ACHIEVING LOW APPROACH NOISE WITHOUT SACRIFICING CAPACITY

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Abstract

Advanced noise abatement procedures such as the Three Degree Decelerating Approach (TDDA) can significantly reduce the noise impact of aircraft during approach. With existing aircraft performance and flight operation uncertainties, however, implementation of the TDDA would require an increase in the initial separation between aircraft that would result in a significant reduction in runway capacity. Simulation results indicate that this reduction in runway capacity is on the order of 50%, which is not acceptable for any procedure that must be used in high traffic scenarios. In this paper, we introduce a Modified Three Degree Decelerating Approach (MTDDA) that provides the same noise benefits as the TDDA with little or no loss in capacity relative to conventional approach procedures. Simulation results indicate that for a representative aircraft mix, the capacity of the MTDDA is within 2% less of the maximum possible capacity using conventional approach procedures.

1. Introduction

The impact of aircraft noise in residential communities is a major factor in the drive to limit the number of aircraft operations that may be performed at airports, and the increasing resistance to airport expansion. Previous work has shown that advanced noise abatement procedures such as the Three Degree Decelerating Approach (TDDA) can significantly reduce the noise impact of aircraft during approach [1][2][3]. In addition, the growing environmental concern at major metropolitan airports in the US and Europe regarding aircraft emissions provides added incentive for development of the TDDA because less fuel is burnt when the engine power is at idle during approach.

In this paper, we (a) describe and present the results of a simulation study to determine the initial separation requirements for the four possible combinations of B737-300 and B747-400 aircraft performing the TDDA, (b) quantify the runway capacity given a randomly sequenced arrival stream of B737-300 and B747-400 aircraft, (c) introduce a Modified Three Degree Decelerating Approach (MTDDA) that is designed to reduce the separation requirements of the TDDA, and (d) show through further Monte-Carlo simulations that the MTDDA provides the same noise benefits as the TDDA with little or no loss in capacity relative to conventional approach procedures.

2. Background and Motivation

In the TDDA procedure, aircraft descend to the runway along a 3° Glide Slope at idle thrust [4]. Thus, the trajectory of each aircraft is highly dependent on its performance in different atmospheric conditions – primarily changing wind speed and direction – and flight operation uncertainties such as the response time of the pilot. The net result is that air traffic controllers must increase the separation between aircraft because there can be significant (and somewhat unpredictable) changes in the trajectories of the aircraft under their control. Recent work by Ho and Clarke has shown that, in the case of a B747-400 trailing a B737-300, an initial separation of over 9 nm is required to ensure that the minimum approach separation of 2.5 nm in not violated during the TDDA [5]. Additionally, they found that the separation at the threshold could vary between 2.6 and 3.5 nm. In the study by Ho and Clarke, the aircraft was assumed to initially be in level flight at an altitude of 7,000 ft above ground level (AGL) and at a speed of 250 knots. At the top of descent, the pilot reduced the aircraft pitch (to -3°) and thrust (to idle) and commenced the decelerating descent to the runway (Figure 1). During the

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decent, the aircraft control functions were performed by the FMS while flap extensions were performed manually. The flap extension schedule was designed to keep the aircraft as clean as possible for as long as possible in order to minimize the drag, which in turn reduces the airframe noise. Upon reaching the final approach speed of 140 knots, the thrust was increased to the level required to maintain the final approach speed.

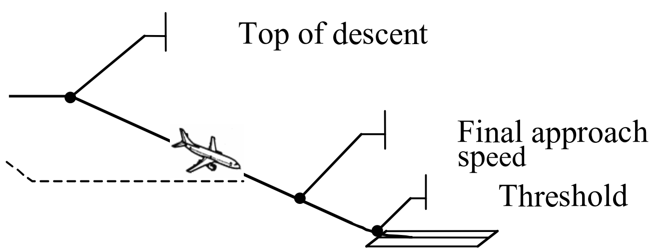

Figure 1. Profile of the TDDA

While Ho and Clarke showed that flight operation uncertainties and differences in aircraft performance could result in significant variability in the aircraft trajectory, they did not determine the impact of this variability on runway capacity. In addition, because they limited their study to the case of a B747-400 trailing a B737-300, they did not explore the case of a large aircraft such as the B737-300 trailing a heavy aircraft such as the B747-400, a situation in which the minimum separation is equal to the en-route separation of 5 nautical miles, and a situation where, because the B737-300 will typically decelerate faster than the B747-400, it is likely that the separation could increase during the approach.

