

# Research Of Airborne Precision Spacing to Improve Airport Arrival Operations

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## I. INTRODUCTION AND PROBLEM DEFINITION

In September 2004, the European Organization for the Safety of Air Navigation (EUROCONTROL) and the United States Federal Aviation Administration (FAA) signed a Memorandum of Cooperation to mutually “develop, modify, test, and evaluate systems, procedures, facilities, and devices to meet the need for safe and efficient air navigation and air traffic control” in the future. In the United States and Europe, these efforts are defined within the architectures of the Next Generation Air Transportation System (NextGen) Program and Single European Sky Air Traffic Management Research (SESAR) Program respectively. Both programs have identified Airborne Spacing as a critical component, with Automatic Dependent Surveillance Broadcast (ADS-B) as a key enabler.

Increased interest in reducing airport community noise and the escalating cost of aviation fuel has led to the use of Continuous Descent Arrival (CDA) procedures to reduce noise, emissions, and fuel usage compared to current procedures. To provide these operational enhancements, arrival flight paths into terminal areas are planned around continuous vertical descents that are closer to an optimum trajectory than those in use today. The profiles are designed to be near-idle descents from cruise altitude to the Final Approach Fix (FAF) and are typically without any level segments. By staying higher and faster than conventional arrivals, CDAs also save flight time for the aircraft operator. The drawback is that the variation of optimized trajectories for different types and weights of aircraft requires the Air Traffic Controller to provide more airspace around an aircraft on a CDA than on a conventional arrival procedure. This additional space decreases the throughput rate of the destination airport.

Airborne self-spacing concepts have been developed to increase the throughput at high-demand airports by managing the inter-arrival spacing to be more precise and consistent using on-board guidance. It has been proposed that the additional space needed around an aircraft performing a CDA could be reduced or eliminated when using airborne spacing techniques.

## II. AIRBORNE PRECISION SPACING CONCEPT

To maintain the arrival rates required for a very busy airport, different terminal area concepts have been evaluated, including: Sequencing and Merging (France and Germany), Required Time of Arrival procedures for CDAs (NUP2+ flight trials in Sweden), and airborne self-spacing concepts. The

National Aeronautics and Space Administration (NASA) has been developing an airborne self-spacing concept called Airborne Precision Spacing (APS) for the past eight years. This work supports a larger effort led by the Federal Aviation Administration to develop a concept of operations, procedures, and requirements for combining airborne self-spacing with CDA operations. Originally called Merging and Spacing, it is now part of the Interval Management development work.

In the APS operational concept, control of the aircraft’s speed, within specific boundaries, is delegated by air traffic control (ATC) to the flight crew in order to precisely achieve an assigned inter-aircraft spacing. The flight crew uses an on-board spacing tool that provides minor speed changes to the flight crew that will achieve the assigned inter-arrival spacing while minimizing the deviations from the CDA.

The controller is supported by a ground-based automation tool which creates an arrival schedule that optimizes the arrival sequence and determines a time interval between each pair of aircraft that meet all spacing constraints (wake vortex, runway occupancy, radar separation, etc). The controller then issues a clearance to the flight crew to perform self-spacing during CDAs, and provides the flight identification of the aircraft they are to land behind and the inter-arrival spacing interval. The spacing tool uses the ownship’s position and route information along with the target aircraft’s position and route information acquired via ADS-B to determine the estimated times of arrival (ETA) at the runway threshold. The difference between the assigned inter-arrival spacing and the predicted difference in ETAs is used to calculate the desired speed for the aircraft. The use of the target aircraft’s route information, made available in this simulation via a new ADS-B message, allows for initiation further from the airport and more stable behavior for a string of arriving aircraft.

A human-in-the-loop study of APS was performed at NASA’s Langley Research Center in the summer of 2008 to evaluate APS usefulness and performance with off-nominal air traffic events.

## III. EXPERIMENT METHODOLOGY

### A. Experiment Objectives

The objectives of this study were to assess pilot acceptability, assess pilot workload, and characterize the spacing performance in terms of the number of speed commands and aircraft spacing at the threshold.

