Abstract

A new allocation of tasks between controller and flight crew is envisaged as one possible option to improve the sequencing of arrival flows. It relies on a set of new spacing instructions where the flight crew can be tasked by the controller to maintain a given spacing with respect to a designated aircraft. The investigations initially focussed on upstream sectors (en-route) highlighting a positive impact on controller activity and on control effectiveness. However, the application to downstream sectors (approach) appeared as an issue. The paper shows how this issue was addressed, in particular the how organisation of roles, the working methods and the airspace have been adapted for the effective use of spacing instructions. It also presents the results from the latest experiment which involved six approach controllers over four weeks. Overall feedback from controllers was positive. The proposed working method, though implying significant changes as compared to today, seems easy to use and assimilate. The analysis of instructions and eye-fixations shows a positive impact on controller activity (relief from late vectoring and earlier flow integration). In terms of effectiveness, the inter aircraft spacing on final is more regular. Concerning aircraft, in addition to receiving fewer instructions, spacing instructions would enable to fly, in approach sectors, under lateral navigation mode (as opposed to fly open vectors). The next step will consist in investigating interaction between upstream and downstream sectors when using an arrival manager.

Acronyms

ADS-B Automatic Dependant Surveillance Broadcast.
ASAS Airborne Separation Assistance System.

E-TMA Extended TMA: en-route sectors performing sequencing of arrival flows before transfer to TMA. Usually exists around dense TMA to organise the traffic in advance, and thus facilitate the integration onto final approach. Arrival manager may be used.

FAF Final Approach Fix.
IAF Initial Approach Fix.
TMA Terminal Control Area (“approach” control).

Introduction

A new allocation of tasks between controller and flight crew is envisaged as one possible option to improve air traffic management, in particular the sequencing of arrival flows. It relies on a set of new spacing instructions where the flight crew can be tasked by the controller to maintain a given spacing (in time or in distance) with respect to a designated aircraft. This task allocation is denoted “airborne spacing” [1]. The motivation is neither to transfer problems nor to give more freedom to flight crew, but to identify a more effective task distribution beneficial to all parties without modifying responsibility for separation provision. Airborne spacing assumes airborne surveillance (ADS-B) along with cockpit automation (ASAS). No significant change on ground systems is initially required.

Airborne spacing for aircraft arrival flows was initially studied from a theoretical perspective through mathematical simulations, to understand the intrinsic dynamics of in-trail following and in particular to identify possible oscillatory effects [2][3][4]. The pilot perspective was addressed through human-in-the-loop simulations [5][6][7] and flight trials [8] to assess feasibility. The air traffic control system perspective was considered through model-based simulations, to assess the impact on
arrival rate [9]. Initial human-in-the-loop investigations were also performed with approach controllers [10].

The work conducted in the project extends these studies along two lines: (1) by addressing the integration of flows and not only the spacing within a single flow; (2) by considering both upstream (extended TMA, E-TMA) and downstream (TMA) sectors and not only TMA. This work allowed developing and refining a set of spacing instructions for arrival sequencing [11][13]. To assess their feasibility, benefits and limits, two streams of air and ground experiments are conducted. The ground experiments initially focussed on E-TMA, highlighted a positive impact on controller activity (increased controller availability, anticipation) and on control effectiveness (more regular spacing at the sector exit point). Although promising for E-TMA, the application of the spacing instructions in TMA appeared as an issue.

The paper shows how this issue was addressed, in particular how the organisation of roles, the working methods and the airspace have been adapted for the effective use of spacing instructions in TMA. It also presents the results from the TMA experiment conducted in 2003. The paper is organised as follows: the next section will briefly introduce the main principles of the spacing instructions considered. The following sections will present the application to the approach, the experiment design and the main findings.