Given the environmental benefits of the TDDA, a more extensive study is required to characterize the separation between different combinations of aircraft (B737-300 trailing a B737-300; B737-300 trailing a B747-400; B747-400 trailing a B737-300; B747-400 trailing a B747-400) and to quantify the impact of the TDDA on runway capacity.

3. TDDA Capacity

We conducted a Monte-Carlo simulation study to determine the capacity loss that could be expected if the TDDA were to be implemented. The specific details of the simulation study are as follows. The aircraft was assumed to be initially in level flight at 7,000 ft AGL at an indicated airspeed of 220 knots. The final approach speed was assumed 135 knots for B737-300 aircraft and 153 knots for B747-400 aircraft. The following flight operation uncertainties were included: pilot delays, the relative order of power reduction and aircraft pitch reduction at the top of descent, and the initial position of the aircraft. The pilot was assumed to be exercising "open loop" control. That is, the pilot followed a pre-planned sequence of control actions without any changes to compensate for difference between the actual trajectory and the planned trajectory. Because the pilot was assumed to be exercising open loop control, the performance for any given aircraft was assumed to be independent of the trailing or preceding aircraft, thus the trajectory for each aircraft was simulated separately and the separation between aircraft pairs was determined by superposition.

The required initial separations are as follows. For the case of a B737-300 trailing a B737-300, an initial separation of 10.1 nm is required to ensure that the minimum separation of 2.5 nm [6] is not violated during the approach. For the case of a B737-300 trailing a B747-400, an initial separation of 9.7 nm is required to ensure that the minimum separation of 5 nm [6] is not violated. For the case of a B747-400 trailing a B737-300, an initial separation of 9.7 nm is required to ensure that the minimum separation of 2.5 nm [6] is not violated. For the case of a B747-400 trailing a B747-400, an initial separation of 8.1 nm is required to ensure that the minimum separation of 4 nm [6] is not violated.

Figure 2 shows the separation profile for a B737-300 trailing a B747-400 given an initial separation of 9.7 nm. The upper curve in the figure is the maximum possible separation that could be achieved during the approach given flight uncertainties and aircraft performance, and the lower curve is the corresponding minimum possible separation. As the figure shows, the separation between the aircraft decreases continually during the approach despite the fact that the B737-300 decelerates faster than the B747-400. This pattern was observed for all four aircraft combinations. The separation at the threshold is therefore the minimum separation throughout the entire approach and it is this separation that determines the capacity of the runway. Specifically, the runway capacity is determined by the expected value of the threshold separation.

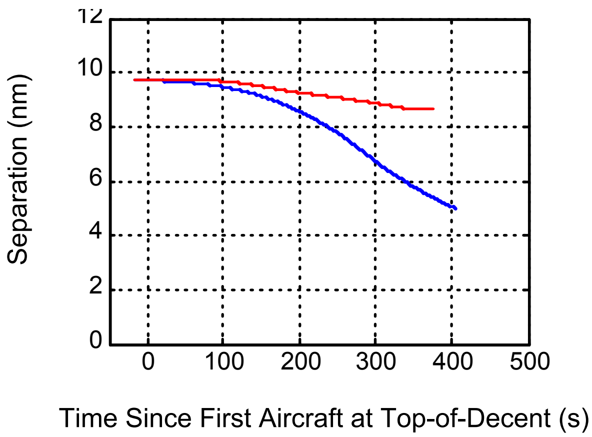

Figure 2. Separation Profile for a B737-300 Trailing a B747-400

Another way to determine the runway capacity is to measure the throughput at the top-of-descent. This is easier to calculate because all the aircraft passing through the top-of-descent are traveling at the same speed and because there is significantly less uncertainty about the separation between aircraft. Using this alternative method, the capacity of a runway that is used purely for arrivals (in terms of the number of landings per hour) is given by the equation

