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Crew Procedures for Continuous Descent Arrivals Using Conventional Guidance

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Abbreviations and Symbols

ADRS	Air Data Radar Simulation
ARIES	Airborne Research Integrated Experiments System
ATC	Air Traffic Control
CDA	Continuous Descent Arrival
CDU	Control Display Unit
CP	Common Point
EADI	Electronic Attitude Director Indicator
EOD	End-of-Descent
FAF	Final Approach Fix
FLCH	Flight Level CHange
FMB	Flight Manual Bulletin
FMC	Flight Management Computer
FMS	Flight Management System
IFD	Integration Flight Deck
ILS	Instrument Landing System
INM	Integrated Noise Model
LNAV	Lateral Navigation
LNFP	Low Noise Flight Procedures
LNG	Low Noise Guidance
MCP	Mode Control Panel
MSL	Mean Sea Level
ND	Navigation Display
nmi	nautical miles
QAT	Quiet Aircraft Technology project
RNAV	Area Navigation
SDF	Louisville-Standiford International Airport
SEL	Sound Exposure Level
STAR	Standard Terminal Arrival Route
TOD	Top Of Descent
VNAV	Vertical Navigation

Abstract

This paper presents results from a simulation study which investigated the use of Continuous Descent Arrival (CDA) procedures for conducting a descent through a busy terminal area, using conventional transport-category automation. This research was part of the Low Noise Flight Procedures (LNFP) element within the Quiet Aircraft Technology (QAT) Project, that addressed development of flight guidance, and supporting pilot and Air Traffic Control (ATC) procedures for low noise operations. The procedures and chart were designed to be easy to understand, and to make it easy for the crew to make changes via the Flight Management Computer Control-Display Unit (FMC-CDU) to accommodate changes from ATC. The test runs were intended to represent situations typical of what exists in many of today's terminal areas, including interruptions to the descent in the form of clearances issued by ATC.

The results showed that the pilots were able to conduct the descents, even when interrupted by ATC with instructions that took the aircraft off of the programmed path, laterally, vertically or both. The uninterrupted descent resulted in the most optimal profile, which translated to the lowest perceived noise levels and lowest amount of fuel burned. These benefits were reduced as the interruptions from ATC increased, but all three CDA run types resulted in quieter and more fuel efficient runs than with current-day procedures. The workload associated with conducting the descents were rated comparable to workload with current-day procedures (non-CDA). Pilots were able to conduct the descents with a minimum amount of time allowed for studying the instructions and charts they were given.

Introduction

The noise generated by aircraft during departure and arrival flight operations continues to be a significant problem at most major airports in the United States. Complaints from the communities surrounding these airports often result in restrictions to the number and type of operations that can be conducted in the surrounding areas. They also result in significant delays to construction of new runways and extension of existing runways. These restrictions in turn limit the capacity of the airport and can result in economic hardship for the airport, airlines, and communities served by the airport.

Improvements to the design of jet engines over the past several decades have reduced jet engine noise and greatly reduced the noise footprint of individual aircraft. However, the increasing number of flights and the expansion of population in the vicinity of airports have prompted renewed interest in methods for noise abatement. Procedural solutions to the noise problem, which involve changing the way pilots operate their aircraft to minimize the perceived noise on the ground below, have been investigated for a number of years, and several promising techniques have been developed. The primary advantage of procedural solutions is that benefits can be achieved without making design changes to the aircraft engines or airframe. The major challenges involved with the use of operational noise abatement procedures include development of acceptable pilot procedures, development of flight guidance

techniques, and development of acceptable procedures for Air Traffic Control (ATC).

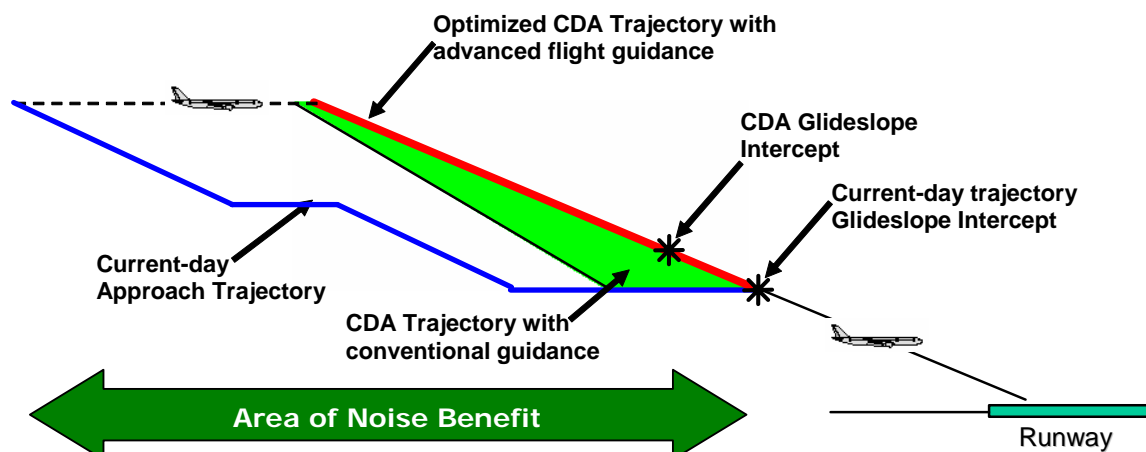
This paper presents results from a study that was conducted as part of NASA's Quiet Aircraft Technology (QAT) Project. The primary goal of the QAT project is to identify technology which can be applied to aircraft and to flight operations that will reduce the community noise generated by aircraft. The objective is to reduce noise by 10 dB, with flight operations contributing 2 dB to the total noise reduction. The element within the QAT Project that addresses the operational issues is called Low Noise Flight Procedures (LNFP), and includes the development of low noise flight guidance, and supporting pilot and ATC procedures for low noise operations. The study described in this paper involved the development and testing of operational procedures for conducting low noise arrivals using conventional aircraft

Background

Continuous Descent Arrival Procedures

The Continuous Descent Arrival (CDA) has been identified as a beneficial method for operationally reducing community noise near airports. As the name implies, a CDA optimally consists of an uninterrupted descent through the terminal area for an arriving aircraft, without any level altitude segments. The CDA is designed to minimize level flight at low altitudes, which produces more noise than descending segments, due to the higher thrust setting required to maintain level flight. Also, the CDA design keeps the aircraft higher throughout most of the descent through the terminal area, which allows for increased noise attenuation (see Figure 1).

Optimized CDA eliminates the level flight segment at low altitude



Considerable research and operational testing of CDA procedures has been conducted, such as in the

studies referenced in 1 and 2. Several airports, such as Heathrow in London and Schiphol in Amsterdam have operational CDA procedures that are used mainly during night-time low traffic density operations. However, there are two major obstacles that limit the ability to use CDAs on a regular basis, especially during high traffic-density periods. One is the lack of custom-designed flight guidance, which is needed by pilots to optimally fly the near-idle thrust continuous descent. The other obstacle is the lack of CDA operational procedures that can be integrated with current ATC procedures. This is particularly important during high traffic density operations, when controllers rely on the ability to issue speed and routing changes for maintaining aircraft separation and spacing. The primary objective of this study addresses the second issue, the develop of procedures that can be used to conduct CDA descents with existing aircraft autoflight modes, with ATC procedures similar to those used in current-day terminal areas. The following two sections expand on the issues of Flight Management Systems and Air Traffic Control, as they relate to the CDA Procedures for this research study.

Flight Management Systems and CDA Procedures

Since the early 1980s, standard avionics on commercial transport aircraft have included systems for managing various aspects of the flight trajectory. A modern Flight Management System (FMS) allows pilots to plan the trajectory for an entire flight, and include Vertical Navigation (VNAV) functions that can compute a performance-based vertical trajectory for the aircraft. The VNAV function also provides flight guidance to follow the computed trajectory, and thus could potentially be used to follow a CDA trajectory. Reference 2 includes a report on a study where CDA procedures were demonstrated, using commercial FMS VNAV functions to conduct the descent. However, limitations in both the basic functionality of VNAV as well as in pilot understanding of the VNAV guidance functionality have prevented widespread adoption of VNAV-based CDA procedures for operational use. The three main limitations associated with use of existing VNAV for CDA procedures are:

- The lack of a standard pre-defined lateral path that is continuous to the runway, and can be used as the basis for a CDA trajectory.
- The lack of flexibility in operation of the VNAV function, that does not allow pilots to easily make speed changes during the descent, while maintaining the CDA trajectory.
- The lack of continuously updated aircraft energy information to allow pilots to manage the descent more noise-efficiently, and to determine whether the high-energy CDA trajectory can be successfully flown.

These VNAV limitations could make it difficult, if not impossible, for aircraft to conduct CDAs in busy terminal areas, where controllers typically rely on tactical procedures to space traffic. The first two items above can be addressed by the design of flexible CDA procedures, such as those developed for this study. The third item was not addressed in this study, which focused on the use of conventional guidance systems.

Traffic Control and CDA Procedures

CDA procedures using VNAV can be readily implemented in the terminal area for single aircraft operations. However, multiple aircraft following CDA procedures for landing at the same or parallel runways, present a significant challenge for ATC. Typically, terminal area air traffic controllers (approach controllers) will utilize vectoring techniques in order to sequence arriving aircraft for landing, and to provide adequate lateral and vertical separation between aircraft. This requires controllers to make

tactical changes to the aircraft heading and airspeed, in addition to using staggered altitude profiles, to facilitate a safe and orderly flow of traffic to the runways. The fixed lateral routing needed for CDA descents is seldom, if ever, used for busy terminal areas. On arrival segments that have defined lateral routing, controllers typically use speed control to achieve and maintain desired spacing intervals between aircraft. Aircraft flying continuous descent arrival procedures have higher energy than those flying current-day procedures, mostly because of their higher altitude throughout the arrival. It may not be possible for an aircraft to dissipate this higher energy if its flying distance is shortened, thus making it difficult to comply with vectors that shorten the aircraft's flight path.

To effectively utilize FMS-based CDA procedures while also maintaining separation in a high traffic density terminal area, controllers must be able to specify changes in the lateral path, airspeed, and altitude of all aircraft. To be usable, CDA procedures must be flexible enough to accommodate these tactical clearances. Procedures developed for this experiment were developed to take these considerations into account.

Related studies

Although the experiment documented in this report does not make use of advanced technologies for conducting CDAs, it is useful to recall a previous study, which examined the use of energy-based guidance to maintain the ideal CDA profile. This study provided researchers with an initial look at the benefit of and pilot acceptability issues associated with an energy-based guidance, called Low Noise Guidance (LNG), for conducting CDAs. The relevance to the current study is in the operational procedures used for the CDA.

The study, documented in reference [3], paired individual subject pilots (acting as the flying pilot) with a researcher (acting as the non-flying pilot). Because this pairing did not truly represent an airline crew, a full set of crew procedures were not developed or evaluated. However, a charted procedure was developed and used, and the pilots were given a set of crew procedures that described how the LNG algorithm could be used to conduct the CDA descent.

The LNG algorithm was designed and tested as a VNAV sub-mode, in a simulated subsonic jet transport aircraft with advanced all-electronic displays. The subject pilots in this experiment were able to use the LNG low noise guidance to effectively conduct low-noise arrivals, with no major problems conducting the descent profiles as outlined in the procedures they were given. This included the test runs where they were required to make route and speed changes. Compared to the Baseline runs noise under the flight path was reduced by at least 2 decibels SEL at distances from 3 nmi out to 17.5 nmi from the runway, with peak reductions of 8.5 decibels at about 10.5 nmi. Fuel consumption was also reduced by about 17% for the LNG conditions compared to Baseline runs for the same flight distance.

More significantly for the current experiment, a Standard CDA procedure, in which the pilots used charted altitude crossing conditions with extended glideslope on final approach (a CDA using conventional guidance), also proved effective in reducing noise and fuel consumption. Without the benefit of continuous VNAV guidance, however, the pilots were not able to consistently achieve continuous descents. The level-altitude segments prior to glideslope intercept resulted in additional required thrust, and subsequently reduced the potential noise benefit. Peak noise reductions of 6.5 decibels and fuel savings of about 8% were achieved with the Standard CDA procedure compared to the Baseline runs.

Although the CDA profile cannot be maintained exactly using only conventional VNAV, the profile

can be approximated, and could still provide a significant noise advantage over current-day procedures. In recent years there has been much interest in the development of flexible CDA procedures that could be used in terminal areas with moderately heavy traffic levels. The degree to which a CDA profile can be maintained is dependent partially on how well the charted procedures are designed, and partially on how much ATC lets the aircraft stay on the profile. The charted and crew procedures used for this experiment were developed with these factors in mind. Planned future experiments in LNFP will explore the extension of these crew procedures to CDAs done with LNG guidance.

Crew Procedures Experiment

Experiment Objectives and Approach

This experiment had three main objectives: 1) evaluate the effectiveness of the CDA procedures using conventional VNAV; 2) identify any potential sources of confusion in the proposed procedure; and 3) conduct an informal assessment of the CDA descent when done with a new energy guidance algorithm.

The first objective, evaluation of the effectiveness of the CDA procedures, required both objective and subjective data, to determine whether or not the pilots could conduct a descent using the CDA procedures, with acceptable levels of perceived workload.

The second objective, identification of potential sources of confusion, is important to the development of a clear and concise CDA procedure, since the CDA differs from current-day procedures in subtle but important aspects. The primary source of data for determining this was from pilot comments and observations of how the crews conducted the descent.

The third objective, assessment of the CDA descent done with energy guidance, was considered an informal assessment, because the energy guidance was not yet fully integrated with the FMS. Because the balanced test matrix did not include the LNG runs, it was not appropriate to conduct statistical analyses on the data from these runs. Pilot comments and profiles of altitude and speed were documented, but a more thorough evaluation and direct comparison with non-energy-based guidance was left for the next experiment.

To achieve these experiment objectives, a series of four simulator test runs was developed, based on a scenario that consisted of a descent and approach into a moderately busy terminal area, Louisville International Airport (SDF). Each of the test runs used for this study had slight variations that represented situations typical of what an aircraft might encounter in that environment. The subject pilots that were recruited to fly the series of test runs were given instructions and information on how to conduct the CDA descent. Following practice time in the simulator, the pilots completed the test runs, during which objective and subjective data were recorded.

Flight simulator

The facility used for this experiment was the NASA Langley Research Center Integration Flight Deck (IFD) simulator (Figure 2). The IFD simulator cab is an engineering cab designed to represent the conventional flight deck of the NASA ARIES (Airborne Research Integrated Experiments System) B-757 airplane. The cab is populated with flight instrumentation, including the overhead subsystems panels, to replicate the B-757. The cockpit contains a “Panorama” visual out-the-window display system. This system provides a 200 degree by 40 degree visual out-the-window display to add realism to piloted experiments.



Figure 2. NASA LaRC Integration Flight Deck Simulator

During these simulation tests, significant cockpit modifications included a non-standard control panel for the Navigation Display (ND), and minor format modifications to the EADI. The non-standard ND control panel was located on the aisle stand just aft of the throttles.

Charts

Charts and procedures were given to the crews upon arrival on the day of their participation. The charted arrival used for this study was called the Bluegrass RNAV Arrival (Figure 3), and was based on the existing CHERI Two Standard Terminal Arrival (STAR) into Louisville. The CHERI Two Arrival brings aircraft arriving from the west on a direct course to the IIU VOR, which is a radio navigational aid located southeast of the airport. Well before this point (usually several miles), aircraft landing to the south are vectored north towards the airport, onto a right downwind or base leg.