### Spacing instructions for sequencing

With the proposed task allocation, the controller remains in charge of analysing the situation and defining solutions. When appropriate, he/she can task the flight crew to execute an instruction with respect to a designated aircraft. Four instructions are proposed for sequencing of arrival flows and can be applied throughout the arrival sectors, from top of descent to final approach. The controller tasks involve sequencing aircraft with the same strategies as today, but using these new spacing instructions when appropriate. These instructions require aircraft to achieve or maintain a particular spacing on common or converging trajectories (Table 1). For 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.

<table>
<thead>
<tr>
<th>Common trajectories</th>
<th>Converging trajectories</th>
</tr>
</thead>
<tbody>
<tr>
<td>To maintain spacing</td>
<td>Remain</td>
</tr>
<tr>
<td>To achieve then</td>
<td>Heading</td>
</tr>
<tr>
<td>maintain spacing</td>
<td>then remain</td>
</tr>
</tbody>
</table>

**Table 1. Spacing instructions for sequencing arrival flows.**

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 however can only abort it in case of a problem onboard such as a technical failure. 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.
3) Termination of the spacing instruction.

For illustration purposes, let us consider the situation of two arrival aircraft converging to a point, then following the same route to the airport. Today, the controller must ensure that the spacing is maintained, and therefore has to continuously monitor the situation and if necessary issue heading and/or speed instructions. With airborne spacing, the spacing is maintained by the flight crew through speed adjustments, relieving the controller of this task. However, the same conditions as today for sequencing need to be respected, e.g. compatible aircraft speeds. An example dialogue between controller and pilot is given in Table 2.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Pilot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designates the target aircraft: “XYZ, select target 1234” (*)</td>
<td>Identifies target aircraft: “XYZ, target 1234 identified, 8 o’clock, 30 miles”</td>
</tr>
<tr>
<td>Gives initial heading, waypoint and desired spacing: “XYZ, heading 270 then merge WPT 90 seconds behind target”</td>
<td>Flies heading 270 Initiates direct when spacing obtained: “XYZ, merging WPT”</td>
</tr>
<tr>
<td>Adjusts speed to maintain 90 seconds</td>
<td></td>
</tr>
<tr>
<td>When appropriate, cancels spacing: “XYZ, cancel spacing, speed 180 knots”</td>
<td>Cancels spacing and follows 180 knots</td>
</tr>
</tbody>
</table>

**Table 2. A typical exchange between the controller and the flight crew.**

* The target aircraft is designated by a unique identifier, here the Secondary Surveillance Radar code.
Application to approach sectors

Ground experiments initially focussed on E-TMA allowed building a method of use and identifying the constraints attached [11]. The application of spacing instructions in TMA was then investigated. An analysis of the specificity of TMA compared to E-TMA along with prototyping sessions led to adapt the method of use and identify how to design the airspace [12].

By definition of the spacing instructions considered, aircraft must be either on common trajectories (“remain” instructions) or on converging trajectories (“merge” instructions). Therefore, trajectories with merge point(s) must be defined in TMA. To avoid complex situations and keep the use simple, there should be a single standard trajectory for each flow, and all trajectories should be converging to a single merge point (located upstream of the FAF). To provide the required anticipation, it seemed necessary to group the arrival control positions into one (i.e. initial/pickup and intermediate/feeder positions grouped), and to man this single position with an executive and a planning controller. The planning controller is thus in charge of early analysis of the sequences (in addition to classical cross-check). It was acknowledged however that these characteristics imply changes in working methods: use of standard trajectories as opposed to radar vectoring; integration on a point as opposed to integration on an axis; a single approach control position as opposed to two distinct positions; and two controllers per position as opposed to one.