$$R = \frac{1}{E(T)} \qquad (1)$$

where $E(T)$ is the expected inter-arrival time, or, in other words, the expected value of the time between successive aircraft. If the fraction of B747-400 aircraft in an infinite arrival stream of randomly sequenced B737-300 and B747-400 aircraft is equal to f, the expected inter-arrival time is given by the equation

$$\begin{aligned} E(T) = {} & \frac{(1-f)^2 \cdot S_{TOD}(737\,|\,737)}{V_{initial}} \\ & + \frac{(1-f)\cdot f \cdot S_{TOD}(737\,|\,747)}{V_{initial}} \\ & + \frac{f \cdot (1-f)\cdot S_{TOD}(747\,|\,737)}{V_{initial}} \\ & + \frac{f^2 \cdot S_{TOD}(747\,|\,747)}{V_{initial}} \end{aligned} \qquad (2)$$

where $S_{TOD}(737|737)$ is the separation at the top-of-descent for a B737-300 trailing another B737-300, $S_{TOD}(737|747)$ is the separation at the top-of-descent for a B737-300 trailing a B747-400, $S_{TOD}(747|737)$ is the separation at the top-of-descent for a B747-400 trailing a B737-300, $S_{TOD}(747|747)$ is the separation at the top-of-descent for a B747-400 trailing another B747-400, and $V_{initial}$ is the common speed for all the aircraft on the initial level flight segment preceding the top-of-descent.

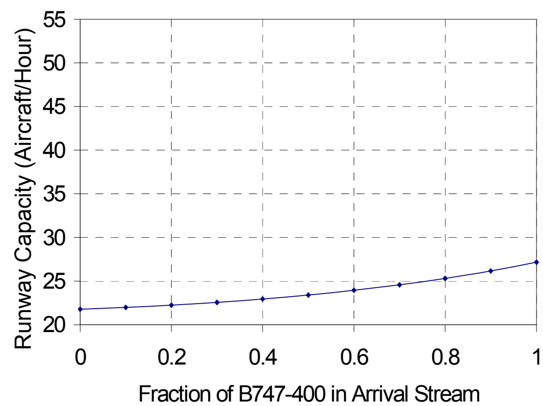

Figure 3. *R* versus *f* for TDDA with Initial Speed of 220 Knots

Figure 3 shows the runway capacity as a function of the fraction of B747-400 aircraft in the arrival stream for the case where the initial speed is 220 knots. As the figure shows, the runway capacity is lowest when there are only B737-300 aircraft in the stream, and greatest when there are only B747-400 aircraft in the stream. The runway capacity varies between 22 and 27 landings per hour depending on aircraft mix. For an airport with a 70/30 mix of B737-300 (a large aircraft) and B747-400 (a heavy aircraft) – the type of mix one might see at a major East Coast airport during the very busy period between 5 PM and 7 PM – the runway capacity is 23 landing per hour.

To determine how these results compare with the best that can be achieved currently, we calculated the capacity for a randomly sequenced arrival stream of B737-300 and B747-400 aircraft using the expected inter-arrival time at the threshold given IFR separation [6] and nominal final approach speeds.

The expected inter-arrival time for a randomly sequenced stream of arrivals (as measured at the threshold) is given by the equation

$$E(T) = \frac{(1-f)^2 \cdot S_{TH}(737 \mid 737)}{V_{737}} + \frac{(1-f) \cdot f \cdot S_{TH}(737 \mid 747)}{V_{737}} + \frac{f \cdot (1-f) \cdot S_{TH}(747 \mid 737)}{V_{747}} + \frac{f^2 \cdot S_{TH}(747 \mid 747)}{V_{747}} \quad (3)$$

where $S_{TH}(737|737)$ is the separation at the threshold for a B737-300 trailing another B737-300, $S_{TH}(737|747)$ is the separation at the threshold for a B737-300 trailing a B747-400, $S_{TH}(747|737)$ is the separation at the threshold for a B747-400 trailing a B737-300, $S_{TH}(747|747)$ is the separation at the threshold for a B747-400 trailing a B747-400, V_{737} is the final approach speed for the B737-300, and V_{747} is the final approach speed for the B747-400.

