Combining Sequencing Tool and Spacing Instructions to Enhance the Management of Arrival Flows of Aircraft

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This paper reports on an experiment conducted with air traffic controllers to investigate the joint use of a sequencing tool and spacing instructions to enhance the management of arrival flows. The experiment simulated two en-route and one approach sectors (total of seven positions). It was shown that sequencing tool and spacing instructions can be jointly used in en-route and in the terminal area, with high benefits particularly in the terminal area. Main benefits are: a positive impact on controller activity (earlier flow integration and relief from late vectoring) and on control effectiveness (more regular inter-aircraft spacing on final approach, a slight increase of throughput and straighter trajectories with no dispersion below 4000ft).

Acronyms

-ADS-B = Automatic Dependant Surveillance – Broadcast
-AMAN = Arrival Manager (sequencing tool)
-ASAS = Airborne Separation Assistance System
-E-TMA = Extended TMA (en-route sectors performing pre-sequencing of arrival flows before transfer to TMA)
-FAF = Final Approach Fix
-IAF = Initial Approach Fix
-TMA = Terminal control area (“approach” control).

I. Introduction

AIRBORNE spacing involves a new allocation of tasks 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 all parties without modifying responsibility for separation provision1. 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 arrival flows of aircraft was initially studied from a theoretical perspective through mathematical simulations, to understand the intrinsic dynamics of in-trail following aircraft and identify in particular possible oscillatory effects2,3,4. Pilot perspective was also addressed through human-in-the-loop simulations5,6,7 and flight trials8 essentially to assess feasibility. The air traffic control system perspective was considered through model-based simulations, to assess impact on arrival rate of aircraft9. The controller perspective is addressed at NASA10,11 through human-in-the-loop experiments. A conservative approach is investigated: airborne spacing is essentially used in the terminal area, with a spacing already achieved (thus through speed adjustments). This implies an initial synchronisation of aircraft, obtained by imposing time constraints before entering the terminal area. This approach allows keeping the same ATC organisation (controller role, airspace structure).

The work performed so far at the EUROCONTROL Experimental Centre allowed developing and refining a set of spacing instructions for sequencing and merging arrival flows of aircraft. To gradually assess their operational feasibility, potential benefits and limits, two streams of air and ground experiments are conducted12,13,14. The

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previous ground experiments highlighted a positive impact on controller activity (increased availability and anticipation) and on control effectiveness (more regular inter aircraft spacing at the sector exit point). However, even if the complete arrival phase was considered, en-route and terminal areas were studied separately. The interaction between en-route and terminal areas when using spacing instruction and a sequencing tool (suggesting sequence order and delays) had to be investigated.

An experiment simulating two en-route sectors (four positions) and one approach sector (three positions) was conducted. The objective was to assess the feasibility of the joint use of spacing instructions (ASAS) and a sequencing tool (AMAN), and its impact on interaction between sectors and on ATC effectiveness. The paper presents the main findings from this experiment. It is organised as follows: the next two sections will briefly introduce the spacing instructions and the sequencing tool. The third section will describe the experiment design and setup, including airspace, roles and procedures. The following section will present the main findings, in assessing the impact on the management of arrival flows, from a local view at a controller level, to a wider perspective at a global system level.

II. Spacing Instructions

The controller tasks involve sequencing aircraft with the same strategies as today. When appropriate, he/she can task the flight crew to execute an instruction with respect to a designated aircraft (target). Three spacing instructions are proposed and can be applied throughout the arrival sectors, 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 or on vector as instructed by the controller.

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, issue 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”)

![Spacing Instructions Diagram](image-url)

Figure 1. Spacing instructions.
In en-route arrivals sectors (E-TMA), the controller tasks involve building sequences with conventional or spacing instructions. In the terminal area (TMA), 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). In the latter, the controller may have then to issue spacing instructions. However, this implies an early identification of the sequence order as the target selection has to be done prior to issuing the instruction. To provide the required anticipation, it was found necessary to man the arrival control positions with an executive and a planning controller (in charge of the early identification of the sequence order, in addition to classical cross-check). There is another restriction when using spacing instructions: it is no longer possible to vector aircraft when under spacing. A specific design of the TMA enables overcoming this restriction while taking advantage of the instructions. The key point lies on the introduction of “sequencing legs” along with the possibility of sending aircraft direct to the merge point at any time (Figure 2). This enables expediting or delaying aircraft while staying on trajectories. 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 LOMAN 90s behind target”.
2. When B reports merging: “B, descent 3000ft, 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 4116” (4116 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 3000ft, cleared ILS approach runway 26”.

