Strategic Design of Long-Haul and Oceanic Aircraft Trajectories in Aviation Operations

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Inefficiencies in Air Traffic Routes

• Aircraft cruise along a horizontal route with a predetermined altitude and speed
• Aircraft route deviates from direct route due to several constraints
  – Terminal area constraints, congested airspace, special use airspace, weather disturbances
• In 2007, routes used by aircraft between top 35 airports in US were 2.9% greater than direct routes
• Similar figure was 4% for top 34 city-pairs in Europe
• Extra distance over direct routes higher for oceanic flights due to lack of radar surveillance and strict entry/exit points
Previous Research

• Extensive literature on developing optimal trajectories for an aircraft that minimize a cost function while satisfying constraints
  – Aircraft models of various complexity, with or without wind
  – Minimum fuel, minimum time, minimize direct operating cost
  – Avoid bad weather, traffic congestion

• Most of the system-wide benefits analysis done under no wind conditions

• Research on reduced oceanic separation standards
  – Better cruise altitudes due to less blockage during climb leading to higher fuel efficiency

• Several flight tests involving city-pairs in US, Europe and Asia
What is this talk about?

• Provide system-wide benefits analysis of wind-optimal routes for long-haul and oceanic aircraft operations
  – Compare the difference between current routes and wind optimal routes
  – Identify city pairs with highest benefit potential and challenge

• Solicit feedback from airline operations staff
  – Impact of airspace costs

• Describe the development of a global air traffic simulation model and applications using this model
Outline

• Strategic Trajectory Design
• Simulation Design
• North Atlantic Operations
• Global Aviation Operations
• Conclusions
Strategic Trajectory Design Considerations
Optimal trajectory using horizontal maneuvers

- Point mass aircraft model
- Find the optimal trajectory given the arrival and departure airports, cruise speed and wind conditions subject to environmental conditions
- Cruise altitude of a flight generally varies from 29,000 ft to 41,000 ft with 6 (12 with RVSM) possible choice of altitude in each direction
- Problem solved by solving several two-dimensional problems

\[
\begin{align*}
\dot{x} &= V \cos \theta + u(x,y) \\
\dot{y} &= V \sin \theta + v(x,y) \\
T &= D = qSC_{d0} + qSKC_L^2 \\
L &= W \\
q &= \frac{1}{2} \rho V^2 \\
\dot{m} &= -f(h,V,T)
\end{align*}
\]
Optimization Subject to Weather/Environmental Constraints

- Optimize horizontal trajectory by determining the heading angle that minimizes the cost function

$$J = \frac{1}{2} X^T (t_f) M X (t_f) + \int_{t_0}^{t_f} \left[ C_t + C_f f + C_r \cdot r(x, y) \right] dt$$

- Solution reduces to solving

$$\begin{align*}
\dot{x} &= V \cos \theta + u(x, y) \\
\dot{y} &= V \sin \theta + v(x, y) \\
\dot{\theta} &= \frac{(V + u(x, y) \cos \theta + v(x, y) \sin \theta)}{(C_t + C_f f + C_r r(x, y))} (-C_r \sin \theta \frac{\partial r(x, y)}{\partial x} + C_r \cos \theta \frac{\partial r(x, y)}{\partial y}) \\
&\quad + \sin^2 \theta \left( \frac{\partial v(x, y)}{\partial x} \right) + \sin \theta \cos \theta \left( \frac{\partial u(x, y)}{\partial x} - \frac{\partial v(x, y)}{\partial y} \right) - \cos^2 \theta \left( \frac{\partial u(x, y)}{\partial y} \right)
\end{align*}$$

- Cost function can be modified to add other conditions
Air Traffic Simulation: Future ATM Concept Evaluation Tool (FACET)