An experiment was conducted in 2002 to assess usability of the spacing instructions in this environment. The overall feedback was positive and the initial analysis suggested a positive impact on activity. However, some points raised could constitute severe limitations, in particular with a high level of traffic. Three were identified. Firstly, controllers mentioned that, although they like the level of traffic, they were not comfortable with the “heading then merge” which required too much effort. This was not anticipated as the “heading then merge” was expected to relieve the controller from critical monitoring and resume actions, which are still needed for the “merge”. Secondly, some airborne spacing initiated by E-TMA might have to be cancelled to integrate aircraft from the other flow. This would increase workload and controllers sometimes found it easier and quicker to get back to conventional control than to re-issue spacing instructions to several aircraft. Thirdly, to delay aircraft for integration, controllers had to issue vectors. This sometimes led to incorrect spacing situations, typically aircraft under “remain” not following the same route. These three limitations were attributed to a traffic not organised enough for spacing purposes, essentially due to numerous aircraft on multiple headings in a poorly structured airspace.

To tackle these limitations for the 2003 experiment, we had to rethink and reformulate the requirements related to the airspace design. The following requirements have been identified:

1) To allow for flow integration with spacing instructions, it should be possible to “expedite” or delay aircraft while staying on trajectories. This can be achieved by adding “sequencing legs” to the standard trajectories along with the possibility of sending aircraft direct to the merge point at any time.

2) To enable direct-to instructions at any time, the whole range of possible paths should be available, ideally without any restrictions. This may impose segregated arrival and departing flows, and no crossing traffic.

3) To allow for delay absorption, there should be “enough” length difference between the longest and the shortest trajectories, e.g. at least 5NM which corresponds to approximately 90s (a slot).

4) To cope with delays in excess, it should be possible to maintain aircraft on their current heading beyond their normal turn.

5) To easily visualise the situation, e.g. respective ordering and spacing between aircraft, sequencing legs could be straight parallel segments.

6) To avoid losing space, every sequencing leg should be separated from the other by a distance lower than the usual spacing value, e.g. 4NM for a 90s spacing.

7) To avoid highly diverging situations (e.g. for aircraft from opposite legs) that could result in losing space, the end of each sequencing leg should ideally not exceed beyond the location abeam the merge point.

8) To avoid any separation issue, sequencing legs should be vertically separated.

These requirements lead to the following airspace design with two entry points (Figure 1).

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1 Approach control position receiving traffic from E-TMA (e.g. via IAF), organising traffic (e.g. stack management, initial vectors to delay traffic or to create gaps between flows) and maintaining spacing before transfer to feeder position. In the US this position is often referred to as “feeder”.

2 Approach control position receiving traffic from pickup position, handling integration onto final approach and runway axis interception before transfer to tower. In the US this position is often referred to as “final”.

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Experiment design

The objective of the 2003 experiment was to assess usability and usefulness of time-based spacing in TMA at very high traffic levels. Two conditions were simulated: without spacing instructions (conventional control but standard trajectories available) and with time spacing instructions (their use was at controller discretion).

The airspace was similar to the one used in the previous experiment. It consisted of two generic approach sectors (APO and APR) derived from an existing environment (Paris), each having two entry points and feeding a single landing runway (Figure 2). The standard trajectories were modified to match the new design requirements. The new trajectories provide a capacity of delay absorption of approximately 1 slot for the base legs and 2 slots for the downwind leg. Merge points are LOMAN for APO and TAMAK for APR, both at 4000ft. Although no departure traffic was simulated, an altitude constraint was applied (FL060 maximum at KAYEN) to strategically segregate arrivals on the APO downwind leg from departures to the South, and thus to allow issuing instruction direct to LOMAN from KAYEN.

Three or more entry points could be handled by defining parallel sequencing legs leading to a single merge point, with the entry points laterally or vertically separated. These additional entry points would allow handling slow aircraft (propellers) with distinct trajectories.

Figure 1. Airspace design with two entry points.

Figure 2. Simulated airspace.

Each sector was controlled by a single approach position manned with an executive and a planning controller. The role of each executive controller (with support from the planning controller) was to integrate the two flows onto final approach, and to transfer them to tower. Required spacing values at transfer were: 90 seconds between aircraft (120 seconds for a medium aircraft behind a heavy) in spacing condition, equivalent to 4.5NM (6NM for medium behind heavy) at 180kt in conventional condition.