On the controller screen, a specific feature has been developed, 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 as a support to co-ordination (TMA able to visualize aircraft coming from E-TMA under airborne spacing).
III. Sequencing Tool

The motivation when introducing a sequencing tool in the experiment was to rely on current capabilities and working practices. At this stage, it was not intended to investigate new functions or advanced usage. For that purpose, a preliminary study was conducted (in collaboration with CENA from DGAC) to understand how the AMAN (Maestro from Sofreavia) is operated today in the Paris area.

The main objective of AMAN is to smooth arrival flows to ensure the capacity in TMA is not exceeded\(^\text{9}\). This is achieved through the indication of “time to lose” (delays) or “time to gain” upstream, in the E-TMA. A secondary objective is to synchronize clusters of aircraft coming from different IAFs, in order to facilitate the final integration in TMA. This is done through the display of the sequence order, and in particular, the indication of “gaps” between clusters at IAFs. The AMAN time scale is in order of 1 minute. It is interesting to note that the objective of ASAS is to maintain spacing between pairs of aircraft with a time scale of 5 seconds. ASAS are AMAN should then be considered as two distinct layers on different time scales.

In the AMAN (Osyris from Barco-Orthogon), two main time horizons were used: an active one (around 40min before touchdown) with automatic sequencing and computation of advisories; a frozen one (around 20min before touchdown) with no re-sequencing as sequences are considered as stable. The AMAN interface displays on each side of a timeline: IAF designator, callsign, aircraft type, wake turbulence category, and “time to lose/gain” (Figure 4). It shows also the estimated time at runway threshold. The interface allows changing flight position in the sequence, packing the sequence (by reducing the gap between two flights), and forcing order for two flights in the sequence.

The AMAN is operated by a “sequence planner” located in the TMA, and AMAN displays are available on each control position (E-TMA and TMA). The method of use was based on current practices, but was refined (in particular when using ASAS) during the training period of the experiment. It can be described as follows:

1. Each E-TMA sector builds sequence as without AMAN.
2. The sequence planner, in order to indicate reliable delays while ensuring fair delay allocation between E-TMA sectors, updates AMAN to reflect the actual sequence and decide an initial order (considering groups of aircraft per E-TMA sector).
3. Each E-TMA sector acts to reduce delays in excess, depending on the TMA structure (e.g. 3min). When using ASAS, in case of heterogeneous delays in a group of aircraft under spacing, E-TMA may have to cancel one (or more) spacing instructions.
4. TMA decides the final order (considering each aircraft individually) with the help of AMAN. When TMA decides a different order, he/she asks the sequence planner to update AMAN (e.g. swap flights).

\(^{9}\) AMAN at Paris Charles De Gaulle airport is also used for the runway allocation and the delivery of expected approach time (typically when holding patterns are used).
IV. Experiment Design and Setup

A. Objective
The main objective of the experiment was to assess the feasibility of the joint use of spacing instructions (ASAS) and a sequencing tool (AMAN), and its impact on interaction between sectors and on ATC effectiveness. A secondary objective was to confirm the results previously obtained when considering en-route (E-TMA) and terminal area (TMA) separately. Two conditions were simulated: one reflecting today’s situation in which controllers could only use conventional instructions (e.g., heading, speed), and the other, in which they could also use (at their discretion) spacing instructions. The sequencing tool was available in both conditions, denoted AMAN and AMAN+ASAS.

