Nationaal Lucht- en Ruimtevaartlaboratorium
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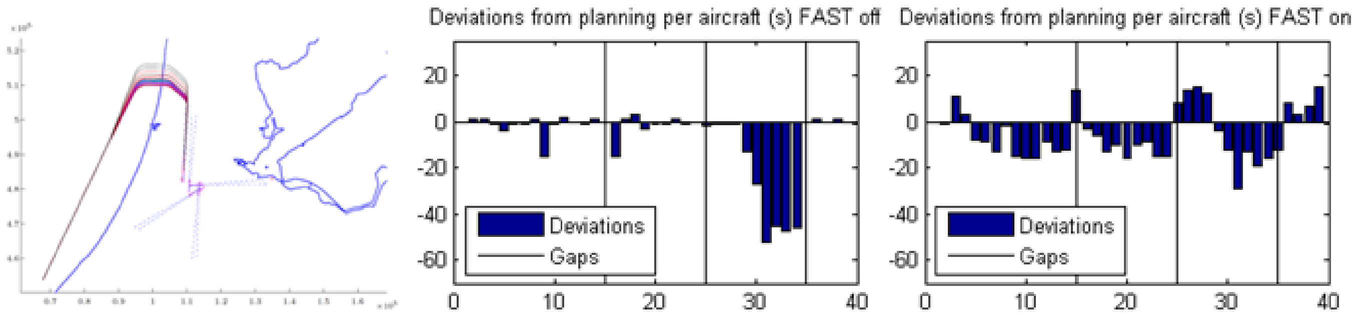
Executive summary

Subliminal Control on CDA final descent operations



Flights in dense final descent CDA flows will deviate when queuing problems will cause instability. Subliminal control will be able to act pro-actively and strive for an even and robust distribution of flights.

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Problem area
There is an urgent need to implement Continuous Descent Approaches (CDAs). For airlines and airports, the interest is to save fuel, and to reduce emissions and noise at low altitude, whilst maintaining current throughput levels.

The EU development programme, SESAR, develops and validates nowadays an operational concept for arrival management enabling delivery of accurately planned flights into a merged sequence over the Initial Approach Fix (IAF) with a tolerance of ±30 s. The problem, however, is to keep the sequence stable over a considerably extended near-idle final approach descent profile. Unfortunately, the controllability of operating CDAs in high density traffic is limited, since the descending profile limits the possibilities to intervene and ensured separation is difficult to be accomplished. The Controller role is labour intensive and time critical in this flight phase, and he has to cope with small control margins in order to apply subtle corrections.

There is a high need to support the Controller, and the proposed research aims to realise this by advisories for instructions to correct for deviations, whilst the nature of these advisories will be compliant with Controller's expectations.
In addition, high frequent and very small corrective instructions can be issued also automatically. These subliminal control instructions are calculated by a Final Approach Spacing Tool (FAST), and issued within a predefined tolerance window. The expectation is to increase achievable throughput

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levels in this way and to make the arrival sequence more robust, without overloading the Controller.

Description of work
The aim of present research was to describe a concept to improve final descent arrival operations and to demonstrate and partially validate by a model-based simulation pro-cess that subliminal control may help to achieve high throughput levels comparable with traditional throughput levels. Because the stability of the tightly sequenced arrival flow is mostly challenged by all kinds of minor disturbances and planning inconsistencies, the chal-lenge was to model the basic causes of disturbance as representative as possible. This yields a model that comprises realistic flight dynamics including the modelling of flight control system, autopilot and auto-throttle etc., but also to include a realistic meteo model, including gust and differences in observed and experienced wind. Finally, an appropriate traffic mix of random-ised arrivals at the IAF ensures a representative scenario. The experi-ment consisted of simulating under varying conditions a fixed sequence of always 40 tightly separated flights, assumed to arrive after merging in the planned sequence over the IAF.

The experiment processed all flights by periodically advancing them 3 minutes flight time, and assessing their status as well as the need to correct for deviations. These corrections could be very small subliminal instructions, instructed by an assumed automatically con-trolled closed control loop, and aiming to increase stability by slightly advancing or delaying the estimated arrival time of applicable flights by small displacements of intermediate waypoints. Whenever, this was not sufficient to ensure planned separation, plausible instructions were advised and implemented to simulate the Controller to take action. These advisories consisted of some discrete displacements of the same waypoints.

Several variables such as traffic density, traffic composition, and wind, were varied to assess the impact on the stability of the queues, evaluating throughput, Controller workload, flight efficiency and the robustness of the sequenced final descent arrival process.

Results and conclusions
Comparing the results between the subliminal-control supported and unsupported scenarios, in most cases, FAST was able to provide subliminal instructions that increased safety and alleviated controller's workload.
It is interesting to mention that, when including planned gaps in the sequence, not for merging purposes but with the goal to support more robust operations, FAST was able to 'fill' the gaps by applying frontloading to traffic behind the gap and by delaying traffic before the gap. This strongly benefits the average separation and therefore increases safety and stability. Also, the model gives indications for the maximum achievable runway throughput of an arrival runway in segregated mode. An estimated threshold of a maximum achievable sustainable mixed-traffic through-put of around 30 landings per hour per runway was confirmed, and in turbulent wind conditions the maximum throughput achieved by the experiments, is around 28 landings per hour.

Applicability
In this research, multiple important stakeholders will have an interest as potential beneficiaries. Due to the pressure to perform routine-based environmental friendly CDA operations, it is assumed that airlines operating from major hub airports will be interested in operating CDAs regularly and on dense traffic flows. Airlines will benefit from reduced fuel consump-tion in the approach phase and airports benefit from the lower noise and emission levels.
In addition to airlines' and airports' benefits, this research shows that subliminal instructions can mitigate the need for additional instructions issued by the Controller. His/her workload will decrease when FAST support is active.
Further, since these subliminal control instructions are in-line with the pilot's and Controller's tradi-tional procedures, the expectation is to facilitate acceptance and the means for transition to this (semi) automatic application.

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Subliminal Control on CDA final descent operations

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[1] TUD

This report is based on an article to be published/published in the Conference Proceedings of the 3rd International Air Transport and Operations Symposium (ATOS 2012), 18th – 20th June 2012, by Delft University of Technology, Delft.

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Summary

In this article a final descent approach procedure is evaluated that performs near-idle descents of tightly sequenced arrivals over a curved approach path towards a single heavy loaded runway. An operational concept is applicable in which a Final Approach Spacing Tool (FAST) assists the Controller with advisories to maintain stability of the arrival flow. Calculated small subliminal control instructions are processed automatically, whilst other more significant required instructions are assumed to be given by the Controller. This process is modelled in MATLAB / Simulink, using an aircraft performance model with realistic modelled flight dynamics, including randomised uncertainties. Simulation results demonstrate significant stability differences for including or excluding assistance by subliminal control instructions. Also, the model gives indications for the maximum achievable runway throughput of an arrival runway in segregated mode fed by a dedicated flow of near-idle CDA operations. The achievable reactivity of the control loop is decisive to improve control on arrival sequence stability, whilst pro-active measures will help to increase the stability.

Contents

Abbreviations

AC	- Aircraft
ADS-B	- Automatic Dependent Surveillance Broadcast
AMAAI	- Aircraft Models for the Analysis of ADS-B based In-trail following
ANSP	- Aeronautical Service Provider
ASAS	- Airborne Separation Assistance System
ATCo	- Air Traffic Controller
ATM	- Air Traffic Management
CDA	- Continuous Descent Approach
Cwl	- Controller workload
ETA	- Estimated Time of Arrival
FAST	- Final Approach Spacing Tool
IAF	- Initial Approach Fix
ILS	- Instrument Landing System
JAR-AWO	- Joint Aviation Requirements-All Weather Operations
FAF	- Final Approach Fix
KPA	- Key Performance Area
KPI	- Key Performance Indicators
NLR	- National Aerospace Laboratory of the Netherlands (NLR)
NM	- Nautical Mile
PFR	- Peak Flow Robustness
R/T	- Radio / Telephony
Rwy	- Runway
SESAR	- Single European Sky ATM Research and Development Programme
TECS	- Total Energy Control System
TUD	- Technical University of Delft

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1 Introduction

Implementation of Continuous Descent Approach (CDA) procedures from Top-of-Descent for dense arrival flows at hub airports is one of the major challenges for advanced ATM in Europe. Several projects under the EU programme, SESAR, are addressing the validation and implementation of procedures to accomplish early and highly accurate sequencing at the Initial Approach Fix (IAF), whilst also final descent procedures are investigated [Ref. 1, 2, and 3]. CDA arrival flows during peak hours on final descent will be tightly sequenced, and will have to follow a relative long curved descending approach path under minimal spacing conditions. This part of the descent is sensitive for instability due to the dynamics of aircraft operations, the manoeuvring process and the limitations of ATCos to intervene under near-idle continuous descent conditions. It is proposed in this article to increase the stability of the arrival sequence by pro-active measures and, in addition to control instructions by the ATCo, to have automatic control instructions at subliminal level. A Final Approach Spacing Tool (FAST)[1] calculates instructions required to achieve optimal stability of the arrival conditions at the runway. As long as possible, automatically generated instructions are submitted within a small pre-defined tolerance window around the actual executive clearance instruction. These instructions are small heading corrections to intercept a slightly moved waypoint, but whenever this is not sufficient to maintain separation, the ATCo is advised to give heading instructions intercepting a waypoint as a traditional procedure solving separation problems. The pilot and aircraft's Flight Management System (FMS) are expected to implement the stretched or reduced approach path, and to intercept the Final Approach Fix (FAF) a predicted time lapse earlier or later.

