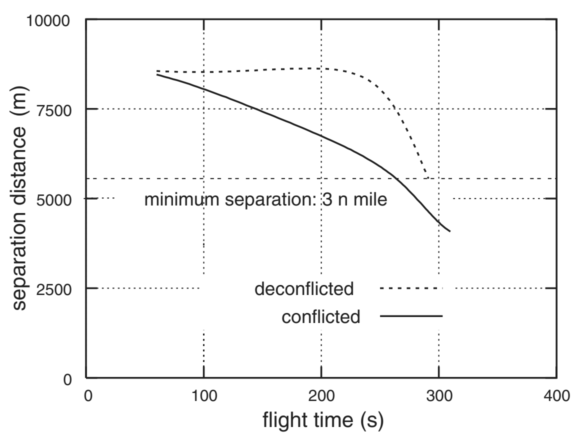


Fig. 7 Time histories of separation distance between two aircraft flying in-trail.

IV. Time-Constrained Single-Event Solutions

Based on the solution behavior observed in the dual-event solutions, it was hypothesized that optimal conflict resolution might perhaps be well approximated by combining two optimal single-event 4-D trajectories, each computed with an appropriately specified fixed transit time. From the results for the deconflicted optimal solution in Table 1, a transit-time constraint of 290 s was inferred for the F100 trajectory, with 300 s for the B747 trajectory. Figure 8 shows some major results pertaining to the vertical flight profile of the time-constrained single-event solutions. Obviously, in the presentation of the results, a time shift of 1 min was applied to the single-event solution related to the trailing aircraft (B747). A comparison of the time-constrained single-event results with the corresponding deconflicted dual-event trajectories, shown in Fig. 6, reveals a remarkably close correspondence between the two solutions, thus confirming our hypothesis. Note in Fig. 8 that when both aircraft conduct an (idle-thrust) glide at 250-kt IAS, the F100 descends more quickly than the B747. This is simply due to the fact that the B747 has a better lift-to-drag ratio.

Figure 9 summarizes the performance results for a range of time-constrained single-event solutions for both the F100 and the B747 aircraft. The composite solution shown in both subfigures applies to the value of the composite performance index (expressed in kilograms) for a single aircraft only. A comparison of the two subfigures reveals quite different behaviors for the two aircraft.

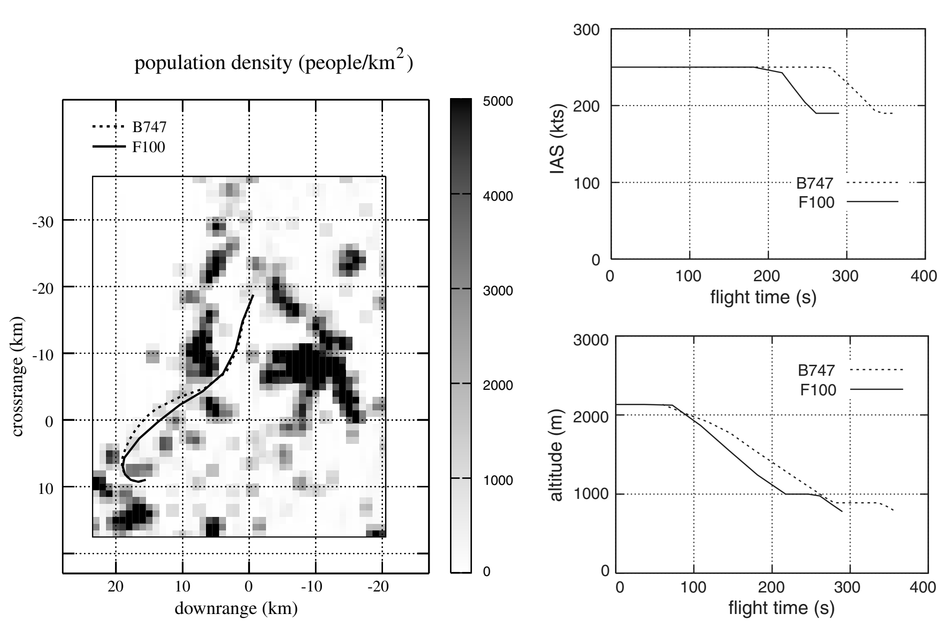
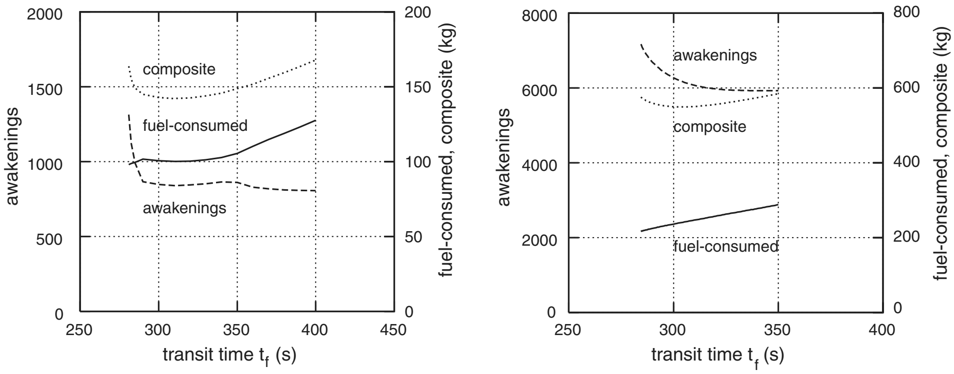