Figure 4 shows the runway capacity as a function of the fraction of B747-400 aircraft in the arrival stream for IFR separation at the threshold [6] and nominal final approach speeds. As the figure shows, the runway capacity varies between 37 and 54 landings per hour depending on aircraft mix. For an airport with a 70/30 mix of B737-300 and B747-400, the runway capacity is 44 landing per hour. Thus, the capacity reduction due to the TDDA in this case would be close to 50%. This is consistent with empirical results from airports that have implemented low noise arrival procedures [3][7].

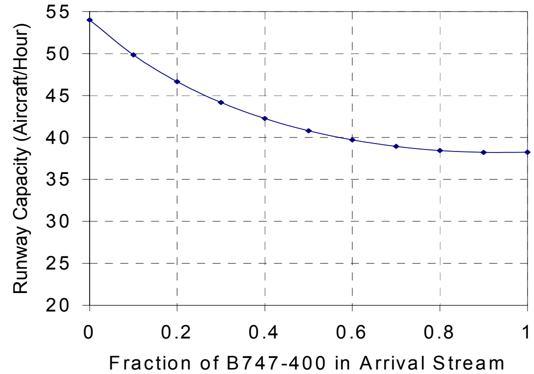

Figure 4. *R* versus *f* for IFR Separation and Nominal Final Approach Speeds

4. TDDA Noise Impact

Figure 5 illustrates the variability in the TDDA speed profile for both aircraft. The dashed curves are the speed profiles for the B737-300 and the solid curves are the speed profiles for the B747-400. For each aircraft, the upper curve indicates the possible upper boundary of the aircraft speed and the lower curve indicates the possible lower boundary of the aircraft speed.

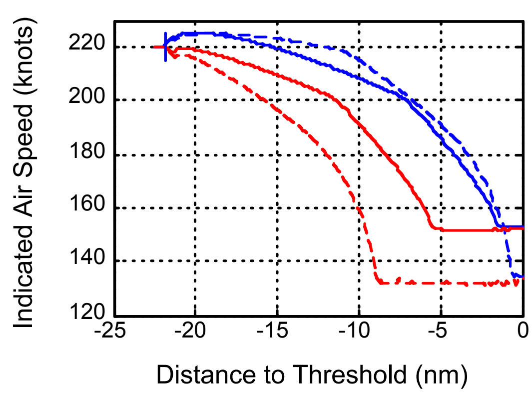

Figure 5. Speed Profile for B737-300 and B747-400 Performing TDDA

It is important to note that, given typical uncertainties, the B737-300 could reach its final approach speed as early as 9 nm prior to the threshold. Since engine power must be re-engaged when the aircraft reaches its final approach speed, the noise level of the aircraft within that last 9 nm would be significantly higher than the best TDDA profile. This indicates that trajectory variability can, in addition to reducing capacity, reduce the effectiveness of the TDDA approach procedure in terms of noise abatement.

5. MTDDA Capacity

A Modified Three Degree Decelerating Approach (MTDDA) was developed to mitigate the effects of flight operation uncertainties on the aircraft trajectory. The first difference between the MTDDA and the TDDA is that the initial speed is maintained for a fixed time after the start of the 3° descent to the runway, i.e. the thrust is not reduced to idle at the top-of-decent, but is reduced to the thrust level required to maintain the initial speed, and then subsequently reduced to idle at a lower altitude. In this nominal "Open Loop" MTDDA, the initial speed of the B737-300 is maintained for 138 seconds after the top-of-descent. The resulting speed profile is shown in Figure 6. As the figure shows, the aircraft reaches its final approach speed approximately 2.5 nm prior to the threshold with little variability.

