Analysis of the Use of Estimated Time of Arrival Broadcast for Interval Management

*Air Traffic Management Research and Development Seminar*

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Outline

- Interval Management Background
- Research Objective
- ETA Discussion
- Simulation Details
- Results
- Conclusions
- Future Work
Interval Management Background

- ADS-B Enabled Next-Gen Application
- Achieves more precise inter-aircraft spacing
- More precise inter-aircraft spacing translates to greater arrival throughput
Interval Management Background

- IM Aircraft implements speed commands from IM avionics to meet ASG at Achieve-by Point
- Speed commands calculated by IM control law
- Control law nulls the error between Target Aircraft’s ETA and IM Aircraft’s ETA + ASG
Interval Management Background

- Avionics standards for IM were recently published to support stand-alone (Federated) IM avionics
  - IM avionics generates 4D trajectories for IM and Target Aircraft
    - Uses assumed decelerations and flight-path angles to generate kinematic 4D trajectories
    - Uncertainties are bounded by procedural altitude and speed constraints
  - ETA for Target Aircraft calculated by IM avionics using predicted 4D trajectory of Target Aircraft

- Can be challenging to calculate an accurate ETA for Target Aircraft
  - Uncertainties in modeling parameters
    - Forecast wind speeds
    - Aircraft performance parameters
  - Uncertainty grows with distance to prediction point
Research Objective

- IM control law needs an ETA for Target Aircraft

- Avionics standards require IM avionics to calculate 4D trajectory for Target Aircraft
  - Accomplished using waypoint altitude and speed constraints on Target Aircraft’s route
  - ETA is calculated from 4D trajectory

- Problem: Uncertainties in Target Aircraft’s route may lead to inaccuracies in ETA

- Objective: Explore performance benefits of a more accurate ETA for Target Aircraft
Obtaining Target Aircraft’s ETA

As specified in Minimum Operational Performance Standards (MOPS) for IM:

- IM avionics generates 4D trajectories for Target Aircraft
  - Uses assumed decelerations and flight-path angles to generate kinematic 4D trajectories
  - Uncertainty bounded by procedural altitude and speed constraints
  - Uses forecast and sensed winds along the IM aircraft’s route

As envisioned in an advanced environment:

- Target Aircraft to broadcast its FMS-calculated ETA using ADS-B
  - Broadcast rates of once per 1-, 10-, and 15-second intervals
- Air/ground trajectory synchronization
  - Includes any delay allocated by the ground system
- Uses forecast and sensed winds along the Target aircraft’s route
ETA Calculations for Target Aircraft

- **Current Environment**
  - ETA calculated by IM avionics using
    - Kinematic equations of motion
    - Altitude and speed constraints on Target’s RNAV procedure
    - Assumed deceleration rates and flight path angles
  - Uses forecast winds along IM aircraft’s route and updates with IM aircraft’s sensed winds
  - Full trajectory update occurs when current winds sufficiently differ from forecast winds
  - At the Achieve-by Point only
  - No knowledge of delay

- **Advanced Environment**
  - ETA calculated by Target’s FMS using
    - Kinetic equations of motion
    - Altitude and speed constraints on Target’s RNAV procedure
    - Target aircraft’s actual performance parameters
  - Uses forecast winds along Target aircraft’s route and updates with Target aircraft’s sensed winds
  - Full trajectory update occurs when current winds sufficiently differ from forecast winds
  - Target broadcasts current ETA once per 1-, 10-, and 15-second intervals (all three cases considered separately)
  - At the Achieve-by Point only
  - Includes knowledge of delay
# Sources of Uncertainty in ETA

<table>
<thead>
<tr>
<th>Aircraft Performance Parameters</th>
<th>Winds On Target Aircraft’s Route</th>
<th>Delay Resulting from Metering Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumes deceleration rates and flight path angles</td>
<td>Uses IM Aircraft’s winds to predict Target Aircraft’s winds</td>
<td>No knowledge of delay assigned to Target Aircraft</td>
</tr>
<tr>
<td>Kinematic equations of motion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uses aircraft specific performance parameters</td>
<td>Uses Target Aircraft’s winds</td>
<td>Air/ground trajectory synchronization enables knowledge of delay assigned to Target Aircraft</td>
</tr>
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<td>Kinetic equations of motion</td>
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</table>
Simulation Details
Environment Overview

- Time-based with fixed 1 Hz step size
- 3-DOF kinetic aircraft model
  - Aircraft types modeled using BADA
- Models major functions of a commercial FMS
  - Trajectory prediction
  - Lateral and vertical guidance and control
- Uses sample algorithm from IM MOPS to generate IM speed guidance
- Winds from NOAA RUC/RAP wind product
  - True winds simulated using 0-hour forecast
  - Forecast winds simulated using 3-hour forecast
- Standard atmosphere model for all pressure, temperature, and density calculations
Simulation Details
IM Control Law

- Uses control law from IM MOPS

- Predicted spacing error is difference in ETAs at the Achieve-by Point and desired spacing interval, $\Delta$:
  \[
  e(t) = ETA_{IM}(t) - ETA_{TARGET}(t) - \Delta
  \]

- Desired ETA of IM Aircraft:
  \[
  ETA_{IM}^*(t) = ETA_{TARGET}(t) + \Delta
  \]

- Spacing control law tracks reference CAS and position:
  \[
  V_{cmd} = V_{IM}^*(ETA_{IM}^*(t)) + k[s_{IM}^*(ETA_{IM}^*(t)) - s_{IM}(t)]
  \]
  where $s$ is along-path position of the aircraft
Simulation Details
Scenario Outline

