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Toward the characterisation of sequencing arrivals

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***Abstract*—This paper proposes a novel approach to understand and characterise the sequencing of arrivals. The proposed approach, essentially data driven, relies on the analysis of the spacing evolution over time between consecutive aircraft. As a case study, it was applied to different sequencing techniques (a baseline and two new ones) in the same approach environment, using track data from human in the loop simulations. The analysis conducted enables to characterise how the spacing evolves in time, and reveals differences among the three techniques in terms of convergence speed. The spacing deviation containment decreases faster with the new techniques, suggesting that the sequencing is anticipated and performed earlier. Typical sequencing patterns have been identified that also reveal the early sequencing. Future work will involve considering different environments and extending the horizon of analysis to capture the complete arrival process.**

Keywords: arrival sequencing, aircraft spacing, approach control, data analysis.

I. INTRODUCTION

This paper proposes a novel approach to understand and characterise the sequencing of arrivals. The proposed approach, essentially data driven and solely based on track data, relies on the analysis of the spacing evolution over time between consecutive aircraft, investigating aspects such as convergence speed and monotony. The underlying motivation is to develop a method to characterise different operating method, route structures or environments, in view of identifying good properties to facilitate the sequencing.

As a case study, the analysis will be applied to three different sequencing techniques on the same approach environment, using track data from human in the loop simulations conducted at the EUROCONTROL Experimental Centre as part of the European SESAR programme.

The paper is organised as follows: after a review of related studies and a brief description of the three sequencing techniques, it will introduce the methodology in particular the computation of minimum time and additional time. The analysis of spacing on the case study will then be presented, followed by the identification of typical sequencing patterns, based on a statistical method of clustering.

II. STATE OF THE ART

A comprehensive framework has been developed by the Performance Review Unit (PRU) of EUROCONTROL to characterise the performances of the arrival management process [1][2][4]. Two key elements introduced are the notions of unimpeded time and additional time in the Arrival Sequencing and Metering Area, an area of 40NM (extended to 100NM in some analyses) from the airport. The unimpeded time is the transit time in the area in non-congested conditions. The additional time is the difference between the actual transit time and the unimpeded time. It represents the extra time generated by the arrival management and "is a proxy for the level of inefficiency (holding, sequencing) of the inbound traffic flow during times when the airport is congested." This indicator is used (together with other indicators such as the flow management delay) in particular to compare the performance of the main airports in Europe and in the U.S.A. [3].

The work presented here builds on these notions of unimpeded time and additional time in an area around the airport, and aims at characterising further how the sequencing is performed. Similar types of indicators were also used at the level of individual flights, such as terminal area transition time deviation, to detect any potential perturbations and assess the resilience of scheduled Performance-Based Navigation arrival operations [5]. Analyses focusing on the spacing on final have been also conducted [6].

When assessing the impact of new concepts in relation with sequencing, detailed analyses have been developed [7][8][9]. They consider different dimensions such as human factor (e.g. workload, radio communications, instructions), flight efficiency (e.g. distance and time flown) and effectiveness (e.g. achieved spacing on final) using simulation data (human in the loop or model based). To highlight the geographically based nature of the sequencing activity, we introduced a geographically based analysis of instructions and eye fixations consisting of displaying these data as a function of the distance from the final point [9]. This enabled to show in particular effect such as late or early sequencing actions.

All these studies aimed at assessing the impact of a new concept, and considered the observable actions for sequencing. Although they informed on the sequencing activity of the controller, the evolution of the spacing is not considered as an element of the analysis. Furthermore, the need for operators related data, in particular instructions, makes uneasy the analysis of current (live) operations. From a control theory perspective, the spacing variable is the key element that should enable the understanding of the human behaviour. Here, we are not aiming at building a mathematical model of the controller, but as stated in [10], “control theory is a good foundation for developing the intuition and judgment needed for smart cognitive systems engineering”.

Numerous analysis of the spacing have been performed in the context of the “airborne spacing” concept when studying the performances of different algorithms or of the flight crews [11][12][13]. Typical analyses involved in particular the relation between spacing accuracy (control error) and number of speed changes/variations (control effort) as well as the effect of the resulting speed profile on the rest on the chain of aircraft. In all these cases however, the situation was such that the spacing could be defined: both aircraft followed known paths.