ATC Environment

A PC-based Air Traffic Control simulation was used to help provide realism to the subject pilots' experience in the simulator. The simulation program used was called the Air Data Radar Simulation (ADRS), a program developed in-house at NASA Ames Research Center for internal NASA use. An air traffic controller operating the ADRS watched the ground tracks of all the simulated air traffic (including the subject crew's aircraft) on a PC display. All other air traffic (excepting the subject crew's aircraft) were pre-recorded and played back during the runs.

Communications between the other aircraft and the controller were scripted and recorded on a desktop

computer as audio files that could be played back at the appropriate times by the controller. The controller also had scripts for the communications with the subject pilots, but had some flexibility for real-time requests or questions from the pilots. The subject pilots were able to hear all the pre-recorded communications, but talked directly with the controller, enabling him to issue clearances and vectors to them in real-time and adjust as needed for each particular situation. Position data for the other aircraft were also transmitted to the simulator, so the subject pilots could see them as traffic targets on their ND.

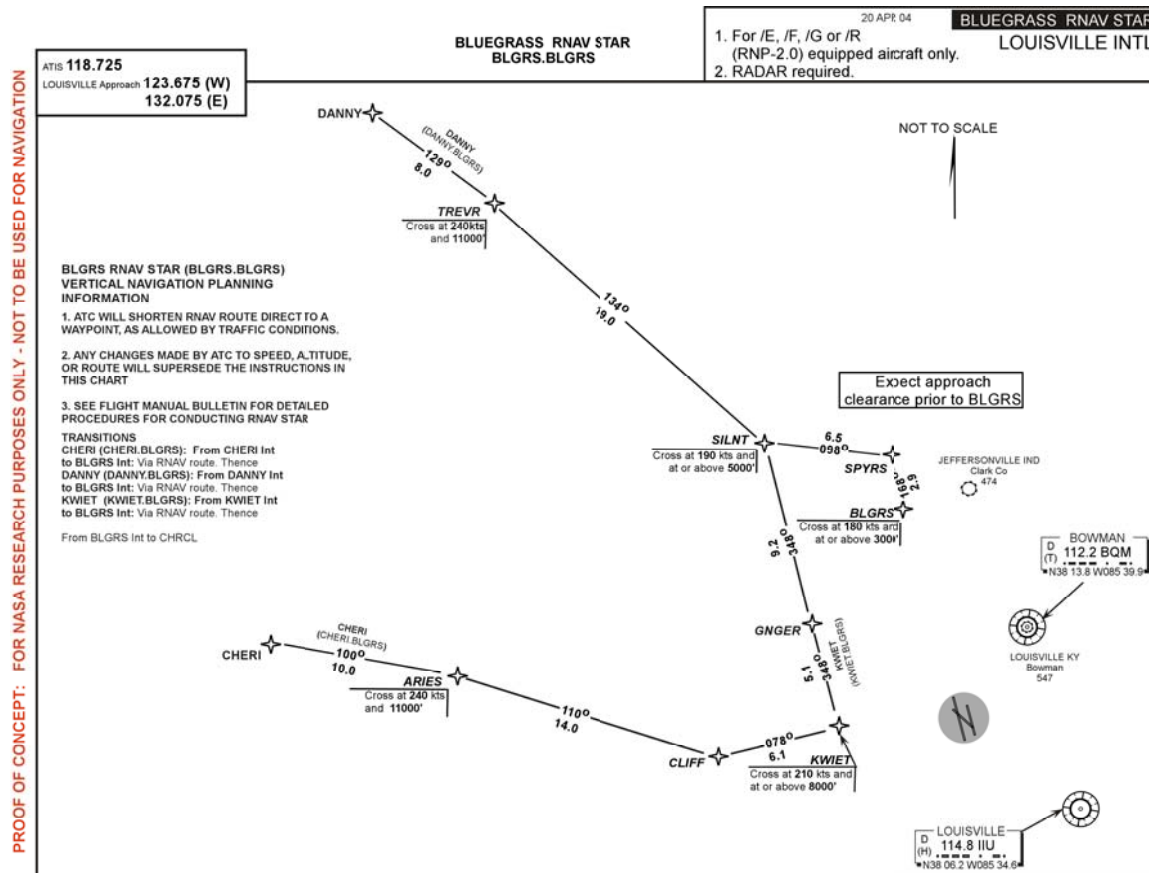


Figure 3. Bluegrass RNAV Arrival used for this experiment.

Test Runs

Four different test runs (conditions) were developed for this experiment: a baseline test run for comparison purposes, and three CDA test runs. The baseline test run consisted of current-day type procedures, including vectors and speeds from ATC. The three CDA test runs each had different levels of complexity, as determined by the amount of intervention required by the pilots. Examples of lateral paths for all test runs are shown in Figure 4, and of vertical trajectories in Figure 5. The four test runs are described in more detail below, and are referred to with the following shorthand notation: a) *Baseline* for the current-day vectoring procedures run; b) *CDA1* for the least complicated (uninterrupted) CDA run; c) *CDA2* for the medium-level complexity CDA; and d) *CDA3* for the higher-level complexity CDA.

Baseline

The Baseline test run was developed to use as a comparison for the other runs. This test run represented procedures in use at SDF. Although current-day procedures can vary widely depending on the specific traffic conditions, the conditions used for the Baseline test run are representative of what could be expected for commercial airplane operators arriving at SDF during moderately busy traffic periods, and were based on recorded tracks from actual operations at SDF. The vertical trajectory had three different segments where the aircraft was level for several miles (at 11000 ft, 6000 ft, and 3000 ft altitudes), which is very typical of what is done in today's environment at most major terminal areas.

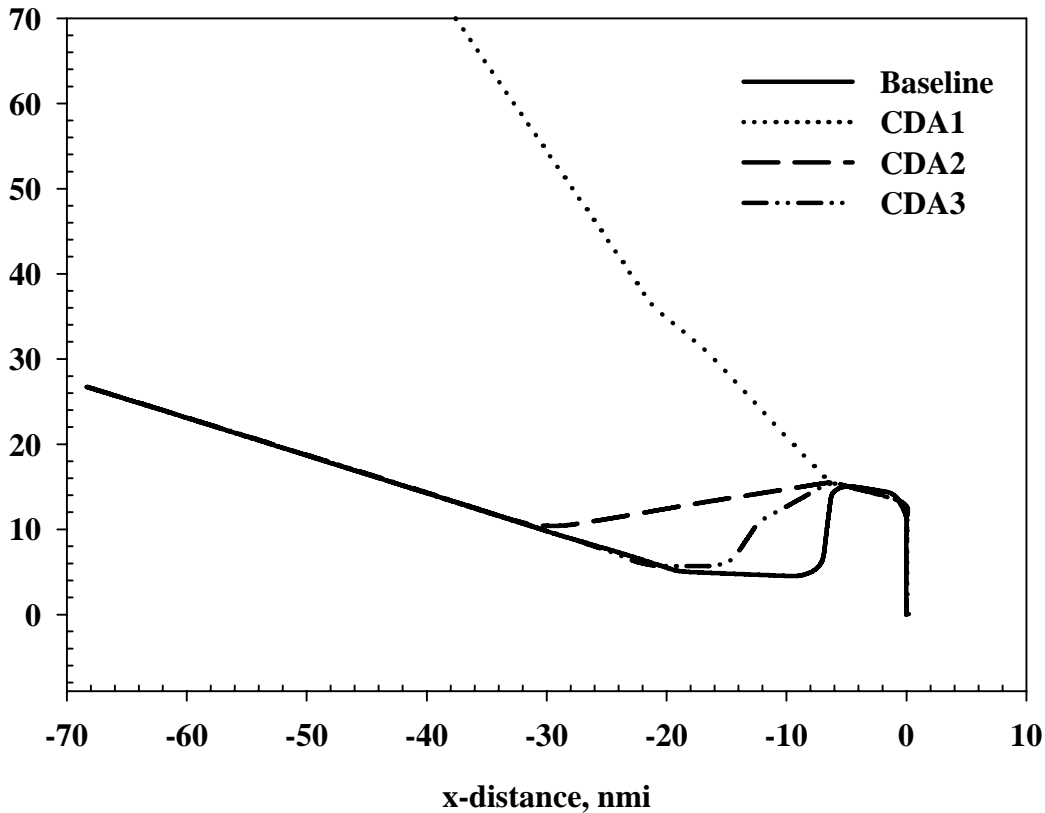


Figure 4. – Lateral paths of test runs.

CDA1

The simplest CDA test run was an uninterrupted descent, flown with no changes to the charted procedure. The north arrival (starting prior to the waypoint DANNY, on a direct track to DANNY) was chosen for this run because it would allow an uninterrupted descent, (ATC did not issue any deviations off the charted profile), and resulted in a run of comparable path length and time to the other CDA test conditions. After being cleared for the CDA, no further instructions from ATC (other than frequency changes) were issued until the approach clearance was issued on the base leg. This resulted in a direct arrival to the waypoint SILNT, which was the first waypoint in common for all the CDA scenarios. When flown properly, the vertical profile for this run had no level segments.

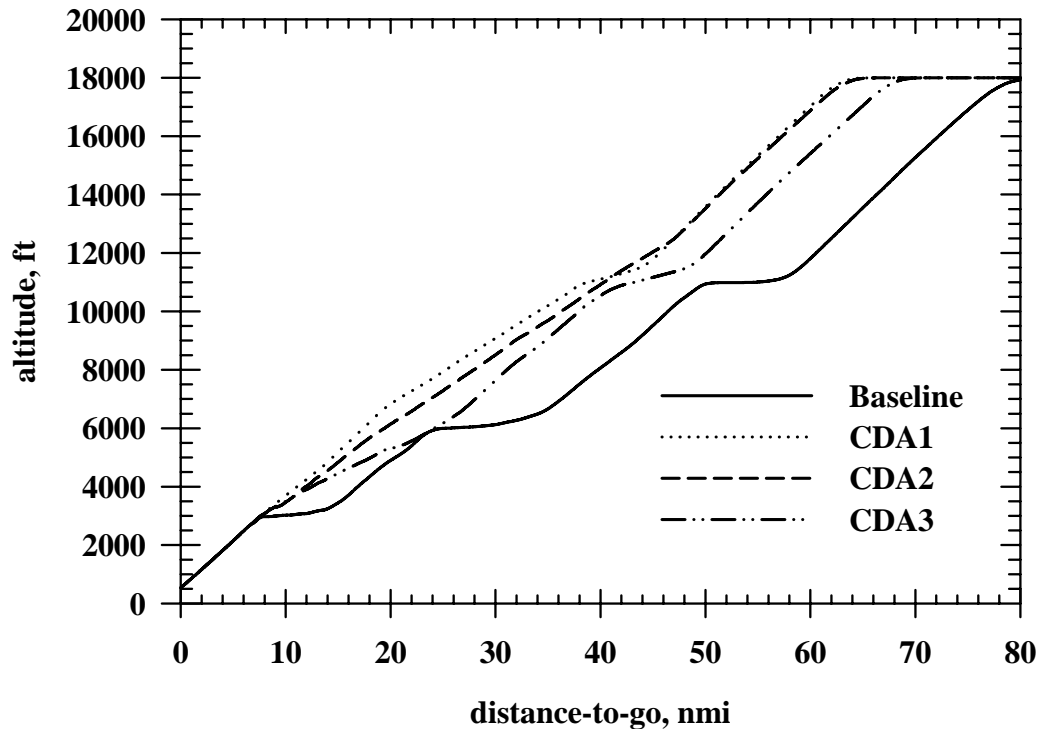


Figure 5. Altitude profiles of test runs

CDA2

The second CDA test run began as a CDA descent, but was interrupted by ATC with a speed and route change that required the crew to come off of the optimal descent profile to some extent. This test run used the arrival transition from the west, beginning prior to the waypoint *CHERI*, on a direct track to *CHERI*. Before arriving at *CHERI*, the crew was cleared for the CDA. Just after *CHERI*, the controller issued a left turn and speed change, taking the aircraft off the CDA and on a direct intercept to *SILNT*. Because the aircraft had not yet reached the deceleration segment at 10,000 ft, and the crew needed to closely watch the VNAV mode and make adjustments to maintain the vertical trajectory, while not exceeding the 250-kt speed limit below 10,000 ft. The resulting lateral path, which shortened the distance to the base leg, was a direct cut across to the waypoint *SILNT*, emulating the vectoring path used by controllers under light traffic conditions. It was expected that this test run would result in a descent that was less optimal than the uninterrupted CDA. The vertical profile for this run had no level segments, but had a slightly more shallow descent in the middle portion of the run.

CDA3

The third CDA test run began the same as the second CDA test run, but included more interruptions from ATC. In this run, the aircraft was allowed to continue farther along the CDA until after the waypoint *ARIES*, when the controller would issue a clearance direct to the waypoint *NGGER*. Shortly after that, the aircraft was taken off the CDA with a vector to the north, essentially paralleling the downwind leg. After the aircraft was established on the northbound heading, the aircraft was then given clearance to proceed direct to the waypoint *SILNT* and resume the CDA. This run involved switching out of Lateral

Navigation (LNAV) and VNAV modes, and closely monitoring the lateral and vertical paths to ensure that the correct trajectory was maintained. The resulting lateral path was not as direct as in the CDA2 runs. The vertical trajectory did not require any level segments if properly flown, but had two segments that were very shallow. It was expected that this test run would result in a descent that was less optimal than the CDA2 run.

Crew Procedures

Procedures for the crew to use as a guideline in conducting the CDA descent were included in a Flight Manual Bulletin (FMB). The FMB described the CDA procedure, and included instructions for pilots on how to manage their speed, altitude, and lateral route while conducting the CDA (see Appendix A). For all test runs, the pilots were instructed to maintain their normal procedures as much as possible, except for the instructions in the FMB that were specific to conducting the CDA. These consisted primarily of autoflight mode operation. Table 1 shows the autoflight modes to be used for each of the scenarios.

Table 1. Autoflight modes used for the four different run types.

Condition	Lateral flight mode	Vertical path mode	Speed mode	FMC route	Comments
Baseline	Heading select	FLCH or VSPD	MCP speeds	CHERI2 STAR	Non-CDA descent
CDA1	LNAV	VNAV	VNAV	BLGRS2 RNAV STAR, DANNY	CDA descent, no route mods
CDA2	LNAV	VNAV	VNAV (w/ speed intervene)	BLGRS2 RNAV STAR, CHERI	CDA descent, route mod w/speed intervene
CDA3	LNAV	VNAV	VNAV (w/ speed intervene)	BLGRS2 RNAV STAR, CHERI	Same as CDA2, but more complex

For the CDA runs the pilots were instructed to remain in VNAV and LNAV as much as possible. This included the times when ATC issued changes in lateral route or speed. The speed changes were to be made using the SPEED INTERVENE function, thereby allowing the aircraft to remain in VNAV guidance. Pilots were cautioned that using SPEED INTERVENE would affect how well the aircraft maintained the vertical path, and they needed to be aware of their position relative to the vertical path. This meant that pilots needed to maintain awareness of the aircraft flight modes as much as possible.

For the baseline run, pilots began in VNAV/LNAV, but were allowed to use whatever vertical mode they wanted after the initial part of the descent. After the initial descent, the aircraft leveled off and the autoflight system reverted to Heading Hold and Altitude Hold. Most of the pilots continued the rest of the descent using Heading Select and Flight Level Change to manage the lateral path and altitude, respectively. Since this test run emulated current-day procedures, the crew procedures were to comply with ATC instructions as normal.

Experiment Design

Run Ordering

The four test runs were repeated twice for each test crew, to allow each pilot to act as flying pilot in each of the four runs. This resulted in eight test runs per crew. Because of the number of runs required, it was not feasible to completely counter-balance the test matrix of runs. A Latin square design was used to

ensure that each run occurred once in each position in the ordering of runs (see Table 2).

