Arrival Management with Required Navigation Performance and 3D Paths

Aslaug Haraldsdottir, Julien Scharl, Matthew E. Berge, Ewald G. Schoemig and Michael L. Coats

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aslaug.haraldsdottir@boeing.com
Overview

- Air transportation system roadmap to NextGen and SESAR
- Required Navigation Performance (RNAV/RNP) and 3D Paths – concept overview
- Arrival management modeling and analysis methodology
  - Arrival management performance analysis overview
  - Arrival management model in Boeing’s Trajectory Analysis and Modeling Environment (TAME)
  - Key system performance parameters
  - Scenario and simulation methodology
  - Analysis results
- Conclusions
The objective is FMS-based operations – the first step towards 4D trajectory-based operations
– Path stretching is required when speed control is insufficient to achieve spacing
– ATC uses advanced automation tools to select path and speed to space traffic
– Paths need to be defined to enable FMS-based execution by the aircraft
– Alternative clearance mechanisms include
  – En-route: “Place/Bearing/Distance” or lateral offsets
  – Arrival transition: “Place/Bearing/Distance”
  – Terminal Area: Pre-defined sets of 3D paths, published and available in both air and ground navigation databases
  – Automation also supports vectoring of non-equipped aircraft

Clearance delivery
– Voice-based 3D path clearances to equipped aircraft
– Non-equipped aircraft receive traditional speed, altitude and heading clearances
3D Paths in Arrival Management

- Ground automation maximizes airport throughput
  - Computes schedule at runways and meter fixes
  - Selects speed control and path stretch to meet schedule
- ATC provides complete path from before TOD to Meter Fix
- FMS optimizes vertical profile
- Terminal Area re-plans from Meter Fix to Runway, if required
- Enables early trajectory-based operations
Arrival Management Event Sequence

1. EGF586 enters CTAS planning horizon, prior to TOD

2. TMA updates sequence and schedule and determines 3 min delay for EGF586 (AAL652 is lead)

3. EDA selects the 3-min path stretch for EGF586 (AAL652 no delay)

4. Controller issues 3D Path Clearance after freeze horizon and prior to TOD

5. Pilot inputs new procedure into FMS and activates new flight plan

6. Aircraft flies new flight plan with RNAV/VNAV

7. Hand off to TRACON at DAS

NASA CTAS automation used as an example to illustrate required arrival management functions
AM Performance Analysis Overview

- Throughput is directly influenced by variability in spacing at the Meter Fix and Runway Threshold
- Spacing variability is influenced by several key parameters
  - Wind prediction accuracy (mean wind and gusts)
  - Navigation accuracy
  - Surveillance accuracy
  - Timing variability introduced by operators
  - Aircraft trajectory prediction model
- Goal is to understand the relationship between these key parameters and traffic metrics
  - Delivery accuracy at Meter Fix and Runway (ATA-STA)
  - Inter-arrival time statistics
  - Delay
- Based on Boeing’s Trajectory Analysis and Modeling Environment (TAME)
  - Monte-Carlo traffic simulation and analysis framework based on MATLAB
Arrival Management Model in TAME

Arrival planning prior to freeze horizon

- Nominal path
  - Nominal speed
  - True mean wind
  - True ac model
  - Nominal trajectory

- True state
- ETA

- Trajectory Predictor
  - ATA0+ ε
  - Prediction Error
    - Wind and temp
    - AC model
    - Surveillance
    - Actuation

- Path options
  - Speed options

- Traffic Scheduler (MRP)
  - D(p)

- Trajectory Selector
  - Planned trajectory

- Wind Model
  - Speed
  - Direction

- Aircraft Model
  - Actual trajectory

- Navigation Model
  - Lateral Accuracy

Traffic performance metrics

Stochastic input sources

Planning prior to freeze horizon includes:
- Nominal path
- Nominal speed
- True mean wind
- True AC model
- Nominal trajectory
- True state

Traffic Scheduler (MRP) takes into account:
- Path options
- Speed options

Trajectory Selector decides on a planned trajectory based on:
- Wind model (speed, direction)
- Aircraft model

Navigation model evaluates:
- Lateral accuracy

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Key System Performance Parameters

- **Lateral navigation performance**
  - Based on Actual Navigation Performance (ANP) metric
  - Levels chosen to represent range of present GPS and radio navigation capabilities