- TFMS
- NOAA
- Weather
- Other Info. Sources
- Aircraft Performance Data
- Adaptation Data
- Winds
- Flight plans & Positions
- Climb
- Cruise
- Descent
- Centers
- Sectors
- Airways
- Airports
- Route Parser & Trajectory Predictor
- User Interface
- Traffic & Route Analyzer
- Conflict Detection & Resolution
- Direct-To Routing Analysis
- Air and Space Traffic Integration
- System-Wide Evaluation Tool
- System-Level Optimization
# Simulation of Baseline and Wind-Optimal Aircraft Trajectories

**Flight Schedules**

**Atmospheric and Air Space Data**

**Future ATM Concepts Evaluation Tool (FACET)**

**Visualization and Analysis of Aircraft Operations**

<table>
<thead>
<tr>
<th>Feature</th>
<th>US</th>
<th>Global</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft Models</td>
<td>BADA</td>
<td>BADA</td>
</tr>
<tr>
<td>Data types</td>
<td>Rapid Update Cycle 13</td>
<td>Global Forecast System</td>
</tr>
<tr>
<td>Domain</td>
<td>CONUS</td>
<td>Global</td>
</tr>
<tr>
<td>Frequency</td>
<td>1 hour</td>
<td>6 hours</td>
</tr>
<tr>
<td>Forecasts</td>
<td>Up to 2 days</td>
<td>Up to 16 days</td>
</tr>
<tr>
<td>Horizontal</td>
<td>13km x 13km</td>
<td>0.5deg x 0.5deg</td>
</tr>
<tr>
<td>Vertical</td>
<td>37 levels</td>
<td>64 levels</td>
</tr>
<tr>
<td>Flight Plans</td>
<td>TFMS</td>
<td>OAG data</td>
</tr>
</tbody>
</table>
Options for Baseline Trajectories

• Filed Flight Plan with a single designator “NATY” representing the changing North Atlantic Track
• Recorded track data from FAA’s Enhanced Traffic Management System (ETMS)
• Recorded track data from Eurocontrol’s Network Manager (Former Central Flow Management Unit)
• Combined ETMS and Network Manager track data complementing the accuracy of ETMS over US and Network Manager over Europe
North Atlantic Operations
Oceanic Flights: How are they different from flights within a country?

- Long highly profitable routes
- Lack of radar coverage and strict entry/exit points
- Separation Standards (New York Oceanic Airspace)
  - Separation Minima 50 NM longitudinal for RNP-10 aircraft
  - More stringent Performance Based Navigation (PBN), Communication by data link (CPDLC) and monitoring of position information by ADS-C is reducing separation standards
  - Separation Minima reduced to 30 NM lateral and 30 NM longitudinal for authorized RNP-4 aircraft (December 2013)
- Lack of uniformity in traffic flow management systems creates inefficiencies and controller workload
- Result
  - Inability to climb to optimum altitude
  - Limited use of wind-optimal routes or user preferred routing
- Good News: US (Nextgen) and Europe (SESAR) making improvements in all these areas
North Atlantic Airspace Operations

- 460,000 flights/year
  - Cruise between 29,000-41,000 feet
  - Airspace congested due to large separation and narrow fuel-efficient flight levels

- North Atlantic Tracks (NAT)
  - Westbound (magenta)
  - Eastbound (cyan)

- Tracks published daily for each major flow
Aircraft Trajectories from Newark to Frankfurt

- Cruise trajectories use typical aircraft models for Boeing 757-200 with medium take off weight
• Benefits vary significantly from day to day to depending on the winds
• Mean fuel savings: 2.4% (Eastbound), 2.2% (Westbound)
• Smaller standard deviation for Westbound flights (1% versus 1.8% for Eastbound flights)
Mean Fuel Savings For Most Frequent City Pairs during July 2012