Table 2. Run ordering used for this experiment.

	1 st run	2 nd run	3 rd run	4 th run	5 th run	6 th run	7 th run	8 th run
Crew #1	5	4	7	3	8	1	2	6
Crew #2	1	8	3	7	4	5	6	2
Crew #3	6	5	8	4	1	2	3	7
Crew #4	4	3	6	2	7	8	1	5
Crew #5	2	1	4	8	5	6	7	3
Crew #6	7	6	1	5	2	3	4	8
Crew #7	8	7	2	6	3	4	5	1
Crew #8	3	2	5	1	6	7	8	4

Subject Pilots

Sixteen subject pilots were used for this study, and were recruited as crews of two (one Captain and one First Officer), both from the same airline. All the subject pilots were required to be currently flying Boeing 757s, to minimize the amount of training time needed for this study. The resulting eight crews were each assigned a day to participate in the study. A single day was required for training and completion of the test matrix of runs. The subject crews represented four different airlines: Continental (1), United (1), American (3), and UPS (3). Crews were specifically requested from UPS because the airspace that was simulated for this study is the primary hub for their operations. Most of the pilots had been flying regularly (more than 100 hours in the previous 90 days) when they participated in the study. A few pilots had not been flying as often, either because they were in managerial positions, or due to the lack of available trips based on their seniority in their current position (Captain or First Officer). This became evident in their workload ratings, which often were higher than the ratings from those pilots that had flown more frequently. Most of the pilots that participated in this study had 5000-10000 hours of total flying time, and greater than 1000 hours in the 757/767 type.

Data collection

The effectiveness of the CDA procedures using VNAV was determined by whether or not its use resulted in a decrease in noise and fuel use. Acceptability and workload associated with the CDA was assessed from questionnaire data, as another measure of the procedure's effectiveness. The second objective, identification of potential sources of confusion, was determined partially from results of how well the pilots were able to follow the procedure, and partially from the pilots' questionnaires.

Objective data

The main parameters used for determining the effectiveness of the CDA from the recorded simulator data were altitude, airspeed, latitude/longitude, throttle activity, and fuel use. Many of these parameters were used for computing noise exposure levels using software programs developed external to NASA. Other parameters of interest were the operating modes (VNAV PATH, VNAV SPD, LNAV), and use of flaps, speed brakes, and landing gear.

All simulation runs were conducted using a nominal, vertically-varying wind field representative of typical winds in the Louisville area (Table 3). The same winds were used in all simulation runs.

Table 3. Winds used during simulation runs

Altitude (ft, MSL)	Wind Speed (Knots)	Wind Direction (True deg)
0	2.4	208
2461	5.7	242
4921	9.2	262
9843	16.0	273
13801	20.7	274
18289	25.9	273
23574	31.8	272
30065	38.9	270
33999	42.3	270

Subjective data

Data such as workload and acceptability ratings are considered subjective, because they represent the pilots' opinions, rather than direct measurements of physical (or simulated) quantities. Subjective data collected for this experiment included workload ratings, ratings of acceptability, clarity, or ease of use, and open-ended questions and comments.

The workload ratings were obtained by means of a Bedford scale [4]. This is a 10-point scale adapted from the Modified Cooper-Harper scale commonly used in flight testing for rating aircraft handling qualities.

The questionnaires that asked the pilots to provide a numbered rating used a 7-point scale, with the mid-point representing the neutral point. Some of the questions required a "Yes" or "No" answer, and others asked for comments or other explanations. Most of the questions on the final questionnaire were also given to the pilots in a pre-test questionnaire, before conducting the test runs in the simulator. When the pilots were given the pre-test questionnaire, they were not told that they would be seeing the questions again after the test runs were completed, thus enabling researchers to obtain "before and after" responses to many of the questions.

Prior to beginning the initial briefing on the study, the pilots were given a test of their knowledge of certain VNAV modes. The nine questions on the test were intended to provide the researchers with some indication of the pilots' level of understanding of VNAV modes that they had developed from their previous flying and simulator experiences. The pilots were not told in advance that they would be given this test, nor were the results discussed with them. Questionnaires are included in Appendix B.

Results and Discussion

Effectiveness of CDA charted procedures

The CDA procedure's effectiveness was assessed by analyzing the noise levels generated during the runs, the fuel used during the runs, and the airspeed and altitude profiles flown.

Noise levels

Noise levels between the Baseline and CDA runs were consistent with results from previous studies [3], which showed a marked reduction in noise levels for the CDA descents. Figure 6 shows curves of the noise exposure level versus distance to the runway for the four different test runs (in this plot no

differentiation is made with respect to Captain or First Officer flying). These curves were generated using the Integrated Noise Model (INM), version 7.0, a proprietary software package obtained from the Boeing Company [5]. The INM software program was also used in the LNG 1.0 study to compute noise exposure levels. The greatest average noise difference between the run types is at about 10 nmi from the runway, where the noise level was reduced by 5dB for the CDA1 and CDA2 runs over the Baseline runs. Overall, most of the average noise level reduction occurred in the segment between 7nmi and 15 nmi from the runway, for all three CDA conditions over the Baseline. As expected, the CDA1 runs (uninterrupted descent) generally had the most reduction in noise levels, although the CDA2 runs showed noise reductions at almost the same level. The CDA3 runs resulted in less reduction in noise exposure level than the other two CDA runs, particularly at distances between 10nmi and 16 nmi from the runway. However, the noise reduction over the Baseline runs was significant in all the CDA runs.

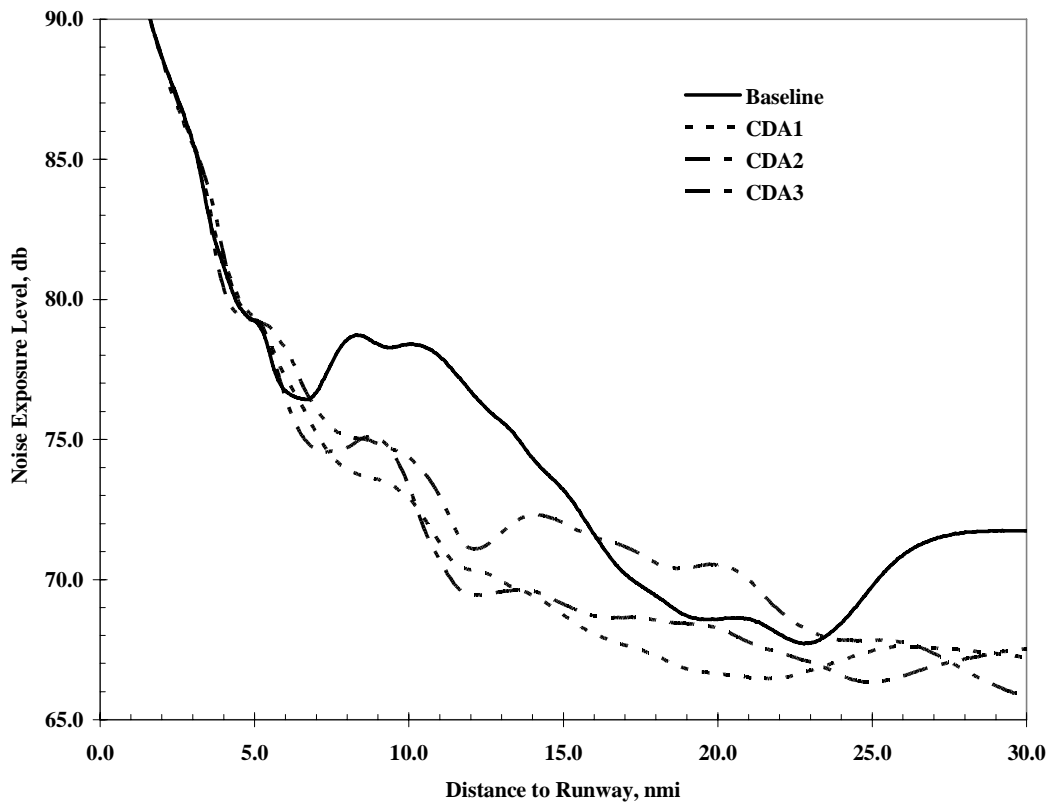


Figure 6. Noise Exposure Level versus Distance to Runway

Fuel use

Figure 7 shows the mean altitude profiles flown in this test, to illustrate the differences in descent profiles across the four different conditions. For analysis, the data from each condition were divided into three segments: before Top-of-Descent (TOD), descent, and final. The before-TOD and descent segments vary in path distance, depending on where the TOD was calculated for each run condition. The final segment is the same for all run conditions.

From figure 7, three different Top-of-Descent locations (expressed as distance-to-go) can be seen: one for the Baseline condition, another for the CDA3 condition, and a third for the CDA1 and CDA2 conditions. In the fuel use analysis, it is useful to identify the distance-to-go locations of these TOD

points, as well as the location of a common point that includes the entire descent profiles for all four conditions. This latter point is located just prior to the Baseline TOD, at a distance-to-go of about 81.8 nm. To simplify the data analysis, the “Common Point” (CP) was established at a distance of 82.8 nm distance-to-go, which is the beginning point for the CDA1 data. For the fuel use analysis, the descent segment is defined as the data beginning either at the individual TOD location for each of the four run types, or the CP, and ending at the 1000-ft (MSL) altitude point.

The 1000-ft altitude point corresponds to a distance-to-go of 1.5 nm. Although the vertical profiles (Figure 7) for all the descents merge prior to this point, it was chosen as the EOD because some of the fuel burn effects of the different test conditions continued up to just prior to this point, and thus affected the fuel use analysis for the descent segment. The final segment includes the remainder of the data (after the EOD point).

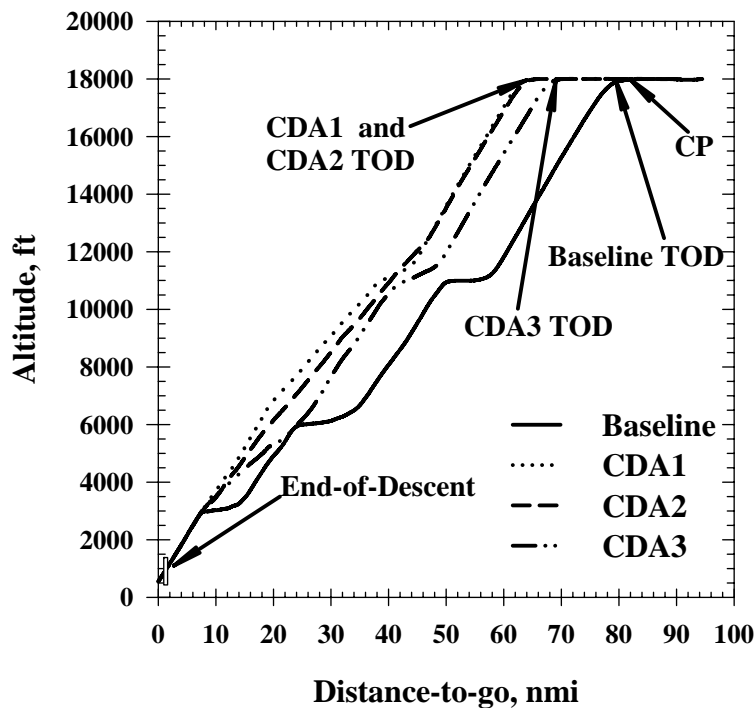


Figure 7. Mean altitude profiles of the test runs.

Table 4 shows the percent mean fuel reduction for the three CDA conditions, as compared to the Baseline condition. The portion of data from the last (final) segment was not included in these calculations because the fuel use was the same for all conditions. The different columns show the percent reduction in fuel use computed from the following points: the beginning of each run condition, the TOD point for each run condition, and the Common Point.

Table 4. Fuel reduction (from Baseline runs)

Run Type	From start of run, %	From own TOD, %	From CP, %
CDA1	25.0	40.5	11.0
CDA2	19.6	37.2	9.4
CDA3	11.6	28.4	6.7

A direct comparison of the fuel used in the descent can be made only if the descent from each condition's TOD location is considered. A comparison of fuel use from the CP provides a realistic estimate of the fuel savings during the descent, because it includes the effect of the fuel burned during the longer cruise portion of the CDA runs. The computations for the descent segments from the CP are based on identical total distance flown (because of how the CP is defined). The longer cruise distance associated with the CDAs lessens the fuel savings, because the fuel burn rate is much higher in cruise, and offsets some of the CDAs' advantage. To get a true picture of fuel savings due to a CDA descent, it is important to include this effect when comparing the data.

As in the LNG 1.0 study [3], there was a marked reduction in fuel use for CDA runs over current-day procedures. The uninterrupted CDA runs (CDA1) resulted in the greatest average fuel reduction, due primarily to the fact that the aircraft was operating at near-idle thrust for a large portion of the descent. In the CDA2 runs, there was more throttle activity as pilots attempted to adjust their speed and trajectory to comply with instructions from ATC. This resulted in a smaller fuel savings versus the uninterrupted CDA1 runs. The CDA3 runs resulted in even smaller fuel savings, due to increased throttle activity over that in the CDA2 runs. However, even the fuel savings in the CDA3 runs is significant to most airline operations, and demonstrates an important advantage of CDA descents over current-day type of descents.

The additional fuel savings measured from the start of the runs are attributed to the shorter distances flown during the CDA scenarios. The distance-to-go (along-track distance to the runway) is shown in Table 5 for the four different conditions. The starting points for the runs were chosen to be at the same great-circle distance from the waypoint BLGRS (the initial approach fix on final), however the resulting distances flown were not the same for the different conditions. The longer distances for the Baseline and CDA3 conditions were due to additional vectoring that was part of the way these conditions were defined. A full tabulation of the fuel and distance numbers for the four conditions are shown in Tables 6 through 9, for each of the run segments (cruise, descent from own TOD, descent from CP, and final).

Table 5. Mean distance-to-go for all conditions (to runway threshold)

Run Type	From start of run, nmi	From own TOD, nmi	From CP, nmi
Baseline	94.5	82.8	82.8
CDA1	82.8	65.0	82.8
CDA2	85.8	65.0	82.8
CDA3	90.2	70.0	82.8

Table 6. Fuel rate in cruise (before own top-of-descent)

Run Type	Fuel used, lb	Path dist., nmi	Fuel use rate lb / nm
Baseline	227.4	11.7	19.4
CDA1	359.4	17.8	20.2
CDA2	395.9	20.8	19.1
CDA3	392.3	20.2	19.4

Table 7. Fuel rate during descent from own TOD to EOD

Run Type	Fuel used, lb	Path dist., nmi	Fuel use rate lb / nm
Baseline	1215.5	81.3	15.0
CDA1	722.9	63.5	11.4
CDA2	763.9	63.5	12.0
CDA3	869.8	68.5	12.7

Table 8. Fuel rate during descent from CP to EOD

Run Type	Fuel used, lb	Path dist., nmi	Fuel use rate lb / nm
Baseline	1215.5	81.3	15.0
CDA1	1082.1	81.3	13.3
CDA2	1101.0	81.3	13.5
CDA3	1134.1	81.3	13.9

Table 9. Fuel rate in final segment (last 1.5 nm)

Run Type	Fuel used, lb	Path dist., nmi	Fuel use rate lb / nm
Baseline	98.0	1.5	65.3
CDA1	96.1	1.5	64.1
CDA2	96.8	1.5	64.5
CDA3	96.3	1.5	64.2

A more detailed analysis can give us an indication of the relative fuel penalties due to a less-optimal descent and to a longer path distance; however it is not possible for this study to definitively assign these percentages in a general sense to all descents. There are many other factors that affect the fuel advantage to be gained from a shorter path or more optimal descent, and in a busy terminal area there are also many sources of possible alterations to the descent that could affect the resulting gain or loss. From the fuel numbers computed for this experiment, it was estimated that neither of the factors stated (path length or a more optimal descent) had a predominant effect on the fuel savings. A dedicated trade study could better answer this question for the more general cases, with variables such as aircraft type, altitude, power setting, wind environment, path length, and descent profile. This is an important issue that should be addressed, as it can influence an operator’s preferences for descent trajectories.