- **Wind model**
  - Mean wind is represented by speed and direction as function of altitude
  - Wind gusts are sized by specifying speed and direction variability of Gaussian processes
  - Wind field does not vary laterally across the scenario

- **Trajectory prediction error**
  - Single aggregated model parameter $\varepsilon$ with mean and standard deviation
  - Standard deviation sized by data from NASA CTAS prediction performance flight test results
  - Mean of $\varepsilon$ represents difference between predicted and actual mean wind and can be sized differently for traffic to each meter fix
Scenario and Simulation Methodology

- Airport and airspace arrival scenario
  - Houston Intercontinental Airport (IAH)
  - Path stretch using lateral offsets in Center
  - Fixed path options in Terminal Area
  - Descent speeds in 5 kts increments between 250 and 290 kts
  - Cruise speeds in 0.05 Mach increments between 0.7 and 0.8
  - Hold at cruise when necessary
  - 4 meter fixes feeding 3 arrival runways
  - Traffic is an OAG-based 75 min arrival rush

- Simulation methodology
  - Studied effect of mean wind prediction error (wind bias) using deterministic simulation
  - Studied stochastic effects using Monte-Carlo simulation methodology
Effects of Mean Wind Prediction Error

- If traffic is balanced, we expect ~25% rate of in-trail separation violations
- **Test case:** Traffic from North-East and North-West merging to a single East-West runway

Error in mean wind prediction is a significant issue for strategic traffic planning
Meter Fix and Runway Delivery Accuracy Results

Monte-Carlo simulation convergence is ensured via t-tests

- Trajectory prediction and wind effects dominate delivery accuracy
- Error grows from the Meter Fix to the Runway
The Need for Spacing Buffers

- Buffers are needed to accommodate spacing variability due to prediction uncertainty.
- Buffers were sized to ensure that the probability of meter fix separation loss is less than 0.5%.
- Buffers lead to reduced throughput and thus produce higher delay.

Buffer analysis for ANP =0.15 nm, $\sigma_{Vw}=10$ kts, $\varepsilon_{MF}=7.5$ s

<table>
<thead>
<tr>
<th></th>
<th>No buffers</th>
<th>25 s (2 nm) MF buffer</th>
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<tbody>
<tr>
<td>Probability of meter fix separation loss</td>
<td>15.2%</td>
<td>0.5%</td>
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<tr>
<td>Average arrival delay</td>
<td>69 s</td>
<td>178 s</td>
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Conclusions

- The 3D Path operational concept is based on integrating advanced navigation with advanced ground automation capabilities
  - Step towards the trajectory-based vision of NextGen and SESAR
  - Strategic traffic plans with accurate navigation performance
  - Implementation is technically feasible in 2008-2012

- Arrival management performance analysis conclusions
  - Trajectory and wind prediction performance dominate delivery accuracy
  - Lateral navigation performance effects are influenced primarily by turns
  - A second planning stage for the TRACON will be required for maximum throughput
  - 2 nm separation buffers at the meter fix are sufficient to accommodate delivery variability for expected concept performance levels

- The TAME toolset provides fast-time technical performance analysis capability for a variety of arrival management concepts
Wind error model details

Modify mean wind vector by magnitude error $\Delta V_w$ and direction error $\Delta \Psi_w$, each drawn from independent filter guaranteeing a zero mean Gaussian time distribution with standard deviation $\sigma$ and period $T$ (NOT VARYING BY ALTITUDE)

Model:

$$V_{wa} = V_w + \Delta V_w$$
$$\Psi_{wa} = \Psi_w + \Delta \Psi_w$$

$$V_{xa} = V_{wa} \cos(\Psi_{wa})$$
$$V_{ya} = V_{wa} \sin(\Psi_{wa})$$

This is NOT vector addition, but statistically the actual wind will average to the mean wind.
Monte-Carlo Convergence Process

Convergence test for metric 5

- 95% Confidence interval /2
- Threshold
- Convergence achieved

MCS run number

Monte-Carlo Convergence Process

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### ANP vs RNP table

Assumes ANP effect dominates RNP (low FTE)

<table>
<thead>
<tr>
<th>ANP (nm)</th>
<th>RNP (nm)</th>
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<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.15</td>
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<td>0.16</td>
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<tr>
<td>1.0</td>
<td>0.51</td>
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</table>
Mean wind prediction error

RIICE MF

Unexpected headwind

Lead aircraft arrives late

Trail aircraft arrives early

DAS MF

Unexpected tailwind

Planned separation

Actual separation