Airborne Spacing in the Terminal Area: A Study of Non-Nominal Situations

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This paper reports on small-scale experiments conducted with air traffic controllers. The objective was to investigate non-nominal situations when using airborne spacing in the terminal area. The following situations were considered: mixed equipage, holding patterns and typical unexpected events (go-around, emergency, radio failure, spacing instructions not correctly executed). In applying the airborne spacing procedure for non equipped aircraft, handling mixed equipage was found to be entirely feasible. Initial trends suggest that 50% equipped aircraft already brings some benefits compared to 0% although not as much as with 100%. Receiving aircraft from the holding patterns and then using airborne spacing for final integration was found feasible and comfortable. Recovering from the unexpected events was found less difficult than initially anticipated and was evaluated as similar to today’s operations.

Acronyms

ADS-B = Automatic Dependant Surveillance – Broadcast
ASAS = Airborne Separation Assistance System
FAF = Final Approach Fix
FMS = Flight Management System
IAF = Initial Approach Fix
INI = Initial Approach Controller
ITM = Intermediate Approach Controller
ILS = Instrument Landing System
TMA = Terminal Control Area (Terminal Manoeuvring Area)

I. Introduction

Airborne spacing involves a new task allocation between controller and flight crew envisaged as one possible option to enhance the management of arrival flows of aircraft. It relies on the ability of the controller to task the flight crew to maintain a given spacing with respect to the preceding aircraft. The motivation is neither to transfer problems nor to give more freedom to the flight crew, but to identify a more effective task distribution beneficial to both parties without modifying responsibility for separation provision. Airborne spacing assumes air-to-air surveillance (ADS-B) along with cockpit automation (ASAS). No significant change on ground systems is initially required.

Airborne spacing for sequencing and merging arrival flows of aircraft is being studied, in particular at NASA, Mitre and EUROCONTROL. The investigations initially considered the air perspective through model-based, human-in-the-loop simulations and flight trials showing the feasibility of the concept. The controller perspective has been addressed at NASA, and a concept of operations for the terminal area has been proposed and validated through human-in-the-loop experiments. A conservative approach was chosen, retaining the existing ATC organisation (controller roles, predefined route structure). Various options were considered (with ground tools, with airborne spacing, with both) in different conditions (traffic synchronised by a time constraint before entering the terminal area, or not synchronised only with a miles-in-trail constraint) and with a mixed equipage. It was shown

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that, in this context and even with a mixed equipage, airborne spacing is feasible and provides benefits, in particular in terms of spacing accuracy.

The work performed at the EUROCONTROL Experimental Centre has allowed the development and refinement of a set of spacing instructions for sequencing and merging arrival flows of aircraft\textsuperscript{9,10}. To gradually assess their operational feasibility, potential benefits and limits, two streams of air and ground experiments were conducted. The previous ground experiments showed that airborne spacing brings high benefits particularly in the terminal area\textsuperscript{11}: increased controller anticipation (earlier flow integration and relief from late vectoring), drastic reduction in number of instructions, more expeditious and orderly flow of traffic (more regular inter-aircraft spacing on final approach, slight increase of throughput, reduced dispersion at low altitude), aircraft under lateral navigation mode (as opposed to open vectors). These experiments however assumed nominal conditions, in particular all aircraft equipped, no use of holding patterns and no unexpected events (e.g. go-around).

Small-scale experiments have been recently conducted to investigate non-nominal situations when using airborne spacing in the terminal area. The focus was on the feasibility and the definition of related procedures rather than collecting data. The following situations were considered: mixed ASAS equipage, holding patterns and typical unexpected events (go-around, emergency, radio failure, spacing instructions not correctly executed). The paper presents the main findings. It is organized as follows: the two next sections introduce the spacing instructions and the experiment design. The following ones present the main findings for mixed equipage, holding patterns and unexpected events.