The issue being that, in the general case, the spacing variable is hard to formally define and measure, or even does not exist. In vectoring for instance, while it is straightforward to measure the spacing at a final common point, it is unclear how to define the spacing between two aircraft being vectored on different paths but whose resume paths to common point are unknown in advance. In this case, the spacing is part of the cognitive process of the approach controller and is not accessible.

The method developed here aims at proposing a notion of spacing for the general case, as an initial attempt to better understand controller sequencing strategy. The idea is to estimate a-posteriori the spacing from flown tracks (from simulations or live operations). The method is thus essentially data driven and does not rely on local operational knowledge or modelling of controller behaviours.

III. Operational Context

The operational environment is the Paris-Orly approach area as simulated in cooperation with DSNA (France) as part of the European SESAR programme [14][15][16]. The arrival runway is fed by two main flows (South-West and South-East) and a minority flow (North-East). Sequencing is achieved today by standard vectoring onto ILS axis (Figure 1). This constitutes the baseline (denoted Vectoring).

The two new sequencing techniques considered aim primarily at improving the final part, in particular securing the ILS interception and reducing noise nuisances even under high traffic conditions, as well as optimising descents, reducing workload and communications.

The techniques consist of sequencing on a common merge point (typically 5 to 10NM from final approach fix) then, from this point, letting the aircraft flying a single trajectory connecting to ILS. The path stretching prior joining the common merge point may be achieved by vectoring (open loop followed by closed loop instructions, denoted Intermediate Point Merge or Intermediate, Figure 2) or by predefined arcs (full closed loop instructions, denoted Point Merge, Figure 3).

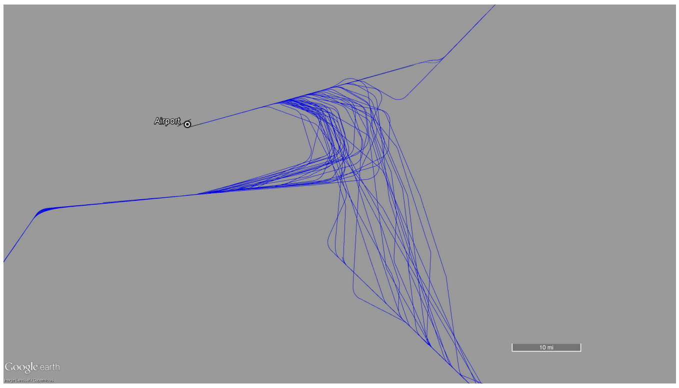

Figure 1. Vectoring onto ILS (Baseline).

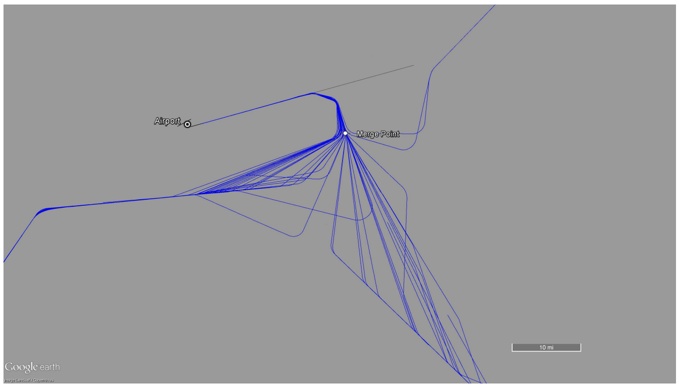

Figure 2. Vectoring and final segment to ILS (Intermediate Point Merge).

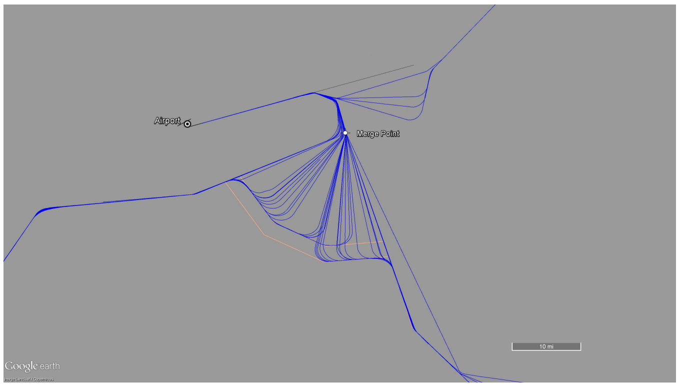

Figure 3. Arcs and final segment to ILS (Point Merge).

