ATM Technology Demonstration 1 (ATD-1)

EcoDemonstrator ASTAR Guided Arrival Research (EAGAR)

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Project Outbrief
January 29, 2015
In Spring 2013, high level NASA and Boeing management were seeking opportunities to collaborate on a flight test activity involving the ecoDemonstrator.

The Airspace Systems Program Office identified FIM as a viable candidate.

ATD-1 accepted the challenge.

Work began in July for a December 2013 flight test.
Objectives

Conduct a rapid collaborative development effort with Boeing to equip the 2013 ecoDemonstrator test aircraft (B787-800) with an ASTAR-based airborne spacing tool.

Conduct a flight test to demonstrate precision spacing between two aircraft with the aid of NASA’s ASTAR algorithm.
Minimum Success Criteria

ATD-1: Successful rapid collaboration between NASA and Boeing

FIM operation: Both Target and FIM aircraft fly from initial waypoint to FAF without interruption (vectors, etc).

Was it feasible in the real world?  YES

FIM software: Continuous progression to achieve assigned spacing goal behind Target aircraft.

Was the software robust and perform as expected?  YES
“Stretch” Success Criteria

Demonstrate consistent final spacing within +/-5 seconds at the FIM termination point.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Delivery Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-7.5</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>3</td>
<td>1.4</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>-3.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Std. Dev.</th>
<th>4.16</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>9.5</td>
</tr>
</tbody>
</table>
Flight Test Approach

Equip the ecoDemostrator with the ASTAR-based application hosted on a laptop PC

Conduct an arrival sequence and connect to a published approach procedure into a dedicated test airport

Target and Ownship aircraft fly on the same route from TOD to runway:

• Start 100-120 miles from runway; line up with ATC help
• Arrival procedure is typed into the FMS, approach is loaded, then full route connected together
• Locate target, enter clearance, and initiate test
The Plan / The Reality

Lab Testing for software integration / Occurred at four locations

Ground Testing aboard the airplane to ensure laptop is receiving required data / ~7 hours over two days

4 meetings with Air Traffic Control supported by Boeing Flight Test Analysis and Flight Test Operations / Many more, but mostly without Analysis or Ops

2 hours of concurrent testing to monitor the system in flight / 8 hours in the air, no NASA personnel taking part

6 hours of dedicated flight time over 2 days, ~6 runs / ~6 hours, 1 day, 5 runs
# Schedule Milestones

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intro ASRB briefing</td>
<td>November 7, 2013</td>
</tr>
<tr>
<td>Simulation Requirements Review</td>
<td>April 30, 2014</td>
</tr>
<tr>
<td>Initial Software build delivered to Boeing</td>
<td>June 11, 2014</td>
</tr>
<tr>
<td>Laptop with ASTAR available for ground testing</td>
<td>June 25, 2014</td>
</tr>
<tr>
<td>1st Dry Run in NASA sim</td>
<td>June 26, 2014</td>
</tr>
<tr>
<td>Boeing Bench Testing</td>
<td>July-September 2014</td>
</tr>
<tr>
<td>ASRB briefing</td>
<td>August 14, 2014</td>
</tr>
<tr>
<td>Boeing Aircraft Ground Testing</td>
<td>November 10-11, 2014</td>
</tr>
<tr>
<td>Function-Complete Code Freeze</td>
<td>December 5, 2014</td>
</tr>
<tr>
<td>Bug-Fix Code Freeze</td>
<td>December 5, 2014</td>
</tr>
<tr>
<td>Final Software build delivered to Boeing</td>
<td>December 6, 2014</td>
</tr>
<tr>
<td>Concurrent Flight Testing</td>
<td>December 6, 2014</td>
</tr>
<tr>
<td>Flight Demonstration</td>
<td>December 12, 2014</td>
</tr>
</tbody>
</table>
Participants

NASA
- Laptop Operator
- Developers supporting flight
- Ground observers within FAA ATC facilities

Boeing
- Developer and Flight Test Engineers supporting the flight
- Test Pilots (2 B787 & 1 T-38)

FAA
- Seattle Center and Grant County Approach Air Traffic Controllers
Target Aircraft Search