II. Spacing Instructions

The controller tasks involve sequencing aircraft with the same strategies as today. When appropriate, the controller has the ability to task the flight crew to achieve then maintain a given spacing with respect to a designated aircraft (target). Three spacing instructions are proposed and can be applied throughout the arrival sectors for sequencing and merging, from top of descent down to final approach. These instructions require aircraft to achieve or maintain a particular spacing on common or converging trajectories (Figure 1). For example, with a “heading then merge”, the task of the flight crew is defined as follows: (1) in order to achieve the desired spacing, the flight crew flies an initial heading issued by the controller, and initiates the resume action when the desired spacing is achieved; (2) in order to maintain the desired spacing, the flight crew adjusts the aircraft speed. It should be noticed that the aircraft is not following the target – it is on his own navigation. As for any standard instruction, the use of spacing instructions is at the controller’s discretion, and he/she can decide to end it at any time. The flight crew can only abort a spacing instruction in case of a problem onboard such as a technical failure. The controller should respect the same conditions as today for sequencing, e.g. compatible aircraft speeds. The use of spacing instructions is composed of three phases: (1) target identification, in which the controller designates the target aircraft to the flight crew, (2) issuing of the spacing instruction, and (3) termination of the spacing instruction. An example dialogue between controller and pilot is as follows:

1. Controller designates the target aircraft using e.g. transponder code (“XYZ, select target 4522”)
2. Flight crew identifies target aircraft (“XYZ, target 4522 identified, 8 o’clock, 30 miles”)
3. Controller confirms the identification (“XYZ, target 4522 correct”)
4. Controller, when appropriate, issues the spacing instruction (“XYZ, continue present heading then merge WPT 90 seconds behind target”)
5. Flight crew continues on heading, then initiates direct when spacing achieved (“XYZ, merging WPT”), then adjusts speed to maintain 90 seconds
6. Controller, when appropriate, cancels spacing (“XYZ, cancel spacing, speed 180 knots”)

![Figure 1. Spacing instructions for sequencing and merging.](image-url)
These instructions were initially developed for enroute arrival sectors having a spacing constraint at a given point (e.g. 8NM at the initial approach fix). However, these instructions were not directly applicable in the type of terminal areas considered due to the absence of routes and merge point\textsuperscript{10}. Furthermore, as aircraft are on their own navigation, vectors can only be used under very specific conditions. The solution lies on the introduction of a specific route structure consisting of a merge point and segments tangent to a circle centred on this point (“sequencing legs”), along with the possibility of sending aircraft direct to this point at any time (Figure 2). This allows performing path shortening or path stretching while staying on lateral navigation mode. In this environment, a pair of aircraft (A and B) is typically managed as follows:

A and B arriving from the same IAF, B under spacing with respect to A:
1. When A reports merging: “B, continue heading then merge WPT 90s behind target”.
2. When B reports merging: “B, descent 4000ft, cleared ILS approach runway 26”.

A and B arriving from different IAF, B under spacing with respect to its preceding aircraft:
1. On contact: “B, cancel spacing, speed 220kts”.
2. Then: “B, select target XYZ”.
3. When A reports merging: “B, continue heading then merge WPT 90s behind target”.
4. When B reports merging: “B, descent 4000ft, cleared ILS approach runway 26”.

Figure 2. Route structure for the terminal area.

III. Experiment Design and Setup

A. Objective

The objective of these small scale experiments was to investigate the use of airborne spacing in the terminal area under non-nominal situations. The focus was on the feasibility and the definition of related procedures rather than collecting data. Thus, the findings consist essentially in comments and feedback. The results obtained for mixed equipage should be considered as initial trends, rather than a full statistical analysis. The following situations were considered: mixed ASAS equipage, holding patterns and typical unexpected events (go-around, emergency, radio failure, spacing instructions not correctly executed). Two sessions of three days were conducted with the same three approach controllers, all very familiar with the use of airborne spacing. Other small scale experiments (not reported in the present paper) have been conducted to further investigate the case of 0% equipped aircraft but with the route structure, to test varied configurations and types of legs (parallel of same direction, non parallel, with segments approximating concentric arcs, with intermediate points).

B. Simulated Environment

The simulated airspace consisted of a TMA with two or three entry points (IAFs) and a single landing runway. The TMA had two positions (frequencies): initial\textsuperscript{2} (INI) and intermediate\textsuperscript{3} (ITM). Each position was manned with an executive controller and the INI was assisted by a planning controller. The INI received the traffic from the enroute sectors and was in charge of integrating flows on the merge point with spacing or direct-to (for non equipped

\textsuperscript{1} Today, often referred to as “pick-up” or in the US as “feeder”.