The technique with arcs has been developed over years at the EUROCONTROL Experimental Centre [17][18] with controllers and pilots, and supported by partners notably DSNA (France), Avinor (Norway) and IAA (Ireland). It is in operations in different places (Oslo, Dublin, Paris ACC, Seoul, Kuala Lumpur, …). The technique with vectoring, although not bringing full benefits, was developed more recently to facilitate controller acceptability and was tested in live trials at Paris-Orly.

IV. METHOD

The notions of unimpeded time and additional time introduced by the PRU are defined for an area e.g. 40NM or 100NM around the airport. These notions can be generalised to any point within the area. Assuming a set of representative trajectories per flow of traffic (e.g. downwind and base), the unimpeded time (denoted minimum time in the following) at a given point can be obtained by taking the minimum time (shortest trajectory as a proxy) of all the trajectories passing through this point (Figure 4). In practice, we will consider the trajectories passing in a close vicinity of the point. This will lead to a discretisation of the area in the form of a map of cells, each containing the minimum time from this cell to the final approach fix (see section V.B “Minimum time”).

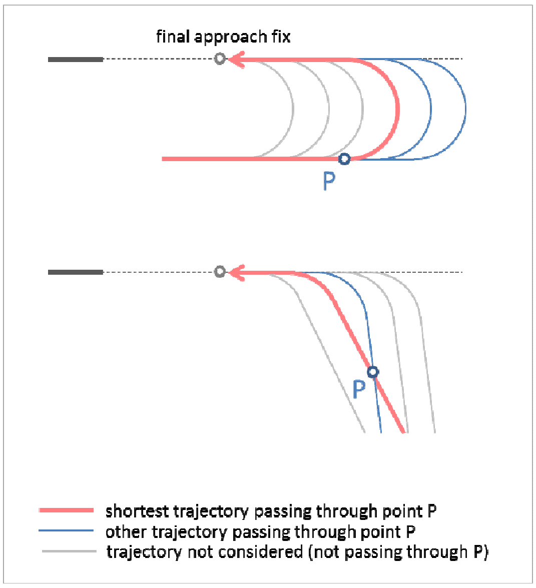

Figure 4. Example of shortest trajectories from a given point for downwind and base.

The additional time for a given trajectory will then be obtained using the minimum time. Precisely, let us define the time to absorb at a time t, as the difference between the time to final (along the actual trajectory) and the minimum time to final:

$$\textit{time to absorb } (t) = \textit{time to final } (t) - \textit{min time to final } P(t)$$

The additional time at a time t, is then defined as the difference between the maximum time to absorb (i.e. the total time that will be absorbed within the area) and the (remaining) time to absorb:

$$\textit{additional time } (t) = \max_{\tau<t} \textit{time to absorb } (\tau) - \textit{time to absorb } (t)$$

The spacing in time will also be obtained using the minimum time. Precisely, the spacing between a pair of consecutive landing aircraft i and j at time t can be simply defined as the difference between their respective minimum times from their positions P at time t:

$$\textit{spacing}_{ij} (t) = \textit{min time to final } P_j (t) - \textit{min time to final } P_i (t)$$

As an example, let us consider the case of two aircraft on downwind, the first one flying the shortest trajectory and the second flying a longer trajectory (Figure 5, top). The additional time for the first remains equal to zero until final point, while it increases for the second one between A and B. The spacing remains constant along the common segment and is equal to the initial spacing; then it increases between A and B until reaching the final spacing, and remains constant until final point (Figure 5, bottom).

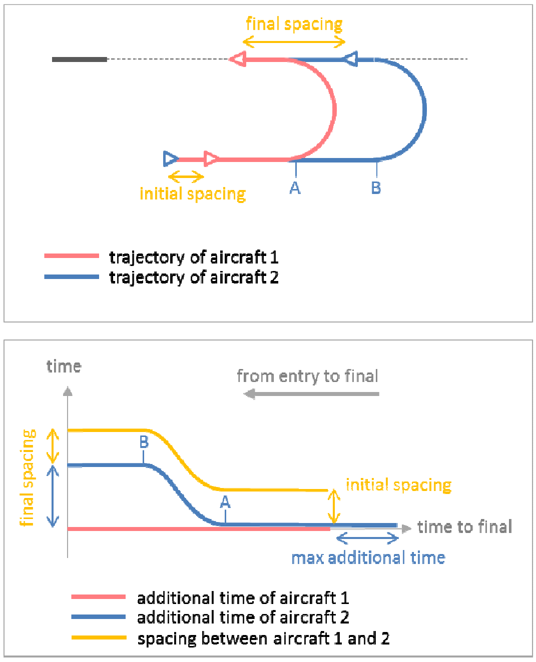

Figure 5. Example of a variation of additional time and spacing.