### B. Facilities (ASTOR and IFD)

This experiment used the Air Traffic Operations Laboratory (ATOL) at NASA Langley Research Center in Hampton, Virginia, which consists of a network of aircraft simulators. This experiment used 7 workstation-based cockpit simulators with experimental displays and pilot interface. Each aircraft simulator is referred to as an Aircraft Simulation for Traffic Operations Research (ASTOR) station. Each ASTOR station is a medium fidelity aircraft and avionics simulation with low fidelity single-pilot interfaces. Each ASTOR contains a high-fidelity six degrees of freedom equations of motion aircraft model, autopilot and auto-throttle systems, software flight management computer, multi-function control display unit, mode control panel (MCP), electronic flight instrumentation system control panel, and the ASTAR spacing algorithm. Figure 1 is a snap shot of an ASTOR station's Primary Flight Display and the Navigation Display.



Figure 1. Primary Flight Display and Navigation Display

The ATOL was connected to the Integration Flight Deck (IFD, Figure 2), a replica of a large commercial transport category aircraft and driven by a high-fidelity aircraft dynamics mathematical model. The cockpit includes standard ship's instruments representative of a line operations aircraft. The cockpit's visual system is a panorama system that provides 200° horizontal by 40° vertical field-of-view. The visual scene used for this experiment was the Louisville, Kentucky (KSDL) terminal environment.



Figure 2. Integration Flight Deck Simulator

### C. Experiment and Scenario Design

The scenarios were modeled on the 2007 flight-trials conducted by UPS for CDA operations at their KSDL hub (Figure 3). Each test aircraft started at a point prior to the top-of-descent (ENL) and flew a CDA to runway 17R at KSDL (the southern route). Each scenario consisted of eight aircraft, all piloted by subject pilots/crews, and was designed to provide a minimum of 5 nautical miles separation at the runway threshold. Seven of the eight aircraft were flown by an individual pilot in a medium fidelity simulator (ASTOR), and the eighth aircraft employed the full mission, high fidelity simulator with subject pilots operating as a two-person crew (IFD). Two confederate controllers were used to provide realistic radio communications and trigger the off-nominal events. Previous research has looked at multiple arrival routes merging to a single runway using step-down descents (in both fast-time and human-in-the-loop) and CDAs (fast-time only). This more simple arrival flow was chosen to match the proposed UPS operations.

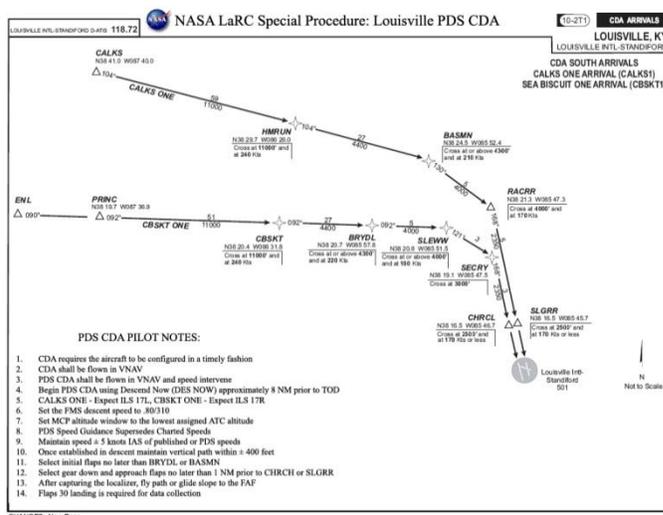


Figure 3. Experiment Arrival Procedure

Each subject pilot flew each of the eight different scenarios. Each scenario included three off-nominal events. The off-nominal events affected only one or two aircraft per scenario and were separated by an aircraft flying a nominal arrival. For the first event, the aircraft was vectored approximately 5 nautical miles off-path during the initial descent then returned to the published arrival prior to terminal radar approach control entry. During the vectoring, the spacing guidance was suspended but the crew could attempt to reengage the spacing tool after returning to the arrival route. The second event involved the aircraft following the vectored aircraft, where spacing guidance was suspended and the crew had to contact ATC (the algorithm does not provide a speed command when the lead aircraft is not on a published route). The third event consisted of either an ATC speed intervention (which forced the crew to suspend spacing guidance until the controller issued "speed at pilot's discretion") or an excessive initial spacing error so the crew would not initiate spacing and the controller would provide conventional guidance. In the latter case, the

spacing tool would determine that it would be unlikely that the aircraft could achieve the assigned spacing interval).