The objective of the research, presented in this article, is to demonstrate the effects of subliminal control in high density traffic performing continuous descent operations. To do so, a concept was developed to support subliminal control. This concept, based on subliminal control instructions during final descent, is implemented in a model-based fast-time simulation process to simulate long tight sequences of an arriving flow over a curved approach path to land at an arrival runway in segregated mode. Several runs are processed to compare the performance of arrival operations under different conditions with subliminal control measures activated or de-activated. Also, sensitivity analysis is performed to compare wind effects, traffic mixes and the frequency of submission of subliminal control instructions. The results are promising and beneficial for all stakeholders involved [Ref. 5].
This paper describes, background and context, followed by a small outline of the concept and the plan to conduct the experiment. Thereafter, the experiment is described, its results and the analysis of results. At the end, some conclusions are added.

[1] A prototype of FAST was developed by NATS [Ref. 4].

2 Background and context

One of the major areas of innovation in ATM is to enable Continuous Descent Approaches (CDAs) for dense arrival flows at hub airports. The justification is that CDAs are fuel efficient and environmental friendly compared to traditional procedures. The problem, however, is that these continuous descending flights are difficult to control. Highly accurate planning, guidance and control is required to accommodate these tightly sequenced procedures, using scarcely available runway capacity. In addition, these hub airports are allocated often in airspace areas, where airspace for dedicated arrival flows is missing and where CDAs are to be separated from other departing and arriving traffic flows. The best achievable result will be often to find the compromise of flying near-optimal, near-idle descent profiles with accurately sequenced, planned and controlled arrival operations.

The aim of early arrival management in SESAR is to deliver tightly sequenced flights over the IAF with a tolerance of ±30 s., compared to an ideal sequence planning [Ref. 3, 12, and 13]. By applying time-based separation, the arrival flow over the IAF is prepared in principle to land with ensured separation, as long as the separation can be maintained during the final descent path. A major problem during final descent is that minimal separation has to be preserved over a considerable distance-to-go whilst near-idle flight profiles are difficult to manage and control. Tight sequencing and the flight dynamics of aircraft makes the queue of arriving flights to a critical queuing problem as soon as the number of succeeding flights increases and disturbances will occur. Because maximum throughput is a primary requirement of airspace users, the question is if equally high throughput levels can be maintained compared with traditional approach procedures, benefitting from an established altitude by levelling-off, vectoring and holding.

The problems to be solved, are to mitigate possible queuing instability and to solve the lack of controllability on descent operations. From queuing theory it is well-known that instability is sharply dependent on critical separation distances, and flow robustness will increase by stable separation and a more evenly distribution of demand. Also known from queuing theory is the impact of guidance and control quality and control-loop frequency on stability of the queue. The ATCo-Pilot control loop (also by datalink) is relatively slow, conservative in timing and not subtle in its decision making. Every well-tuned automation process will perform better regarding its frequency, its accuracy of decision making and precision of timing [Ref. 6 and 7].

This dilemma is understood, and for example ASAS applications are considered sometimes as a solution to improve the robustness of spacing of final descent CDAs in lower airspace. These applications, however, mainly focus on self-separating air traffic where each aircraft contains a control module that separates the own aircraft from the target aircraft, making use of available state information of the surrounding aircraft. The states information available to each control module is defined as the 'information structure'. Research by Slater and Chu shows that increasing the amount of information available to each control module significantly improves the sequence's performance with respect to maintaining separation minima and stability [Ref. 6 and 7]. Since it is not yet feasible in self-separating traffic to achieve the state information of all aircraft in the sequence and since coordination problems are not yet solved, optimal performance can not be reached by these applications in the near future. Fortunately, all required information will be available on the ground: By making use of ADS-B signals and radar data the relevant information can be retrieved by a centralised ground-based controller. This forms the basis of the choice to use a ground-based tool in the concept under investigation.

In this article, a concept of subliminal control on CDAs is proposed and evaluated. The advantages of the concept are significant:

- Subliminal instructions are natural extensions of traditional instructions and are compliant with the traditional way of ATCos to perform executive control on air traffic.
- All exception handling is naturally dealt with. Whenever, the Controller intervenes this will overrule the subliminal instruction clearance in force.
- The Controller monitoring task will decrease in effort when the stability of the sequence will increase.
- The validation and verification is relatively simple because there is one centralised algorithm which determines the optimal distribution of sequenced flights as well as the instructions needed to accomplish the most robust distribution of flights under control.
- Transition is relatively simple because the frequency of advised instructions may augment gradually and also a seamless transition can be supported from manual instructions by R/T to automatic instructions, uplinked and processed.
- Insufficiently equipped flights, not able to participate in the subliminal control process, can be treated in a natural way, possibly increasing workload, but never excluding the applicability of the algorithm.

In addition, there are specific advantages to apply ground-based centralised subliminal control:

- Once there is one supervising algorithm to regulate the arrival flow, the algorithm may promote frontloading when this improves robustness.
- Also, relaxation by increased spacing can be part of the decision making process. This is possible only because it is part of an ATM strategy, implemented under responsibility of the ANSP, and endorsed by the authority of the Executive Controller.
- Finally, the ATCo can decide to delay or advance flights by instructing vectors, which allows better control over descent manoeuvring flights than speed corrections, and therefore also subliminal control instructions can do the same.

All together, a subliminal control algorithm can be developed to maximise robustness and stability of the flow, and this is expected to allow higher throughput under more stable operational conditions. Ultimately, subliminal control is expected to enhance Controller's capabilities where there are physical and mental limitations of what the human being can accept and deliver.

3 Operational Concept

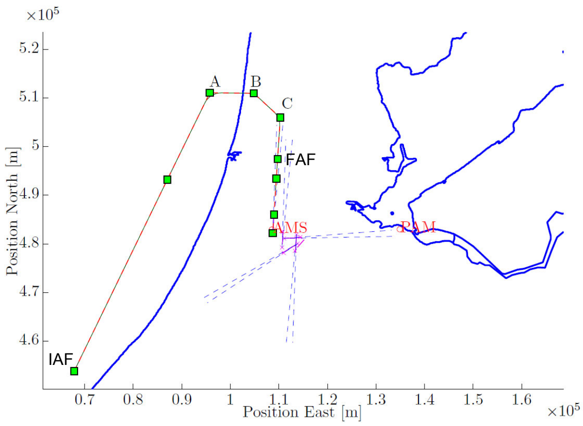

Figure 1 – Lateral profile of near-idle CDA final descent ground track, used to assess benefits by subliminal control

Final descent CDAs are difficult to control. Typically up to 30 NM out, at an altitude of 7.000 ft or above, the arrival sequencing is assumed to be accomplished already. The requirement in SESAR is to deliver CDAs at the Initial Approach Fix (IAF) with an accuracy of ±30s [Ref. 3]. It can be assumed that the arrival sequencing is not yet established in a perfect tight and time-based separated way, but the arrival flow will be orderly sequenced and at most a merging process with another arrival flow might still be needed; in all other respects the remaining descent of each flight is following a continuous descending curved approach path along a down-wind and cross-wind leg to intercept a Final Approach Fix (FAF), and thereafter the ILS for landing. (See the example, derived from a CDA final approach path for Schiphol, Amsterdam, Rwy 18R, Figure 1, and further also Ref. 5).

The problem and limitation in controlling final descent CDAs is the tight sequencing over a considerably long descent path, the dynamics of the aircraft limiting the ability to maintain minimum spacing and the limitation of the Controller to react in an adequate way to correct for deviations. In the ideal case, of an undisturbed near-idle descent, there is no intervention. However, when interventions are needed, the control loop of ATCo and pilot is simply not precise and accurate enough to correct for deviations of dense flows and, at the same time, to maintain the near-idle descent profile. Traditional instructions are typically with a tolerance of:

- 10 kts. for speed instructions,
- 10 deg. for heading instructions to stretch or to shorten the curved approach path, and
- A frequency and response on instructions that should not exceed probably one instruction per 3 minutes per flight, depending on the number of flights under control and the required precision of giving instructions in due time. The achievable frequency is limited after all by all other ATCo tasks like surveying, monitoring, decision making and problem solving.

Automation support may help to alleviate the task of the ATCo. Short-term trajectory prediction will be used in support of monitoring, conflict detection, and problem solving by short-term conflict alerts and the planning of medium-term separation at the runway. FAST, the Final Approach Spacing Tool, will calculate periodically, based on time-based separation, a distribution of arrivals that is optimised for flow robustness by:

- Advancing flights whenever flights are reducing maximum throughput by performing unnecessary large separation,
- Relaxation of estimated separation whenever planned sequencing allows slightly delaying flights and whenever there is opportunity to delay.
- Slightly advancing flights whenever there is opportunity to advance and whenever the traffic load behind the actual flight suggests creating more space for other arrivals.
- Whenever the calculated subliminal measures are not sufficient to ensure safe separation of the arrival sequence, an ATCo advised instruction is calculated correcting for the foreseen separation infringement, and at the same time, disabling subliminal control for that flight.
- Whenever this is not sufficient to support ensured separation, an ATCo advice is calculated to instruct a flight to leave the sequence.