Profiles flown

Altitude

Mean vertical profiles (and standard deviations) for each of the four different run types are shown in Figures 8a, 8b, 8c, and 8d.

Figure 9 shows the mean crossing altitudes for all four runs at the four waypoints in the segment between 5nmi and 20nmi before the runway. The altitudes are shown only at these waypoints because the altitudes at the others were not dependent on the type of run, and were the same. The difference is especially large at the waypoint SILNT, which marks the beginning of the base leg. The uninterrupted CDA runs (CDA1) had the highest mean crossing altitude, followed by the CDA2 runs, then the CDA3 runs, and finally the Baseline runs with the lowest mean crossing altitude. These higher crossing altitudes contributed to the lower noise levels seen in this part of the descents.

Airspeed

Mean airspeed curves for the four run types are shown in Figures 10a, 10b, 10c, and 10d. The symbols on the graphs show the mean and standard deviation of the crossing speed at the last four waypoints prior to the runway. Figure 11 shows in more detail the crossing speeds at the last four waypoints before the runway. Although the standard deviation is on the order of 10 kts around the top-of-descent point, generally it is within 10 kts throughout the run (for each of the four run types), including at the waypoint crossings. This would indicate that during most of the runs, speed was managed within normal allowances observed by transport pilots (+/- 10 kts).

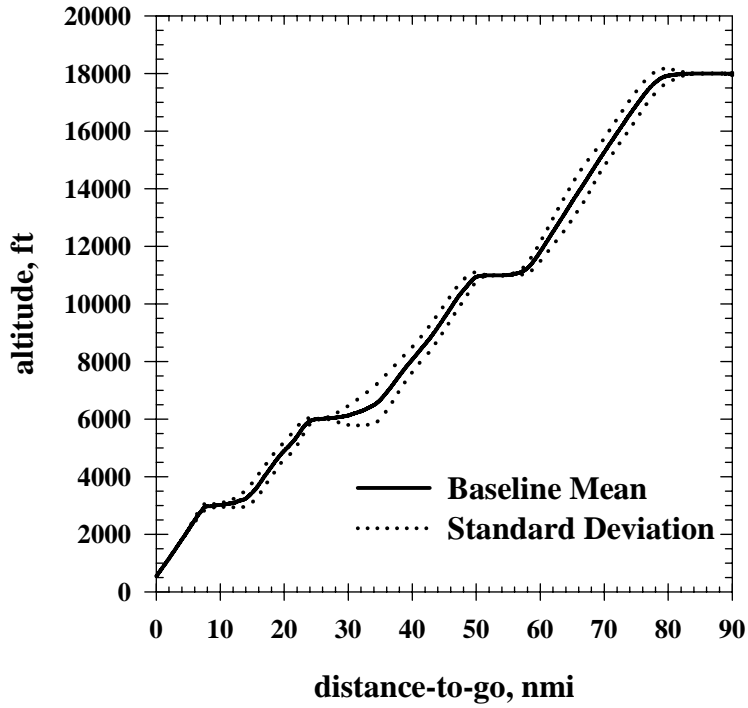


Figure 8a. Mean vertical profile for Baseline runs.

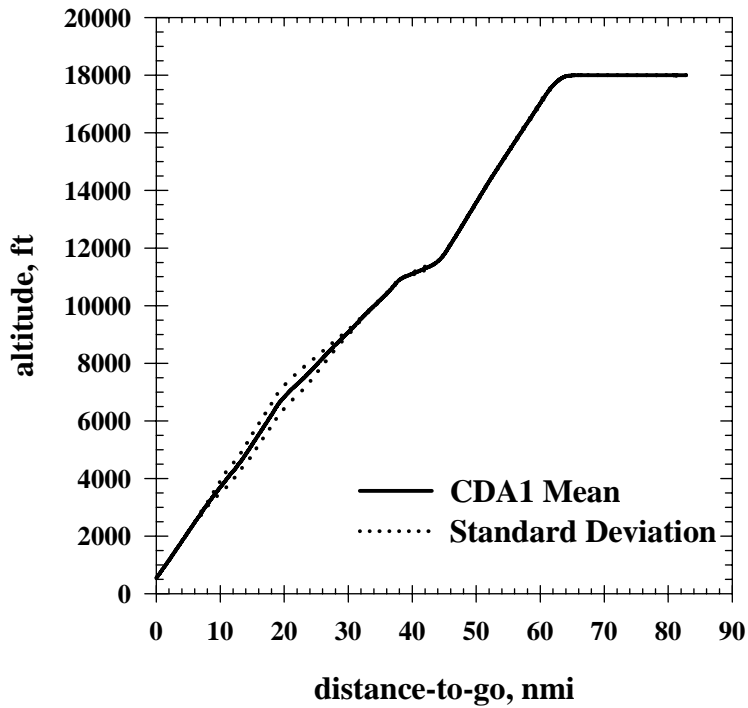


Figure 8b. Mean vertical profile for CDA1 runs.

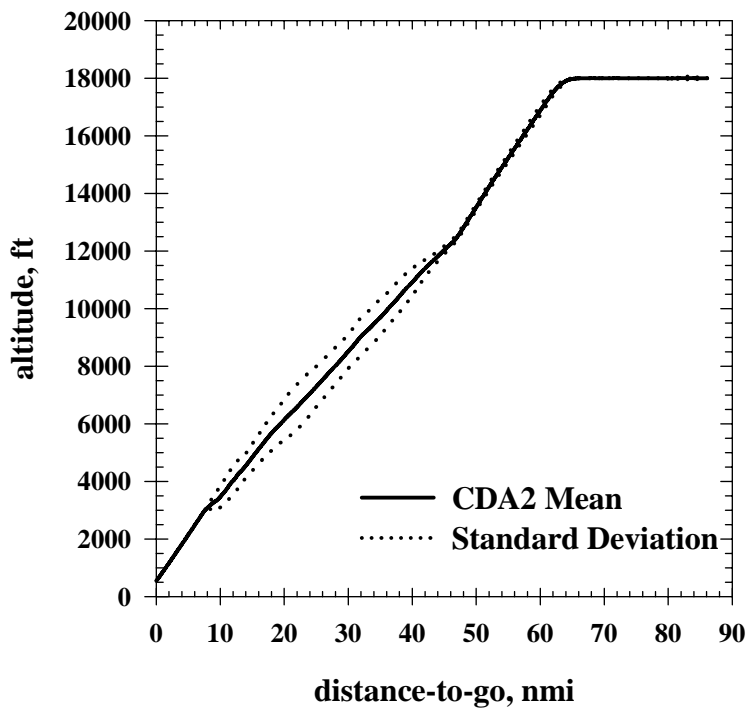


Figure 8c. Mean vertical profile for CDA2 runs.

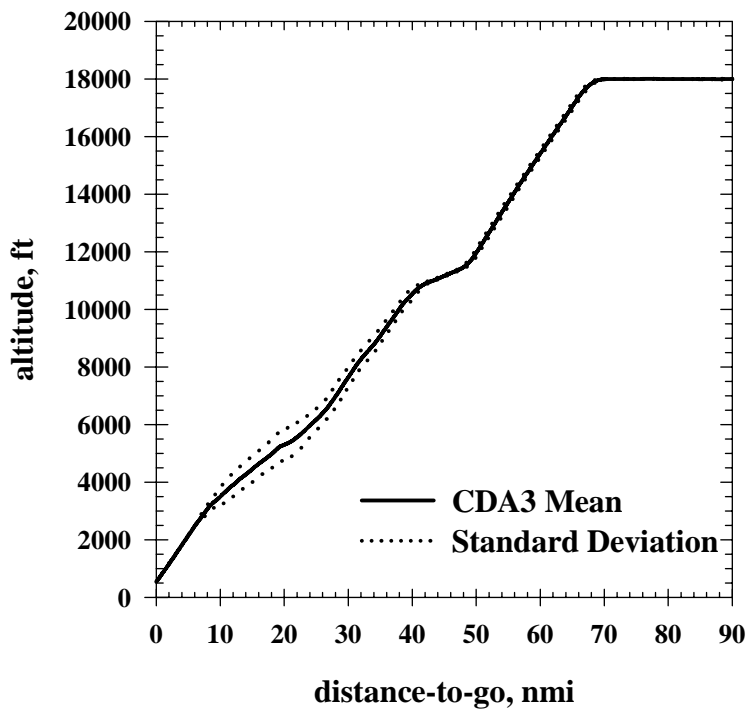


Figure 8d. Mean vertical profile for CDA3 runs.

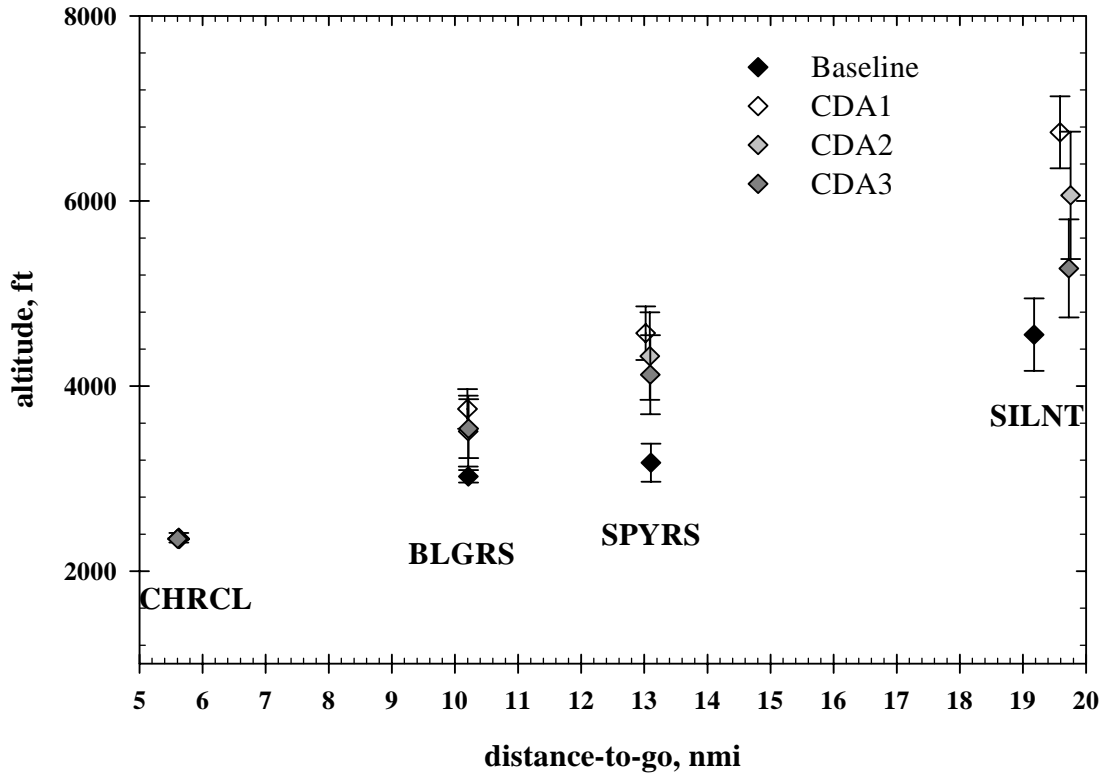


Figure 9. Crossing altitudes at last four waypoints.

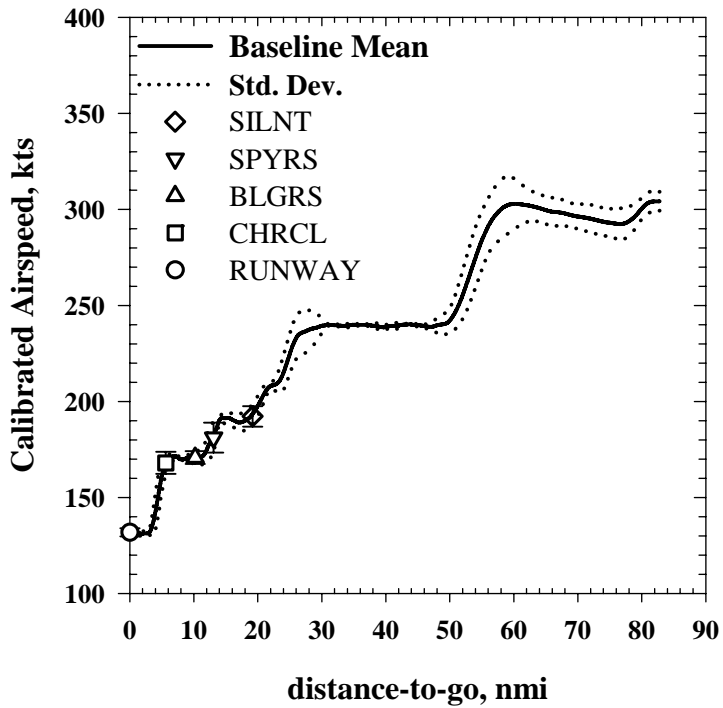


Figure 10a. Mean and standard deviation of airspeed for Baseline runs

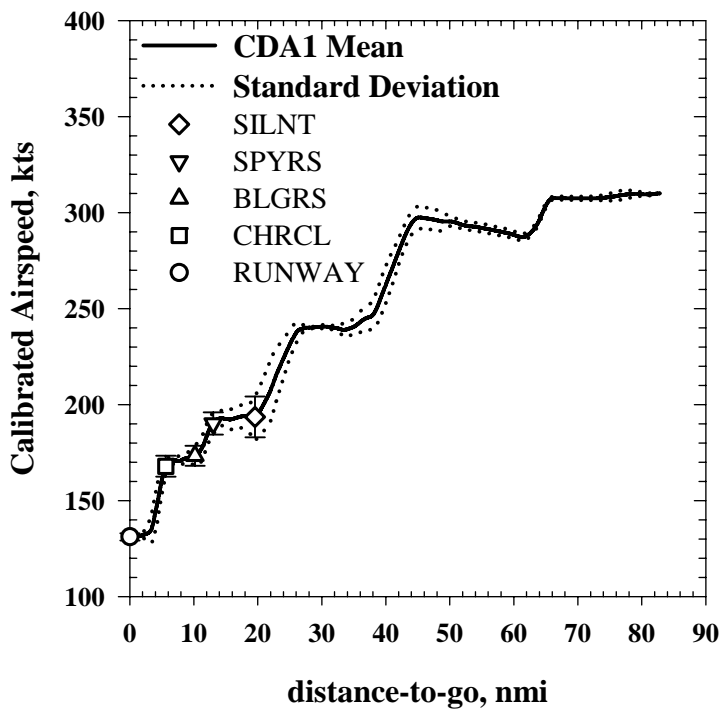


Figure 10b. Mean and standard deviation of airspeed for CDA1 runs

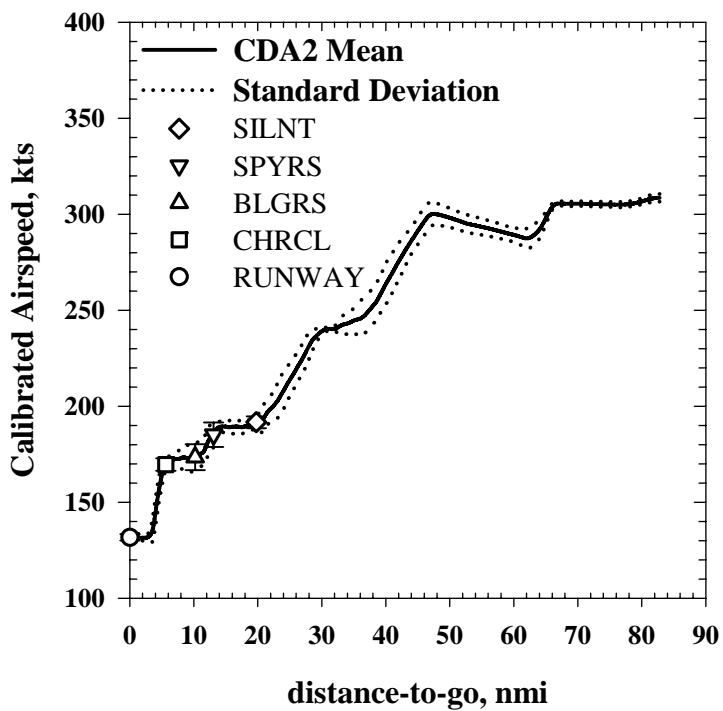


Figure 10c. Mean and standard deviation of airspeed for CDA2 runs.