- Alaska Airlines B737NG
- ASTOR Simulated Model
- FAA Global Express 5000
- T-33
- T-38
Airport Search

It took several months to settle on an airport

- Seattle, WA – KSEA
- Phoenix, AZ – KPHX
- Moses Lakes, WA – KMWH
- Denver, CO – KDEN
- Glasgow, MT – KGGW
Avionics Architecture Overview
Diagnostic Tool Screenshot
Scheduling and Spacing Technologies

Flight Deck-based Interval Management

ASTAR Ver. 12

Build: EAGAR_14_5_2014DEC05R-PARTS.exe

Navigation Database Cycle 201412
Demo Arrival Location
Full Route Structure
Concurrent Testing Route Structure

Test location dependent on weather

Development team built routes to cover all areas

Location was decided the morning of test (over ocean)

Olympia Arrival built, tested, and e-mailed up while still flying
First FIM
Dec. 6 Concurrent Testing

IM Ops conducted over 64 nmi (77→13 nmi from Rwy) ~20 minutes
Dec. 6 Concurrent Testing

**Ownship speeds and time-error**

- **ProfileCas**
- **CmdEnd**
- **CAS**
- **RTE**

24 sec to speed change
16 sec to speed change
Dec. 6 Concurrent Testing

Ownship speeds and time-error

Run Time (sec)

Speeds (kt)

Time-error (sec)

ProfileCas
CmdEnd
CAS
RTE
EAGAR
Demonstration Flight
Flight Demonstration Materials

Flight Test Plan and Communication Protocol packet

Boeing Flight test plan

Controller Briefing Packet

Pilot Flight Test Cards

Briefing packet for ground observers at FAA ATC facilities
Test Setup

VHF radio frequency required to enable communication between the airplane and chase

Flight Interphone jacks and headsets at participant locations on B787

Ethernet connections from the cockpit to the ASTAR laptop

115 volt/60 Hz power available at all workstations

All laptops adhered to workstations with Velcro

All participants properly briefed
Test Requirements

Contiguous US – flight testing

Daylight only, VMC

See and Avoid – 14CFR 91.113(b)

Sparsely populated area or over water only

Coordinate with applicable ARTCC in advance. Stay under ATC control, or pre-coordinated agreements.

Below FL180, local altimeter setting used by both aircraft
Test Sequence

- Depart KBFI and fly test profile into KMWH to the FAF

<table>
<thead>
<tr>
<th>Run #</th>
<th>Initial Speed</th>
<th>Initial Altitude</th>
<th>Arrival T-38</th>
<th>Arrival B787</th>
<th>In-Trail Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>280</td>
<td>FL220</td>
<td>SUBDY</td>
<td>SUBDY</td>
<td>13 nm</td>
</tr>
<tr>
<td>2</td>
<td>280</td>
<td>FL220</td>
<td>KNOCK</td>
<td>KNOCK</td>
<td>16 nm</td>
</tr>
<tr>
<td>3</td>
<td>280</td>
<td>FL220</td>
<td>SUBDY</td>
<td>SUBDY</td>
<td>10 nm</td>
</tr>
<tr>
<td>4</td>
<td>280</td>
<td>FL220</td>
<td>SUBDY</td>
<td>KNOCK</td>
<td>Initial fixes at same time (7.5 nm)</td>
</tr>
<tr>
<td>5</td>
<td>280</td>
<td>FL220</td>
<td>SUBDY</td>
<td>KNOCK</td>
<td></td>
</tr>
</tbody>
</table>

Schedule: Run 1 / T-38 refuel / Run 2-4 / T-38 refuel / Run 5

- Upon conclusion of demonstration, return to KBFI.
Input winds: A selection of altitudes was requested by cockpit, the best altitudes available for input follow.