The simulated final descent CDA procedure comprises:

- The flight approaches the IAF with known predicted approach path and landing time. The ETA is made available (by assumed down-linking), and the optimised distribution of the actual arrival flow is calculated. The ATCo is assumed to give a clearance for the planned CDA, and thereafter the subliminal control mechanism is activated.
- FAST calculates periodically, with intervals between 1 and 3 minutes, instructions to implement an optimised descending flow. The optimised conditions imply an optimisation towards stability with best possible spreading of arrivals in the sequence, creating "robustness". The algorithm shall take into account conflict-free routing along the descent path and at touch-down [Ref. 5].
- Subliminal instructions consist for example of waypoint heading instructions determined by moving a significant waypoint with a continuous varying off-set of values between -1000m and +1000m. The instructions are directly implemented without intervention, or during an implementation transition process, by limited intervention for approval by ATCo and Pilot.
- Other advised instructions are implemented by ATCo-Pilot intervention, and thereafter the flight is excluded from further subliminal control instructions.
- Instructions by ATCo-Pilot intervention are either vector instructions to pass over off-set waypoints with discrete displacements between for example 1000 to 5000 meter, or instructions to remove the flight from the sequence. In the last case, the aimed throughput can not be maintained and, after leaving the sequence, the flight shall re-enter the sequence and will create therefore significant flight inefficiency and overhead in workload.
- The procedure shall guarantee in this way that all flights will pass the FAF and runway threshold with ensured safe separation, except those flights removed from the sequence.

This concept is implemented within a model-based experimental environment using MATLAB/Simulink. This model is as realistic as possible regarding the simulated flight performance and dynamics, but physical transactions and human interactions are not modelled. The aim is to assess the validity of application of subliminal control techniques for control on dense arrival flows during final decent operations, and to validate achievable benefits in terms of throughput, workload, flight efficiency and safety.

4 Set-up and Conduct of Experiment

4.1 Experimental objectives

The model-based experiment on final descent CDAs has been set up to give answers on the impact of queuing behaviour on throughput, controller workload, flight efficiency and safety:

- **Capacity(Throughput)**: Throughput is most critical for acceptance of CDA procedures in dense flows in operational service at large airports. The flow dynamics has direct impact on achievable peak load throughput and sustainable throughput.
- **Capacity (Controller workload)**: Subliminal control aims to reduce workload by positively influencing the stability of the descending traffic flow. The experiment observes when flow stability is impacted negatively, and when ATCo intervention is required. The observations address only differences in workload for different scenarios, and therefore the measured results will have relative and indicative significance.
- **Efficiency**: The performance of CDAs is anyhow flight-efficient compared to traditional arrival profiles, however, this difference is not assessed because traditional procedures are not modelled. The experimental observations that directly impact flight-efficiency are the aborted CDAs, and these numbers will give a strong negative indicator for the feasibility to perform final descent CDAs for that specific scenario.
- **Safety**: The model calculates so-called Peak-Flow Robustness (PFR), which relates the planned density of arriving traffic peaks to actually realised density of these peaks. The reason to introduce this performance indicator is that subliminal control instructions are aiming to implement a more balanced distribution of arriving flights over time compared to non-intervening scenarios, for which only human-modelled ATCo intervention is available to ensure separation. The outcome gives an indication of the achievable balanced spread of arriving traffic, and the associated robustness of the sequence is an indicator of reduction of possible safety alerts and hazards.

Along these lines of performance measuring, three hypotheses were posed to asses the validity of the concept:

1. **Ensured separation**: High-density CDA sequences supported by FAST and using subliminal control instructions will accomplish increased stability of separation of arrivals.
2. **Decreased workload**: Use of subliminal control on high-density CDA sequences will decrease the extra workload required to ensure safely separated arrivals.
3. **Sustainable throughput**: Support by subliminal control will increase the sustainability of high density throughput of CDAs significantly.

4.2 Modelling aspects

The modelled fast-time simulation experiment simulates one representative CDA approach path, assuming this path to feed one runway, passing three movable waypoints by a down-wind and cross-wind leg (see Figure 1). Each waypoint can be selected for subliminal instructions by offsets up to a maximum of ±1000m, and for emulated ATCo instructions by offsets between +1000m and +5000m or between -1000m and -5000m (not advised in the experiment). This will allow to calculate (small) vectoring track corrections in parallel to the nominal approach path at subliminal as well as ATCo controlling level, both contributing to perform separation ensured landings (see Figure 2). When it is not possible in this way to maintain the sequence and to ensure separation, a flight will be removed from the sequence.

Regarding this procedure, two issues are to be noticed:

- Operations to re-insert removed flights into the sequence are not modelled. These CDA-aborted flights are disregarded, and are only taken into account as decrease in throughput and increase in workload.
- The concept requires de-confliction along the tracks and the runway; however, the present modelling supports de-confliction at the runway only. This may require some extra constraining conditions, possibly resulting in a (slight) decrease in throughput.

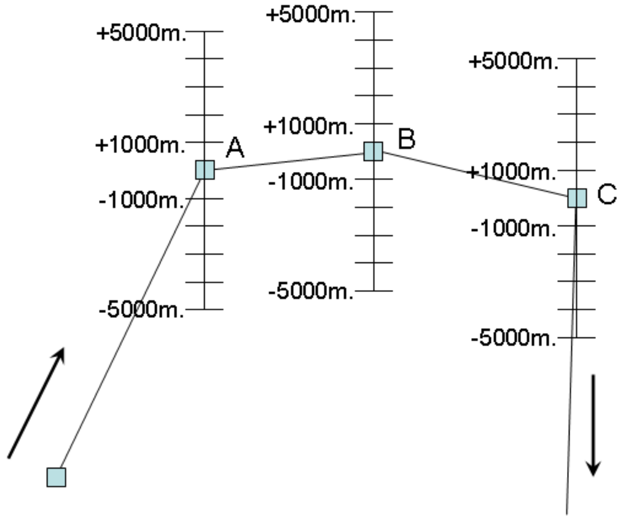

Figure 2 – Figure to illustrate options for subliminal vectors (±1000 m.) and ATCo advised vectors (between ±1000 m. and ±5000 m.) over 3 waypoints on the cross-wind leg.

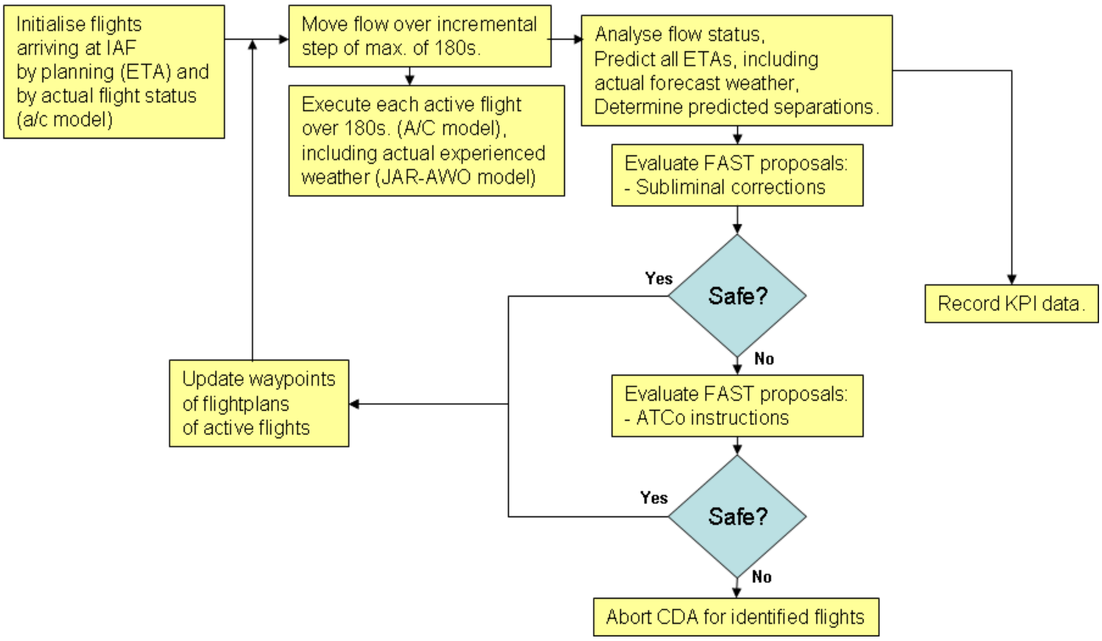

Figure 3 – CDA Final descent subliminal control simulation model

The MATLAB model can be decomposed in several components (see Figure 3). The following components are discussed below:

- Aircraft and weather modelling
- Trajectory prediction
- Evaluate FAST proposals

- ***Aircraft and weather modelling***:

The research performed for the subject of interest requires high quality aircraft modelling. The reason is that queue stability in final descent is part of the flight that is subject to highly dynamic aircraft performance behaviour, and, moreover, precisely the flight dynamics can be one of the main causes of queuing instability. The AMAAI modelling toolset of NLR (Aircraft Models for the Analysis of ADS-B In-trail Modelling) is developed to offer sensitivity on flight performance behaviour caused by flight dynamics. This toolset is exactly satisfying the requirements to simulate this phase of flight with sufficient realism (Ref. 8). This simulation toolset simulates an aircraft's flight trajectory using point-mass performance data, applying a full set of 3D point-mass equations of motion, and supports state-of-the-art modelling of flight dynamics. The modelling of functionality to control the aircraft's flight dynamics is based on the so-called Total Energy Control System (TECS), and the modelling of meteo conditions is based on the JAR-AWO model, generating a wind speed profile including turbulence modelling. See Figure 4, and also References 9, 10, and 11.