The first aircraft in every scenario used standard flight management system guidance including speed guidance to fly the aircraft from its starting position to the runway. All other aircraft were assigned a spacing instruction and expected to use the provided speed guidance whenever possible. The speed guidance was bounded to be within 10% of the published CDA speeds and to meet the 250 knot below 10,000 ft mean sea level (MSL) restriction. All of the aircraft used ILS auto-land procedures to the runway threshold.

The pilots entered the assigned lead aircraft’s flight number and spacing interval via the control display unit (CDU, see Figure 4). The speed guidance was presented to the crew on the Primary Flight Display (PFD, see Figure 1, shown as “PDS 210”). After crossing the FAF, the spacing tool would command the planned final approach speed. This ensured the aircraft would have a stable final approach and allow for the most precise spacing at the runway threshold. Autopilot and auto-throttle were used by all aircraft in this test.

Since the measure of runway throughput is measured at the runway threshold, APS is designed to deliver the assigned spacing interval at the threshold. Because each aircraft will have a different final approach speed and ensuring a safe and stable approach is paramount, the spacing tool takes the planned final approach speed into account when calculating the ETA at the threshold. The spacing tool will provide the planned final approach speed to the crew in time for them to be able to decelerate to that speed and be stable by 1000 ft AGL.



Figure 4. Control Display Unit (CDU)

The instruction was to achieve 150 seconds spacing at the runway threshold. All aircraft were started at altitudes between flight level (FL) 330 and FL370 and cruise speeds of 0.80 or 0.82 Mach. The environment included a truth wind that was spatially homogeneous except for an altitude variation ranging from 10 knots at 242° at 30 ft above ground level, to 90 knots at 250° at 45,000 ft MSL. The wind forecast provided to the scheduling tool and the aircraft’s FMS was intentionally set to an error of half the magnitude of the wind speed with a 20° clock-wise rotation error. All aircraft were modeled as the same type of heavy, two-engine, narrow-body transport aircraft, although with different initial gross weights. This weight difference caused a range of final approach speeds.

D. Subject Pilots

Participants consisted of 26 commercial airline pilots employed by major U.S. air carriers, with twenty-five males and one female aged between 38-60 years. Ten of the participants were captains, and the other 16 were first officers.

On average, the pilots had 18 years of airline experience and over 10,000 hours of airline flying experience.

IV. RESULTS AND DISCUSSION

A. Acceptability of Procedures

An evaluation of the procedures’ acceptability was obtained from the pilots via post-scenario and post-experiment questionnaires, and post-experiment group debriefing sessions. These data indicate that the pilots found the APS concept and procedures acceptable. Descriptive statistics (mean rating scale values) include:

- Comfortable with APS procedures: 1.77
  - 1 – very comfortable, 7 – very uncomfortable
- Can APS be integrated into current flight deck: 2.31
  - 1 – easily integrated, 7 – cannot be integrated
- Confident the speed guidance was correct: 1.81
  - 1 – very confident, 7 – not confident
- Acceptability of APS by phase of flight: 1.60
  - 1 – very acceptable, 7 – very unacceptable
- Potential for APS enhancing safety: 2.58
  - 1 – safety enhanced, 7 – safety compromised

B. Pilot Workload

Pilots used a Modified Cooper-Harper Subjective Workload Rating Scale, which ranges from 1 (low) to 10 (high), to provide a workload assessment after each simulated flight scenario. The pilots’ mean rating was 1.87, indicating that the task they were instructed to perform was easy/desirable; their mental effort was low; and desired performance was attainable.