\textsuperscript{2} Today, often referred to as “feeder” or in the US as “final”.

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aircraft) instructions. The INI transferred the aircraft to the ITM once on navigation to the merge point. The ITM was in charge of descending the aircraft, maintaining spacing (for non equipped aircraft) with speed instructions, and transferring them to the tower. The TMA had two or three parallel sequencing legs and a merge point (Figure 3). The legs were vertically separated by 2000ft to provide a spare level in case of unexpected event. Although no departure traffic was simulated, an altitude constraint was applied to strategically segregate arrivals on the downwind leg from departures to the South. The required spacing at final approach fix was 90 seconds (120s for a ‘medium’ behind a ‘heavy’ aircraft). Traffic samples were close to the maximum landing capacity (36 to 40 arrivals per hour with 20% of ‘heavy’). For the ‘mixed equipage’ scenarios, 50% of aircraft were ASAS equipped aircraft. It was assumed that all aircraft were transmitting their position and velocity (‘ADS-B out’) and could be used as target aircraft by ASAS equipped aircraft. For the other scenarios, all aircraft were ASAS equipped.

Figure 3. Terminal area with three parallel sequencing legs (2nm apart, vertically separated) and a merge point (LOMAN). Initial approach fixes (entry points) are ODRAN, PONTY and EPERN. Final approach fix is FAO26.

IV. Mixed Equipage

Having distinct procedures for equipped and non equipped aircraft (respectively sequencing legs with merge point and open loop radar vectoring as in today’s operations) was incompatible. Indeed, trajectories of aircraft under radar vectoring (late integration on the axis) would interfere with those of aircraft under airborne spacing (early integration at a point). Thus, the only way identified to handle mixed equipage was for the non equipped aircraft to follow the equipped aircraft procedure: controllers kept the non equipped aircraft on the sequencing legs and when appropriate issued a ‘direct-to’ the merge point, without using heading instructions (Figure 4). This procedure was used also in the run with no equipped aircraft as it was found useful.

In this context, handling mixed ASAS and non-ASAS aircraft was found to be entirely feasible. ASAS was used whenever possible as it was found more comfortable, enabling reduced workload and communications. Without ASAS equipped aircraft, the frequency would have been busier and the spacing on final less accurate. However, non-equipped aircraft required more monitoring compared to equipped aircraft or to today situation. The sequence order was decided according to the position of the flights and not according to the aircraft equipment (i.e. ASAS or not) as it is more convenient to follow the “natural” arrival order. The spare flight level per sequencing leg was found useful (as a backup), despite a slightly larger speed differences between the default flight levels (10kt in ground speed with 2000ft, compared to 5kt with 1000ft).

Despite the limited number of exercises (one for 100%, three for 50% and three for 0% equipped aircraft), initial trends can be observed which suggest that 50% equipped aircraft already brings some benefits compared to 0%, although not as much as with 100%: reduction in the number of manoeuvre instructions (Figure 5, left) and more accurate inter aircraft spacing on final (Figure 5, right). Concerning the manoeuvre instructions, with 100% and even with 50% equipped aircraft, the reduction can be observed for speed and direct. This is due to the fact that the controller had to sequence non equipped aircraft with one direct to the merge point and then with speed instructions, in comparison with one spacing instruction to sequence equipped aircraft. Concerning the inter aircraft spacing, a reduced dispersion around the required spacing value can be observed with 100% and even with 50% equipped aircraft. These results are in line with those obtained by NASA with 75% equipped aircraft, although there are differences in the use of ASAS (e.g. use of standard routes)\(^8\).
Figure 4. Controller interface in a mixed equipage situation showing spacing links (orange for target selection, green when under airborne spacing) and highlights (in yellow) of non ASAS equipped aircraft.

![Diagram showing controller interface with spacing links and highlights for non ASAS equipped aircraft.]

Figure 5. Initial trends for manoeuvre instructions (left) and spacing on final (normalised at 90 seconds, right).

![Graphs showing initial trends for manoeuvre instructions and spacing.]