### Top 10 Airport Pairs

<table>
<thead>
<tr>
<th>Rank</th>
<th>Origin-City Pair</th>
<th>Rank</th>
<th>Destination-City Pair</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>New York/London</td>
<td>6</td>
<td>Boston/London</td>
</tr>
<tr>
<td>2</td>
<td>New York/Paris</td>
<td>7</td>
<td>Washington, DC/London</td>
</tr>
<tr>
<td>3</td>
<td>Newark/London</td>
<td>8</td>
<td>Chicago/Frankfurt</td>
</tr>
<tr>
<td>4</td>
<td>Chicago/London</td>
<td>9</td>
<td>San Francisco/London</td>
</tr>
<tr>
<td>5</td>
<td>Los Angeles/London</td>
<td>10</td>
<td>New York/Madrid</td>
</tr>
</tbody>
</table>

### Mean Savings, %

<table>
<thead>
<tr>
<th>Mean savings, %</th>
<th>Eastbound</th>
<th>Westbound</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td>2</td>
<td>3.0</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>4</td>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td>5</td>
<td>3.0</td>
<td>2.5</td>
</tr>
<tr>
<td>6</td>
<td>3.5</td>
<td>3.0</td>
</tr>
<tr>
<td>7</td>
<td>3.0</td>
<td>3.5</td>
</tr>
<tr>
<td>8</td>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td>9</td>
<td>3.0</td>
<td>2.5</td>
</tr>
<tr>
<td>10</td>
<td>3.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>
Fuel Savings Between City Pairs (July 2012)

Eastbound

Westbound

Mean savings, %

Top 100 airport pairs

Atlanta/Paris

Lisbon/Newark
## Highest Potential Fuel Savings

<table>
<thead>
<tr>
<th>Airport Pairs</th>
<th>Rank</th>
<th>Savings (%)</th>
<th>Aircraft/ (Rank)</th>
<th>Baseline Fuel (kg)</th>
<th>Savings (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KATL-LFPG</td>
<td>1</td>
<td>10.6</td>
<td>B767-300 (1)</td>
<td>34,500</td>
<td>3,660</td>
</tr>
<tr>
<td>KCLT-EDDF</td>
<td>2</td>
<td>7.4</td>
<td>A330-300 (4)</td>
<td>41,700</td>
<td>3,090</td>
</tr>
<tr>
<td>KSFO-EDDF</td>
<td>3</td>
<td>7.3</td>
<td>B777-200 (2)</td>
<td>56,400</td>
<td>4,120</td>
</tr>
<tr>
<td>KSEA-EHAM</td>
<td>4</td>
<td>6.1</td>
<td>B767-300 (1)</td>
<td>34,800</td>
<td>2,120</td>
</tr>
<tr>
<td>KORD-EGLL</td>
<td>5</td>
<td>6.0</td>
<td>B767-300 (1)</td>
<td>32,200</td>
<td>1,930</td>
</tr>
<tr>
<td>KMIA-EHAM</td>
<td>6</td>
<td>5.4</td>
<td>B767-300 (1)</td>
<td>30,900</td>
<td>1,670</td>
</tr>
<tr>
<td>LPPT-KEWR</td>
<td>1</td>
<td>5.8</td>
<td>B757-200 (5)</td>
<td>18,500</td>
<td>1,070</td>
</tr>
<tr>
<td>LLBG-KPHL</td>
<td>2</td>
<td>4.2</td>
<td>A330-200 (6)</td>
<td>53,100</td>
<td>2,230</td>
</tr>
<tr>
<td>LEMD-KMIA</td>
<td>3</td>
<td>4.0</td>
<td>B767-300 (1)</td>
<td>32,200</td>
<td>1,288</td>
</tr>
<tr>
<td>LEMD-KJFK</td>
<td>4</td>
<td>3.5</td>
<td>A340-300 (7)</td>
<td>37,800</td>
<td>1,320</td>
</tr>
<tr>
<td>LFPG-KMIA</td>
<td>5</td>
<td>3.4</td>
<td>B767-300 (1)</td>
<td>34,800</td>
<td>1,180</td>
</tr>
<tr>
<td>EIDW-KPHL</td>
<td>6</td>
<td>3.3</td>
<td>B757-200 (5)</td>
<td>18,100</td>
<td>600</td>
</tr>
</tbody>
</table>