<table>
<thead>
<tr>
<th>Altitude</th>
<th>Direction °</th>
<th>Speed kts</th>
</tr>
</thead>
<tbody>
<tr>
<td>FL230</td>
<td>190</td>
<td>64</td>
</tr>
<tr>
<td>FL210</td>
<td>193</td>
<td>54</td>
</tr>
<tr>
<td>FL180</td>
<td>190</td>
<td>40</td>
</tr>
<tr>
<td>16,000</td>
<td>260</td>
<td>19</td>
</tr>
</tbody>
</table>
### Input Speeds to ASTAR

<table>
<thead>
<tr>
<th>Run</th>
<th>Cruise Speeds</th>
<th>Descent Speeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.65 Mach / 280 knots</td>
<td>0.62 Mach / 270 knots</td>
</tr>
<tr>
<td>2</td>
<td>0.76 Mach / 340 knots</td>
<td>0.62 Mach / 270 knots</td>
</tr>
<tr>
<td>3</td>
<td>0.64 Mach</td>
<td>0.62 Mach / 280 knots</td>
</tr>
<tr>
<td>4</td>
<td>0.65 Mach / 300 knots</td>
<td>0.62 Mach / 280 knots</td>
</tr>
<tr>
<td>5</td>
<td>0.65 Mach</td>
<td>0.62 Mach / 280 knots</td>
</tr>
</tbody>
</table>
Weather at Grant County Airport

Initial METAR at KMWH 7000’ OVC

ATIS for KMWH (During Run 2): Calm, 10 miles visibility, 8500 OVC, Temp 6, Dewpoint 4, Altimeter 29.73.

Icing at 10,000 ft.

AIRMET in the vicinity with wind shear
RUN 1: Delivery Accuracy -7.5 sec. early

- Both aircraft on SUBDY Arrival
- 13 nm separation planned (12.5 nm actual)
- 120 seconds planned (112.5 @ FAF)

FIM Distance: 94.5 nm
FIM Time: 20 min 11 sec

Performed go-around at 11:54:55
Run 1 Profile
Run 1

- 3 speed inversions
- 13 speed commands (1 command/1 min. 33 sec)
- B787 performed a go-around b/c T-38 was on runway

Grant County International Airport, Moses Lakes, WA
Run 1: Joining SUBDY Arrival
Run 1: Turn at UPBOB
Run 1: Turn to Final
Run 2: Delivery Accuracy +1.5 sec. late

- Both aircraft on KNOCK Arrival
- 16 nm separation planned (24.12 nm actual)
- 120 seconds planned, **150 sec. actual** (151.5 @ FAF)

FIM Distance:
89.9 nm

FIM Time:
17 min 54 sec
Run 2

- 3 speed inversions
- 14 speed commands (1 command / 1 min. 17 sec.)

Ownship departs ahead of T-38 and holds, but gets disoriented for the initial setup. T-38 performs a teardrop entry.

Causes ownship to get behind schedule, maintains 340 kts. airspeed to try to make up the distance.
Run 3 & 3A
Run 3

Poor setup prior to run

• ASTAR on ~8 min. with no pairing

• OWNSHIP OFF PATH message

• Cockpit stated B787 was on path

• Paired 8 sec. prior to shutdown

• 6.14 nm separation at shutdown
Run 3A: Delivery Accuracy +1.4 sec. late

- Both aircraft on SUBDY Arrival
- 10 nm separation planned (6.23 nm actual)
- 120 seconds planned, (121.4 sec @ FAF)

FIM Distance: 43.78 nm
FIM Time: 10 min 48 sec
Run 3A
Run 3A

- 1 speed inversion
- 7 speed commands (1 command / 1 min. 17 sec.)
- Forecast winds were not entered on this run due to time constraints
Run 4: Delivery Accuracy +2.0 sec. late

- T-38 Target on SUBDY Arrival, B787 Ownship on KNOCK Arrival
- 7.5 nm separation planned with concurrent arrival at IAFs
- Poor initial setup
- 1.63 nm along route separation
- 120 seconds planned
  (122 @ FAF)

FIM Distance: 71.59 nm
FIM Time: 17 min 40 sec
Run 4
Run 4
Run 4

About where we achieved 3 nm spacing
Run 4

Unpaired for 5 seconds, right here
Run 4

- 4 speed inversions
- 13 speed commands (1 command / 1 min. 26 sec.)
Run 5: Delivery Accuracy -3.5 sec. early