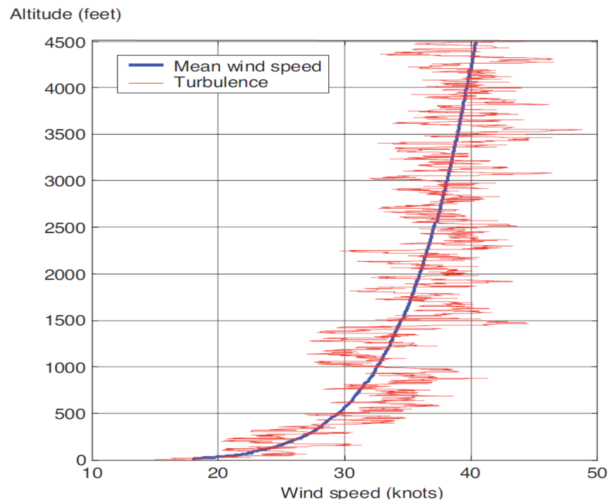

Figure 4 – Example of processing emulated wind conditions in final descent, including turbulence

- ***Trajectory Prediction:***

A strongly simplified trajectory prediction facility had to be developed in order to keep the complete CDA-flow simulation model manageable regarding model complexity and processing time. Therefore, a table-driven trajectory predictor was designed, sufficient elaborate to run the experiment. This trajectory predictor was dimensioned to support 3 AC-types (B747-400, B737-800, F-100), 3 way-points, including 4 displacements for each waypoint, 3 wind speeds and 3 wind-speed directions. The trajectory predictor table was generated by running the model for all identified trajectories, and during processing runs predictions were determined by interpolation. The tabulated predictor was appropriate to generate predictions for small deviations between IAF and FAF, but it yields simplifications that might be more significant than the anticipated future difference between the quality of airborne and ground-based trajectory prediction.

- ***Evaluate FAST proposals:***

All flights in final descent are periodically checked for the need to optimise their track by small vectors over one or more of the three waypoints. Subliminal corrections are typically smaller than ±20s. by waypoint shifts of a maximum of ±1000m. Given all flights in-trail for final descent, the optimal distribution can be derived from the achievable most robust distribution of flights. This gives a slightly wider distribution in general than the minimum separation. Thereafter, individual flights and their flightplans are updated, possibly pro-actively, with corrections that yield small track extensions as well as track reductions.
When subliminal corrections fail to ensure separation for a flight, this flight is selected for an ATCo advised instruction by discrete waypoint displacements between 1000m and 5000m, which leads to corrections up to typically a maximum of ±60s. Whenever a flight is selected for an ATCo instruction, further subliminal corrections are disabled for this flight. Moreover, ATCo instructions are selected only to ensure separation by delaying the following AC, and not to optimise the distribution of flights over the descent path.
When also ATCo instructions fail to ensure separation, the descent procedure is aborted. The flight is assumed to be removed from the sequence, and disregarded. The flight is also not considered anymore for landing results, which leads to decreased throughput and increased workload.

4.3 Conduct of experiment

The conduct of the experiment was executed by running one sequence of 40 flights for a large number of variations on one traffic scenario. One scenario variable yields randomised variations of arrival times over the IAF, and another randomised variable created gust variations if wind was applicable. Randomised values for the IAF flight arrival variable determined 5 different scenarios processed systematically each time in order to generate some statistical significance. The other scenario variables were applied partly systematically, forming the Baseline research, and partly ad hoc by individual runs, performing some sensitivity analysis.

The air traffic demand of each scenario consisted of the same order of 40 sequenced flights, arriving over the IAF, and those 40 flights consisted of:

- 10% Heavies, represented by B747-400 (5 flights)
- 40% Mediums, represented by B738-800 (15 flights)
- 60% Mediums, represented by F-100 (20 flights)
- No Lights

Based on minimal standard separations, this would require 3870s. landing time, leading to a theoretical maximum achievable flow density of 37 arr./hour for this specific scenario.

The Baseline research consisted of 40 variations of running each time these 5 scenarios of IAF arrival time variations. These 40 variations were obtained by (See Table 1):

1. Switching subliminal control "On"/"Off", and assessing and comparing effects of subliminal control on achievable separation at the runway.
2. Adding 3 gaps of ~1 minute per run, and assessing the impact of some slack time on robustness of sequence stability by comparing "Gaps" with "No-gaps".
3. Processing 5 different levels of density of air traffic demand, varying from 1.1 to 1.5 times the minimal required separation time (excluding the gaps), and assessing the impact of variations of flow density. This yields planned flow-density scenarios with the following characteristics (including 5 Heavies):
    - 33 arr./hour (tightness 1.1x minimum separation)
    - 31 arr./hour (tightness 1.2x minimum separation)
    - 28 arr./hour (tightness 1.3x minimum separation)
    - 26 arr./hour (tightness 1.4x minimum separation)
    - 24 arr./hour (tightness 1.5x minimum separation)
4. Processing with wind "Yes/No", whilst wind "Yes" was set to wind of 10 kts. at ground level, parallel to the runway and opposite to landing.

Table 1 - Variation in scenarios by Modelling experiment, Baseline research (200 runs)

Exp. Run	Sublim.Ctrl On/Off	Gaps / No-gaps	Wind Yes/No	Density 33 arr/h	Density 31 arr/h	Density 28 arr/h	Density 26 arr/h	Density 24 arr/h
1-5	On	No-gaps	No	5x	5x	5x	5x	5x
6-10	Off	No-gaps	No	5x	5x	5x	5x	5x
11-15	On	Gaps	No	5x	5x	5x	5x	5x
16-20	Off	Gaps	No	5x	5x	5x	5x	5x
21-25	On	No-gaps	Yes	5x	5x	5x	5x	5x
26-30	Off	No-gaps	Yes	5x	5x	5x	5x	5x
31-35	On	Gaps	Yes	5x	5x	5x	5x	5x
36-40	Off	Gaps	Yes	5x	5x	5x	5x	5x

Resuming, the Baseline experiment allowed assessing the impact of changing variables on 5 different scenarios of a fixed set of 40 flights. The other stable and fixed variables were:

- The planned nominal CDA profile being the same profile for each AC type, apart from calculated instructions.
- The types of aircraft, although representative, were limited in this experiment to 3 different types of aircraft only.
- The aircraft weight was always the nominal reference weight, being default for all flights.
- The wind was limited to standard wind of 10 kts. parallel to the runway, when wind "Yes" was selected, and always the same amount of uncertainty by gust modelling was added.
- The planned and controlled IAF arrival conditions were set in all scenarios with randomised ±30s. accuracy, arriving over the IAF with a uniform randomised distribution and in fixed order.

The additional sensitivity analysis aimed to get a view on those areas that were excluded from more systematic research. The extra scenarios, processed to perform sensitivity analysis, were:

1. An extra scenario to process a sequence of Medium-type aircraft only and to assess increased throughput.
2. A scenario with ±20 degrees cross-wind in order to assess the impact of some varying wind conditions on planning, control and throughput.
3. Scenarios with a calculation loop frequency of 90s. instead of 180s. to assess the impact of higher feed-back loop frequency on the convergence, guidance and planning by subliminal control. The default frequency of 180s. is close to human performance, and the expectation is that a higher frequency feed-back loop would be more successful in correcting deviations.

All together, the Baseline research required to process 200 runs, and the Sensitivity analysis another 240 runs that were processed and analysed. The questions to be answered by analysis, were, how these scenario variations would perform, and next to assess under varying conditions how successful they were to achieve ensured separation, decreased workload and sustainable throughput.

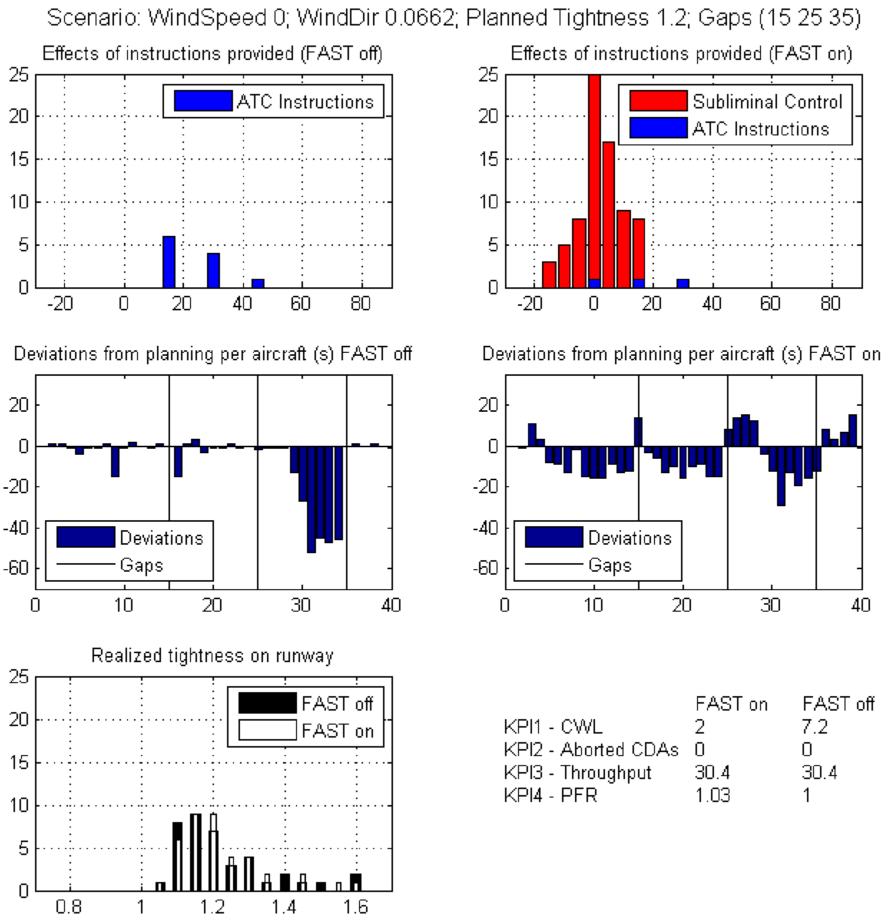

Figure 5 - Example dashboard with overview of 2 runs (“FAST on”/”FAST off”)

4.4 Measured and observed Key Performance Indicators (KPIs)

The applicable Key Performance Indicators (KPIs) were related to:

- Measuring (extra) Controller Workload (Cwl) by number of instructions to correct the sequencing by deviating from the common CDA near-idle profile,
- Measuring time differences to assess planning corrections and actual separation,
- Measuring runway throughput per hour, and
- Measuring Peak-Flow-Robustness (PFR) (see above).

