Flight Management System
Technology for Trajectory-Based Operations

Presented to CNS/ATM Conference 2007
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Approved for public release
Trajectory-Based Operations

Basis for strategic planning and tactical operations including separation management.

• Part of operational concept for the Next Generation Air Transportation System (NG-ATS).

• Four-dimensional (4-D) trajectory is the cornerstone of Trajectory-Based Operations for improved predictability

• “Open-ended” flight maneuvers (such as vectoring) reduce predictability.

• “Closed” trajectory-based maneuvers (such as a lateral offset) improve predictability.
Controlled Time of Arrival

Generated by a Time-Based Metering system to merge traffic from metering fixes to a runway.

- A key capability of an FMS is to “self-deliver” to a specified waypoint at a Required Time of Arrival (RTA).
- The FMS efficiently operates a flight with a user selected **Cost Index (CI)** and a **Continuous Descent Approach (CDA)**.
- Accurate ETAs need to be downlinked from the aircraft to close the loop with ground control.

**Cost Index (CI)**

$CI = \frac{\text{time cost}}{\text{fuel cost}}$

**Continuous Descent Approach (CDA)**

- **Dive and Drive Approach**
- **Distance**
- **Altitude**
- **CDA**
Terminal Procedures with Trajectory-Based Operations

Increased arrival/departure throughput and efficiency.

- Increased predictability
- Reduced track distances
- Reduced voice communications & vectoring

More efficient vertical profiles with reduced fuel consumption.
Approach Procedure with RNP SAAAR

SAAAR: Special Aircraft and Aircrew Authorization Required.

- Narrower lateral TERPS (e.g., RNP-0.3 or less, no secondary)
- Guided turns/Lower RNP on missed approaches (RF and RNP-0.3 or less)
- Curved segments anywhere along the approach (RF legs)
- Reduced obstacle clearance (Vertical Error Budget)

Predictable lateral and vertical path. Low flight time variation between aircraft when speed constraints are applied.
Time Control at Metering Fix

Runway landing sequence/spacing obtained by assigning a Controlled Time of Arrival at each metering fix.

- Requires aircraft to use RNP SAAAR approach procedure.
- Fine tuning for runway spacing through speed adjustment only after passing metering fix – ground based clearance.

Control Time of Arrival at metering fix by:

- Ground control – Use Center-TRACON Automation System (CTAS) and Traffic Management Advisor (TMA) tools to issue RTA at metering fix to arriving aircraft.
- Aircraft – Control with speed variation using RTA mode (existing RTA capability).
- Ground control – For additional delay, assign lateral offset from predetermined start and end points specified on the arrival chart (modified lateral offset capability) or lower altitude (modified cruise-descent capability).
Controlled Arrival Time Sensitivity

Standard comparison profile:

- 200 nm from destination runway
- FL390 cruise altitude
- Metering fix 40 nm@12,000 feet from destination runway
- 737-800, 104 KLB GW, CI=30

Conditions examined:

- Speed variation using CI control
- Lateral offset using variable offset distance
- Early descent using Cruise-Descent
Speed Variation Using CI Control

Cost Index (CI) is a hidden variable to control speed for RTA.

- Low CI (-50) = **Minimum Speed**
- High CI (500) = **Maximum Speed**
- Zero CI = **Minimum Fuel Burn**
Lateral Offset Using Variable Offset Distance

Specified start and end points within the STAR.

- 45° path to/from parallel offset path.
- Variable offset distance assigned depending upon time delay needed.

Lateral offset paths shown in 5 NM increments

Specified start point

Specified end point

Minutes Delay

0 1 2 3

Fuel Burn (lbs)

0 100 200 300

Offset Distance (NM)

5 10 15 20

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Early Descent Using Cruise-Descent

Descending to lower cruise altitude results in slower TAS with same Cl.

- FL390
- FL350
- FL300
- FL250
- FL200
- FL150

Cruise-Descent Flight Level

Minutes Delay

Fuel Burn (lbs)

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CDA After Metering Fix

Fixed path with gradient to final approach.

- Assigned airspeed from metering fix to final approach, determined by ground controller for final approach spacing.

250 knots or as assigned by ATC
Expect to cross at 12,000 feet

3500 feet

Final spacing adjusted by ground control clearance

Delay Minutes

Assigned Airspeed

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Required Time of Arrival (RTA)

Algorithm is based on speed variation.
- Fixed lateral path, fixed cruise altitude

RTA is enabled for any point in the flight plan.
- Available on 737 aircraft since 1986.
- Recent change made to improve RTA control to the runway.