- T-38 Target on SUBDY Arrival, B787 Ownship on KNOCK Arrival
- 7.5 nm separation planned with concurrent arrival at IAFs
- 10.83 nm along route separation
- 120 seconds planned
  (116.5 @FAF)

FIM Distance: 85.88 nm
FIM Time: 18 min 33 sec
Run 5
Run 5
Run 5

- 3 speed inversions
- 14 speed commands (1 command / 1 min. 20 sec.)
## Altitude and Distance

<table>
<thead>
<tr>
<th>Run #</th>
<th>Initial Speed</th>
<th>Initial Altitude</th>
<th>T-38 @ FIM Start</th>
<th>B787 @ FIM Start</th>
<th>Planned In-Trail Distance</th>
<th>Actual In-Trail Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>280</td>
<td>FL220</td>
<td>21875</td>
<td>22998</td>
<td>13 nm</td>
<td>12.51 nm</td>
</tr>
<tr>
<td>2</td>
<td>280</td>
<td>FL220</td>
<td>16625</td>
<td>22388</td>
<td>16 nm</td>
<td>24.12</td>
</tr>
<tr>
<td>3</td>
<td>280</td>
<td>FL220</td>
<td>11425</td>
<td>12908</td>
<td>10 nm</td>
<td>6.23</td>
</tr>
<tr>
<td>4</td>
<td>280</td>
<td>FL220</td>
<td>19050</td>
<td>22739</td>
<td>7.5 nm</td>
<td>1.63</td>
</tr>
<tr>
<td>5</td>
<td>280</td>
<td>FL220</td>
<td>20825</td>
<td>22313</td>
<td>7.5 nm</td>
<td>10.83</td>
</tr>
</tbody>
</table>
FIM Distance

- Objective was to get between 80-100 nm of data

<table>
<thead>
<tr>
<th>Run #</th>
<th>FIM Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>94.5</td>
</tr>
<tr>
<td>2</td>
<td>89.9</td>
</tr>
<tr>
<td>3</td>
<td>43.8</td>
</tr>
<tr>
<td>4</td>
<td>71.6</td>
</tr>
<tr>
<td>5</td>
<td>85.9</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>77.14</strong></td>
</tr>
</tbody>
</table>
Run 1
Run 2
Run 3A
Run 4
Run 5
Altitude

Dual Route

KNOCK Arrival

SUBDY Arrival
Groundspeed 2

Run 2

Groundspeed (kt)

FIM Aircraft DTG (nmi)

FIM
TGT
Groundspeed 3

Run 3

Groundspeed (kt)

FIM Aircraft DTG (nmi)

FIM
TGT
Groundspeed 5

Run 5

FIM
FIM Aircraft DTG (nmi)

Goundspeed (kt)

FIM
TGT

0
100
200
300
400
500
140
120
100
80
60
40
20
0
Groundspeed Deviation 1

![Groundspeed Deviation Graph](image)

- **Y-axis:** Groundspeed Deviation (kt)
- **X-axis:** FIM Aircraft DTG (nmi)

Legend:
- **FIM**
- **TGT**
Airspeed 1

Run 1

- ProfileCAS
- CmdCAS
- CmdEnd
- CAS

FIM Aircraft DTG (nmi) vs Airspeed (kt)
Spacing Error 1

![Graph showing Spacing Error (sec) against FIM Aircraft DTG (nmi)]
Groundspeed Deviation 2

Run 2

FIM
TGT

Groundspeed Deviation (kt)

FIM Aircraft DTG (nmi)
Airspeed 2

Run 2

- ProfileCAS
- CmdCAS
- CmdEnd
- CAS

Airspeed (kt) vs. FIM Aircraft DTG (nmi)
Spacing Error 2

Run 2

Spacing Error (sec)

FIM Aircraft DTG (nmi)
Groundspeed Deviation 3

Run 3

Groundspeed Deviation (kt)

FIM Aircraft DTG (nmi)

FIM
TGT

-80 -60 -40 -20 0 20 40 60 80
140 120 100 80 60 40 20 0
Airspeed 3

Run 3

FIM Aircraft DTG (nmi)

ProfileCAS
CmdCAS
CmdEnd
CAS
Spacing Error 3

Run 3

Spacing Error (sec)