These KPIs were assessed for each pair of runs, assessing by default the impact of subliminal control (“FAST on”) on successful final descent arrival operations, and comparing this with (“FAST off”), calculating and executing advisories to ATCos only. Figure 5 gives an example for one pair of runs with one flight “Fast-off” and one flight “FAST-on”. The first two pictures show number of planning corrections against time-to-win/time-to-lose in seconds; the second two pictures show deviations from planning for each flight in the sequence; and the last picture shows the distribution of realised separations at touch-down for both runs.

This figure represents one pair of runs with given tightness (1.2), and therefore with given demand (31 arr./hour) and by definition with almost identical throughput. The in real-life achievable throughput is determined by those experimental runs that processed the sequence with separation control with acceptable quality to adopt that process in real-life. The more robust and stable the realised separations at touch-down, the more likely that this mode of operations turns out to be acceptable and sustainable.

5 Results and Analysis

5.1 Results by individual runs

The graphical results of pairs of runs could show the success of application of subliminal control for some, but not for all, pairs of runs. The beneficial effects of one successful pair of runs (Figure 5) will demonstrate:

- Comparing the number and corrective size of instructions, "FAST on" adds a relative large number of small instructions, causing a decrease in the required number of ATCo instructions. This is the expected positive effect to reduce (extra) workload by flightpath corrective instructions. Whenever possible, subliminal control takes action pro-actively to increase the stability of a sequence of separated flights.
- Looking at the resulting deviations from planning per flight, there is a noticeable difference between activated subliminal control ("FAST on") and "FAST off". In the "FAST off"-case, and without corrective instructions, only "noise" will be visible, when actual performance deviates from predicted performance. Only at a late stage, forced intervention leads to knock-on effects (for flights 29-34 in Figure 5). In the "FAST on" case, however, subliminal control makes active use of available spare capacity to make the arrival flow more robust against separation problems. Small front-loading and delaying instructions help to reduce the chance of disruptive effects. (See for another example with gaps in the sequence in front of ACs 15, 25 and 35, Figure 6.)

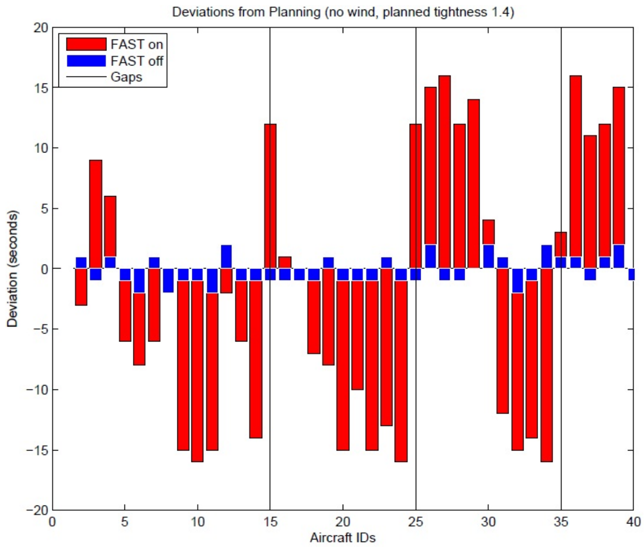

Figure 6 – Example of optimising the spread of

- Also in Figure 5, the distribution of actually separations at landing, shows less tightly separated landings for the subliminal assisted arrival flow. This is very beneficial if it helps to reduce the chance that arrivals are removed from the sequence by aborting the descent procedure.
- Finally, the KPIs summary of this example presents no aborted CDAs (which is quite essential), decrease of extra workload by subliminal control, and enhanced Peak Flow Robustness. This last entity indicates a more favourable distribution of arrivals over available time, and essentially this is the same as what is presented by slight improvement of "Realized tightness on runway", Figure 5.

5.2 Baseline research

The following figures show KPI results of Baseline research:

1. Results of the basic flows without wind of a sequence of 40 flights for different arrival densities,

2. Figures for the same scenarios without wind, but now including gaps, and
3. Figures for the same scenarios, but now including gaps and including wind.

Figure 7 presents Controller workload (Cwl) for the basic flows. At very high density (tightness 1.1, 33 arr./h), there is anyhow high workload by Controller intervention, and subliminal control was often disabled, and could not be effective any more. Most effectively Cwl decreased by support of subliminal control for tightness 1.2 (31 arr./h) and 1.3 (28 arr./h), but for 1.4 (26 arr./h) and 1.5 (24 arr./h) there was not much to do anymore to safely separate the sequence; the arrival flow was already robust by low density of demand.

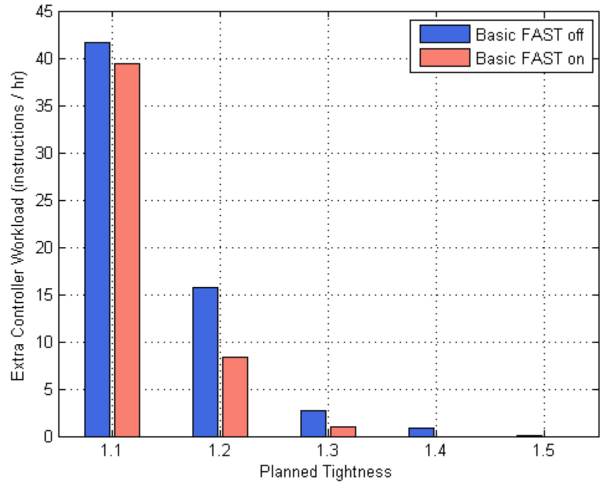

Figure 7 – Controller workload, Basic flows, no wind

Figure 8 presents throughput for the basic flows:

- Sustainable throughput is equal to demand, in principle, and as long as aborted CDAs will not cause any decrease of throughput. Above 30 arr./hour (tightness 1.1) the number of aborted CDAs is unacceptably high for this nominal scenario.
- Peak density throughput is a more complex variable. FAST is not able to improve traffic distribution for high flow density, and at low density the peak load is expected to be almost equal for "FAST on" and "FAST off".
- Most favourable, subliminal control contributes at tightness 1.3 to keep the peak density low at a more safe and robust level.

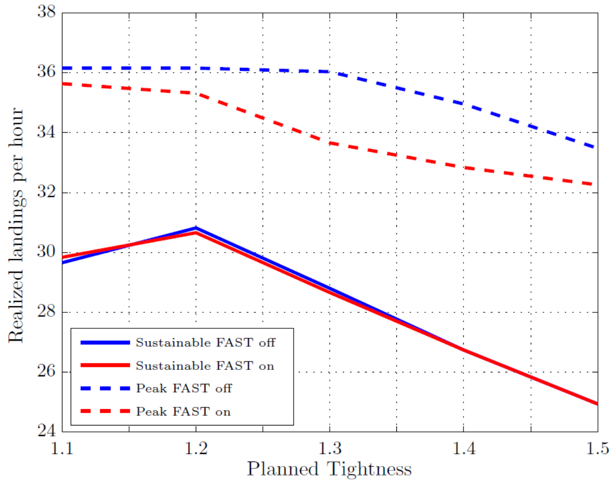

Figure 8 – Throughput, Basic flows, no wind

Figure 9 presents Peak Flow Robustness for the basic flows. For this most simple case, the result is straightforward. For very high densities, there is no opportunity to improve the robustness since subliminal control is continuously overruled by advices to ATCo (tightness 1.1); for higher tightness (lower flow density) the robustness improves.