V. RESULTS

A. Data preparation

The case study is applied on a dataset from real time simulations assessing three different sequencing techniques (Vectoring, Intermediate and Point-Merge), as detailed in section III. The experimental conditions were designed to ensure that the three scenarios can be compared with minimum bias. The traffic samples were close to the runway capacity (around 36 arrivals per hour).

The geographical focus of the study is the manoeuvering area, within 40NM from the Final Approach Fix (FAF). This corresponds to a shortest trajectory duration around 10 minutes, from the area entry to the FAF. To take into account additional flying time due to sequencing (up to 5 minutes), we selected flight trajectory data starting at 15 minutes from the FAF and checked that we captured all of the trajectories in the selected area.

The dataset consists of 907 flights with their 4D positions (longitude, latitude, altitude, time), updated every 5 seconds. The sample size distribution among the three scenarios is 303 flights for Vectoring, 354 for Intermediate and 250 for Point-Merge. These sample sizes are considered sufficiently large to be representative. The sample size differences are explained by the number of measured exercises for each scenario.

We are interested in typical arrival flights that enter and exit the focus area. In particular, this excludes go-around, aircraft not flying over the FAF and flights with exceptionally short flying time.

A data preparation step ensures the selection of the relevant flight data: typical flights within the chosen geographical scope. At the end of this preparation, 680 flights (76% of the full dataset) are used for the analysis: 212 (70%) for Vectoring, 304 (86%) for Intermediate and 164 (66%) for Point-Merge.

B. Minimum time

As presented in section IV, minimum times are computed in all the cells of a 2D mesh covering the focus area on the basis of recorded data. For the case study, the minimum time-to-final is computed per flow and scenario.

Depending on the considered analysis and amount of data available, other discriminant items like runway orientation, low visibility procedures, altitudes, aircraft types etc. may be considered.

The selected cells size shall not be too large to allow for accurate trajectory deviations assessment. It shall not be too small, as the number of flights per cell will be insufficient to ensure reliable estimates (as a rule of thumb, 10 flights per cell can be considered as a minimum).

For this case study, cells are 1/3NM squares, corresponding to an average flying time per cell of 5 seconds (i.e. data update value). This was considered to be the minimum reasonable size to pick.

The result of this computation is shown on Figure 6, with colors depicting the minimum durations, from red (15 minutes) to blue (lower than 1 minute).

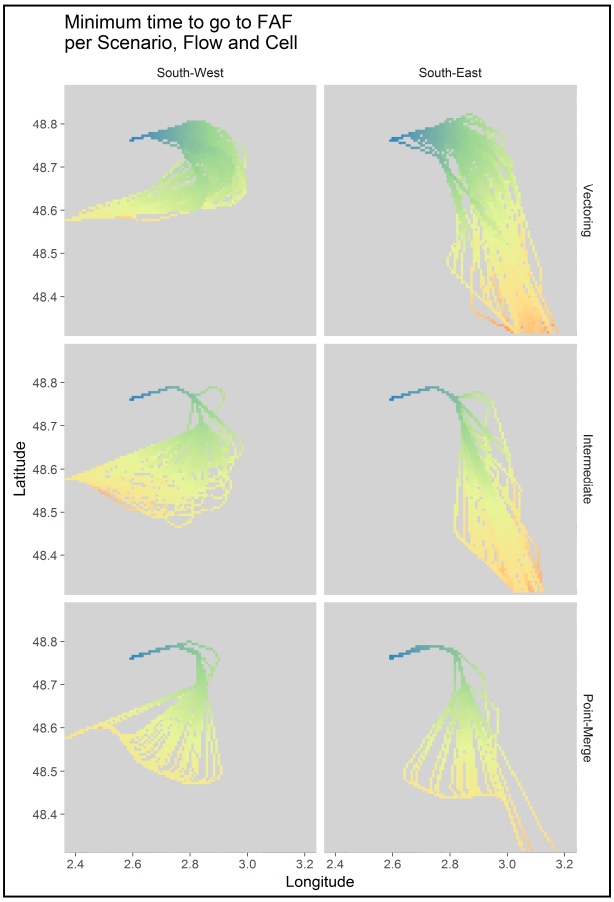

Figure 6. *Cells of minimum time-to-final, all scenarios, South flows.*

C. Additional time

Flight additional time is defined in section IV as the difference between the maximum time to absorb and the remaining time to absorb. It is estimated for each flight, at every radar data update.