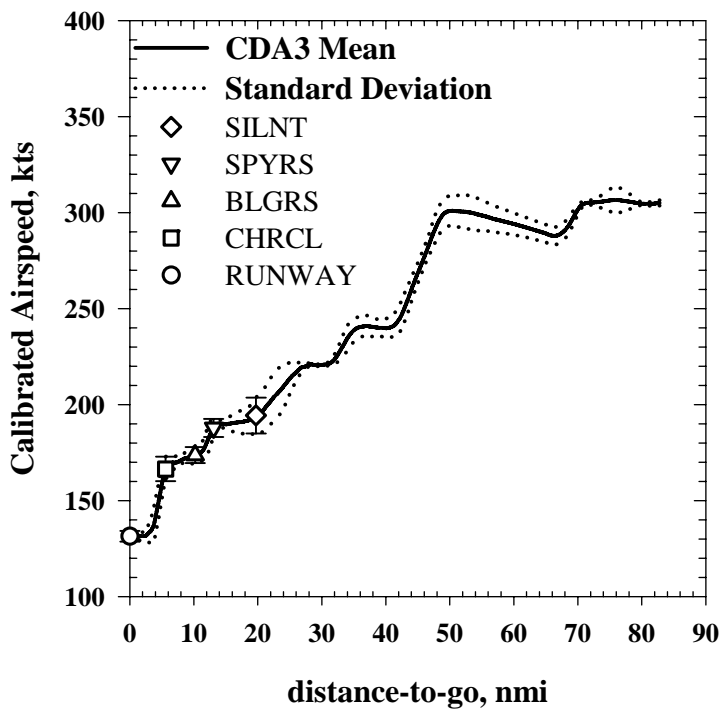


Figure 10d. Mean and standard deviation of airspeed for CDA3 runs.

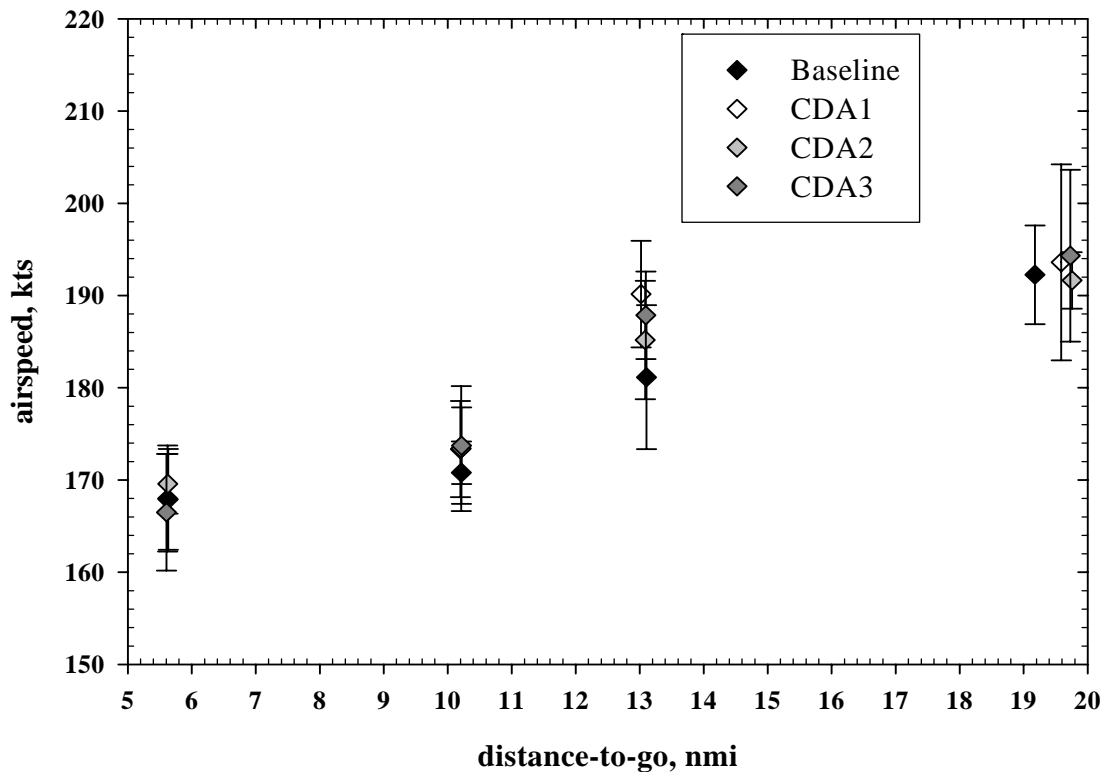


Figure 11. Mean and standard deviation of crossing speeds for all run types.

Thrust

Mean thrust levels are shown in Figures 12a, 12b, 12c, and 12d for each of the four run types. Integrating the area under the mean thrust curves for the four run types gives an indication of which curve has overall higher thrust levels during that portion of the run. Only the last 60 nmi of each run were used, so that the CDA runs were not unfairly penalized with the higher thrust settings associated with the longer distance flown at cruise altitude. The CDA profiles, by their nature, remain at higher altitudes until closer to the runway, meaning that the aircraft is operating at higher thrust settings for a longer period of time before the descent is initiated. Table 10 shows these thrust levels for the four runs types are shown, normalized by the Baseline run to indicate reduction in thrust levels during the CDA runs.

Table 10. Normalized area under mean thrust curves.

Run type	Sum of mean thrust levels
Baseline	1.00
CDA1	0.49
CDA2	0.51
CDA3	0.61

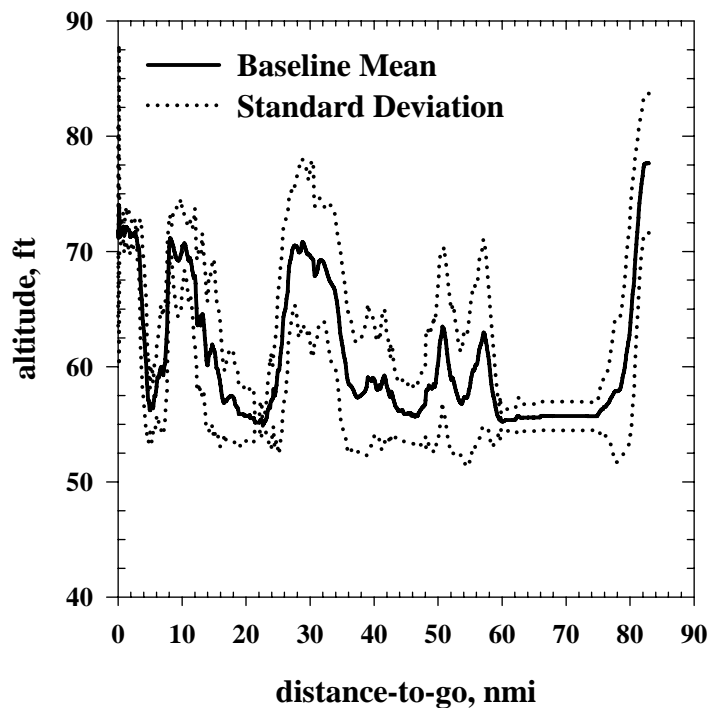


Figure 12a – Mean and standard deviation of thrust for baseline runs.

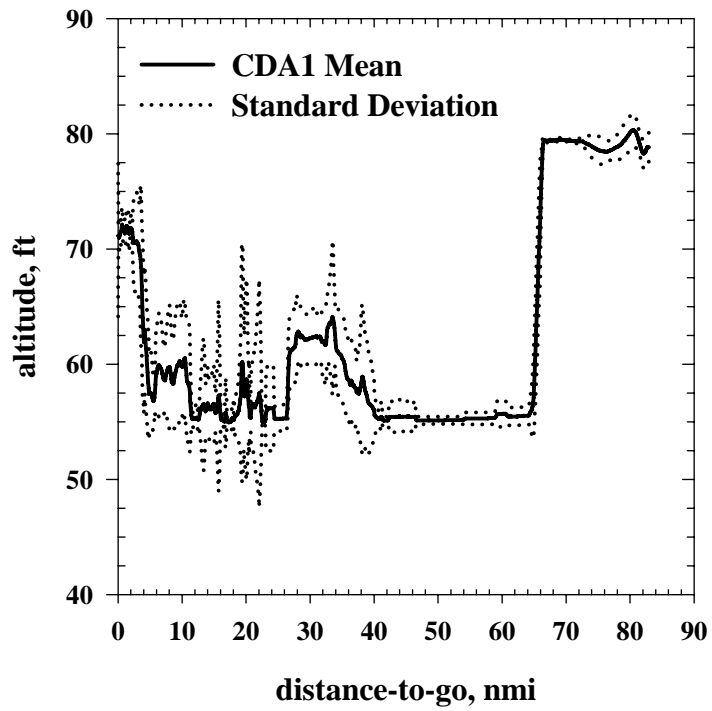


Figure 12b – Mean and standard deviation of thrust for CDA1 runs.

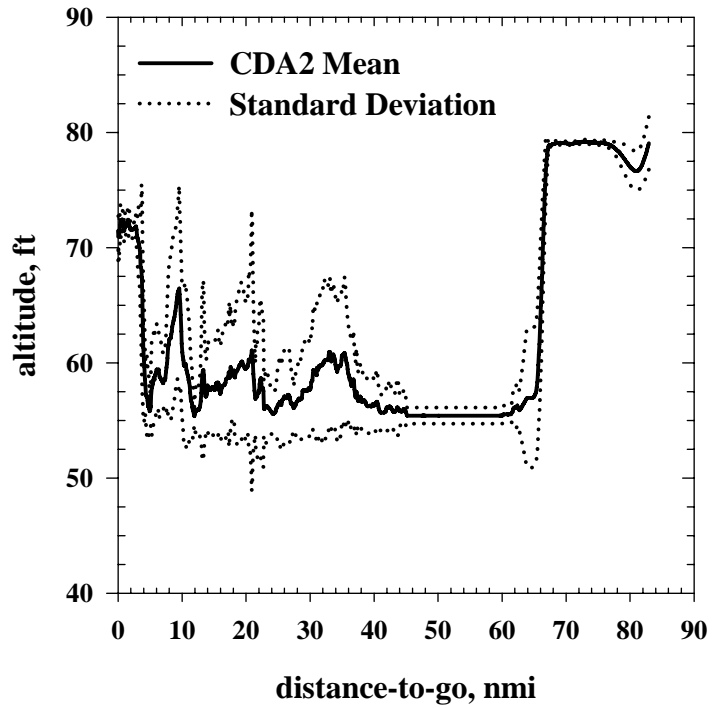


Figure 12c – Mean and standard deviation of thrust for CDA2 runs.

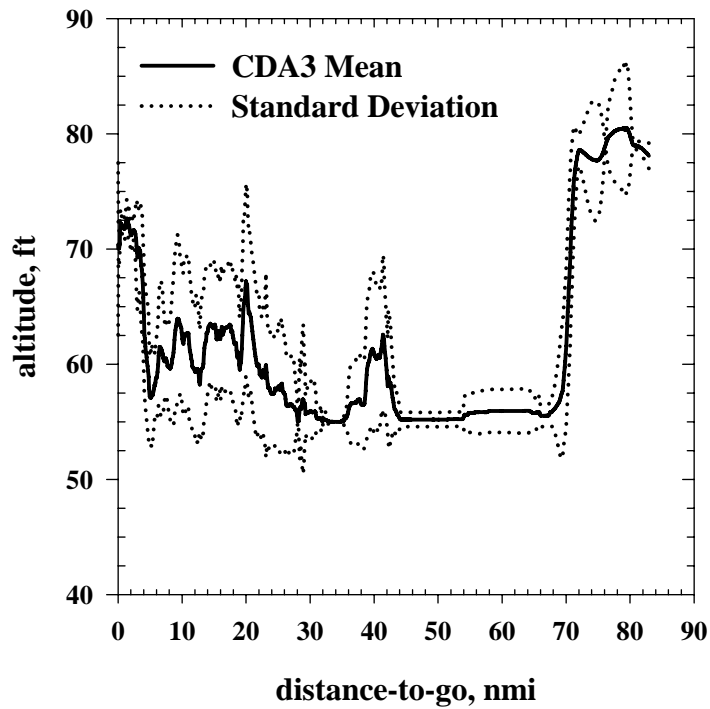


Figure 12d – Mean and standard deviation of thrust for CDA3 runs.

The mean thrust levels for the four run types are plotted together in Figure 13. Comparing the last 15-20 nm of this curve with Figure 6 (which shows the mean noise levels for the four run conditions) shows some similar patterns, indicating that the thrust levels strongly affected the perceived noise levels computed with the INM program.

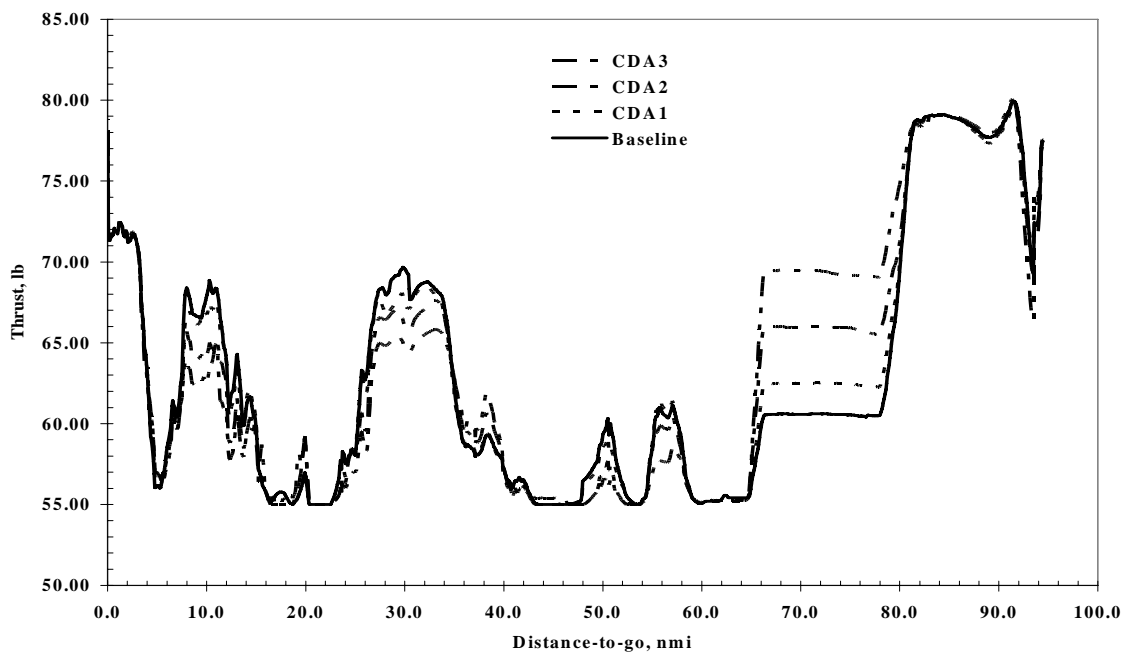


Figure 13. Mean thrust levels for four runs types, last 30nmi of runs.