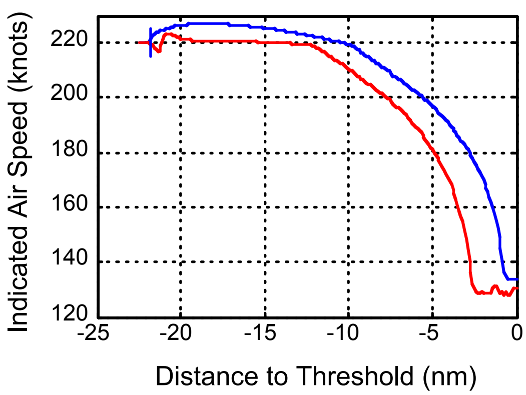

Figure 6. Speed Profile for B737-300 Performing an Open Loop MTDDA

In the nominal Open Loop MTDDA for the B747-400, the initial speed is maintained for 120 seconds after the top-of-descent. The resulting speed profile is shown in Figure 7. As the figure shows, the speed profile for the B747-400 is very similar to the speed profile for the B737-300. That is, the aircraft reaches its final approach speed approximately 2.5 nm prior to the threshold with very little variability. In both case, the Open Loop MTDDA has a fixed, pre-determined, flap schedule that, when combined with a fixed, pre-determined, speed hold, will nominally get the aircraft to its final approach speed at 2.5 nm prior to the threshold.

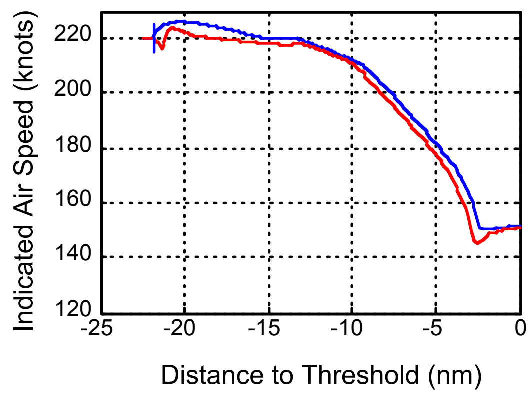

Figure 7. Speed Profile for B747-400 Performing an Open Loop MTDDA

The required initial separations for the Open Loop MTDDA are as follows. For the case of a B737-300 trailing a B737-300, an initial separation of 5.6 nm is required to ensure that the minimum separation of 2.5 nm is not violated during the approach. For the case of a B737-300 trailing a B747-400, an initial separation of 8.4 nm is required to ensure that the minimum separation of 5 nm is not violated. For the case of a B747-400 trailing a B737-300, an initial separation of 4.7 nm is required to ensure that the minimum separation of 2.5 nm is not violated. For the case of a B747-400 trailing a B747-400, an initial separation of 6.5 nm is required to ensure that the minimum separation of 4 nm is not violated. The runway capacity for the Open Loop MTDDA – like the TDDA, this capacity is calculated using Equation 2 -- varies between 34 and 39 landings per hour depending on the aircraft mix (Figure 8). For an airport with a 70/30 mix of B737-300 and B747-400, the runway capacity is 36 landing per hour, or 83% of the best possible runway capacity for that aircraft mix. While this result is encouraging because of the significant improvement over the TDDA, is it is not sufficient to enable such a procedure to be used in a high traffic scenario. Thus, additional modifications must be made to the TDDA.

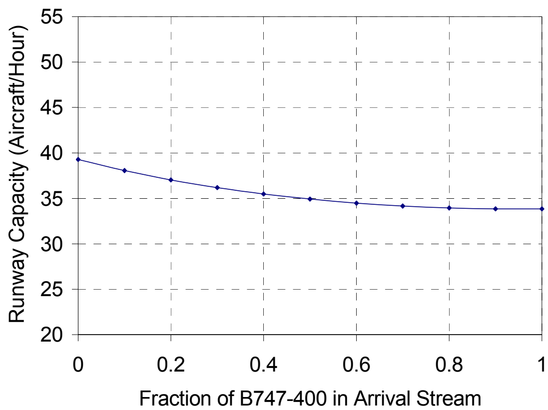

Figure 8. *R* versus *f* for Open Loop MTDDA with Initial Speed of 220 Knots

So far, we have assumed that all the aircraft are under open loop control. That is, the pilot follows a pre-planned sequence of control actions without any changes to compensate for difference between the actual trajectory and the planned trajectory. If appropriate guidance is available, however, the pilot could exercise "closed loop" control, i.e. adjust the MTDDA parameters to avoid separation violations even if the separation at the top-of-descent was smaller. To assess this hypothesis, we simulated the Open Loop MTDDA with all possible combinations of the control parameters that ultimately determine the trajectory of an aircraft performing an open loop MTDDA. The two control parameters are the duration of the initial speed hold and the speeds at which flap extensions occur.