- 60 wind conditions
  - Winds were chosen randomly and uniformly to include dates from all months in 2012 and 2013

- 6 aircraft types
  - A319, A320, B737-700, B757-200, B767-300, CRJ9

- Pre-conditioning of aircraft pairs
  - Nominal schedule established from true trajectory times in specific wind conditions
  - Gaussian initial errors ($\mu = 0, \sigma = 20\ sec$)

- First aircraft delay is modeled by adjusting the RNAV procedural speed constraints so that the aircraft flies a slower speed profile
  - Results in approximately 30 seconds of delay for Target Aircraft

- Uniformly distributed delay conditions between 0 and 30 seconds for each aircraft in the string except the first aircraft
Simulation Details
Routes & Delay Allocation

- **KPHX Arrivals**
  - EAGUL5, GALLUP
  - KOOLY4, SSO
  - Merge point at YOKXO

- **Achieve-by Point & Planned Termination Point** are collocated at YOKXO

- **Delay is simulated by reducing speed constraints** at EAGUL, PAYSO, and TINIZ by 10 knots
Results

Metrics

- **Spacing performance at the Achieve-by Point**
  - Measured as the 95% bound on the absolute spacing error
    \[
    Spacing \ Error(ABP) = t_{IM}(ABP) - (t_{Target}(ABP) + \Delta)
    \]
  - IM MOPS specifies that the IM tolerance is 10 sec, 95%

- **Reliability measure**
  - Percentage of IM operations where spacing performance is less than
    - 10 seconds
    - 15 seconds
### Results

**Metrics**

- **Aggregate metrics show little improvement in advanced environment**

<table>
<thead>
<tr>
<th></th>
<th>Delivery Accuracy (sec, 95%)</th>
<th>Reliability: 10 Seconds (%)</th>
<th>Reliability: 15 Seconds (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current IM Environment</td>
<td>5.65</td>
<td>99.73%</td>
<td>99.95%</td>
</tr>
<tr>
<td>Advanced IM Environment – 1 Second Update</td>
<td>5.18</td>
<td>99.77%</td>
<td>99.91%</td>
</tr>
<tr>
<td>Advanced IM Environment – 10 Second Update</td>
<td>5.19</td>
<td>99.78%</td>
<td>99.91%</td>
</tr>
<tr>
<td>Advanced IM Environment – 15 Second Update</td>
<td>5.18</td>
<td>99.76%</td>
<td>99.90%</td>
</tr>
</tbody>
</table>
Results
Spacing Performance by Wind Condition

- No easily identifiable trends by wind condition
**Results**

**Spacing Performance by String Position**

- Some improvement between current and advanced environment, but improvement is negligible over the course of the string

<table>
<thead>
<tr>
<th></th>
<th>IM Aircraft 1</th>
<th>IM Aircraft 2</th>
<th>IM Aircraft 3</th>
<th>IM Aircraft 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current IM Environment</td>
<td>5.16</td>
<td>5.51</td>
<td>5.41</td>
<td>6.36</td>
</tr>
<tr>
<td>Advanced IM Environment – 1 Second Update</td>
<td>4.40</td>
<td>4.81</td>
<td>5.24</td>
<td>5.93</td>
</tr>
<tr>
<td>Advanced IM Environment – 10 Second Update</td>
<td>4.39</td>
<td>4.84</td>
<td>5.21</td>
<td>5.93</td>
</tr>
<tr>
<td>Advanced IM Environment – 15 Second Update</td>
<td>4.39</td>
<td>4.81</td>
<td>5.19</td>
<td>5.95</td>
</tr>
</tbody>
</table>
Results
Trajectory Analysis

- Differences due to assumed and actual information
- Differences due to Target Aircraft delay
- Differences due to Kinematic (IM avionics) vs Kinetic (FMS) trajectories
Results
Predicted Flight Time Change

- Reflects the amount of error the IM avionics needed to correct at any given point along the IM aircraft’s route

\[
\text{Predicted Flight Time Change}(x_{IM}) = \text{ETA}_{IM}(x_{IM}) - \left( t_{Target}(ABP) + \Delta \right)
\]
Results
Predicted Flight Time Change

- 95% bounds on absolute value of Predicted Flight Time Change in current and advanced environments

- Minimal differences due to constrained procedures and limited scope of simulation
Results
Predicted Flight Time Change

- 95% bounds on absolute value of Predicted Flight Time Change for 1-, 10-, and 15-second ETA broadcast update rate

- Differences are too small to be seen

- Minimal differences due to length of time between full Target trajectory updates
Conclusions

- An advanced environment that includes ETAs broadcast by the Target Aircraft and air/ground synchronization offers little IM performance benefit over the current environment
  - In spite of uncertainties present when IM avionics calculates ETA for Target Aircraft

- Minimal performance benefit likely due to
  - The use of highly-constrained RNAV routes
  - Limited scope of the simulation (one geographic location)
    - i.e., bigger performance differences may be observed when subject to different wind conditions and route geometries

- Negligible differences between different update rates
  - Due in part to the amount of time between full Target trajectory updates
Future Work

- Quantify tolerable uncertainty in:
  - Wind forecast errors for Target Aircraft when using IM Aircraft’s winds
  - Amount of unknown delay allocated to Target aircraft

- Understand the degree to which Target Aircraft’s RNAV procedure must be constrained

- Compare Target Aircraft full trajectory update rates to actual FMS update rates to determine if the impact of broadcast rate should be examined further