Paris (LFPG), Frankfurt (EDDF), Amsterdam (EHAM), London (EGLL), Lisbon (LPPT), Tel Aviv (LLBG), Madrid (LEMD), Dublin (EIDW), Atlanta (KATL), KLCT (Charlotte), KSFO (San Francisco), KSEA (Seattle), KORD (Chicago), KMIA (Miami), KEWR (Newark), KPHL (Philadelphia), KJFK (New York)
Separation Minima

- Organized Track System (OTS)
  - Vertical separation: 1000 feet (flight level assignment)
  - Lateral separation: 60 NM (ensured by track design)
  - Longitudinal separation: 10 minutes (track entry time and speed)

- Future modernized ATC system
  - Move away from OTS
  - Vertical separation: 1000 feet
  - Horizontal separation: 30 NM
  - Time separation: 3 minutes

Potential conflicts in the horizontal plane:

\[ \Phi_{ik} = 2 \]

Aircraft protection zone
De-confliction Strategy

• Four-dimensional grid for conflict detection
  – Two aircraft located in the same cell indicates a potential conflict
  – Sampling time step ($\Delta T$) = 1 min (Assuming $V_{\text{max}} = 600\text{kts}$, $\Delta T < 3\text{ min}$)

• Results based on reducing conflicts by adjusting departure times within limits (0-30 min) to time shift trajectory while maintaining wind-optimal routing properties

• Optimization algorithm for conflict resolution
  – Simulated annealing with local gradient search
• Number of potential conflicts distributed over different regions and time
• Other Approaches: Combination of delay on the ground and rerouting
- Boeing 767-300 with medium take off weight; Cruise FL 350; 480 knots, 3.5% potential fuel savings = 1,200 kg
- Air Navigation Service Providers (ANSP) and Airports charge airlines for their services
Air Navigation Service Providers (ANSP) and airports charge airlines for en route, terminal and communication charges.

Determines the aircraft heading angles subject to the airspace charge model and en-route wind conditions to minimize the total operating cost:

\[ J = \int_{t_0}^{t_f} \left[ C_t + C_f f(m, h) + U_{ei} f_{ei}(MTOW)V \right] dt \]

Airspace charge for a country \( i = U_{ei} f_{ei}(MTOW) d_i \)

eg. \( f_{ei} = (MTOW / 50)^{50} \)

\( U_{ei} = 35 \text{ cents/km over continental US} \)

and = 13 cents/km in the oceanic airspace

MTOW = Maximum Take-off weight
Airspace Charges (Boeing 747-400)

X-axis: Longitude
Y-axis: Latitude
Bar: $/km

---- Fixed Cost

US

Atlantic Ocean

Europe

$57.6
$93.2
$57.6

$57.6

$57.6

$57.6

$57.6

$57.6

$57.6
Transatlantic Optimal Trajectories
Chicago to London

August 18, 2014
### Transatlantic Optimal Trajectories

**Chicago to London**

<table>
<thead>
<tr>
<th>Trajectory Type</th>
<th>Fuel Burn (kg)</th>
<th>Airspace Distance (km)</th>
<th>Airspace Charges ($1,400)</th>
<th>Fuel Cost ($51,700)</th>
<th>Total Cost ($53,100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Track</td>
<td>56,800</td>
<td>4,474</td>
<td>$1,400</td>
<td>$51,700</td>
<td>$53,100</td>
</tr>
<tr>
<td>Fuel-optimal</td>
<td>55,100</td>
<td>5,383</td>
<td>$1,800</td>
<td>$50,200</td>
<td>$52,000</td>
</tr>
<tr>
<td>Cost-optimal</td>
<td>55,600</td>
<td>5,040</td>
<td>$1,400</td>
<td>$50,600</td>
<td>$52,000</td>
</tr>
</tbody>
</table>

- **Cost-optimal Route**
- **Fuel-optimal Route**
- **Flight Track**

**Map: Chicago to London**

- **Chicago**
- **London**
- **SONDRESTROM**
- **REYKJAVIK**
- **EISN**
- **NEW YORK**
- **SANTA MARIA**
Potential Daily Savings Over Baseline Flight Track