The traffic entered each approach sector already sequenced (8NM at 250kt without spacing or 90s with spacing). This was achieved by scripts to ensure identical deterministic experimental conditions among runs. In condition with spacing, aircraft arrived in TMA under spacing (all the traffic was equipped). The traffic level was 34 arrivals per hour with sequences of up to 7 aircraft.

The working environment was similar to today, making use of progress paper strips. Graphical markings dedicated to spacing instructions were available, consisting of markers set around the position symbols of the aircraft under airborne spacing and of its target, and of a link between them (Figure 3). These markings served as a reminder and also allowed to visualise aircraft coming from E-TMA under airborne spacing. Concentric circles centred on each merge point allowed for an early identification of sequence order by the planning controller.

3 It was initially envisaged 36 arrivals per hour but this appeared hardly manageable without spacing instructions and with only one control position. Without spacing instructions, a second control position would have been required. However, to allow comparing human related measurements (e.g. eye tracker), it was decided to keep one control position in both conditions.
The experiment was structured around two main sessions: two weeks of training and two weeks of measured exercises. One week break between the two sessions enabled controllers to further assimilate the concept. During the measured exercises, each controller participated once as executive controller on both sectors and in both conditions.

Main findings

Human factors

Overall feedback was positive. In addition to acknowledging usability, controllers perceived benefits in terms of workload reduction, increased anticipation in sequence building and more regular spacing on final. They also suggested that the spacing instructions would allow them to handle more aircraft and to reduce frequency congestion. The instructions were also thought to make stacks easier to handle. However, controllers questioned their ability to detect unexpected events and recover from degraded situations. Finally, the applicability to other TMA was questioned.

The new airspace was considered somewhat unusual but well adapted to the spacing instructions. It helped structuring the way of working and led to more standardized practices. One limitation was related to the standard trajectories. When aircraft had to maintain their heading on the sequencing leg beyond the standard turn point (e.g. to lose time), the controller had to issue a “continue heading” instruction, otherwise the aircraft would turn by default. This was a source of errors (controllers forgot on some occasions to issue the “continue heading”) thus increasing workload. Another limitation was related to the distance between the legs (4NM). With a target aircraft on the “inner” leg, the current spacing was already near the required one, sometimes larger.

The number of issued spacing instructions is an indicator of both usability and motivation. This was analysed using the percentage of aircraft under spacing when passing the merge point. The resulting percentages were very high in both sectors: 86% in APO and 85% in APR. The “heading then merge” instruction was predominantly used (83% of the spacing instructions).

The analysis of NASA-TLX questionnaires and Instantaneous Self Assessment (ISA) of workload suggest that airborne spacing induces a reduction of the mental and temporal demand for the executive controller but not for the planning controller. Objectively, there is a drastic reduction in the number of manoeuvre instructions (heading, speed, level, spacing), larger in APO (53%) than in APR (36%). Even when adding the number of target selection messages, there is still a reduction, again larger in APO (48%) than in APR (28%).

Method of use

The controller tasks essentially consist in maintaining aircraft spacing within the same flow (keeping aircraft under “remain”) and handling multiple flow integration on final (with “merge” or “heading then merge”). For aircraft within the same flow arriving under spacing, the controller has to decide for every pair of aircraft, whether to retain it or to cancel it in order to integrate aircraft from the other flow(s). 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 LOMAN 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 1234” (1234 is the code of A).
3) When A reports merging: “B, continue heading then merge LOMAN 90s behind target”.
4) When B reports merging: “B, descent 4000ft, cleared ILS approach runway 26”.