Future enhancements:
- Compensation for control error tolerance when reporting trajectory early in the flight.
- Include lateral offset and/or cruise altitude variation when additional delay is required.
RTA to the Runway

Results from SAS trials in 2001.

- Larger deviation at runway due to constrained speed late in descent.

Typical flight data

<table>
<thead>
<tr>
<th>RTA Target</th>
<th>Max</th>
<th>Mean</th>
<th>STD</th>
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<tbody>
<tr>
<td>Top of STAR</td>
<td>7 Sec</td>
<td>4.8 Sec</td>
<td>2.7 Sec</td>
</tr>
<tr>
<td>Runway</td>
<td>21 Sec</td>
<td>12.7 Sec</td>
<td>7.3 Sec</td>
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</table>

![Diagram showing the relationship between distance to RTA waypoint and time]

- Latest Arrival Time
- Earliest Arrival Time
- Climb
- Cruise FL350
- Descent Phase
ARINC 702A Supplement 1 was defined for early implementation.

- Implemented in 737 FMS with U10.6 and U10.7 software
  - Output on dedicated ARINC 429 bus.
  - ACARS downlink of trajectory intent as interim datalink.

Flight trials started in October 2005.

- European Commission (EC) supported activity, NUP2+, in Sweden.
- RTA contracting to the runway.
- CDA makes use of FMS vertical trajectory predictions to preserve capacity.
- Slot swapping, ground holding.
## ACARS Downlink: Stockholm to Malmo Flight

**Route:** ESSAESMS10

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<table>
<thead>
<tr>
<th>Point Type</th>
<th>Lat / Lon</th>
<th>Turn Radius</th>
<th>Altitude</th>
<th>Time!</th>
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Arrival Management

Collaborative Information Exchange System

- Designate flight for Green Approach
- Send approach to aircraft
- Enable request of trajectory downlink
Arrival Management

Display flight details

- Trajectory profile is plotted
- Time and altitude at each point is displayed
1. Lift-Off

2. OFF message including ETA for Arlanda arrival is sent via data link to ATC Arlanda.

3. 3 min before ToD, ground system automatically requests 4DT in order to get accurate ETA/RTA from aircraft.

4. ATC sends Green Approach STAR to aircraft. This STAR is defined all the way to ILS. Pilot updates FMS and pushes more accurate ETA.

5. 40 min before ETA, ground system requests full remaining trajectory description in order to be able to plan for this aircraft and merge it with ordinary traffic. Based on this, the Approach controller may choose to assign an RTA constraint to the aircraft.

6. ATC request RTA close to the latest down linked ETA in order to get accurate ETA/RTA from aircraft.

7. Aircraft accepts RTA.

8. ATC sends Green Approach STAR to aircraft. This STAR is defined all the way to ILS. Pilot updates FMS and pushes more accurate ETA.


Descent
Example From Live Trial

In the new downlinked 4DT messages, the time separation at HMR had increased from 1 to 2 minutes.

Sends RTA 06:48:00 to SAS075 and RTA 06:51:00 to SAS2059.

RTA Accepted via 4DT downlink
SAS075 confirms GA HAMMAR1V with ETA 06:49
RTA Accepted
SAS2059 confirms GA HAMMAR1V with ETA 06:50

Controlling to time resulted in physical separation of 10NM at OM.
More than 650 Green Approaches flown to date… (and counting) resulted in:

- 204 Metric Ton CO2 reduction yearly
- 715 kg of NOx reduction yearly
- 130,000 kg of fuel saved

SAS-Sweden 36,000 Green Approaches per year into Stockholm alone

- $5.8M fuel reduction yearly
- 23,000 Metric Ton CO2 reduction yearly
- 79 Metric Ton of NOx reduction yearly
- Large noise reductions (being quantified)

SAS and LFV are expanding Green Approaches throughout domestic Sweden
NUP2+ Steps for 2007

Downlink 4D trajectory via ADS-B.
Update FMS with enhanced software for better predictions and improved RTA to the runway.
Conduct controller simulations with mixed equipage and high traffic.
Operate regularly in peak traffic (>57 movements/hr), mixed equipage, CDAs and validate capacity unchanged or increased.
Plans to expand the operations in 2007 to adjacent regions in “core-Europe” in order to begin developing end-end benefits to participating airline operations.
Conclusion

Trajectory-Based Operations are supported by current FMS capabilities

Key FMS capabilities include:

• Required Time of Arrival (RTA) to points near the runway
• Auto-loading flight plan information
• Trajectory reporting with accurate predictions
• Continuous Descent Approaches (CDA)

Results to date show significant economic incentive for expanding Trajectory-Based Operations