The following graph (Figure 7) presents additional time vs. actual time-to-final per scenario with a smoothed curve for every flight (smoothing is applied to reduce the aliasing effect of cells).

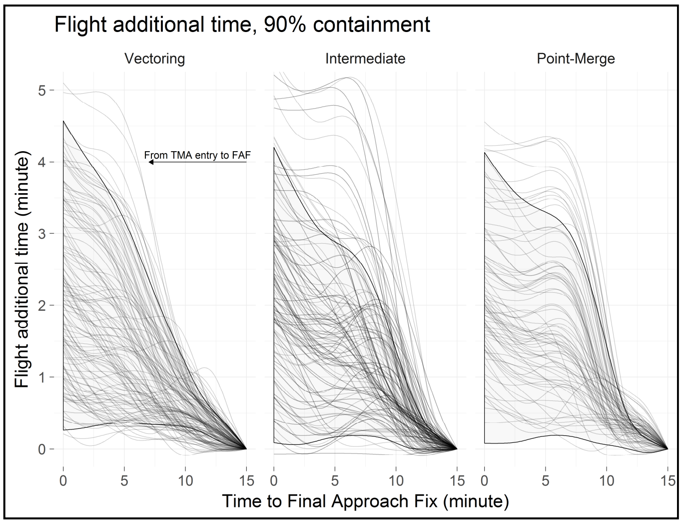

Figure 7. *Flights additional time curves per scenario.*

Flat parts on a curve occur when the flight is following its minimum path while steep rates appear when the additional time is increasing quickly (i.e. the delay is currently implemented).

The containment area covers the 5% to 95% additional time quantiles values. It can be seen that the evolution of the curves shows some differences in the sequencing work per scenario.

In particular, for Point-Merge, a regular pattern of fast delay absorption (large additional time increase over a small period of time) is observed from 7.5 to 10 minutes before the final, followed by a plateau; for Vectoring, it seems that there is progressive delay absorption with no marked plateau and a greater spread of the curves. The Intermediate scenario curves seem to be less homogeneous.

To facilitate the scenarios additional time comparison, Figure 8 shows the median additional time curve per scenario with different colors.

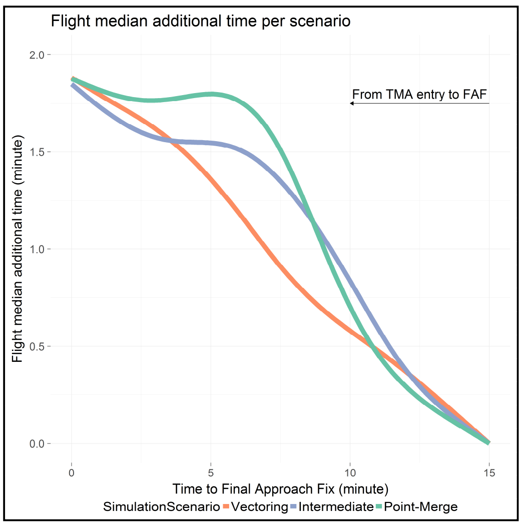

Figure 8. *Flight median additional time curves per scenario.*

The three median curves all end with a similar additional time close to 2 minutes at FAF: the same amount of additional time is applied on average for all the three scenarios.

However, the curves shapes differ, as detailed below, starting from TMA entry (15 minutes look-ahead time) to FAF.

In the 7.5-10 minutes x-range, for Point-Merge, additional times increases by 55s (from 35s at 10 minutes to 90s at 7.5 minutes), while for Vectoring, it is 20s (from 35s to 55s). The Intermediate scenario falls between these two cases, with a 35s increase (from 45s to 80s).

This illustrates that additional time is absorbed over a more concentrated area in Point-Merge than for the other scenarios. This can also be seen by the flight curves density in the 7.5 minutes time-to-final area. The 7.5 minutes time corresponds to the minimum time to fly direct from the Point-Merge arcs to the FAF.

In the 2.5-7 minutes range, for Point-Merge and Intermediate, there is a plateau, where little additional time is absorbed, whereas for Vectoring it continues to be absorbed in a continuous fashion.