B. Participants and Schedule
Four en-route controllers (Aix-Marseille, Paris and Roma) and four approach controllers (Barcelona, Paris Orly and Roma) took part in the experiment. They all had the appropriate qualification. Aged between 28 and 52 (mean 38), their experience ranged from 3 to 25 years (mean 12). Among the approach controllers, two participated to previous experiments of the project (in particular the last one conducted a year before) and thus had significant experience on ASAS. Among the en-route controllers, one is operating today with an AMAN and one participated to a previous experiment. The preparation, the execution and the data analysis of the experiment involved three controllers (en-route and approach) part of the project team having significant experience on ASAS and knowledge of AMAN.

The experimental design required each controller to play the same traffic on a given position in both conditions. This led to 16 measured runs. The simulation lasted four weeks between November 8th and December 10th, 2004. It was composed of two periods. The first one included training on spacing instructions (4 days) and refinement of the method of use with spacing instructions and a sequencing tool (6 days). The second period included data collection (6 days) and exploratory runs (2 days). A week break took place between the two periods to help controllers further assimilate the concept.

C. Airspace
The airspace was derived from an existing environment (Paris area) with two en-route arrival sectors (E-TMA) and one approach sector (TMA) feeding a single landing runway (Figure 5). The airspace, used in previous experiments, was assumed to be representative of a dense airspace and generic enough to allow for an easy assimilation by the participants. The two E-TMA sectors were denoted AE (Arrival East) and AW (Arrival West). Both sectors can be characterized by one main flow coming from South, a second flow to be integrated early (coming from West and East respectively for AW and AE) and a third flow that can be integrated only in the last part of the E-TMA sectors (about 10NM before transfer to TMA). The TMA sector (denoted APS, Approach South) was characterized by two entry points (IAF), denoted ODRAN (AW) and MOTEK (AE). In condition AMAN, the TMA was a radar vectoring area. No standard trajectory was available. In condition AMAN+ASAS, a merge point was defined in each E-TMA sector (CODYN in AW and OKRIX in AE, located 20NM upstream each IAF). In TMA, specific standard trajectories (denoted sequencing legs) along with a merge point (LOMAN, located 10NM upstream the FAF) have been defined for the effective use of the spacing instructions. The sequencing legs are vertically separated.

D. Roles
Seven positions were simulated, four for E-TMA and three for TMA. Each E-TMA sector was manned by an executive and a planning controller. In condition AMAN, the TMA sector was manned with three controllers: a pickup*, receiving the traffic from different en-route sectors, in charge of preparing the flow integration; a feeder**, receiving the traffic from the pickup, in charge of the final integration and the axis interception before transfer to the tower; a sequence planner in charge of the sequencing tool. In condition AMAN+ASAS, the pickup and feeder positions were grouped into a single control position, manned with an executive and a planning controller††. The sequence planner role was still present. The co-ordinations were handled by the sequence planner in condition AMAN, by the planning controller in condition AMAN+ASAS.

* In the US, “pickup” and “feeder” are often referred to as “feeder” and “final”.
†† This organization of roles has been identified in previous experiments as the most appropriate when using spacing instructions: it enables the required anticipation, particularly the early identification of sequence.
E. Traffic
Traffic samples were based on recorded data from autumn 2004. They were composed of arrival flights to the airport simulated and transit or over flights in order to increase realism in E-TMA. The initial traffic samples were rescheduled to ensure predefined and deterministic experimental conditions among the runs. The traffic demand over the considered period was slightly less than the estimated TMA capacity for arrivals (36 arrivals per hour compared to a maximum of 38). This was to simulate challenging situations while avoiding using holding patterns which were not part of the experiment. Nevertheless, the traffic was made of peaks (2 or 3 per hour) exceeding the TMA capacity, in order to “force” E-TMA controllers to smooth the peaks (with the help of AMAN) prior entering the TMA. The traffic was equally balanced between the two IAFs. Traffic samples only contained jet aircraft with “heavy” (20%) and “medium” (80%) wake turbulence categories. All the aircraft were equipped to be target and to receive spacing instructions.