Figure 9 shows the range of B737-300 speed profiles, and thus the range of separation that can be achieved by changing these parameters i.e. the control authority. The solid curve in the figure is the nominal speed profile. The right most dashed curve is the speed profile that is achieved when the duration of the initial speed hold is increased and the flaps are extended to the next position at the minimum speed for the current flap position. The left dashed curve is the speed profile that is achieved when the duration of the initial speed hold is decreased and the flaps are extended to the next position at 10 knots above the speeds for the nominal flap schedule. The left most dotted curve is the speed profile that is achieved when the duration of the initial speed hold is further decreased and the flaps are extended to the next position at 20 knots above the speeds for the nominal flap schedule.

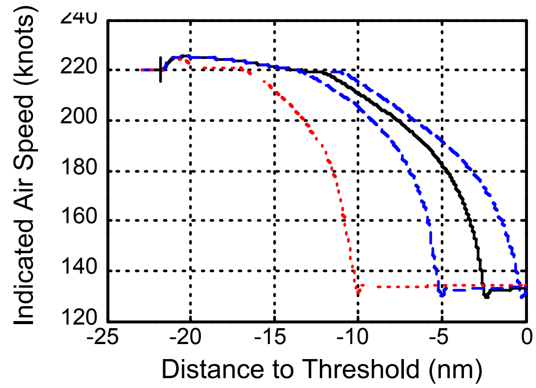

Figure 9. Control Authority for B737-300 Performing MTDDA

As the figure shows, the control authority is not symmetric i.e. it is easier to shorten than to lengthen the distance over which the deceleration occurs. As the figure also shows, the control parameters provide pilots with significant control authority. Thus, it is possible to reduce the initial separation between aircraft if the pilot is allowed to exercise closed loop control, because the control parameters can be adjusted both in the nominal procedure and in real time to compensate for the reduced separation. This is particularly encouraging given the fact that the algorithms required to determine the optimal values for the control parameters have been developed [8][9] and the pilot interfaces required to facilitate and support human control of these procedures are being developed [10].

Given the advanced state of the algorithm and interface development efforts, we decided to investigate the range over which the MTDDA could commence in order to meet a specific speed target -- the final approach speed -- at a specific distance prior to the runway threshold, so that we could determine if the introduction of closed loop control would allow us to reduce the initial separation between aircraft. The rationale being that any reduction in the initial separation would result in an increase in the runway capacity (see Equation 2). As Figure 10 and Figure 11 show, the point at which the thrust reduction could commence can vary by as much as 5 nm without changing the ability to meet the specific target. It is feasible, therefore, in the case of the Closed Loop MTDDA, to reduce the initial separation between all aircraft combinations by 1 nm, relative to the Open Loop MTDDA, and still have sufficient residual control authority to compensate for aircraft performance and flight performance uncertainties.