In the 0-2.5 minutes range, the Intermediate scenario shows a higher rate of delay absorption (about 20s remaining to absorb, from 95s to 115s at 2.5 minutes from FAF), while the two other scenarios have to absorb a lower delay within that range (about 10s for Point-Merge and 15s for Vectoring).

Actual time absorption areas are identified by measuring the maximum (among the flights) additional time evolution rate per cell. This is presented on the next figure (Figure 9): red cells correspond to the highest rates, where additional time increased sharply (at least for some flights), while blue cells match areas where nearly all flights follow their minimum trajectory.

As expected, the arcs on Point-Merge are highlighted with red/orange cells, while we see more yellow and orange areas for Vectoring and Intermediate where greater path-stretching is applied. It can be observed also some yellow-green cells on the final approach to the FAF, linked to speed reduction below the speed of the faster aircraft in the sample, for all scenarios.

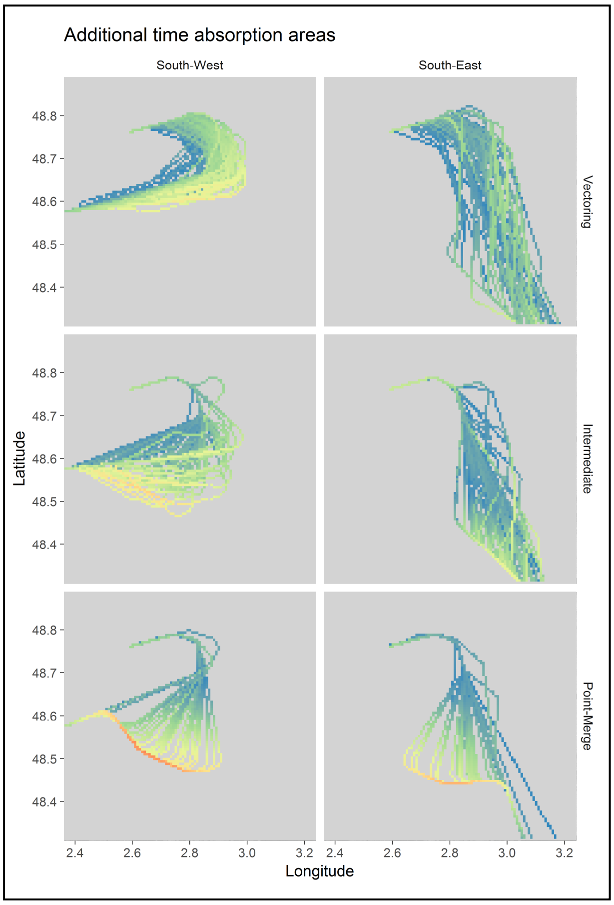

Figure 9. *Map of additional time derivative 90% quantile value per 2D cell, flow and scenario.*

D. Spacing

The spacing between two successive landing aircraft i and j at time t, is defined in section IV as the difference between their respective minimum times to final at time t. This is illustrated on Figure 5.

The spacing deviation is defined as the spacing adjusted for the actual spacing at FAF: a zero value corresponds to the final spacing, whereas negative (resp. positive) values correspond to an actual spacing lower (resp. higher) than final spacing over FAF requiring, for example, path stretching (resp. shortening).

This adjustment for final spacing allows for more readable graphs and to correct for the different spacing requirements related to wake-vortex categories.

The following graph (Figure 10) illustrates the spacing deviation curves (smoothed to reduce cells aliasing effect) for all pair of aircraft per scenario[1]. It also shows a 90% containment area (from 5% to 95%) of the spacing values.

[1] Flight pairs with a final spacing greater than 200 seconds are discarded: it is assumed that no typical spacing work was needed in this case.