F. Procedures
The traffic had to be sequenced by each E-TMA prior to be transferred to the TMA. Minimum spacing values were: 8NM at 250kt in condition AMAN (value used today in the actual sectors) or 90 seconds\footnote{This value was retained as it corresponds to the standard spacing required at runway threshold. However, 90s is not equivalent to 8NM at 250kt. Despite this difference, experimental conditions will not be impacted as the capacity is determined by the number of aircraft in the TMA.} in condition AMAN+ASAS. In addition, each E-TMA sector should not transfer aircraft with an AMAN “time to lose” of more than 3min (maximum value which can be absorbed in the simulated TMA). For the TMA, the minimum spacing values at transfer to the tower were: 90s between aircraft (120s for a medium aircraft behind a heavy) in AMAN+ASAS condition (ICAO standard at the runway threshold), equivalent to 4.5NM (6NM for medium behind heavy) at 180kt in AMAN condition. The minimum standard separations were 5NM in en-route and 3NM in approach. Although no departure traffic was simulated, an altitude constraint was applied (FL060 max at KAYEN) to strategically segregate the arrivals from ODRAN to (potential) departures to the South (from an independent runway of the same airport). No restricted area and no holding patterns were simulated.

G. Controller Working Position
The controller working position was similar to today, making use of flight progress paper strips. An AMAN display was available on each position, on a dedicated screen (Figure 6). Graphical markings dedicated to spacing instructions were available on the radar screen. Concentric circles (range rings) centered on each merge point helped identifying the sequence order by the planning controller.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Simulated airspace (approach fixes left, sequencing legs and merge points right).}
\end{figure}
H. Pseudo-Pilot Working Position

The pseudo-pilot position allows an operator to execute controller instructions for several aircraft at a time. ASAS capabilities have been developed, enabling to automatically maintain spacing within the tolerances of ±5s. Two pseudo-pilots were associated to each E-TMA sector and three to the TMA.

V. Main findings

The main findings are presented in four sections. The first three sections correspond to local views at a controller level. They address the impact on human factors, activity and performance for E-TMA, TMA, and for the interaction between E-TMA and TMA (through the sequence planner). The last section presents a wider perspective and addresses the global performance of the system, E-TMA and TMA together.

A. E-TMA

Human factors

Controllers felt that the joint use of AMAN and ASAS was acceptable and beneficial. However, they raised the difficulty caused by the two different time horizons: decision to use ASAS has to be made early (when deciding the sequence order), before AMAN could give indications. When AMAN gave indications, spacing instructions were already issued. Large “time to lose” required delaying actions (aircraft vectoring), which imposed canceling corresponding spacing instructions (restriction inherent to our definition of the spacing instructions). Another difficulty was anticipated: the usefulness of using ASAS with a medium level of arrival flights. Nevertheless, despite the constraints when using jointly ASAS and AMAN with a medium level of arrivals, the benefits provided by ASAS were considered by the controllers as more important than the cost induced. The spacing instructions were used as much as possible considering the medium level of arrivals (50% of arrivals were under spacing), which reflects controllers motivation to use them. The use of AMAN and ASAS had no visible impact on workload, as the gain observed when using spacing instructions (reduction of heading and speed instructions) was counterbalanced by the need to cancel some spacing instructions.

Human activity

The impact on controller activity was assessed through the analysis of maneuver instructions. Four types of instructions were analyzed: heading (including direct-to), speed, altitude and (when applicable) spacing. For each sector, two areas were considered: the sequence building area (from sector entry until 80NM from IAF) and the sequence maintaining area (from 80NM down to IAF). Two observations can be made (Figure 7): no impact on sequence building, but a slight positive impact on sequence maintaining with slightly fewer speed and heading instructions. This is in line with controller’s feedback.

§§ ASAS was found to be really useful under high levels of traffic. Compared to the previous E-TMA experiments conducted in 2001 and 2002 in which the TMA (not manned) was fed by a single IAF, the number of arrival flights on each E-TMA sectors had to be reduced in the present experiment (18 per hour compared to 31) to avoid exceeding the capacity in TMA.