V. Holding Patterns

A holding stack was defined for each IAF. It was identified that, to ensure every aircraft enters properly the sequencing leg when leaving the stack (avoids overshoot), the stacks had to be located upstream from each leg. One was located at ODRAN (IAF), while for the other, a point (PONTY) had to be created upstream MOTEK (IAF). All the traffic was ASAS equipped. ASAS instructions were cancelled by E-TMA prior to entering the stack. The upstream sector was manned with a controller feeding the aircraft in the stacks. It was identified during the preparation that two flight levels are required for each of the sequencing legs. Indeed, when leaving the same stack, because aircraft had to follow the same trajectory, no lateral separation can be provided, thus a vertical separation is required.
The immediate feedback was that receiving aircraft from the holding patterns and then using airborne spacing for final integration was found feasible and comfortable. Indeed, the traffic was sent from the holding patterns in a very homogeneous way (same speed at predefined and stable altitude) compared to the situations where it was sent directly (not holding) from the upstream sectors. However, the lack of accurate knowledge of when aircraft will actually leave the holding patterns forced the controller to delay the identification of the sequence order (order decided when entering the sequencing leg – not when entering the TMA), which consequently delays the setting-up of airborne spacing (target selection then spacing instruction). This was not reported as a limitation, rather as a change. In terms of effectiveness, with or without ASAS, there is an intrinsic variability in the holding pattern exit conditions, leading to discontinuities and in turn to heterogeneous spacing on final. ASAS and its associated airspace structure were found very effective to remove these discontinuities and to provide more predictability.

VI. Unexpected Event

The motivation was to refine procedure – not to assess the detection capability of the controllers. For that purpose, prior to the runs, situations were described and an initial recovery procedure was agreed. During the runs, controllers could ask to freeze the simulation to discuss the procedure. The unexpected events selected were those raised during previous controller experiments and safety sessions (hazard assessment) requiring a dedicated recovery procedure. The selected situations were: go-around, emergency, radio failure and two cases of a spacing instruction not correctly executed resulting in an infringement of the required spacing. The situations were simulated as follows:

- Run 1: emergency (one occurrence), speed not reduced during “merge” (two occurrences), “merge” performed instead of “heading then merge” (two occurrences).
- Run 2: radio failure (one occurrence), “merge” performed instead of “heading then merge” (two occurrences).
- Run 3: go-around, emergency (one occurrence each).

C. Go-around

The go-around occurred while in contact with the tower (i.e. aircraft on the ILS and no more in contact with the TMA executive controller). The tower was not manned, however in order to get realistic situations, the appropriate co-ordinations and actions were simulated. Handling this situation was not found more difficult than with current practices. The controllers could easily identify where to re-integrate the aircraft in the sequence and quickly get back to a nominal situation. The refined standard procedure is to join one IAF in order to complete a new approach using the sequencing legs and when appropriate spacing instructions. This requires re-integrating the aircraft in a sequence of aircraft possibly with a target selected or under spacing (which implies deselecting a target or cancelling an existing spacing instruction, then issuing two new spacing instructions). However, in some cases, and according to the traffic situation, the aircraft can be re-integrated before the IAF, for instance by being vectored to a track parallel to the sequencing legs. As today, the aircraft will have to be transferred early enough to the TMA in order to be re-integrated in the sequence as soon as possible. Early speed reductions could be requested to upstream sectors to ease the re-insertion of the aircraft into the sequence. Depending on traffic conditions, holding patterns may be opened.

D. Emergency

The two emergencies occurred before the IAF and did not lead to a runway closure (in that case holding patterns or another runway would be used). As for the go-around, handling this situation was not found more difficult than with current practices. As today, the difficulty was to identify where to integrate the aircraft in the sequence due to speed difference. As today, there is no standard procedure for emergencies but key steps were identified. First, controllers need to identify where to integrate the emergency assuming that it will fly direct to LOMAN keeping high speed. Then, controllers have to create a gap in the sequence. This could be achieved by taking any interfering aircraft already direct to LOMAN out of the sequence (and put them back later, in a similar way as a go-around) and by maintaining any interfering aircraft not yet direct to LOMAN on the sequencing legs. Finally, the first aircraft after emergency should be set on direct to LOMAN as a first aircraft of a new sequence. The emergency shall not be used as a target as it is keeping a high speed, not compatible with a standard speed (e.g. 250kt max below FL100). A “merge at least” may be issued for the emergency in case it is catching up the preceding aircraft (however this may mean that the preceding should have been taken out of the sequence). As today, early speed reductions could be applied in upstream sectors to delay the aircraft after the emergency, and possibly holding patterns.
E. Radio failure