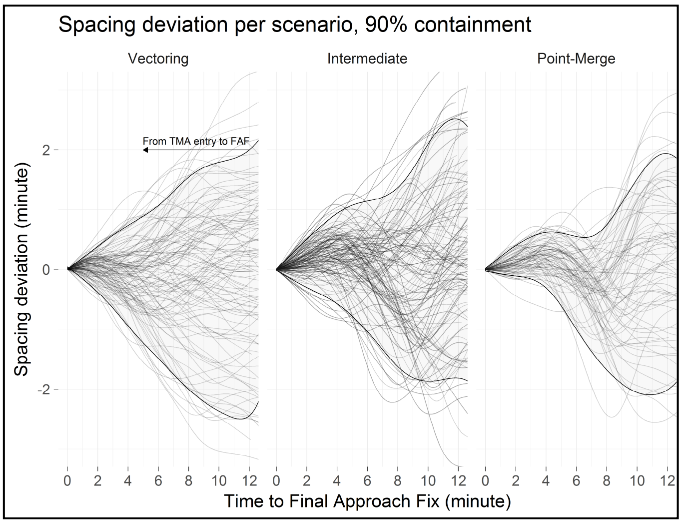

Figure 10. *Spacing deviation curves per scenario, with 90% containment.*

It is clear that the containment of the three scenarios differ in shapes: nearly symmetric for Vectoring, with a linear convergence to zero; strong reduction of the upper containment curve for Point-Merge, from 7 to 10 minutes of time-to-final, before a plateau until 2 minutes where the spacing work is resumed. The Intermediate scenario containment blends both vectoring and Point-Merge characteristics.

In order to complement the containment comparison above, the span of the containment curves (max-min) at each time step is presented on the figure below (Figure 11). It illustrates the global progress of the spacing toward the final spacing between aircraft pairs.

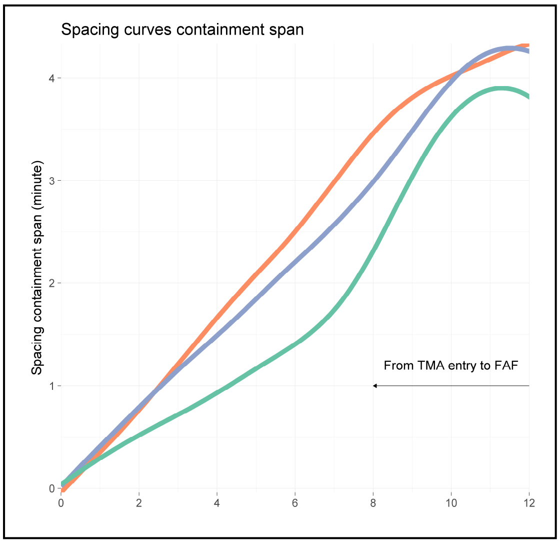

Figure 11. *Spacing deviation containment span per scenario.*

The vectoring curve is above both other curves (Intermediate and Point-Merge) and is nearly linear from 0 to 9 minutes from the FAF: this suggests that spacing is established progressively, at a regular rate.

The Point-Merge curve is below both other curves at all times, with an inflexion point around 7 minutes (higher convergence speed before 7 and lower after), corresponding to the arcs area: spacing is established in two phases, the first one providing the greater part of the convergence toward the target spacing, the second one providing the remaining adjustments. Looking at the Figure 10 it can be observed that the highest convergence speed is on the upper part of the containment, representing aircraft pairs with a need for spacing reduction.

As seen before, the Intermediate scenario blends characteristics of Vectoring and Point-Merge, with a curve between the two others: closer to Point-Merge in the 7 to 12 minutes range and then, getting closer to Vectoring, notably in the 0 to 4 minutes range. It can also be observed that, for a given containment span, it is obtained at different look ahead times.

For example, a 3 minutes spacing span is reached around 9 minutes before the final for Point-Merge, 8 minutes for Intermediate and about 7 minutes for Vectoring. This difference is even more marked (2.5 minutes) for a 2 minutes spacing span, with 7.5, 5.5 and 5 minutes of anticipation respectively for Point-Merge, Intermediate and Vectoring. This suggests a greater anticipation/convergence speed in the sequencing with Point-Merge.

These high-level metrics can be refined by the identification of typical spacing patterns throughout time according to scenario. This is done by clustering the spacing curves (cf. Figure 10) into k number of groups. We selected a robust k-means clustering technique (Partitioning Around Medoids, PAM [19], calculations performed using GNU R [20] and the cluster package [21]): it aims to partition all the aircraft pairs spacing curves into k clusters in which each curve belongs to the cluster with the nearest mean, serving as a prototype of the cluster.

A number of three (selected empirically) distinct clusters is devised per scenario. On Figure 12, the typical pattern associated to each cluster is represented by a thick colored line.

Three typical patterns are observed for all scenarios: the "already-on-target" patterns, starting and staying close to zero (middle curves for all scenarios); the "extra-spacing" upper patterns, starting above zero; the "need more spacing" lower patterns (or flights sequence swap cases).