CDA Usability Ratings

To obtain a subjective measure of the CDA usability, the subject pilots were asked to rate the difficulty of conducting a CDA descent with VNAV, using a seven-point rating scale as shown in the figures below. Usability is another measure of the effectiveness of the procedures, because the pilot will not use them if they find them to be too difficult. The pilots were asked in separate questions to rate the difficulty of the procedures for managing altitude, path, and speed. Figures 14a, 14b, and 14c show the mean and standard deviation of the pilots' responses to these questions. The pilots were asked these questions both before and after the test runs were conducted, and both results are shown in the figures.

The mean ratings for all pilots for managing altitude, path, and speed were all below 3. This indicates that, overall, they felt the procedures were below average in difficulty (although some pilots rated the procedures higher than 3).

Differences between the responses on the questionnaire taken before the test and those on the questionnaire taken after the test were not statistically significant. For the question about managing speed (figure 14c), the "after" rating was slightly higher (slightly more difficult) than the "before" rating, indicating that, after having conducted the test runs, the pilots felt the procedures to be slightly more difficult. Although pilots rated the procedures easy to use, the researchers observed that the crews did not always follow them as they had been briefed.

The procedures for managing altitude between the waypoints CHERI and BLGRS are:

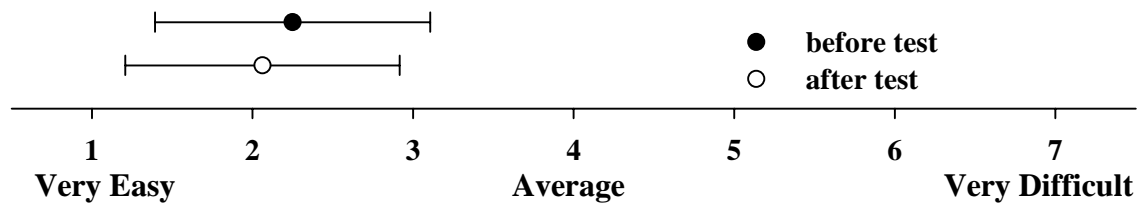


Figure 14a – Means and standard deviations of pilot ratings of procedures for managing altitude.

The procedures for managing the lateral path between the waypoints CHERI and BLGRS are:

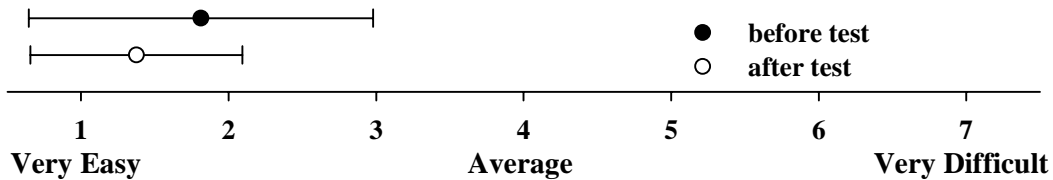


Figure 14b – Means and standard deviations of pilot ratings of procedures for managing lateral path.

The procedures for managing speed between the waypoints CHERI and BLGRS are:

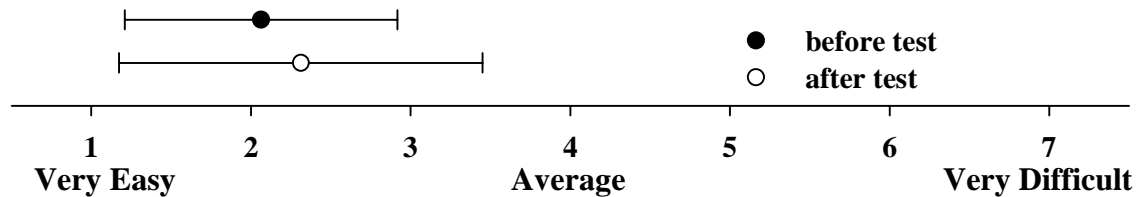


Figure 14c – Means and standard deviations of pilot ratings of procedures for managing speed.

Pilot ratings for acceptability of CDA chart

Pilot ratings for acceptability of the CDA chart are shown in Figure 15. The pilots rated the chart acceptable, with means and standard deviations of the ratings under 3, indicating that they understood the procedures well (before the test). Ratings taken after the test showed slightly more consistency. Pilot comments also supported these ratings.

For most pilots, the BLGRS RNAV chart is:

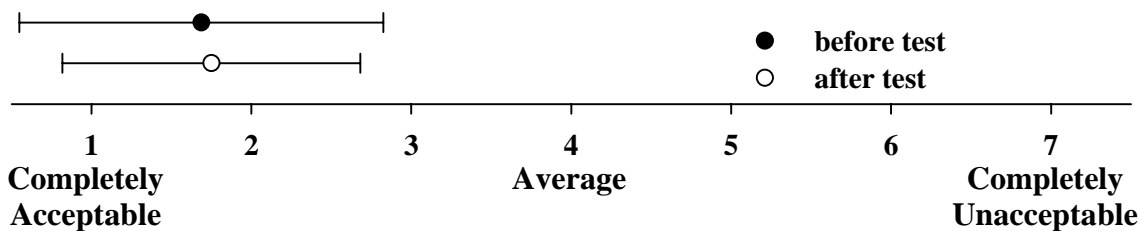


Figure 15 – Means and standard deviations of pilot ratings of BLGRS RNAV chart.

Pilot Workload Ratings

Pilots were asked to rate the perceived workload at various points during each of the runs, using a Bedford rating scale (see Figure 16) for determining the rating. The Bedford scale asks the subject to provide a rating indicating their spare mental capacity. Spare capacity is the pilot’s ability to attend to secondary tasks, and gives an indication of how much work is required to attend to the primary task. In this experiment the primary task was managing the CDA descent. Examples of secondary tasks for the pilots are changing the radio frequency and completing checklists. The Bedford scale has been used and evaluated in many studies, and can provide a more sensitive workload rating than a rating that is administered after the run has been completed [4].

The workload rating is determined by following the decision tree illustrated on the scale, beginning at the bottom. If the response to the question is yes, the pilot continues to the next question above. When the response is “yes”, the pilot continues to the right, where the statement that best represents the workload level must be chosen. The number next to that statement is the pilot’s workload rating. For this experiment, these workload ratings give an indication of whether the CDA crew procedures can be integrated into a current-day flight deck environment relatively easily.

For this study, the pilots' workload ratings were solicited at five different locations during each run, in the order and at the locations shown in Figure 17. The first location (marked 1 in the figure) was shortly after the start of the run, during the cruise portion. The second location (2) was during the initial part of the descent, before any changes were made to the descent trajectory. It was expected that pilot workload ratings at these two locations would be low. The third location (3) was after the pilots had completed the ATC-issued changes to the descent. It was anticipated that the ratings at this location would be substantially higher than at the first two. The fourth location (4) was on the base leg of the traffic pattern., after all the CDA runs would have been back on the CDA descent again, and in VNAV. The last location (5) was on final approach after the last waypoint of the CDA procedure, and before the final approach fix (FAF), named CHRCL. At this location, all runs (including the baseline run) would have been equivalent, since they were all on the Runway 17R ILS Approach procedure (the CDA procedure ended at BLGRS).

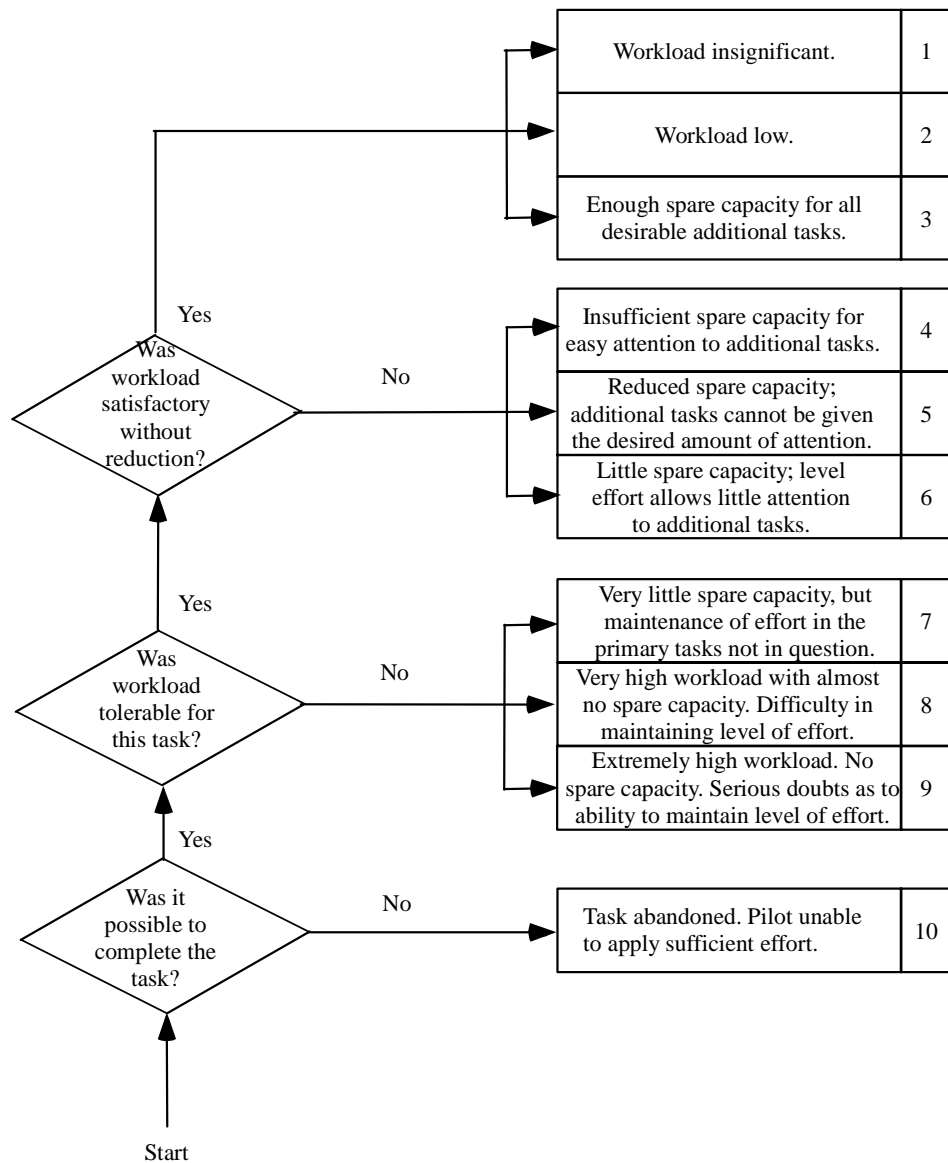


Figure 16. Bedford Workload Rating Scale

Each pilot provided their own workload ratings by making a mark on a paper scale that was provided to each of them. Since both pilots were providing individual workload ratings, they were asked to not comment orally on their ratings during the actual test runs, so that they did not influence each other's ratings. During the initial oral briefing, the pilots were given time to study the workload rating scale. They also were required to use it during the practice runs in the simulator, so they could become accustomed to the rating scale itself, and to the approximate locations where they would be asked to provide ratings.

Results from the pilot workload ratings are shown in Figure 18. The mean and standard deviation of the ratings are shown separated by run condition for each of the five locations where the ratings were provided.

At each location except the third one (before SILNT), workload ratings were very similar across the four run conditions. For the "Before SILNT" location, the workload was rated highest for the CDA with multiple interruptions, lower for the CDA with one interruption (CDA2) runs, followed by the uninterrupted (CDA3) runs, and lowest for the baseline runs. This indicates that the pilots felt the Baseline runs to be lowest workload, which makes sense because this is the procedure with which they are the most familiar. This was followed, in increasing order of workload, by the CDA conditions in order of increasing complexity, which also makes sense. A statistical analysis (Mann-Whitney Rank Sum Test) on the data indicated a statistically significant difference ($P=0.013$) only for the comparison of workload ratings for the CDA3 runs versus the Baseline runs at the third location (before SILNT).

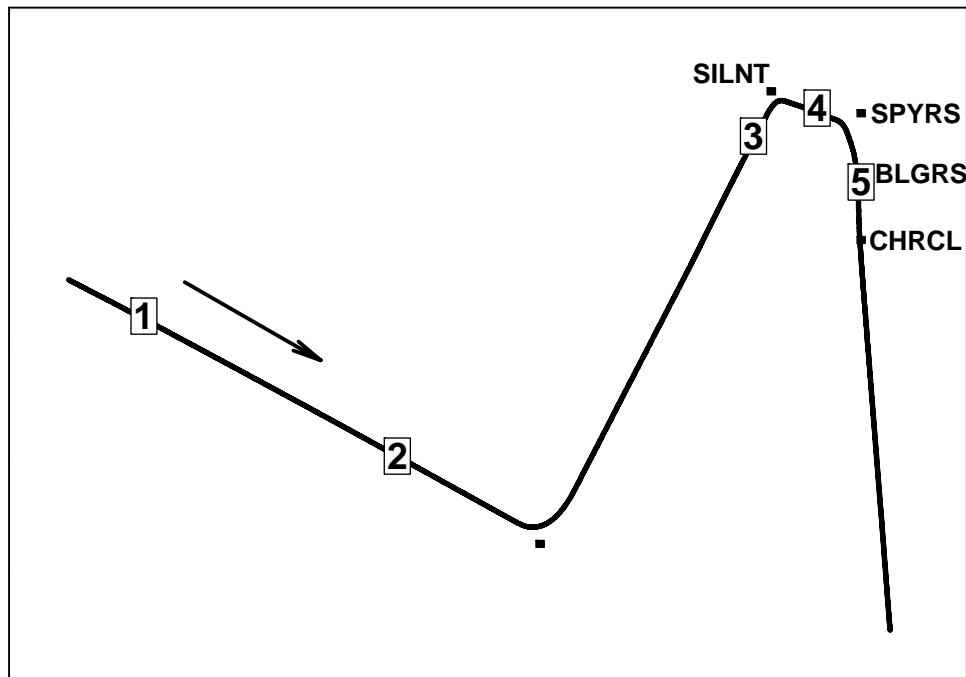


Figure 17 – Locations for workload assessments.

Overall, the mean workload ratings for the first location (Cruise) were the lowest, as expected since the aircraft was fully coupled in cruise flight. At each of the last two locations (Base Leg and Final), the workload ratings were very similar across the four run conditions. The ratings at these two locations were about the same as for the Before SILNT location. This suggests that the pilots felt that the workload associated with the CDAs, including the modifications issued by ATC, was about the same as the workload associated with final approach.

The means for all the conditions at all the locations were below three, indicating that workload levels were considered to be within acceptably low levels, and that the pilots felt that the workload associated with the CDA procedures conducted with VNAV was comparable to that associated with current-day operations.