Figure 6. Controller working positions (E-TMA left, TMA right).
Effectiveness

The quality of the sequencing activity was analyzed through the two main operational constraints applying in E-TMA: the spacing at IAF (Figure 8) and the delay value at transfer to TMA (Figure 9). In condition AMAN, it can be observed that the distribution of spacing at IAF is rather flat (although on the figure, spacing in displayed in time while the required one was in distance). In condition AMAN+ASAS, a peak around 90s can be observed but no case below 85s. In both conditions, large values represent gaps in the initial traffic. In terms of delay, aircraft entered the TMA with a “time to lose” below 2min on average, although some cases were above the maximum value (+5min instead of +3min maximum). No significant impact can be observed: this confirms the compatibility between ASAS and AMAN. It is interesting to analyze the delay absorbed in E-TMA. The average value is zero, which corresponds to a traffic not exceeding the capacity in the TMA over the period considered. However, the standard deviation about 3min reveals the presence of peaks of traffic, forcing controllers to delay or expedite some aircraft to avoid temporally exceeding the capacity in the TMA. This confirms a posteriori the appropriateness of the traffic samples (but this was also validated prior the experiment).

Figure 7. Maneuver instructions per sector area (AW left, AE right).

Figure 8. Inter aircraft spacing at initial approach fix (AW left, AE right).
Human factors

Similarly to the previous experiment (2003), the feedback on ASAS was very positive. Controllers perceived several benefits, such as a reduction of the number of instructions with fewer messages on frequency, increased anticipation and a more accurate spacing on final. With the joint use of AMAN and ASAS, controllers felt that the two arrival flows were very well sequenced and synchronized. In addition to facilitate the flow integration, this enabled an early and easy identification of the final sequence order, in particular to decide if and which ASAS pairs had to be cancelled to integrate aircraft from the other flow. The early identification was also facilitated by the display of the proposed sequence order on the AMAN screen. This is a significant improvement compared to the 2003 experiment (focus on TMA with no AMAN) where the difficulty was stressed for the planning controller to identify which ASAS pairs to cancel.

Generally, receiving aircraft under airborne spacing was preferred as the transfer conditions remained more stable. When needed, the cancellation of an ASAS pair (to integrate aircraft from the other flow) was usually requested by the TMA to the E-TMA. This enabled TMA to further anticipate the preparation of the flow integration with ASAS. The required co-ordination fitted in with current practices, with the support of the graphical links.

As in 2003, the organization of roles, the working methods and the airspace design were well accepted and seemed quite easy to assimilate. It was again observed that the use of ASAS in a highly structured airspace led to more standardized practices (almost no differences of strategies among the controllers).

The high rate of use (87% of aircraft under spacing when passing the merge point, 85% in 2003) confirms both the usefulness and the usability of the joint use of ASAS and AMAN. Although the perceived workload remained globally unchanged, a drastic reduction of maneuver instructions was measured (63%). The reduction was even larger than in 2003 (45%) due to the new extended legs limiting the need to issue “continue heading”.

However, despite the 1000ft vertical separation, controllers were not comfortable with the reduced distance between these new legs (2NM instead of 4NM). A double separation was preferred, either 3NM and 1000ft, or 2000ft. Some unexpected events (e.g. due to pseudo-pilot mistake, aircraft turning to the merge point too early, without having the correct spacing) raised again the need to define fallback procedures. A pseudo-pilot mistake confirmed the need to have the outer leg lower than the inner leg, to avoid risk of conflict if an aircraft turns and descend***.

Human activity

The impact on controller activity was assessed, in two steps, through the analysis of maneuver instructions (Figure 10). In condition AMAN, the analysis will consider the two control positions as grouped. The total number of each type of maneuver instructions shows drastic reductions: level by 50%, speed by 70% and heading by 95%. The reduction of heading and speed results from the use of standard trajectories along with spacing instructions. The reduction of level instructions can be explained by the split in two positions, requiring intermediate levels to ensure

*** This risk was identified prior the experiment but was not considered as probable.
aircraft vertical separation. The inter-individual differences observed in condition AMAN (large standard deviations) are not observed with AMAN+ASAS (small standard deviations). In line with results obtained in 2003, this suggests that the use of ASAS leads to more standard working practices.

To go a step further and to understand the modification of the activity, we analyzed the distribution of maneuver instructions (heading, speed and spacing) as a function of distance to the final approach fix (Figure 11). In condition AMAN, a bulk of instructions shows up around 10NM upstream the FAF, whereas in condition AMAN+ASAS, it is shifted at 30NM with few instructions issued after. These results suggest that the flow integration is made earlier, with no late vectoring. This confirms controller feeling of increased anticipation. In addition, in condition AMAN, varied strategies can be observed from the individual distributions (not shown). In contrast, in condition AMAN+ASAS, a strategy common to all controllers can be observed. All these results are consistent with those obtained in 2003†††.