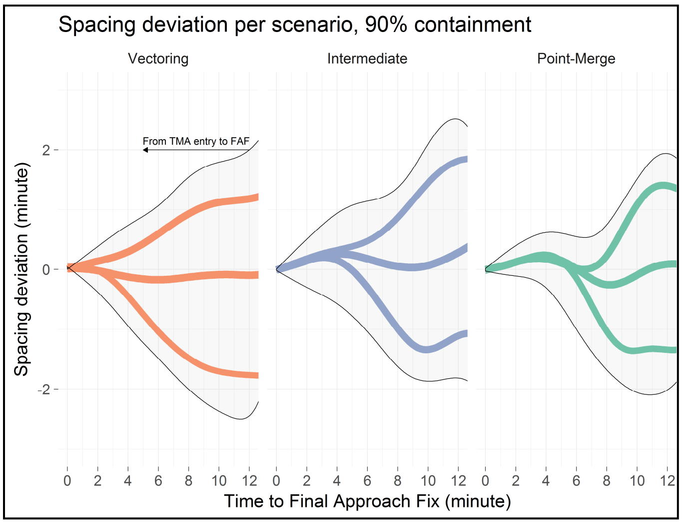

Figure 12. *Typical sequencing patterns per scenario, with 90% containment.*

Comparing the "already-on-target" patterns, Vectoring shows the more stable, monotonous evolution. Point-Merge and Intermediate have a bump, breaking the curve monotony: the target spacing is reached (around 6 minutes before the FAF for Point-Merge) and then the spacing deviation increases to a maximum of 15s above the target before converging again. This increase usually occurs when the trailing aircraft turns towards the merge-point.

On the "extra-spacing" patterns, Vectoring has a nearly flat part from 12 to 9 minutes, where the spacing deviation does not evolve; then it starts to decrease toward the target in a linear fashion until 3 minutes, where only fine-tuning occurs. Point-Merge starts to have a very high decreasing spacing deviation from 10 to 8 minutes, reaching the target spacing before the bump already described in the previous case. Intermediate have a spacing deviation decreasing rate between Vectoring and Point-Merge in the 10 to 8 minutes range, then it keeps a lower constant decreasing rate (no bump) until the FAF. Its initial spacing deviation value is above the ones observed for the other cases by about 30s.

Comparing the "need more spacing" patterns, Vectoring shows a symmetrical shape as its "extra spacing" one, with the target spacing obtained 2 minutes before the FAF. Point-Merge spacing deviation starts to evolve around 9 minutes, reaching the target at 6 minutes and then follows the bump pattern described before. Intermediate spacing deviation shares the Point-Merge characteristics, with a lower spacing evolution rate, reaching the target at 5 minutes before the FAF and following a small bump pattern.

VI. CONCLUSION AND PERSPECTIVES

The approach introduced that focused on the analysis of spacing over time was applied to three sequencing techniques: a baseline (vectoring), a new one (full closed loop) and an intermediate (open and closed loop). It used tracks data from human in the loop simulations on the same approach environment.

The analysis enables to characterise how the spacing evolves in time, and reveals differences among the three techniques. Starting from a similar initial spacing situation, the spacing converges at different speeds. While the spacing deviation containment decreases in a linear way in baseline, it decreases faster with the new technique. For instance, a 2min span is obtained approximately 2.5min earlier, and a 1min span about 2min earlier. This suggests that the sequencing is anticipated and performed earlier. Typical sequencing patterns have been identified (using a statistical method of clustering), that also reveal the early sequencing. The new techniques however contain cases of non-monotonous spacing variations that should be further investigated.

The approach introduced, which is essentially data driven, takes advantage of data now easily available through various sources and providers, and does not require detailed local operational knowledge. Future work will involve considering other environments with similar sequencing technique (vectoring) and/or with new one. It will also involve extending the horizon of analysis to capture the complete arrival process, e.g. from top of descent and further out.

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Eric Hoffman is the Deputy Head of the ATC unit within the R&D division of EUROCONTROL. He has over 20 years of R&D experience in air traffic management, investigating a variety of subjects like Airborne Separation Assurance Systems or 4D Trajectories concepts. The highlights of his team research work include Jane's Air Traffic Control (ATC) Maastricht Award for Human Factors in 1998 and the development of the Point Merge sequencing techniques to improve arrival operations, now in operation or being deployed at several airports around the world. He has led EUROCONTROL participation in a number of EC

Framework Programme R&D projects. He holds engineering and Master's degrees from ENSAE/Sup'Aéro (Toulouse, France) and a PhD from Georgia Tech (Atlanta, USA) all in Guidance & Control.

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