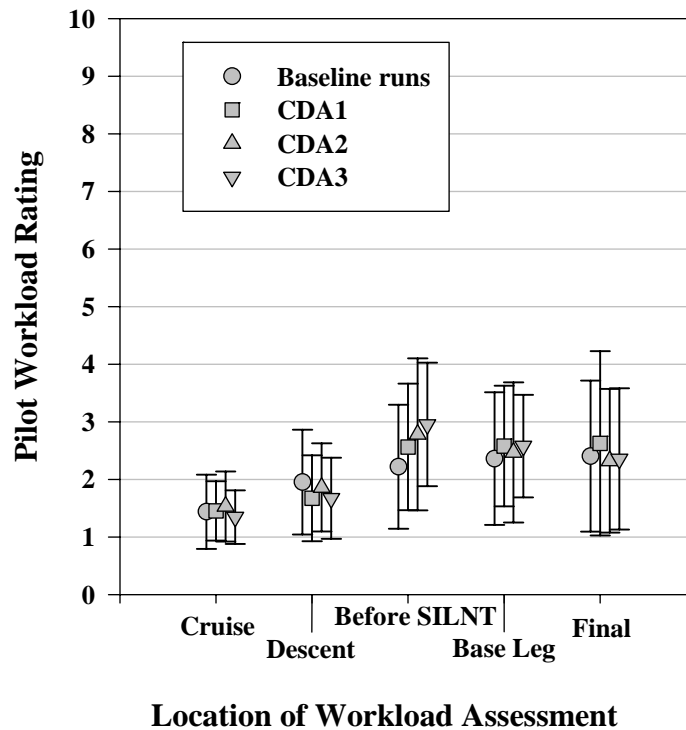


Figure 18 – Means and standard deviations of pilot workload ratings

Clarity of CDA procedures

Assessment of the clarity of the CDA procedures gives an indication of whether the procedures are confusing or should be modified to clarify potential sources of confusion. This assessment was done by obtaining pilot opinions using a structured questionnaire. Results from the specific questions that address clarity of the procedures are shown in Figures 19a, 19b, and 19c, separated by “before” and “after” the test responses. Mean ratings indicated that most of the pilots felt that they understood the procedures for managing altitude and lateral path well, both before and after having completed the test runs, but slightly better after the test. The differences between the “before” and “after” responses for these questions were not statistically significant.

The procedures for managing altitude between the waypoints CHERI and BLGRS are:

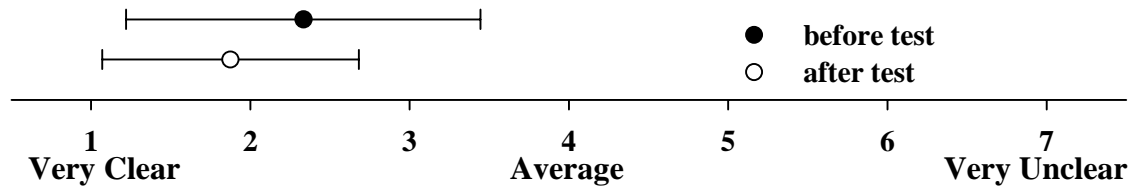


Figure 19a - Pilot ratings of procedures for managing altitude.

The procedures for managing the lateral path between the waypoints CHERI and BLGRS are:

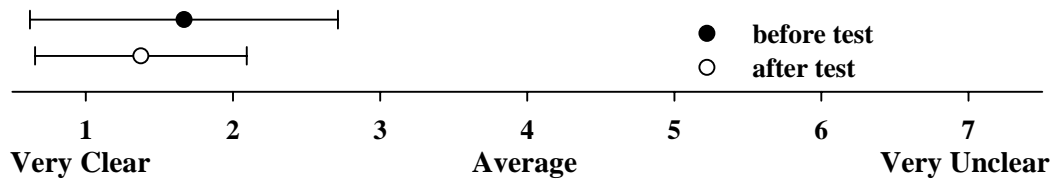


Figure 19b - Pilot ratings of procedures for managing lateral path.

Procedures for managing speed were rated as being slightly less clear after having completed the runs (Mean = 1.87 before the runs, versus M=2.5 after the runs), however the differences were not statistically significant. The pilots' comments on the questionnaires indicated that some needed further clarification on the procedures for managing speed.

The procedures for managing speed between the waypoints CHERI and BLGRS are:

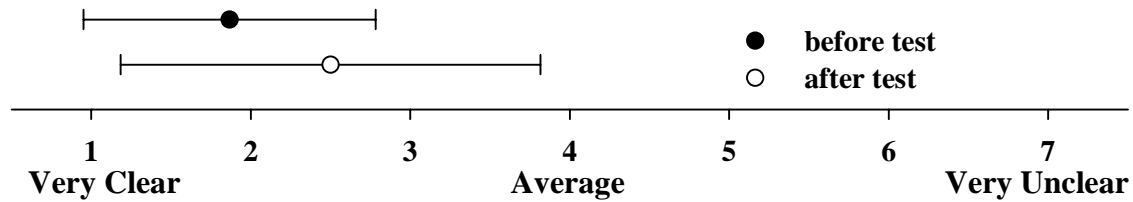


Figure 19c - Pilot ratings of procedures for managing speed.

Ratings for overall level of understanding of the procedures improved by more than a point after the test compared with the ratings taken before the test (Figure 20). A Mann-Whitney Rank Sum test on the difference in the ratings for this question showed this to be a statistically significant difference (P=0.038).

Please rate your overall understanding of the CDA Arrival procedure:

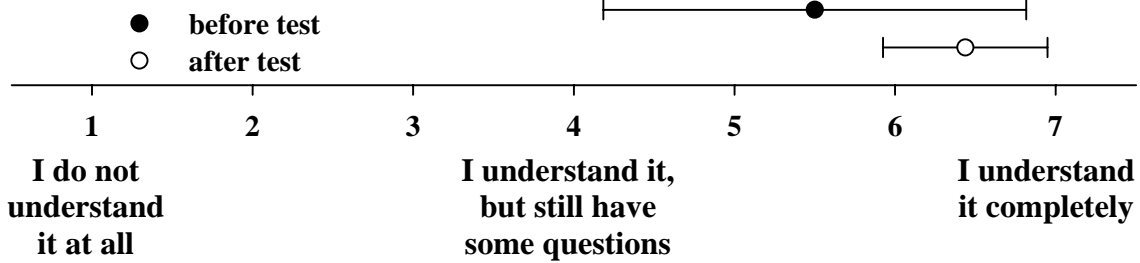


Figure 20 - Pilot ratings of overall understanding of CDA Arrival Procedure

Identification of potentially confusing aspects of procedure

An important observation made during this test was that most of the subject pilots descended such that they crossed the waypoint SILNT at the charted restriction, rather than above that altitude, as was specified in the chart. This action partially defeated the purpose of having this type of restriction, which was to maintain a higher vertical profile, while also maintaining flexibility in the crossing restriction to allow for wind and equipment variations. Since many pilots would probably revert to habits from their previous training and also aim to cross “AT” the published altitude, a solution to this would be to modify the chart, making this altitude higher. Although it would take away some of the flexibility in the procedure, it would help ensure that the aircraft stayed higher during a noise-sensitive part of the arrival. Without additional pilot training or automation that could provide better guidance for conducting this type of descent, changing the charted restrictions is the easiest way to ensure that a higher vertical profile is maintained.

Pre-test VNAV Questionnaire

Prior to starting the briefing before the start of the simulation, the subject pilots were given a short questionnaire to assess their knowledge of the VNAV modes. This was meant to be a way of determining their level of awareness of which mode the aircraft was in during portions of the descent, but the results were not associated in any way with the data analysis. Although the wording of the questions can affect the answers given, it was clear that many pilots could not recall the autoflight modes that would be displayed during the situations presented in the questions. Since the set of subject pilots for this experiment was small, a more dedicated survey over a much wider population would be necessary in order to draw any general conclusions regarding pilots’ mode awareness and understanding. However, some interesting trends were observed from this group of pilots’ responses.

Among the questions that were answered correctly by most (more than 75%) of the pilots were the ones that asked about the trade-off of path and speed when in VNAV PATH or VNAV SPEED modes (i.e., whether speed is sacrificed to maintain path, or vice versa). However, most pilots were not able to correctly identify the modes to which VNAV switched during the initial descent (to IDLE, then THROTTLE HOLD). Less than half (44%) recognized that, upon glideslope capture the commanded speed would revert to the current aircraft speed. More than half (63%) knew that the speed would revert back to the FMC programmed speed after the Mode Control Panel (MCP) speed window was closed (speed intervene function was de-selected). Most (69%) recognized that the VNAV mode during descent with the aircraft close to its VNAV path would be VNAV PATH if the MCP window was closed and VNAV SPEED if the MCP window was open. Another similar question asked what mode the aircraft

would be in if it was in a VNAV descent with the MCP speed window open (without specifying how close the aircraft might be to its VNAV path), but only half recognized that the aircraft would be in VNAV SPEED mode (speed intervene) as long as the MCP window was open. Although it is understood that there can be slight differences in the mode logic depending on specific implementation and other factors such as the phase of flight, it was expected that the pilots would understand that the nature of the questions pertained to the descent procedure, as was mentioned in the text of the questions.

The results of these questions indicated that, with current training levels, many of the subject pilots in this experiment were not as aware of the autoflight modes as they would need to be to fly an optimal CDA descent using VNAV. The most optimal CDA descents require a careful exchange of kinetic and potential energy (speed and altitude) as the aircraft descends. To best execute a CDA with conventional guidance requires a solid understanding of the interactions of the VNAV modes, the MCP windows, and FMC pages, and how they will affect and be affected by the pilot's control of throttle and speedbrakes.

Pilot Comments from Questionnaire

After all the runs were completed, the subject pilots each individually completed a questionnaire, which included some open-ended questions that gave them an opportunity to make suggestions for improvements. The questionnaire is included in Appendix A, and some of the pilot comments are summarized in this section.

Charted Information

Pilots were asked whether there was any other information they would like to see on the charts. Their answers included suggestions for other information often seen on charts, such as obstacles and terrain, or highlighting crossing restrictions at the waypoints, or in some other way making them more clear. Other suggestions included adding distance to the runway from the various waypoints, and straight-line distances between the waypoints, for when ATC gives a clearance to "proceed direct to" a waypoint.

FMB Information

When asked about whether there was any information missing from the CDA Flight Manual Bulletin that would be helpful, most of the pilots felt that there was not much missing. The most significant comments concerned clarification of the altitude to maintain when vectored off the CDA, and that it should be emphasized more that a very important part of the procedure is to not level off. Other suggestions included having a briefing summary guide (highlighting the procedure), and having ground speed read-outs to help with planning the altitude profile.

Potential for LNAV or VNAV confusion

The pilots were asked if they could think of situations where a pilot not familiar with LNAV or VNAV might become confused when using this procedure. The vast majority of the pilots said that they did not think there would be any problems with operating in LNAV for most pilots. The only comments on possible ways that a pilot could become confused might be when capturing the localizer, if the aircraft showed a slight deviation from LNAV on the navigation display, and another pilot mentioned that after getting speed and other changes to the route from ATC, it was possible for a pilot to get "behind", however to a much lesser degree than with VNAV.

For VNAV however, there were many comments on situations that could be confusing. These

situations involved trying to get back on the VNAV path after having been taken off of it, and pilots not understanding (or trusting) VNAV enough to use it effectively to conduct a VNAV descent. One pilot suggested simplifying the procedure by eliminating intermediate fixes (going direct to CHRCL); one pilot commented that some pilots who are newer to VNAV might get confused between VNAV SPD and VNAV PTH. Some pilots felt that most pilots were trained enough to handle most situations, and others felt that a CDA procedure required a greater understanding of VNAV than the average line pilot currently has. One pilot commented that a “simple bottom line pamphlet” or discussion on VNAV was needed, to explain how speed and path are interchanged during a VNAV descent.

Post-test Pilot Comments

Based on observations of pilots’ behavior during the test runs and conversations with pilots after the test runs, researchers identified opportunities for improvement, and noted some common problems in the way the pilots conducted the CDA descents. Post-test questionnaires also provided some insight into what aspects of the procedures were considered unclear or in need of further clarification by the subject pilots, such as with regard to management of airspeed. None of the pilots appeared to have any problem understanding the objectives of the CDA procedures during the pre-test briefing, and they all indicated that they understood the procedures, including the FMB and charted instructions, prior to conducting the test runs.

Another issue that was mentioned by a few pilots in post-test discussions was the fact that some pilots prefer to be on the lower side of the energy profile (i.e., they prefer to decelerate and descend sooner in the descent) than the ideal CDA profile, which keeps the aircraft higher and delays the landing configuration. These pilots felt that being lower on energy would help them to better comply with changes from ATC, such as if they are asked to shorten the path to the runway.

Introduction to Low Noise Guidance

After completing the test runs and questionnaires for this experiment, the pilots were returned to the simulator and given an introduction to the LNG tool and displays. This consisted of a single abbreviated run with a researcher explaining the operation and features of the LNG tool. After this, the pilots were allowed to complete a test run similar to the CDA3 test run, but using the LNG guidance instead of conventional VNAV. The LNG guidance was activated simply by having VNAV engaged. This is in keeping with future plans for the concept, which is to include LNG as a sub-mode of VNAV.

Although simulator data, simulator displays, and verbal comments from the pilots were recorded, the pilots were not asked to complete any workload data or other questionnaires. The simulator data showed that the noise level (as computed by the INM program) was less for the LNG runs than for the comparable CDA run done with VNAV. Because this experiment was designed to be an evaluation of CDAs using conventional guidance technology, no attempt was made to include the LNG test runs as part of a balanced test matrix with the other runs. Thus, a direct comparison of the LNG and non-LNG runs is not truly valid, but it can give us an idea of what could be expected in a study where a direct comparison was made.

Concluding Remarks

This simulation study investigated the use of Continuous Descent Arrival procedures for conducting a descent through a busy terminal area, using conventional automation (in the form of VNAV). The procedures and chart were designed to be easy to understand, and to make it easy for the crew to make

changes via the Flight Management Computer Control-Display Unit (FMC-CDU) to accommodate changes from ATC. The test runs were intended to represent situations typical of what exists in many of today's terminal areas, including interruptions to the descent in the form of clearances issued by ATC.

The results showed that the pilots were able to conduct the descents, even when interrupted by ATC with instructions that took the aircraft off of the VNAV path, laterally, vertically or both. The uninterrupted descent resulted in the most optimal profile, which translated to the lowest perceived noise levels and lowest amount of fuel burned. The potential fuel savings could be significant, on the order of 10% to 20% less fuel used in the descent segment. These benefits were reduced as the interruptions from ATC increased and took the aircraft off its optimal descent path, but all three CDA run types resulted in quieter and more fuel efficient descents than with current-day procedures. The fuel results from this experiment did not show a definitively predominant effect on fuel use of either path length or how optimal the descent was, but dedicated trade studies could provide more insight into this important issue.

The workload associated with conducting the descents were rated comparable to workload with current-day procedures (non-CDA). Pilots were able to conduct the descents with a minimum amount of time allowed for studying the instructions and charts they were given. Minor improvements to the chart and procedures were identified that can clarify the altitude and speed constraints and clearances, and reduce the potential for confusion.

The actions and comments of many of the pilots in this experiment suggest that a CDA procedure requires more understanding of VNAV than the average line pilot currently has, particularly with respect to knowledge of the VNAV modes and their interactions with the MCP and FMS.

At the conclusion of the test runs, pilots were introduced to an energy-based concept for conducting CDA descents. Reactions were very positive from the subject pilots, with all of them indicating that this type of guidance could make CDA descents much easier to conduct, with the only cause for concern being to ensure that the aircraft speed was below the flap extension speed prior to reaching the flap extension point that is generated and displayed on the ND by the low-noise algorithm.