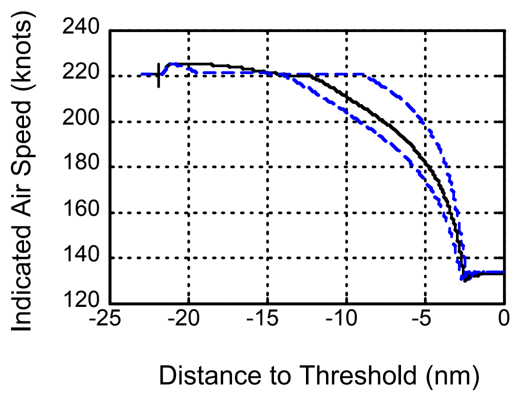

Figure 10. Range Over Which B737-300 Could Commence MTDDA and Still Meet Target

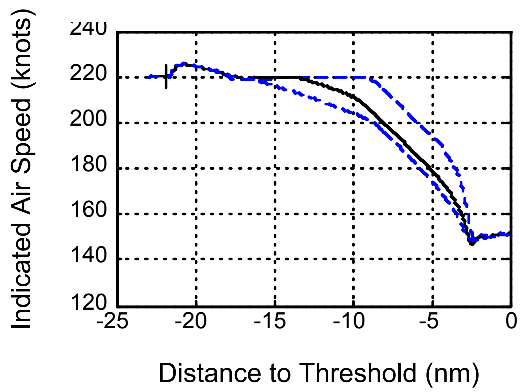

Figure 11. Range Over Which B747-400 Could Commence MTDDA and Still Meet Target

The required initial separations for the Closed Loop MTDDA would be as follows. For the case of a B737-300 trailing a B737-300, an initial separation of 4.6 nm would be required to ensure that the minimum separation of 2.5 nm is not violated during the approach. For the case of a B737-300 trailing a B747-400, an initial separation of 7.4 nm would be required to ensure that the minimum separation of 5 nm is not violated. For the case of a B747-400 trailing a B737-300, an initial separation of 3.7 nm would be required to ensure that the minimum separation of 2.5 nm is not violated. For the case of a B747-400 trailing a B747-400, an initial separation of 5.5 nm would be required to ensure that the minimum separation of 4 nm is not violated. The runway capacity for the MTDDA would then vary between 40 and 48 landings per hour depending on the aircraft mix (Figure 12), and for an airport with a 70/30 mix of B737-300 and B747-400, the runway capacity would be 43 landing per hour, or 98% of the best possible runway capacity for that mix.

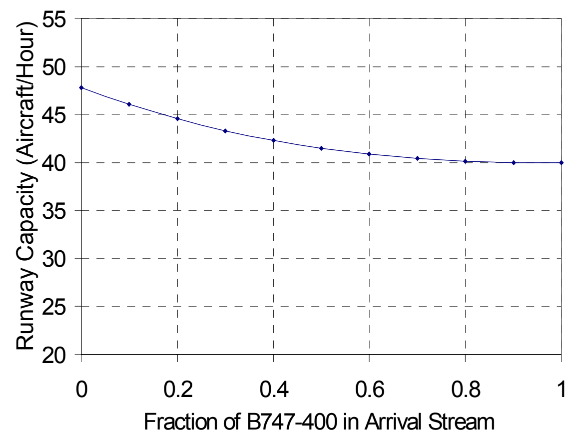

Figure 12. *R* versus *f* for Closed Loop MTDDA with Initial Speed of 220 Knots

6. MTDDA Noise Impact

Figure 13 shows a typical thrust profile for a B737-300 performing the MTDDA. As the figure shows, the thrust required for the initial speed hold is significantly lower than the thrust required for the level flight segment prior to the top-of-descent. The thrust required for the initial speed hold is significantly lower than the thrust required during the last portion of the descent to the runway when the final approach speed must be maintained. Given that the aircraft is furthest from the ground during the portion of the descent when the initial speed his being maintained, the difference between the noise impact of the MTDDA and the TDDA will be minimal because the intensity of noise decreases with the square of the distance between the source and the receiver. A similar result is observed for the B747-400. In fact, because the B747-400 has a lower deceleration rate, the B747-400 throttle setting to maintain the initial speed will be even lower than that for the B737-300, and the difference between the noise impact of the TDDA and the MTDDA is even less for the B747-400 than for the B737-300.