24,994 transatlantic flights during July 2012; varied daily 706-855 flights

- Save 2,070 metric tons CO₂ emissions
- Daily Savings

Cost-optimal Trajectory
Fuel-optimal Trajectory

Airspace Charge
Fuel Cost
Total Cost

$ Thousands

-100
100
300
500
700
900
1100
Optimal Trajectory Daily Cost Difference

Fuel-optimal Trajectory - Cost-optimal Trajectory

- Produces additional 623 metric tons CO$_2$ emissions
Global Air Traffic Network

- Airports have unique 4-letter designation
  - First and second letter indicates continent/country/region
  - London Heathrow (EGLL), Chicago O’Hare (KORD)

- Global air traffic between airports can be captured as traffic flow between airports located within and between 23 regions (3 letters of the alphabet I,J and X are not used)

- 23 Regions grouped into 6
  - North America (US, Canada, Mexico, Alaska, Caribbean)
  - South America
  - Europe
  - Africa
  - Mid-East/Asia (Middle East, Russia, China, India)
  - Pacific Ocean (Australia, South Pacific, South-East Asia)
### Busiest Airports and Aircraft Types (June 2014)

#### Top 10 Airports

<table>
<thead>
<tr>
<th>Rank</th>
<th>Airport</th>
<th>Total Departures and Arrivals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Chicago (KORD)</td>
<td>2,608</td>
</tr>
<tr>
<td>2</td>
<td>Atlanta (KATL)</td>
<td>2,387</td>
</tr>
<tr>
<td>3</td>
<td>Dallas (KDFW)</td>
<td>1,936</td>
</tr>
<tr>
<td>4</td>
<td>Los Angeles (KLAX)</td>
<td>1,646</td>
</tr>
<tr>
<td>5</td>
<td>Denver (KDEN)</td>
<td>1,565</td>
</tr>
<tr>
<td>6</td>
<td>Beijing (ZBAA)</td>
<td>1,488</td>
</tr>
<tr>
<td>7</td>
<td>Charlotte (KCLT)</td>
<td>1,436</td>
</tr>
<tr>
<td>8</td>
<td>Frankfurt (EDDF)</td>
<td>1,371</td>
</tr>
<tr>
<td>9</td>
<td>Houston (KIAH)</td>
<td>1,370</td>
</tr>
<tr>
<td>10</td>
<td>London (EGLL)</td>
<td>1,338</td>
</tr>
</tbody>
</table>

#### Top 10 Aircraft Types

<table>
<thead>
<tr>
<th>Rank</th>
<th>Aircraft Type</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Airbus A320</td>
<td>14,036</td>
</tr>
<tr>
<td>2</td>
<td>Boeing 737-800</td>
<td>12,252</td>
</tr>
<tr>
<td>3</td>
<td>Boeing 737-700</td>
<td>6,861</td>
</tr>
<tr>
<td>4</td>
<td>Airbus A319</td>
<td>6,279</td>
</tr>
<tr>
<td>5</td>
<td>Bombardier CRJ-900</td>
<td>4,633</td>
</tr>
<tr>
<td>6</td>
<td>Airbus A321</td>
<td>3,764</td>
</tr>
<tr>
<td>7</td>
<td>Embraer E-190</td>
<td>2,285</td>
</tr>
<tr>
<td>8</td>
<td>Bombardier DH8D</td>
<td>2,222</td>
</tr>
<tr>
<td>9</td>
<td>ATR 72</td>
<td>2,199</td>
</tr>
<tr>
<td>10</td>
<td>Embraer ERJ 140</td>
<td>1,974</td>
</tr>
</tbody>
</table>
Simulation of Global Air Traffic

- Global Air Traffic simulated using Official Airline Guide (OAG)
  - Provides aircraft type and departure times for all commercial traffic between city-pairs