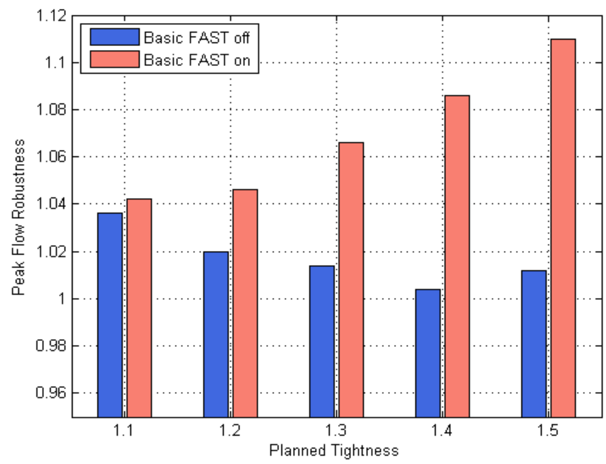

Figure 9 – Peak Flow Robustness, Basic flows, no wind

Figure 10 (left) presents Controller workload (Cwl) with and without gaps for basic flows. The three gaps of one minute have positive effects on the number of required Controller instructions as well as on the effectiveness of subliminal control for the high density scenarios (tightness 1.1 and 1.2). Figure 10 (right) presents throughput with and without gaps for basic flows. Gaps are causing a slight decrease of throughput, but offer opportunities to increase the stability of the flow. The positive effect is demonstrated for tightness 1.1 (33 arr./h). The sustainable throughput increases because the number of aborted CDAs decreases. Also, subliminal control benefits from gaps when the observed peak load slightly decreases, suggesting an improved spread of tightly sequenced flights.

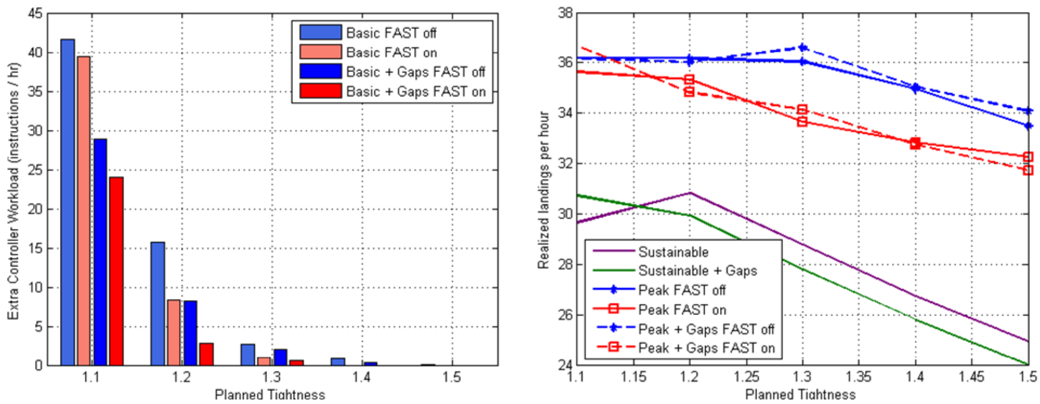

Figure 10 – Controller workload (left) and Throughput (right), Basic flows, including gaps, and no wind

Figure 11 presents PFR with and without gaps. Again, the gaps offer always some opportunities to improve the observed PFR. Essentially, PFR values benefit from gaps to increase robustness by “FAST on”, except for tightness 1.5 where there is not much to win anymore.

Regarding peak flows, it should be noted that peaks of dense traffic are selected from scenarios with varying levels of flow density. This yields 4 peaks within 40 flights (100%) for traffic tightness 1.1, and 1 peak of 2 flights (5%) for tightness 1.5. The conclusion is that PFR values deserve most confidence if there are several peaks comprising a significant part of the traffic.

Figure 12 presents the effects of wind on workload, processing the Baseline flows. The outcome of all “wind”-results is less evident than results without wind, which is caused very likely by the relative heavy impact of unpredictable effects on corrective measures. This tends to converge to a general conclusion that predictability and quality of information provision is likely to determine the boundary conditions for feasible control on tight sequences of flights. Other constraining conditions may exist as well, but at least, high quality weather prediction data (now-cast information), seems to be indispensable for dense CDA final descent procedures.

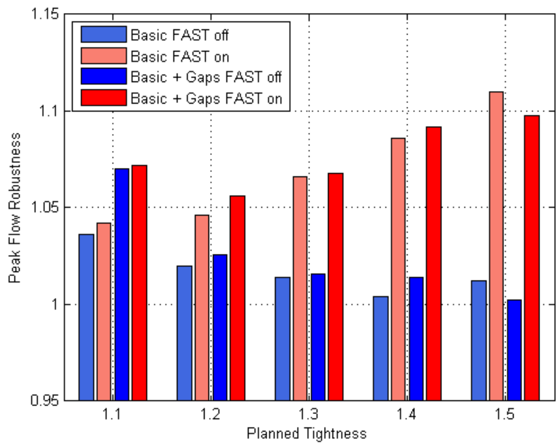

Figure 11 – Peak Flow Robustness (PFR), Basic flows, including gaps, and no wind

The effect of wind on Controller workload is negative, significant more instructions are to be given under a modest wind scenario, including uncertainty by turbulence. The pre-arranged gaps are improving the situation, and “FAST on” helps to reduce the need for instructions. The most acceptable option regarding (extra) workload starts from flow densities of 28 arr./h (tightness 1.3).

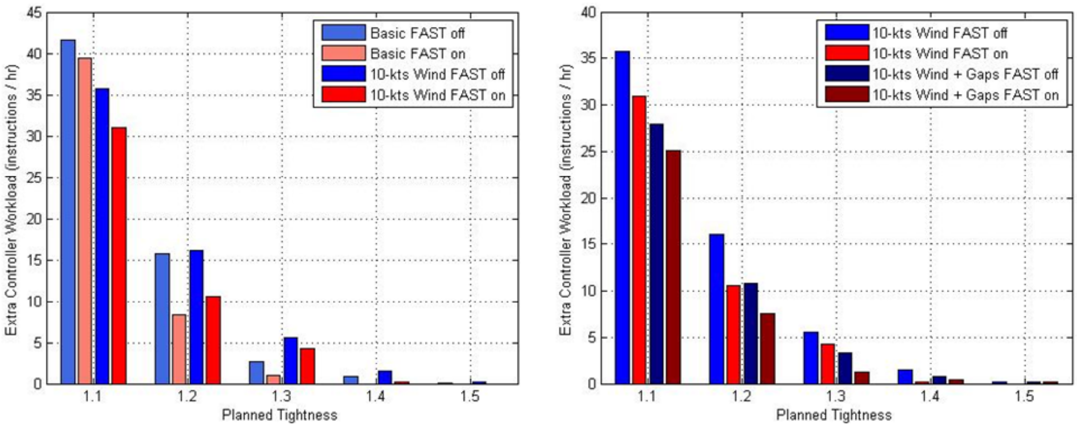

Figure 12 – Basic flows, Controller workload, no-wind/wind (left) and Controller workload, wind/wind+gaps (right)

The next picture of the basic flows, Figure 13, presents the effects of wind on Peak-Flow Robustness (PFR). Positive effects are almost drowned out by noise effects due to wind. Subliminal control measures give some evidence for positive effects for well manageable flow densities (tightness 1.2 and above).

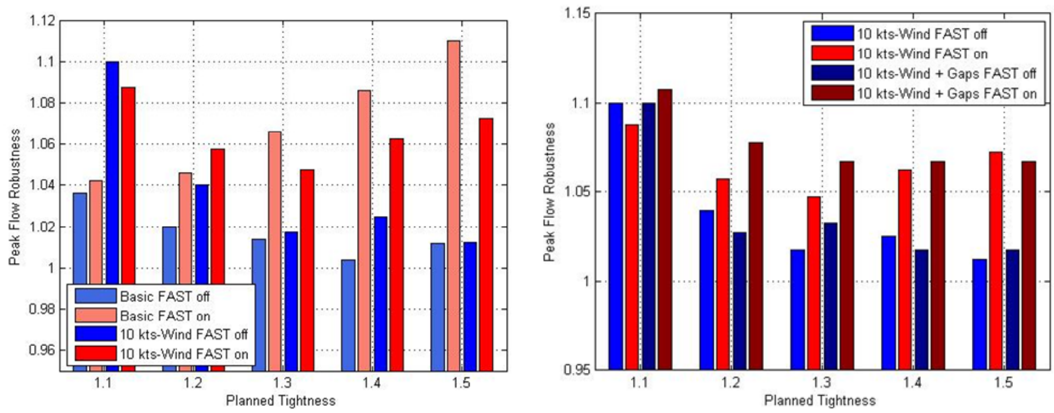

Figure 13 – Basic flows, Peak-Flow Robustness, no-wind/wind (left) and Peak-Flow Robustness, wind/wind+gaps (right)

Finally, Figure 14, shows a histogram of CDA aborted flights for several runs. As can be seen, there are few CDA-aborted flights under no-wind conditions, whilst this number is unacceptably high for all wind scenarios. In this context, four remarks are to be noticed regarding these CDA-abort cases:

- The process decides to a CDA-abort when ATCo track deviation instructions, moving fixed waypoints 5000m., is not sufficient anymore to maintain separation. In real-life, this may lead to interrupt CDA operations temporarily, and resuming CDA operations later on. This is practised at some airports already today for low density CDA arrival traffic.
- The CDA-abort procedure is activated by detection of separation violation problems. The violation problem comprises often only a few seconds, and the distribution, observed under wind conditions, have few outliers above 15 sec. (see Figure 15)
- An important cause of separation problems is identified by problems with trajectory prediction, causing a difference between planned and realised trajectories. In the experiment, this is caused by a table-driven interpolation process, in real-life this maybe caused by differences between observed weather conditions and experienced weather conditions, and/or by deficiencies in quality of ground-based trajectory prediction models. (See wind effects, Figure 16, second row graphs.) There is