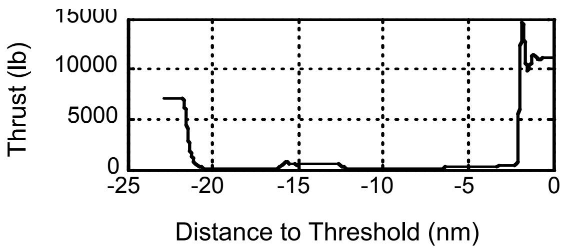

Figure 13. Thrust Profile for B737-300 Performing MTDDA

7. Discussion

It is clear from our analysis, that the TDDA offers significant noise abatement benefits. What is also clear, is that introduction of the TDDA, with existing aircraft performance and flight operation uncertainties, would require an increase in the initial separation between aircraft that would result in a significant reduction in runway capacity. As the simulation results have shown, the reduction in runway capacity is on the order of 50%, which is not acceptable for any procedure that must be used in high traffic scenarios. Thus, to date, the TDDA is only used for nighttime operations or other low traffic scenarios.

In this paper, we have introduced the MTDDA, a new procedure that is specifically designed to mitigate the capacity deficit that is observed with the TDDA. This goal is achieved by making two important changes to the TDDA. First, the initial speed is maintained for a fixed time after the start of the 3° descent to the runway, i.e. the thrust is not reduced to idle at the top-of-decent, but is first reduced to the thrust level required to maintain the initial speed, and then subsequently reduced to idle at a lower altitude. Second, the pilot is allowed to exercise closed loop control. There are two reasons why these changes mitigate the capacity deficit of the TDAA. First, the initial speed hold reduces the flight operation uncertainties that would normally have been introduced at the beginning of the TDDA. Thus, any uncertainties that are introduced have a shorter time to influence the trajectory of the aircraft. Second, the addition of closed loop control, allows the pilot to compensate for these uncertainties. That is, the closed loop control provides disturbance rejection capabilities.

One important feature of the MTDDA is that, while it provides similar noise abatement benefits to the TDDA, it also provides more reliable noise benefits because the control parameters will be adjusted to ensure that the final approach speed is achieved at the desired distance prior to the runway threshold, and the thrust will not be increased from idle, and thus increasing the noise impact, before that point. Thus, the MTDDA is a robust low noise approach procedure, from a noise abatement perspective, that is suitable, from an air traffic control perspective, for high traffic scenarios.

Another important feature of the MTDDA is that the separation profiles for aircraft exhibit "closing" characteristics, i.e. the minimum separation occurs at the threshold. Thus, if the separation at the threshold separation can be predicated accurately, it could be used as the main reference for the separation through out the entire procedure. This would be very beneficial if, as has been proposed [9][10], pilots were given the task of maintaining the desired separation. The hypothesis being that, if pilots focus on the predicted separation at the more distant threshold, they will filter out the higher frequency effects of the changing instantaneous separation, and thus make a smoother and consistent transition to the final separation. This would simplify the separation assurance task for both the pilots and the ground controllers.

8. Future Work

Several issues must be resolved before the MTDDA can be successfully implemented. To that end, we plan to:

- Explore the robustness of the MTDDA to variable wind conditions.
- Determine the optimum initial speed and initial altitude at the top-of-descent, both from the noise impact perspective and from the air traffic control perspective. This optimization will be done with real realistic constraints such as existing approach procedures, population distribution along the flight path, geographic features and wind conditions for specific airports.

- Develop algorithms and decision aids to help the controller determine the initial separation between aircraft in the case where the initial separation can be changed in response to the wind conditions.
- Develop algorithms and decision aids to help the controller monitor the separation between the aircraft to verify the separation against the planned trajectory.
- Develop algorithms and decision aids for airborne separation assurance. This will require distributed air-ground automation systems
- Assess the impact of the MTDDA on the roles of the controllers (Center, TRACON, and Tower) and the pilot.

Many of these tasks stem for the fact that any procedure must be robust to widely varying operating condition. Some of the tasks stem from the fact that, in practice, approach paths may be curved to avoid specific communities (for noise reasons) or specific airspace (for air traffic control reasons). In this case, multiple streams of aircraft performing MTDDA will have to be merged into a single stream for a given runway. Thus, the separation task will become even more challenging. We hope to develop algorithms and decision aids that are flexible enough to accommodate these scenarios.

Acknowledgements

This work was supported by the National Aeronautics and Space Administration under grant NAG2-1554.

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