FIM Aircraft DTG (nmi)
Groundspeed Deviation 4
Spacing Error 4

Run 4

ADS-B / ISS failure
Groundspeed Deviation 5
Spacing Error 5

Run 5

Spacing Error (sec)

FIM Aircraft DTG (nmi)
“Cleared SUBDY descent down to 5000”

Pilot: "Stuck at 5000 until Clearance"
Vertical Track Error 4

Run 4

Vertical Error (ft*1000)

FIM Aircraft DTG (nmi)

-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6

140 120 100 80 60 40 20 0

FIM
TGT
Vertical Track Error 5
Horizontal Track Error 1

Run 1

Horizontal Error (nmi)

FIM Aircraft DTG (nmi)

FIM
TGT

1.5
1
0.5
0
-0.5
-1
-1.5

140 120 100 80 60 40 20 0
Horizontal Track Error 3

Run 3

Horizontal Error (nmi)

FIM Aircraft DTG (nmi)

FIM
TGT
Horizontal Track Error 4

Run 4

- Horizontal Error (nmi)
  - FIM
  - TGT

- FIM Aircraft DTG (nmi)
Horizontal Track Error 5

Run 5

Horizontal Error (nmi)

FIM Aircraft DTG (nmi)
Test Issues

- ADS-B was experimental and circuit breaker had to be reset just prior to testing (day of concurrent testing)
- Floating point issue with the Rockwell ISS unit
- Cmd speeds on inbound track sometimes below landing airspeed limitation for B787 (155 CMD v. 165 Stall for config.)
- T-38 fuel limited: Shortcut the route and time he had available to fly – affected aircraft positioning and decision making
- T-38 was vertically challenged to dodge icing and stay within the algorithm performance
- Winds aloft were not given until in the air.
- In-trail distances ranged 22.6 nm instead of 8.5 nm (We went almost three times the planned in-trail distance range – FIM can handle slop.)
Test Issues

- Substitute pilots the day of the demonstration.
- Pilots have no reference to perform FIM, no training – compare to simulation testing in RAPTOR/CA 5.3.
- T-38 performed teardrop entries, B787 didn’t
- T-38 was GPS limited: Entered MWH, not KMWH to prevent flight plan termination. No time/ability to re-input everything.
- ATC re-input new flight plans after every run - High workload.
- Other conversations on a single party line meant waiting to issue speed commands, sometimes 20-30 seconds.
- B787 overly aggressive with the speed brakes on initial run, then under aggressive on subsequent runs.
- Simulation studies designed the simulated aircraft to fly route to the runway. Unintended consequence: No summary log if the aircraft doesn’t land.
Safety Issues

• Fuel leak in one of the wings, while being fixed a second leak was discovered. Boeing suggested they would fly off the gas in the other wing and central tank. (not discussed in prebrief)

• Icing along route using an aircraft not equipped with deice

• 1 out of 2 radios lost at startup on T-38 – Pilot could either communicate with ATC or the B787, but not both. He decided if he declared it, the test would get cancelled.

• Resulted in ATC confusion, because T-38 was communicating when not expected. (B787 was communications leader)

• B787 was eager to get to same frequency with T-38 because it was the only way either could know what the other a/c was doing (or else T-38 had to leave ATC frequency)
Lessons Learned

• Key logging for the Flight Test Gateway output (when we check to see where aircraft are located in reference to us)
  - Allows for a point of reference
• Streamline route building, testing, and packaging
• Realtime .kmz graphics on Google Earth
• Color coordination on the .kmz files to recognize On/Activate/Execute periods graphically
• Large database for queries to pull in different data sets
• Training – Better pilot understanding of FIM and test setup. If one does teardrop, then “follow the leader”.
• Summary logs without Weight-on-Wheels
Lessons Learned

- We have all the ADS-B data for other aircraft while we flew.

- We can build new custom routes that allow us to FIM behind them in simulation and further verify our software and algorithm.
Lessons Learned

- ASTAR In/Out data
- ERAM displays from Seattle Center
- Boeing providing flight deck display videos and timestamp
- Analysis meeting scheduled Friday, Jan. 30, 2015 to discuss gathered data