When asked if this concept represents an acceptable workload trade-off compared with current day operations, 25 of the experiment’s 26 pilots responded positively. The majority of the pilots (92%) had no difficulty interfacing with the spacing tool, and 81% reported following the spacing commands without error.

C. Spacing Performance

Key performance metrics include the additional number of speed commands and aircraft spacing at the runway.

The arrival procedure had five planned speed changes including the deceleration to the final approach speed. Crews saw a median of six additional speed changes. With flight times between 23 and 42 minutes, this resulted in an average of one change every five minutes with a maximum of one change every two minutes. Previous research indicated speed changes of up to one per minute were acceptable to pilots.

Table 1. Commanded Speed Changes by Segment

Flight Segment	Speed Changes Per Aircraft	
	Due to Published CDA Procedure	Additional Spacing commands from ASTAR algorithm
Cruise	0	0.5
Initial descent	1	0.6
Terminal descent	1	1.4
Final approach intercept	1	0.6
Final approach	1	2.8
FAF to runway	1	0.1

Table 1 shows the number of commanded speed changes, with most of the speed changes within the final 30 miles of the arrival. Prior to 11,000 ft constraint (cruise and initial descent), there was approximately one additional change due to spacing. In the final approach segment, there were almost three speed changes per arrival. The fine tuning of the speed during the final segments is what provides the precise spacing. Speed changes were limited to 10 knot increments based on the proposed implementation for the UPS fleet. However, anecdotal data from testing runs suggests that smaller speed changes may provide improved precision without significantly increasing the number of speed changes.

In 119 of the data runs, the pilot was able to follow the spacing guidance to the runway threshold. The measured inter-arrival time is the difference between when the lead and spacing aircraft crossed the runway threshold. The distribution is shown in Figure 5. Two-thirds of the aircraft were within 2.5 seconds of the assigned interval.

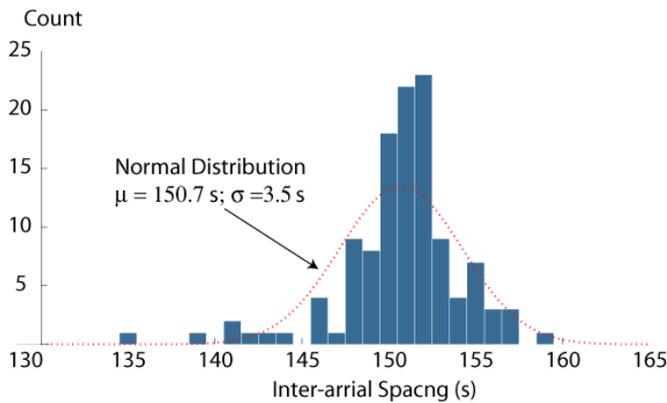


Figure 5: Measured inter-arrival spacing and corresponding normal distribution curve.

Fuel use measurements were compared between those aircraft that performed an uninterrupted CDA against those that performed an uninterrupted CDA with spacing. No statistically significant difference was found due to the addition of spacing. This was a surprising result as we expected a small fuel penalty due to the additional speed changes. However, the speed changes were generally small and the pilots only had to apply a small amount of thrust or drag to change the speed and maintain the optimal vertical path. Additional studies are needed to strengthen these results, but this is a very promising find.

## V. CONCLUSIONS

This evaluation verified that from a pilot perspective it is reasonable and beneficial to combine airborne spacing with CDAs. Workload ratings verify that the spacing tool was easy to use, added relatively little additional workload, and integrated well into the normal operations. Performance data show that the aircraft were able to fly CDA descents and still precisely manage their inter-arrival spacing, even when off-nominal events and forecast wind errors are introduced into the operation. The delivery precision and overall flow stability should allow the use of CDAs while maintaining, or even increasing, the runway throughput. From an operator's perspective, this would allow the realization of the fuel and noise savings without negatively impacting their normal operations. Current research is extending this idea to more complex arrival environments including multi-runway operations.