Effectiveness

The quality of the flow integration was analyzed through the inter aircraft spacing on final (Figure 12). The distribution shows a strong impact of the condition: with AMAN+ASAS, almost all the aircraft are within 90s ±5s with some cases above (corresponding to gaps in the traffic) but no case below 85s. In contrast, with AMAN, the distribution is more flat, with some cases below 85s (most corresponding to catching up situations). Two aspects related to the quality of flight service can also be assessed. The analysis of the maneuver instructions per aircraft reveals that, in condition ASAS, more aircraft received fewer instructions. The global reduction observed on the controller side is also valid when considering each aircraft individually. In addition, we compared the time spent on the heading select mode (HDG) and on the lateral navigation mode (NAV). In condition ASAS, aircraft are most of the time on NAV; the time under HDG is limited to the “continue heading then merge”. In condition AMAN, 60% is on HDG, 40% on NAV (although controllers were not supposed to use the standard trajectories in that condition).

††† In 2003, an eye-tracker was used which allowed applying the geographical analysis to eye-fixations. A similar shift could have been observed, showing that the locus of attention is moved upstream with ASAS.
C. E-TMA / TMA Interaction

Human factors
As sequence planner, controllers felt benefits of the joint use of AMAN and ASAS. They mentioned a better awareness of the sequence order (the ASAS markings were usable and intuitive enough to understand the situation upstream and downstream), an earlier identification of the sequence order leading to an earlier stabilization of the sequence with a better delay absorption, and a better synchronization of the flows. Controllers stressed however the limitations of the AMAN used in the experiment, mainly in terms of limited temporal horizon and also due to the need to explicitly stabilize the sequences. The joint use of AMAN and ASAS has a very little impact on the sequence planner workload, in slightly reducing the overall workload, but slightly increasing the temporal demand of the tasks. Even though it required an initial training and despite some errors in the manipulation of its interface, the AMAN tool was globally usable.

Human activity
The main task of the sequence planner was to prepare the flow integration by deciding an initial order between groups of aircraft from each flow. To assess the impact on the flow integration, we analyzed the sequence order at the FAF and, more precisely, the number of consecutive aircraft from a same IAF. With AMAN, flow integration is mainly made aircraft by aircraft (aircraft from one IAF, then aircraft from the other, etc). With AMAN+ASAS, the integration is more often made pair of aircraft by pair of aircraft. This is consistent with the trend observed in 2003 (even though, in the absence of sequence planner, the integration order was decided by the planning controller). These results reflect an efficient strategy of flow integration: taking advantage of spacing already assigned while limiting the length of blocks to avoid penalizing aircraft.

A secondary task was to stabilize the sequence order early enough to ensure that AMAN indications were consistent and stable. No change in this task was observed, as sequence order was systematically stabilized in both conditions.

Effectiveness
The quality of the sequence planning activity was analyzed through the main objective given to the sequence planner: the protection of the TMA against exceeding number of aircraft. We analyzed the instantaneous number of aircraft in the TMA (every two minutes). No significant impact is visible on the average, standard deviation and maximum values (Figure 13). The protection of the TMA is not modified.

A secondary objective was to facilitate the final integration in the TMA by synchronizing the flows. A perfect synchronization would mean achieving the desired final spacing (90s or 120s) between clusters from each IAF, with no actions in the TMA (clusters “staggered”). For that purpose, we analyzed the interval between clusters coming from each IAF. A value of zero between two clusters indicates a perfect synchronization. A similar mean value can be observed, but a slightly smaller dispersion in condition AMAN+ASAS suggests a more homogeneous synchronization.