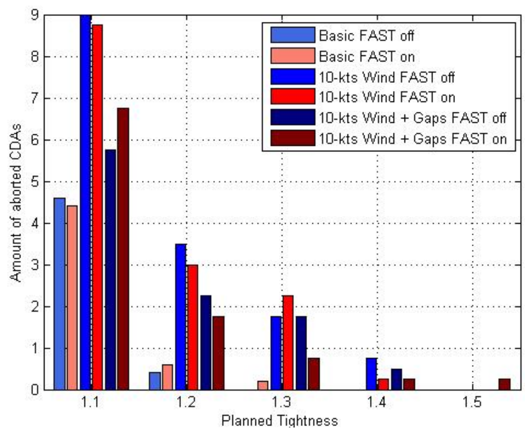

Figure 14 – CDA aborted flights for wind/no-wind scenarios

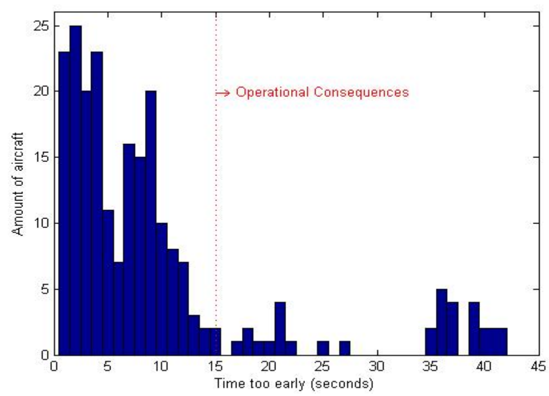

Figure 15 – CDA aborted flights for wind scenarios, distribution of separation violations

no evidence that real-life tolerances are more or less significant than the experienced tolerances under the modelled wind conditions. Anyhow, information on wind conditions has a significant impact on the quality of CDA advisories and subliminal control measures, and high quality predictability is therefore clearly key to success.

- All measures to ensure separation were processed in the model for arrival planning and flight execution by applying time-based separation instead of distance-based separation. This is in compliance with expected future standards of operation. [See for example SESAR Ref. 2 and 3.] However, it should be noted that throughput under these operational procedures is suffering less reduction of capacity by head-wind conditions than distance-based operations. Nevertheless, the throughput decreases, but this is caused by prediction problems and aborted CDAs (See Figure 14 and Figure 15). The measured sustainable throughput varies for tightness 1.3 for example from 28 arr./hour for the no-wind conditions to 26 arr./hour for 10 kts. head-wind.

Stemming from the observed PFR-results and CDA-abort numbers, the question arises, how large the deviations are that have to be corrected and how unpredictable deviations relate to the impact of small subliminal control actions? How effective is the planning information and does it allow controlling flow stability under weather uncertainty caused by ordinary wind conditions?

Firstly, looking at the results above, the size of observed deviations is evidently wind-dependent and also the lack of ability to correct is wind-dependent. This leads to a conclusion that the model has to be improved yet for its main feed-back loop, calculating corrections for executed deviations and executing these corrections.

Looking in more detail to experienced wind conditions, the analysis above showed some of the characteristics of operations with wind. Figure 15 showed the distribution of observed infringements of separations measured over 4.000 flights processed under head-wind conditions. Another indication for the relationship between observed track deviations and calculated and instructed subliminal control measures is given by Figure 16, comparing a “Fast-off”/”Fast-on” run for “Wind-on”, “No-Gaps” conditions. With “Fast-off” a few ATC instructions are causing deviations from planning, all other deviations are caused by wind, with “Fast-on” the deviations are composed from wind and subliminal control measures. The actually processed sequences of flights suggest that under the present modelled conditions the deviations and the corrections are similar in size and frequency, whilst subliminal control is still able to have some success in realised tightness on the runway. Nevertheless, this result suggests also that improvement is still possible.

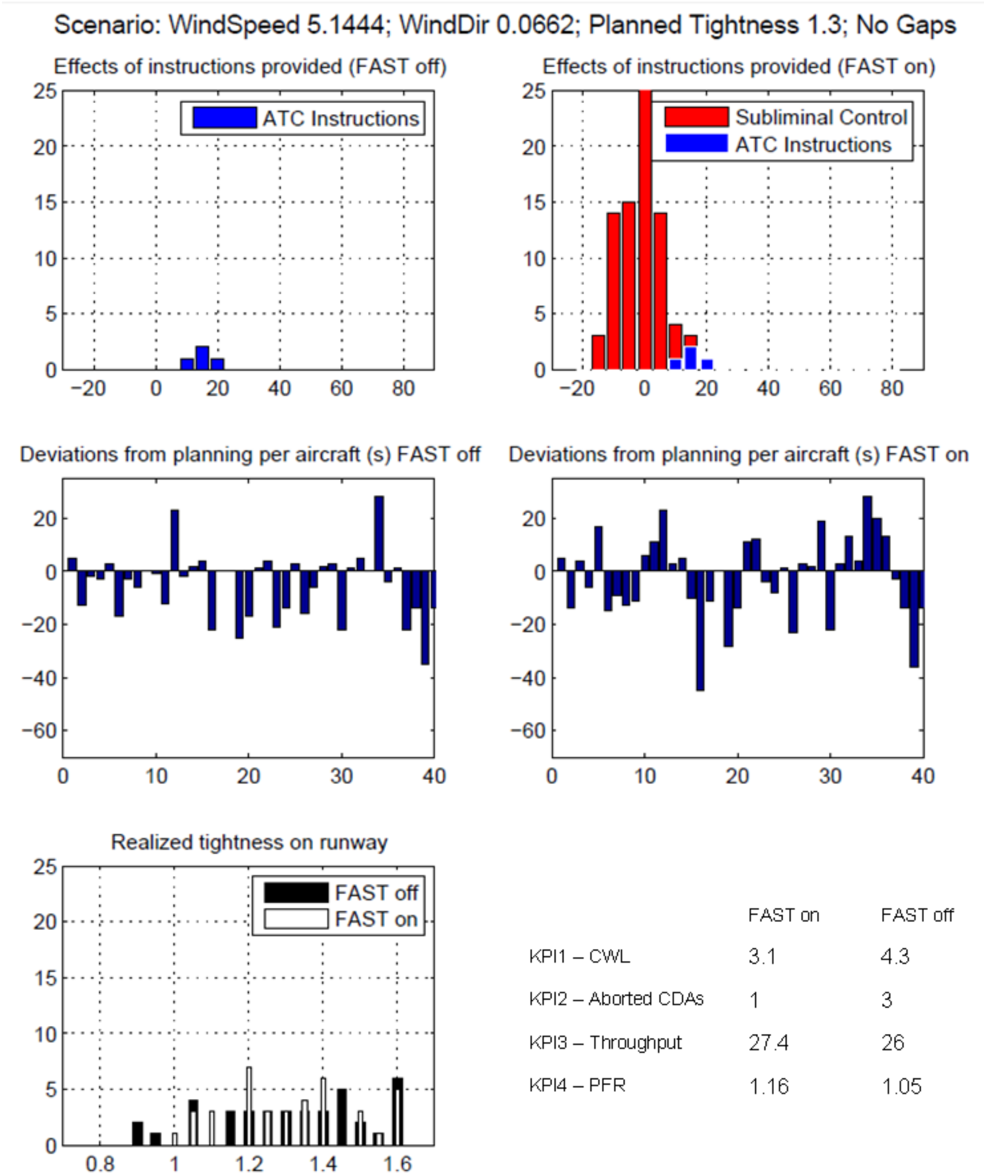

Figure 16 - Example dashboard with overview of 2 runs ("FAST on"/"FAST off"), wind on, tightness 1.3 (28 arr./hour)

5.3 Sensitivity analysis

Three cases were investigated briefly to get a better feeling of the weak and strong points of the concept for subliminal control on final descent operations:

- Processing a scenario without Heavies will assess throughput under simplified conditions,
- Processing cross-wind scenarios will assess some variations on wind sensitivity, and
- Processing subliminal control with double update frequency will assess the impact of feed-back accuracy on measured performance levels, expecting enhanced control on separation planning.

The first issue, to process a scenario without Heavies, gave simple evidence. The throughput of a flow of 40 Mediums increases from the measured mixed-scenario throughput of 28 arr./h for a planned tightness of 1.3, to a throughput of 30 arr./h for the same planned flow density.

The second scenario to process cross-wind scenarios, gave evidence as well. In-flight control procedures are influenced by applicable head-wind or tail-wind components. The (subliminal) control measures are subject to reduced or extended periods of control over the same track distance, and therefore the effectiveness of control measures is expected to increase by head-wind and to decrease by tail-wind. This is confirmed by experimental results.

The third one to evaluate, a double update frequency scenario, comprises to process a scenario which performs a re-planning every 90s., instead of every 180s. Evaluating the results of processing this scenario was the most complex and demanding one. The increase of accuracy by higher frequency competes with loss of accuracy due to limitations of predictability. The results showed some improvements by the higher update rate, but this was not convincing. It yields a conclusion that the modelling, in particular trajectory prediction, has to be refined in order to be in better balance with the update rate. Also, the allocation of waypoints could be improved possibly by enabling maximum correction potential. Finally, it should be noted that wind impact and subliminal control corrections are similar in size, and in order to be effective, this impose high requirements on the correctness of prediction and calculated corrections. Also, this gives way to further improvements.