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4 As identified during the flight deck experiment conducted in Spring 2004, this means also a short time between receiving the instruction and initiating the resume.
**Controller activity**

To understand the impact of airborne spacing on controller strategies, the first step consisted in analysing the type of manoeuvre instructions used. Four types of instructions were analysed: heading (including direct-to), speed, altitude and spacing (when applicable). The respective reductions of manoeuvre instructions were 67% for speed and 73% for heading (Figure 4). For all types of instructions the reduction was higher in APO than in APR. In APO, speed instructions were reduced by 71% and heading by 81%. In APR, the number of speed instructions was reduced by 64% and heading instructions by 59%. The sector configuration might explain the difference. In the conventional condition without airborne spacing, intercepting the final in APO required multiple successive heading instructions, whereas in APR one heading instruction was enough to accomplish this task. Under airborne spacing, aircraft merged to a point located before intercepting the final. Once at this point, aircraft resumed flying along the standard trajectory and did not require further vectoring from the controllers.

The second step consisted in analysing the distribution of manoeuvre instructions as a function of distance to a reference point (Figure 5). In APO, a bulk of instructions can be observed 10NM before the FAF without airborne spacing, and 30-35NM before the FAF with airborne spacing. In addition, with airborne spacing, almost no manoeuvre instructions were given in APO between 35NM out and the FAF. In APR, the impact is less apparent but still visible: the bulk of instructions is shifted 5NM upstream, and almost no manoeuvre instructions were given between 20NM out and the FAF. These results suggest that, with airborne spacing controllers could integrate the flows earlier and could be relieved from the late vectoring. These results confirm the controllers perception of increased anticipation. In the conventional condition, varied strategies were observed from the individual geographical distributions. In contrast, in the condition with spacing, a strategy common to all controllers was observed. This suggests that airborne spacing tends to standardise the sequencing activity.

To assess the impact of airborne spacing on the controllers’ monitoring task, the geographically based analysis used for instructions was applied to eye fixations (Figure 6). In APO, fixations were concentrated in the final area (between 5 and 20NM from the FAF) in the conventional condition, and further away (between 25 and 40NM from the FAF) in the condition with spacing. In APR, similar to the instructions, the impact is less apparent but still visible: fixations were concentrated between 5 and 20NM before the FAF in the conventional condition, but further away (between 15 and 30NM from the FAF) in the condition with spacing. These results clearly show that airborne spacing moved the controller’s locus of attention upstream. It is noteworthy that the distribution of fixations is in line with the distribution of instructions and confirms the increased anticipation.

**Effectiveness**

The quality of flow integration was analysed using the inter aircraft spacing at the FAF and the number of aircraft passing over the FAF. The distribution of inter aircraft spacing shows a strong impact of airborne spacing (Figure 7). The spacing deviation is below ±5s for 75% of the aircraft with airborne spacing, and below ±5s for only 31% in the conventional condition. In APR, the same number of aircraft passed over the FAF during the analysed period. In APO, in half of the exercises, more aircraft flew over the FAF with airborne spacing than in the conventional condition. The analysis of the runs with a replay tool showed that aircraft did enter the sector at the same time in both conditions, but without spacing, aircraft had to fly longer trajectories, which resulted in additional delays until passing the FAF. Two aspects related to the quality of flight service are presented here: flight efficiency and pilot perspective. In terms of flight efficiency, with airborne spacing, aircraft trajectories are straighter (Figure 8) and time and distance flown per aircraft are reduced (10% and 5% respectively). The analysis of the number of manoeuvre instructions per aircraft shows that with airborne spacing more aircraft received fewer instructions. In addition, we compared the time spent using the heading select mode (HDG) to the time spent using the lateral navigation mode (NAV). Aircraft spent more time under NAV (80%) in the condition with spacing than in the conventional condition. Furthermore, the HDG mode in the condition with spacing mainly corresponded to “continue heading”, as opposed to heading changes in the condition without spacing. In addition to the duration of using HDG or NAV, and based on the geographical distribution of instructions, it is interesting to note that the HDG mode was used on the sequencing legs (between 40 and 20NM from FAF) in the spacing condition, and in the last part (less than 20NM from FAF) without spacing.
Figure 4. Manoeuvring instructions repartition.

Figure 5. Geographical distributions of instructions.