Fig. 8 Vertical flight profile details of time-fixed optimal trajectory solutions; transit-time constraints are 290 s for F100 and 300 s for B747.



a) F100 b) B747

Fig. 9 A performance comparison of noise-optimized arrival solutions for fixed flight times.

In particular, the awakenings curve pertaining to the F100 exhibits a somewhat peculiar behavior. The reason for this behavior is that three transit-time regions exist with distinctly different resolution strategies. For transit times ranging from about 290 to 345 s, all solutions feature the same lateral flight path (see Fig. 6a), but exhibit vastly different speed/altitude profiles. The solution for a transit time of 290 s remains at the 250-kt speed limit for as long as possible, whereas the solution for a transit time of 345 s, speed is reduced to the lower limit of 190 kt as early as possible. From Fig. 9a, it can be concluded that the transit-time constraint has only a marginal effect on both fuel consumption and the expected number of awakenings (which slightly increases with transit time) in this region. For flight times in excess of 345 s, lateral flight-path stretching takes place, keeping the speed profile essentially the same. In this region, fuel consumption increases (more or less proportionally) with transit time, whereas the expected number of awakenings slightly reduces. For values of the transit time less than 290 s, the lateral flight path is shortened, basically by directly overflying the population centers. This obviously results in a fairly steep increase in noise impact, accompanied by only a slight reduction in fuel consumption. In the case of the B747, the optimal solution entails a modification of the lateral profile for any value of the transit time. Only for transit times in excess of about 300 s do the speed profiles of the B747 change, in the sense of early speed reductions. The findings are completely in agreement with the observations made earlier with respect to the dual-event solutions.

V. Conclusions

In this paper, it was demonstrated that the NOISHHH single-event tool was successfully extended to a dual-event version. The dual-event version of NOISHHH proved to be very useful in the discovery of how in-trail air traffic separation conflicts can be resolved optimally from an environmental perspective. In the limited number of numerical experiments that were conducted, it was found that the way conflicts are resolved depends heavily on the aircraft type. Two different aircraft types were examined in this study: the Boeing 747-400 and the Fokker F100. It was shown that in-trail conflict resolution for the heavy four-engine B747 primarily results in a modification (i.e., shortening or stretching) of the lateral flight path. In contrast, for the smaller F100 twin jet, it was found that conflicts are essentially resolved by altering the flight characteristics in the vertical plane (altitude/speed profiles). Our research also revealed that the dual-event trajectories that optimally resolve the separation conflict can be closely approximated by time-constrained (4-D) single-event solutions. This result holds out great promise for the development of a future air-traffic-management concept that relies on 4-D trajectory-based operations to improve throughput capacity in concert with environmental considerations.

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