5.4 Impact of Subliminal Control on Capacity and Throughput

Four KPIs were analysed, each having their impact on runway capacity whilst operating CDAs:

- **Controller workload**: Workload is correlated with traffic density in the first place. The tighter the sequence, the more extra workload is needed to solve separation problems.
- **Number of aborted CDAs**: The number of aborted CDAs was artificially high in the experiment due to simplified decision making, but the number of aborted CDAs decreased systematically due to increased sequencing stability activities with “FAST-on”.
- **Throughput**: During experimental runs, the measured throughput received direct benefits only by reduction of the number of aborted CDAs; in other respects throughput was equal to demand and thus input to each scenario.
- **Peak Flow Robustness (PFR)**: Experimental runs could demonstrate systematic improvement in performance by measuring PFR. This increase of PFR value indicates that traffic is distributed in the sequence in such a way that the risks of hazards and sequence disruption will decrease by application of subliminal control.

The challenge of operating CDAs is to maintain high density throughput in a sustainable way to cope with traffic demand. Therefore, the central question of this research can be formulated as:

Is support of subliminal control on continuous descent operations, in addition to conventional air traffic control, improving the sustainability of high density throughput?

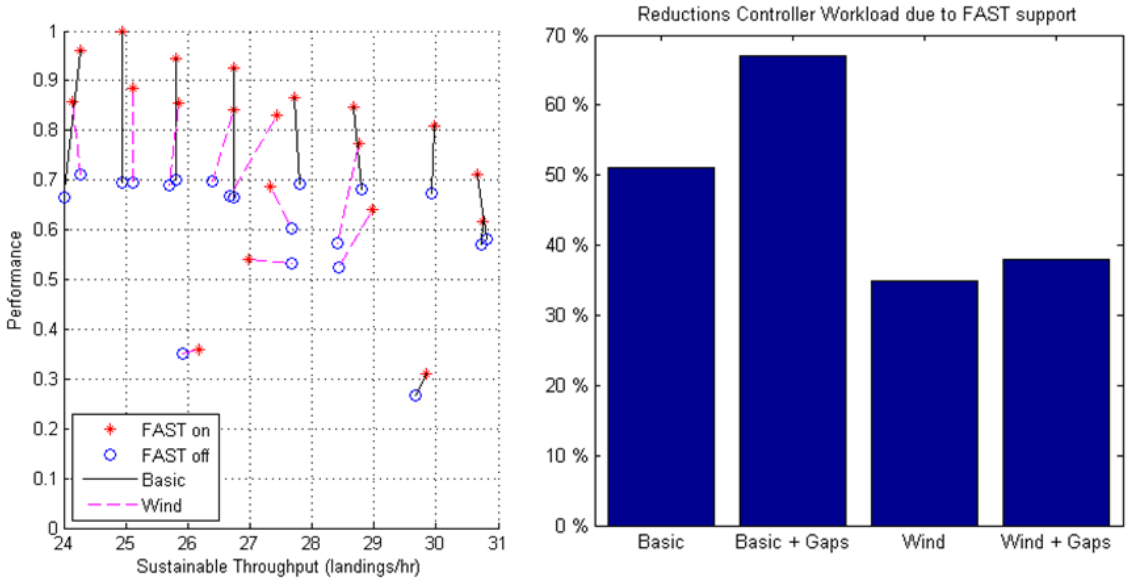

Figure 17 - Differences in performance with and without subliminal control, summarised over all scenarios(left) and the reduction in (extra) controller workload due to subliminal control(right)

To answer this question, the results of the experiment are combined in two figures, summarising experimental results and their outcome (see also Ref. 5):

- Figure 17 (left) presents relative performance improvements for three KPIs against applicable throughput for all scenarios. “FAST-on” is systematically performing better, whilst “No-wind” has a higher score than scenarios with wind. The conclusion is that subliminal control improves the performance of final descent CDAs which may support a higher level of sustainable throughput.
- Figure 17 (right) presents the percentage of saved (extra) workload due to subliminal control, and “extra” means in this context extra to maintain the stability of the sequence.
- Figure 18 presents the realised separations at touch-down by a histogram that counts the relative separation of each landed pair, which takes into account differences in relative landing intervals imposed by the arrival flow density (traffic demand). The picture demonstrates that “FAST-on” is able to support enhanced control over dense

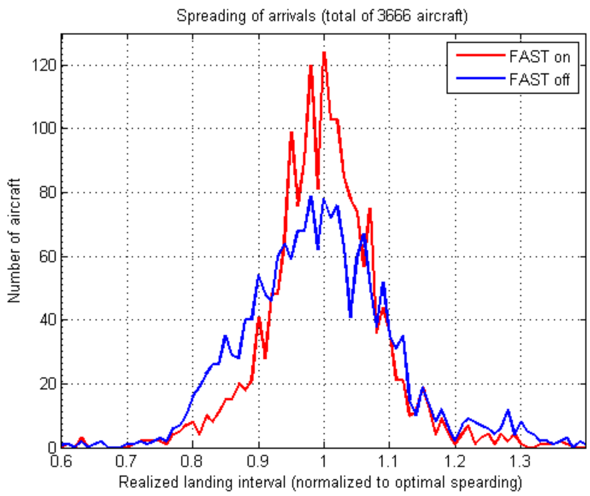

Figure 18 – Distribution of separations at touch-down, including (FAST-on) and excluding (FAST-off) subliminal control

arrival flows by realising separations close to the average separation. And, as a consequence, enhanced control over realised separations at touch-down will support the justification of decreased landing intervals.

6 Conclusions and Recommendations

The concept to increase stability of final descent CDA arrival operations by subliminal control has definitely some very attractive features, and application of the concept will support the justification of decreased landing intervals. The achievable benefits are described by the concept and partly demonstrated and validated by the model-based experiment:

- Control by lateral vectoring is easier and more intuitive to perform by ATM during descent, whilst control on the vertical profile is left to the aircraft.
- Subliminal control instructions are refined extensions of control instructions given by nature by ATCos, and whenever the ATCo gives an instruction, this will overrule subliminal control in an intuitively understandable way.
- The implementation of subliminal control can be done seamless and gradually, starting from low-frequent manual advisories. Another option is for example to uplink subliminal instructions automatically, whilst pilots may accept commands manually. This will make the introduction more acceptable and will allow mitigating potential hazards.
- The operational concept can be brought to operation, operating independent of traffic mixes and airborne equipment available, and operating under full responsibility of the ANSP.
- The benefits of implementation of subliminal control are increased stability of CDA arrival queues, whilst saving workload and preserving highest possible throughput.

The results and analysis of the experiment show that subliminal control works optimal under moderate conditions with not extreme high-density arrival flows and whenever planning and prediction are not too much challenged by unpredictable deviations, caused in particular by wind. Given the number of observed CDA abort cases, the need to enforce the stability of the final descent arrival flow seems evident, but in most evaluated runs it was demonstrated that subliminal control could provide the means to improve flow stability. Improvement was reached by taking pro-active measures to slightly advance or delay arrivals. It can be concluded from the experiment that subliminal control is able:

- To support **ensured separation** by increased robustness of the CDA final descent arrival flow,
- To decrease the **ATCo workload** required to maintain stability and to ensure separation, and
- That higher **sustainable throughput** is achievable when using support by subliminal control, by enhanced control on separation.

Given the present results it can be recommended to continue research on this very critical part of an operational concept to operate CDAs of dense arrival flows at hub airports. Improvement of stability of these flows in final descent is likely to become ultimately the most critical issue of these operations. Two concrete proposals for continuing this research could be:

- The model developed in MATLAB/Simulink operates fairly well under nominal conditions. The modelling of aircraft behaviour and control measures works fairly well as well. What can be improved, is the trajectory prediction function and the relationship between predicted wind and experienced wind. Also, enhanced determination of arrival target values may help to be more effective in small-scale corrective decision-making, and this will improve the quality of subliminal control measures as well as the advisories for Controller interventions.
- The model is quite detailed in modelling flight dynamics and experienced wind conditions. The present research has accomplished procedures to correct for deviations and to increase flow stability. It would be worth to validate the complete model on real-life applicability. This could be executed in a passive mode by recording and assessing real-life CDA operations under low density conditions and to compare CDA control measures with the present level of modelling.

To continue research in this way could be the most effective way to bring the concept to operation. It helps that the concept is appropriate to be implemented in a step-wise and incremental way. As soon as the algorithm generates well applicable advisories, the tool can be brought to operation by generating appropriately dimensioned advisories with a manageable update frequency, taking into account Controller workload. Whenever such a semi-automatic process provides the benefits as expected, more automation can be added.

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8 About the Authors

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He received his master degree in Experimental Physics at the University of Amsterdam in 1973. He worked for NLR since 1980, the first 13 years on ICT subjects, thereafter on the development of operational concepts and their validation. He contributed to the development of a 6-degrees of freedom moving-based flight simulator as well as to the development of the real-time ATC simulator of NLR. Last projects comprised amongst others contributions to EU-funded projects like Gate-to-Gate, C-ATM, EPISODE-3 and ERAT.

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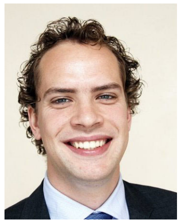

Geert Mulder studied Aerospace Engineering at Delft University of Technology between 2004 and 2011. He is specialized in the field of 'Optimization of Flight Operations' and conducted the research accompanying this article as partial fulfillment of the requirements for the degree of Master of Science within NLR facilities. In January 2012 he starts as a Management Trainee at KLM Royal Dutch Airlines.

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