Figure 6. Geographical distributions of eye fixations.
Figure 7. Inter-aircraft spacing at FAF. For a required spacing of 120s, the spacing value is normalized at 90s.

Figure 8. Trajectories.

Safety

When using spacing instructions, controllers seemed to have more time to deal with aircraft, which could increase safety at very high traffic levels. However, controllers felt that their monitoring is reduced once spacing instructions have been issued and raised safety concern. The analysis of periods between successive eye fixations on the same aircraft shows that aircraft were more frequently fixated in the condition with airborne spacing than in the condition without.

To detect cases of loss of separation, we looked for aircraft with less than 3NM longitudinal separation. We found 16 aircraft out of the 1072 controlled (less than 1.5%). All cases occurred in the conventional condition. No case was detected in the condition with spacing. The analysis of the losses of separation showed some diverging path geometries but that all cases occurred when integrating aircraft from both legs.

The use of spacing instructions required controllers to respect initial applicability conditions and then to maintain them during the procedure. Typical incorrect applicability conditions are: too small initial spacing, target not direct, incompatible speeds, incompatible instructions. For only 8% of the “heading then merge”, the initial spacing was appropriate. For less than 0.7% of the “heading then merge”, the target was not direct to the waypoint. For only 8% of the “heading then merge”, aircraft had similar speed. Less than 1.5% of the aircraft under spacing received incompatible instructions (e.g. a speed while under “remain”, a heading while under “merge”).

Lessons learnt

The overall airspace design seems globally well adapted to spacing. Two main modifications will be made to cover comments made by the controllers.

Firstly, to avoid the need to explicitly maintain an aircraft on heading, the sequencing legs will be extended (e.g. with end point as clearance limit). It could be noticed that, as aircraft will stay on trajectories all the time (unless an unexpected event occurs), they could be flying in lateral navigation mode. Thus, the instruction “heading then merge” could be extended to a “follow route then merge” and aircraft would no longer be on an open vector.

Secondly, to avoid inducing a short reaction time for the pilot (and possibly losing space) for cases at which the target aircraft is on the inner leg and the instructed aircraft is on the outer leg, the distance between sequencing legs will be reduced. However, to be able to easily distinguish between aircraft on different legs, they have to be graphically separated. A value of 2NM seems appropriate. A distance between legs below separation minima implies that legs shall be vertically separated.
Conclusion

A stepwise process was followed to apply, in TMA, spacing instructions initially developed for E-TMA. The organisation of roles, the working methods and the airspace have been gradually refined for the effective use of spacing instructions. Overall feedback from controllers was positive. The proposed working method, though implying significant changes as compared to today, seemed easy to use and assimilate. The analysis of instructions and eye-fixations shows a positive impact on controller activity (relief from late vectoring and earlier flow integration). The inter aircraft spacing on final is more regular. Concerning aircraft, in addition to receiving fewer instructions, spacing instructions would enable to fly under lateral navigation mode in TMA (as opposed to fly open vectors).

So far, only full equipage has been considered. The significant evolution in the working method brought about by spacing instructions seems applicable and even potentially beneficial to conventional operations. This may suggest such evolution as a natural preparatory step to a gradual introduction of spacing instructions, e.g. for mixed equipage.

Concerning the flight deck experiments, the last one carried out in Spring 2004 aimed at assessing feasibility of the spacing instructions in this new environment, and their impact on pilot activity. No show stopper was identified.

The next step on the ground side will consist in investigating more varied situations, including mixed equipage, defining fallback procedures and addressing the issue of interaction between E-TMA and TMA through the use of an arrival manager. Beyond, remains the issue of applicability to other airspace that should be addressed through collaboration with national administrations. Initial investigations of applicability to Frankfurt, London and Paris have been conducted [14].

References


Keywords

Airborne Separation Assurance System (ASAS), ADS-B, airborne spacing, approach control (TMA), controller activity, eye movement analysis.

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