These two results are in line with what was anticipated: no impact on the protection of the TMA, but a slight improvement in synchronization.
D. E-TMA and TMA

Safety
The overall feeling on safety was an improvement with ASAS, in particular by providing more anticipation, reducing the risks of misunderstanding in reducing the number of communications. However, controllers felt their monitoring of aircraft under spacing was reduced, and questioned their capability to quickly detect drifting situations. They also raised the need to define recovery procedures for abnormal situations. No impact of ASAS on the number of losses of separation was identified. In terms of conventional instructions, no impact of ASAS on the occurrence and/or mitigation of errors could be identified. In terms of spacing instructions, controllers issued appropriately, efficiently and safely the instructions, in particular they ensured in most of the cases that applicability conditions were respected. In E-TMA however, controllers had more difficulties respecting the applicability conditions. This was due to large speed and altitude difference in the traffic. A pseudo-pilot error that resulted in a loss of separation in condition ASAS illustrated that safety when using ASAS also relies on the airspace structure, in particular on the design of the sequencing legs (altitude of the legs should be swapped).

Effectiveness
At a system level, three aspects were analyzed: trajectories, flight efficiency and throughput. In terms of trajectories flown (Figure 14), when no impact can be seen in E-TMA, a significant impact is visible in TMA: trajectories are straighter with no dispersion after the merge point. There is no impact on flight efficiency: distance and time flown are similar. Concerning throughput (i.e. number of aircraft passing the FAF during the measured period of 45min), a preliminary analysis was carried out to ensure the absence of sensitivity to the measured period (a similar throughput was obtained when considering 4 sliding periods of 15 minutes). It can be observed (Figure 15) that the throughput is slightly increased: on average, 2 more aircraft pass the FAF in condition AMAN+ASAS (26) than in condition AMAN (24), with a reduced dispersion among the runs (standard deviation between 25 and 27 with AMAN+ASAS, and between 23 and 27 with AMAN).

It is essential to remind that, under the conditions of the experiment, the throughput was increased while maintaining (or improving) the transfer conditions (spacing at FAF) and possibly safety (this is only a subjective feeling from participants – no exhaustive data is supporting this). As experimented, the increase of throughput does not appear to be detrimental to the quality nor to the safety of control.
Figure 14. Example of flown trajectories (AMAN left, AMAN+ASAS right).

Figure 15. Throughput (number of aircraft passing the final approach fix during 45min).

VI. Conclusion

An experiment simulating two en-route sectors and one approach sector was conducted. The objective was to assess the feasibility of the joint use of spacing instructions and a sequencing tool, and its impact on interaction between sectors and on ATC effectiveness. A secondary objective was to confirm the results previously obtained when considering en-route and terminal area separately.

The positive feedback previously obtained on spacing instructions was confirmed. As expected, the sequencing tool allowed smoothing flows, which ensured the capacity in the terminal area was not exceeded. In en-route, spacing instructions and sequencing tool, used as two distinct tools operating at different time scales, were found to be compatible and complementary. In the terminal area, spacing instructions benefited from the proposed sequence order displayed on the sequencing tool. The number of heading and speed instructions was reduced, slightly in en-route and drastically in the terminal area. Their geographical distribution suggests an increased anticipation in the terminal area (earlier flow integration and relief from late vectoring). Receiving aircraft under airborne spacing in the terminal area was preferred as transfer conditions remained more stable. In case a spacing instruction had to be cancelled (to integrate aircraft from the other flow), the required co-ordination fitted in with current practices. In the terminal area, the inter aircraft spacing on final was more regular, and the throughput was slightly increased. In addition, trajectories were straighter with no dispersion below 4000ft. Finally, aircraft remained under lateral navigation mode (as opposed to open vectors).
All the results are consistent with those obtained from the previous experiments: same positive impact in the terminal area and reduced positive impact in en-route due to fewer arrivals per sector (offering fewer opportunities to use spacing instructions). Spacing instructions and a sequencing tool can be jointly used in en-route and in terminal areas, with high benefits particularly in terminal areas. The next steps will consist in assessing benefits in more complex environments (e.g. mixed equipage, non specialized runway, additional entry point, holding patterns) and with new capabilities (e.g. controller-pilot data-link communication). Beyond, one key issue is the applicability to other airspace that should be addressed through collaboration with air navigation services providers. Initial investigations of applicability to Frankfurt, London and Paris have been conducted.

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