42,661 flights/day, 1988

80910 flights/day, 2013
Global Air Traffic Density

- Air Traffic Density: Number of aircraft passing through each unit area in a day
Distribution of Air Traffic Between 23 Regions

- Airports in the globe have unique 4 letter designation
  - Divided into 23 regions depending on their location
  - Letters I, J and X not used
Evolution of Global Air Traffic Network between 1988, 2013 and 2034

- Airports grouped into 6 regions by location
  - North America (K,C,M,P,T), South America, Europe (E,L,B), Middle East/Asia (O,U,Z,V), Pacific Ocean Countries (Y,A,N,W,R) and Africa (H,G,D,F).

Numbers in the figure represent percentage of total global traffic.
Impact of Wind on Global Aviation Operations

- Global air traffic schedules from OAG data and wind data from GFS for first Wednesday of each month in 2010
- Long-haul flights (more than 2000 miles) inside and between six regions
Seasonal variation of Long-haul flights

- Traffic peaks during summer in NA and between NA-EU
- Flights within Mid-East/Asia has a peak in Feb-March
Wind-optimal Time Savings Over Great Circle Routes

<table>
<thead>
<tr>
<th>Region Pairs</th>
<th>NA-NA</th>
<th>MA-MA</th>
<th>PO-PO</th>
<th>PO-MA</th>
<th>MA-PO</th>
<th>EU-MA</th>
<th>MA-EU</th>
<th>EU-NA</th>
<th>NA-EU</th>
<th>NA-PO</th>
<th>PO-NA</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Flights</td>
<td>7,717</td>
<td>2,434</td>
<td>2,448</td>
<td>1,788</td>
<td>1,564</td>
<td>3,427</td>
<td>3,996</td>
<td>5,497</td>
<td>5,377</td>
<td>1,446</td>
<td>1,495</td>
</tr>
<tr>
<td>Savings &gt;10 min</td>
<td>157</td>
<td>146</td>
<td>75</td>
<td>173</td>
<td>101</td>
<td>219</td>
<td>420</td>
<td>1,772</td>
<td>992</td>
<td>632</td>
<td>588</td>
</tr>
</tbody>
</table>
Concluding Remarks

- Aviation is the glue for conducting economic activity in the globe
- Aircraft Manufacturers, Airlines, Air Navigation Service Providers and Government Organizations need national, regional and global Air Traffic Management (ATM) models to make policy and investment decisions
- Described the development of a global air traffic simulation model and two applications using this model
  - Evolution of global air traffic
  - Savings from wind-optimal routes
- Simulation can be used to evaluate global strategies and policies to deal with
  - Impact of aviation emissions
  - Impact of climate on aviation
Concluding Remarks

- Extended the FACET US ATM Simulation capability to simulate global air traffic
- Presented two applications using the capability
  - Evolution of global air traffic
  - Savings from wind-optimal routes
- Simulation can be used to evaluate global strategies and policies to deal with
  - Impact of aviation emissions
  - Impact of climate on aviation
Concluding Remarks

• Developed cost-optimal trajectories for the transatlantic flights using the airspace charge model
  – Potential daily savings compared to baseline flight tracks:
    $600,000 in fuel cost, $360,000 in airspace charges, and 2,070 metric tons CO₂ emissions
  – Potential daily savings compared to fuel-optimal routs:
    -$180,000 in fuel cost, $410,000 in airspace charges, and -623 metric tons CO₂ emissions

• Identified the airport pairs and airspace regions that have the highest fuel burn reduction potential by considering airspace charges

• The difference between wind-optimal routes and cost-optimal routes increases as the fuel price decreases
What is in this talk?

• Aviation is the glue for conducting economic activity in the globe
• Aviation has an impact on climate and climate impacts aviation operations
• Aircraft Manufacturers, Airlines, Air Navigation Service Providers and Government Organizations need national, regional and global Air Traffic Management (ATM) models to make policy and investment decisions
• Many regional models of ATM and lack of global ATM models
• Describe the development of a global air traffic simulation model and applications using this model