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Appendix A

Flight Manual Bulletin

INSTRUCTIONS TO SUBJECT PILOTS

FLIGHT MANUAL BULLETIN

Revision 4.2, 5/07/2004

CONTINUOUS DESCENT APPROACH (CDA)**BACKGROUND AND SUMMARY**

The Continuous Descent Approach (CDA) has been identified as a beneficial method for operationally reducing community noise near airports. A secondary benefit of the CDA is lower fuel usage during the descent. The CDA is designed to minimize level segments during approach, especially at low altitudes. This keeps the aircraft higher and at reduced thrust settings during most of the descent in the terminal arrival area. Typically, the altitude crossing restriction at the Initial Approach Fix (IAF) of the Instrument Landing System (ILS) approach is raised so that glideslope intercept occurs approximately at the turn to final approach. A CDA can be flown accurately with a Flight Management System (FMS) -equipped aircraft, however the way in which the vertical profile is managed can vary substantially across pilots and aircraft types. If the vertical profile is not managed properly, the aircraft could reach the IAF altitude early, requiring an undesired level segment to the IAF. Properly managing the aircraft's total energy (speed and altitude) throughout the descent can minimize this problem. To best comply with altitude and speed restrictions, while remaining close to the optimal descent trajectory, the CDA should be flown with vertical guidance in the VNAV (Vertical Navigation) mode. To conduct an effective CDA descent with VNAV, pilots should have a good understanding of how this mode transitions among its sub-modes and interacts with other autoflight systems to meet speed and altitude constraints.

A CDA was developed for Louisville International Airport (SDF) by modifying the Cheri Two Standard Terminal Arrival Route (STAR). The new procedure, called the Bluegrass RNAV Arrival, is a CDA procedure, and includes lateral transition segments to the ILS IAF, named BLGRS. The depicted routes represent the longest routing necessary to accommodate high traffic conditions. Air Traffic Control (ATC) Approach Control will issue instructions to descend on the Bluegrass RNAV Arrival. Prior to turning onto the downwind leg, the route will typically be shortened via a "direct to" clearance to a waypoint closer to BLGRS. While on the arrival, the crew is responsible for complying with charted speed and altitude crossing restrictions. ATC may also issue speeds and/or altitudes that are different from those shown on the chart. The crew must comply with any new instructions issued by ATC, until instructed to resume the RNAV Arrival. The crossing conditions at BLGRS allow for a smooth transition to the ILS approach, however ATC may clear the aircraft for a different type of approach.

This bulletin describes clearances, instructions, and crew procedures for conducting the CDA. The last page contains a checklist for conducting the CDA with standard VNAV functions.

NOMINAL CDA CLEARANCES

Descent clearance for the Bluegrass RNAV Arrival:

- *"Descend via the Bluegrass RNAV Arrival";*
"Proceed direct ABCDE, then descend via the Bluegrass RNAV Arrival"

This clearance may be issued at any time, and allows the crew to descend on the BLGRS RNAV Arrival until the fix BLGRS. Typically it is issued before the initial fix on the arrival (CHERI, DANNY, or KWIET). However, this descent clearance may also be issued in conjunction with a "direct to" one of the other waypoints on the arrival. This allows the aircraft to continue descending on the remainder of the RNAV arrival, via the indicated waypoint. The crew must comply with all charted altitude and speed restrictions from (and including) that waypoint on, unless otherwise instructed by ATC.

Pilots shall advise ATC upon beginning the descent ("...leaving 18000 feet..."). Pilots shall advise ATC upon initial contact that they are descending on the Bluegrass RNAV Arrival ("...descending through XXXXX feet on the Bluegrass RNAV Arrival").

Deviations from the RNAV Arrival:

At any time after initiating the descent, ATC may issue speed, heading, or altitude changes that are different from those on the RNAV Arrival. Subsequent instructions may be issued to continue the descent on the Arrival. Examples of instructions taking the aircraft off the Arrival are listed below (these may be issued individually or grouped):

- *"Turn left (right), heading XXX."*

This instruction takes the aircraft off of the RNAV Arrival. A new, FMC-programmed lateral route is required in order to continue descending on the Bluegrass RNAV Arrival. ATC-issued instructions must be complied with until the crew is cleared to again descend via the Arrival, at which point the charted restrictions once again apply.

- *"Descend and maintain YYYY."*

This instruction requires the crew to descend and maintain the ATC-issued altitude until instructed otherwise by ATC. If the crew is subsequently cleared to continue descending on the Arrival, the crew must revert to the charted altitude profile; this begins with the first waypoint (the "to" waypoint) on the arrival, where it is re-joined. If there is no altitude restriction at this waypoint, the last ATC-issued altitude is used.

- *"Reduce speed to XXX knots."*

This instruction requires the crew to maintain the issued speed until instructed otherwise by ATC. If the crew is subsequently cleared to continue descending on the Arrival, the crew must revert to the

charted speed profile; this begins with the first waypoint (the “to” waypoint) on the arrival, where it is re-joined. If there is no speed restriction at this waypoint, the last ATC-issued speed is used.

- *"XX miles from Churchill (CHRCL), cleared ILS Runway 17R approach, maintain XXX kts to Churchill."*

This is a normal approach clearance, and is issued prior to the IAF waypoint (BLGRS).

CREW PROCEDURES FOR CONDUCTING THE CDA

While descending on the RNAV Arrival, keeping the aircraft in full LNAV/VNAV mode best enables the crew to comply with charted altitude and speed constraints, and to maintain a profile close to the optimal CDA profile. If ATC issues instructions that take the aircraft off of the RNAV Arrival, the crew may use other autoflight functions to comply with the verbal instructions, but should remain in VNAV as much as possible throughout the descent to achieve the most efficient profile.

Lateral Route Management

The Bluegrass RNAV Arrival and transitions are defined in the FMC database using all the waypoints shown on the chart, ending at BLGRS. This sequence of waypoints defines the longest route, and can be easily modified to a shorter route when instructed by ATC. Unless traffic conditions do not permit it, ATC will shorten the RNAV route by issuing instructions to proceed directly to a waypoint close to BLGRS. For timely compliance, the crew may use the HDG (heading select) function on the Mode Control Panel (MCP) to turn towards the cleared waypoint, while remaining in VNAV. To proceed on the RNAV route, the crew must modify the FMC route to go “direct-to” the indicated waypoint. After the new route is executed, the crew must then re-engage LNAV and VNAV (if not already engaged) to continue.

Altitude Management

With the aircraft in VNAV, the descent will be managed according to the VNAV vertical profile. However, it is crucial that pilots monitor throughout the descent the amount of deviation from the programmed VNAV path using the vertical path deviation indicator on the Navigation Display (ND). If the aircraft’s path deviates too much from the programmed path, it might not be possible to recapture it until the aircraft is on final approach. This could result in VNAV exhibiting unexpected behaviors. If the aircraft path were excessively low, an extended level segment might result, producing excessive noise. If the aircraft path were excessively high, it might not be possible to intercept the glide slope and continue the approach.

If the pilot feels that VNAV is not managing the vertical path in an acceptable manner, speedbrakes and throttle should be used to augment VNAV guidance, or another pitch mode may be selected to better comply with the vertical profile.

Speed Management

With the aircraft in VNAV, speed is controlled by the autoflight guidance to comply with the speed profile programmed in the FMC. If ATC issues a speed change, the crew must use the VNAV speed intervene function to comply with the ATC instruction in a timely manner. Speed intervene is selected by pushing the MCP SPD knob to open the MCP speed window and dialing in the new speed. Descending in VNAV-speed-intervene will likely cause the aircraft to deviate from the

programmed vertical profile. This increases the possibility that the descent could be completed too early, and the aircraft would level off prior to intercepting the glide slope. This is not the optimal vertical profile, since this low-altitude level segment is what a CDA descent is designed to avoid. To minimize the possibility of having a level segment, the crew may adjust the aircraft descent rate (using thrust while in THR HOLD and VNAV SPD) to obtain a better profile and meet the next waypoint constraint.

If the crew is then cleared to resume the RNAV Arrival while still in VNAV-speed-intervene, they may either continue in VNAV-speed-intervene (managing all subsequent charted speed reductions by dialing them in the MCP speed window), or they may return to full VNAV.

If the crew chooses to de-select the VNAV-speed-intervene function and return to full VNAV, the SPD knob must not be pushed until after crossing the next speed-constrained waypoint on the RNAV arrival. If the SPD knob is pushed prior to that, the aircraft may revert to the old VNAV descent speed (unless the new one is programmed into the FMC). The old descent speed could be much higher than the current aircraft speed, and might cause the autoflight guidance to command a sharp acceleration, followed by an attempt to decelerate again to the next constraint speed.

It is crucial to monitor the vertical path deviation indicator on the ND whenever the speed intervene function is used, as this will affect how well the aircraft remains on the vertical path. The crew may use another pitch mode to ensure compliance with all restrictions (including the maximum speed requirement below 10,000 feet), if they feel that remaining in VNAV will not do so. Speedbrakes should be used to add drag if needed.

Flap and Gear Deployment

To maximize noise reduction, the landing gear extension should be delayed until the Final Approach Fix. If speed is nominal, landing gear should be extended at the FAF. If speed is more than 10 kts high approaching the FAF, gear should be extended early to enable the aircraft to achieve a stabilized approach by 1000 feet AGL.

Flap deployment should follow the normal speed schedule. As speed is reduced throughout the descent, the corresponding flaps should be deployed.

CDA Approach with VNAV
Checklist

- Must have active route in FMC with LNAV/VNAV engaged to fly CDA automatically.
- Compliance with charted altitude crossing restrictions is critical, unless instructed otherwise by ATC.
- VNAV will automatically command descents and decelerations to comply with programmed constraints
- Use throttle, speedbrakes, or other pitch mode if required to adjust vertical path and comply with restrictions, if needed
- Expect normal approach clearance

LNAV, VNAV, Auto-throttle.....Armed / Active
Approaching altitude-constrained waypoint.....Dial MCP ALT window to next constraint
Altitude.....Monitor and comply with charted constraints
Speed.....Monitor and comply with charted speeds
Flaps.....as required for current speed

If ATC issues clearances off the RNAV route:

Lateral..... re-program FMC, and engage LNAV
Altitude.....dial MCP ALT window to new altitude
Speed.....use speed-intervene
(If rejoining the RNAV Arrival, return to top of checklist.)

At glideslope capture.....manage speeds with MCP SPD
At FAF, if speed/altitude are acceptablegear down

Appendix B

VNAV Functions Test

and

Post-Test Questionnaire

VNAV Functions

At Top-Of-Descent while in VNAV, the aircraft throttle mode will transition from Speed (SPD) to _____ to _____. (Assume that the MCP altitude window has been dialed to the next lower constraint, and the cruise and descent speeds are the same.)

While descending in VNAV, with the aircraft close to the VNAV path and the MCP speed window closed (blank), what pitch mode would you expect to see? _____

Please explain _____

While descending in VNAV, with the aircraft within 100 ft of the VNAV path and the MCP speed window open, what pitch mode would you expect to see? _____

Please explain _____

While descending in VNAV, with the MCP speed window open, what pitch mode would you expect to see? _____

Please explain _____

In VNAV PATH mode, the pitch guidance is _____ on elevator, meaning that the aircraft sacrifices _____ to maintain _____.

In VNAV SPEED mode, the pitch guidance is _____ on elevator, meaning that the aircraft sacrifices _____ to maintain _____.

While in an uninterrupted VNAV descent (not in speed intervene), prior to reaching 10,000 ft altitude the aircraft will

While in descent with the MCP APPROACH mode armed, upon glideslope capture the speed command reverts to _____

While descending in VNAV with the speed intervene function, what happens to the command speed when the MCP speed window is closed (speed knob is pushed, exiting the speed intervene function)? _____

Post-Test Questionnaire

BLGRS RNAV Chart

After flying the BLGRS RNAV Arrival CDA procedure, please describe:

- 1) The vertical profile that must be maintained during the descent between the waypoints CHERI and BLGRS

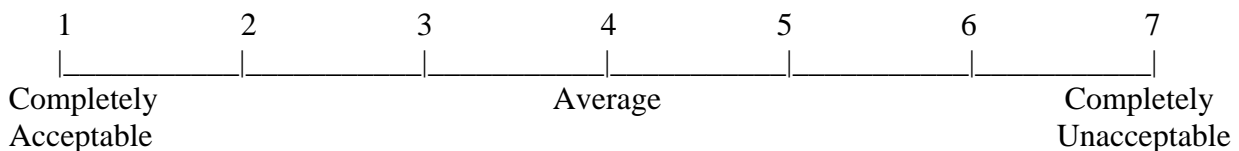
- 2) The speeds that must be maintained during the descent between the waypoints CHERI and BLGRS

- 3) The lateral path that must be maintained during the descent between the waypoints CHERI and BLGRS

- 4) Is there any other information you would like to see on chart? Y N
 a. If yes, please explain

- 5) Did you have enough time to adequately study the chart? Y N
 a. If no, how much time would be needed?

- 6) For most pilots, the BLGRS RNAV chart is:



CDA Crew Procedures

After flying the BLGRS RNAV Arrival CDA procedure, please rate how you feel about the following items, and provide comments, if desired:

1) The procedures for managing altitude between the waypoints CHERI and BLGRS are:

1	2	3	4	5	6	7
Very Easy		Average			Very Difficult	

1	2	3	4	5	6	7
Very Clear		Average			Very Unclear	

Comments:

2) The procedures for managing speed between the waypoints CHERI and BLGRS are:

1	2	3	4	5	6	7
Very Easy		Average			Very Difficult	

1	2	3	4	5	6	7
Very Clear		Average			Very Unclear	

Comments:

3) The procedures for managing the lateral path between the waypoints CHERI and BLGRS are:

1	2	3	4	5	6	7
Very Easy		Average			Very Difficult	

1	2	3	4	5	6	7
Very Clear		Average			Very Unclear	

Comments:

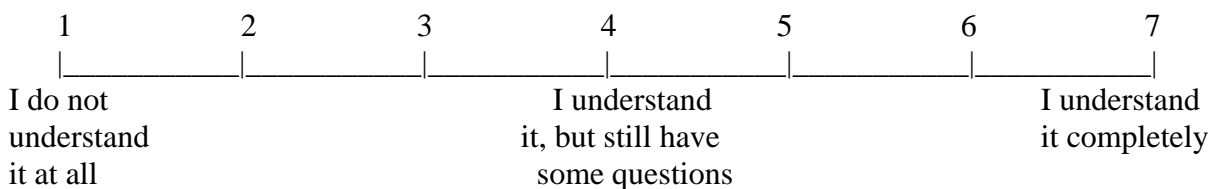
4) Is there any information missing from the FMB that you think would be helpful for understanding how to conduct the CDA? Y N

If yes, please explain

11) Did you have enough time to adequately study the procedures? Y N

If no, how much time would be needed?

12) Please rate your overall level of understanding of the CDA Arrival procedure:



13) Do you have any suggestions for improvements to the crew procedures?

14) Can you think of any situations where a pilot who is not very familiar with VNAV might become confused regarding what the altitude or speed of the aircraft should be while conducting this type of descent procedure?

15) Can you think of any situations where a pilot who is not very familiar with LNAV might become confused regarding what the lateral path of the aircraft should be while conducting this type of descent procedure?

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14. ABSTRACT This paper presents results from a simulation study which investigated the use of Continuous Descent Arrival (CDA) procedures for conducting a descent through a busy terminal area, using conventional transport-category automation. This research was part of the Low Noise Flight Procedures (LNFP) element within the Quiet Aircraft Technology (QAT) Project, that addressed development of flight guidance, and supporting pilot and Air Traffic Control (ATC) procedures for low noise operations. The procedures and chart were designed to be easy to understand, and to make it easy for the crew to make changes via the Flight Management Computer Control-Display Unit (FMC-CDU) to accommodate changes from ATC. The test runs were intended to represent situations typical of what exists in many of today's terminal areas, including interruptions to the descent in the form of clearances issued by ATC.					
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