A standard radio failure procedure was defined (IAF, ZABOU/LAURI, LOMAN). The radio failure occurred in the enroute sectors. Handling this situation was again not found more difficult than today. However, controllers were concerned by the risk that the radio failure aircraft would start descent before leaving the sequencing leg, thus crossing the level of the other leg. The steps are similar to the emergency: identify where to integrate the radio failure, create a gap in the sequence, and set on direct to LOMAN the following aircraft (Figure 6). However, as today, when identifying where to integrate the radio failure, more margin ahead (than for the emergency) should be taken as flight crew might not exactly follow the procedure. To reduce the uncertainty, the procedure could be improved by removing the intermediate point (ZABOU/LAURI). As the radio failure may reduce more than anticipated, some margin behind should be taken and it should not be used as target. As today, speed reductions should be applied upstream and possibly holding patterns.

F. Spacing instruction not correctly executed

Two situations simulated one aircraft (under spacing) catching-up with its target. These situations were not rated as serious cases by the controllers: they should be quickly detected through usual radar monitoring and easy to handle. The recovery procedure could be described as follows: first, issue a “cancel spacing” along with a speed reduction, then if appropriate re-select target (when not retained) and re-issue a spacing instruction (generally “merge”). In case aircraft are too close (e.g. about to infringe separation) due to a very late detection (rated as unlikely to occur), further actions are required. First, take the aircraft out of the sequence. Then:

- If no aircraft under spacing behind: vector the “non compliant” aircraft on a track parallel to the sequencing legs and, when appropriate, re-select target and re-issue a spacing instruction (generally “continue heading then merge”).
- Otherwise: “cancel spacing” for the following aircraft (now number one of a new sequence) and handle the “non compliant” aircraft similarly to a go-around situation.

Four “continue heading then merge” instructions were correctly read-back by the pseudo pilots but intentionally executed as “merge” instructions. With every case the mistake was detected very quickly and was found easy to handle by the controllers. In such cases, the recovery procedure as discussed by the controllers could be described as follows: first, issue to the “non compliant” aircraft a “cancel spacing, retain target” along with speed instructions (generally 220kt). Then, vector the aircraft on a track parallel to the sequencing legs. Finally, issue a new spacing instruction (generally “continue heading then merge”).

![Figure 6. Radio failure situation. A large gap in the sequence created by the controllers ahead of the radio failure (JKK4431 in yellow) can be seen. Behind, aircraft are delayed on the sequencing legs.](image-url)
VII. Conclusion

In applying the airborne spacing procedure for non equipped aircraft, handling mixed equipage was found to be entirely feasible. Spacing instructions were used whenever possible as it was found more comfortable, enabling reduced workload and communications. However, non equipped aircraft required more monitoring compared to equipped aircraft or to today situation. Initial trends suggest that 50% equipped aircraft already brings some benefits compared to 0% (reduction in the number of manoeuvre instructions and more accurate inter aircraft spacing on final) although not as much as with 100%. Receiving aircraft from the holding patterns and then using airborne spacing for final integration was found feasible and comfortable. Indeed, the traffic was sent from the holding patterns in a very homogeneous way compared to the situations where it was sent directly from the upstream sectors. Recovering from the unexpected events was found less difficult than initially anticipated and was evaluated as similar to today’s operations. For go-around, emergency and radio failure, the difficulty was, as today, to identify where to integrate the concerned aircraft in the sequence. The cases of spacing instructions not correctly executed were not rated as serious: they should be quickly detected through usual radar monitoring and easy to handle. The general principle to handle such situations when using spacing instructions is to “isolate” the aircraft experiencing the problem (i.e. take it out of the sequence) and not to act on the whole sequence.

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References