Two perspectives on Graph-based Traffic Flow Management

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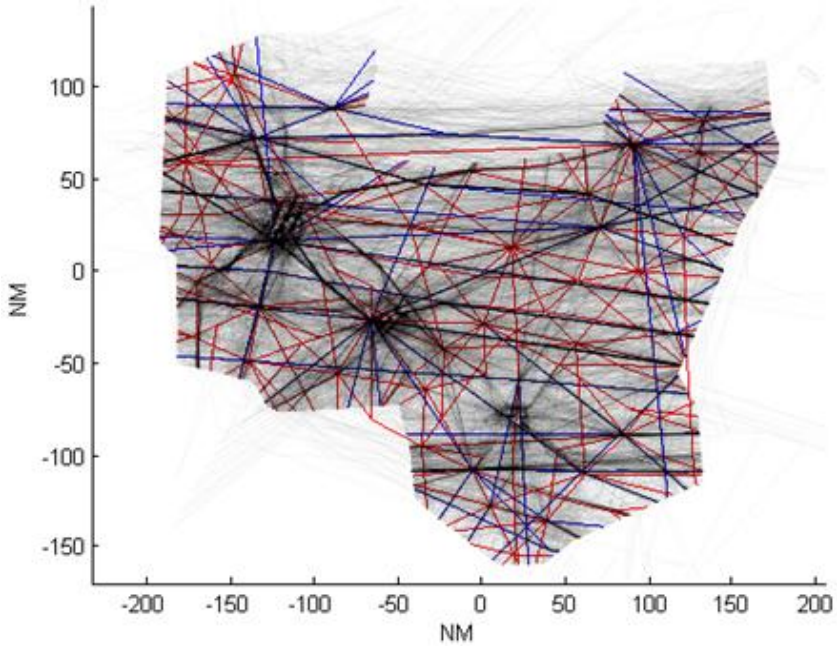
Presentation Outline

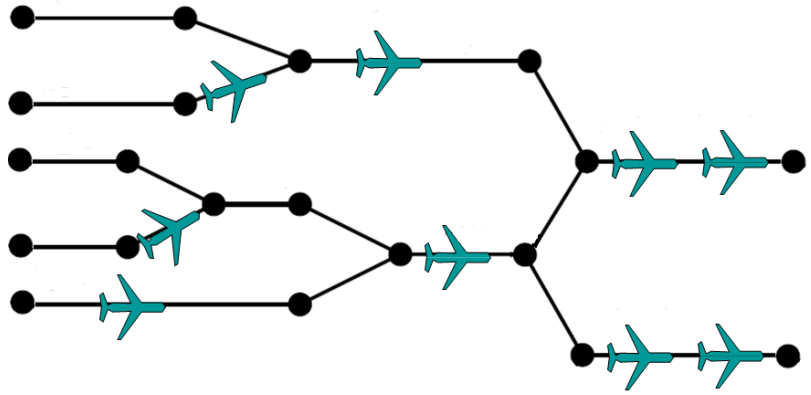
- Introduction
- Graph Abstraction of the Airspace
- Traffic Flow Management on the Network Model
- Mean Field Games Approach
- Conclusion & Future Work

Introduction : Motivation

- Expected growth of Air Transportation
- Need for decision support tools for mid-term and long-term Traffic Flow Management
- Current tools based on filed flight plans and prediction of aircraft arrival times

Introduction : Why build a TFM framework ?





Density Plot for one day of Traffic (ETMS data) compared with Air and Jet routes in the Cleveland center

- Traffic is more diverse and complex that what the air routes alone suggest.
- Need for a precise and accurate understanding of the airspace.

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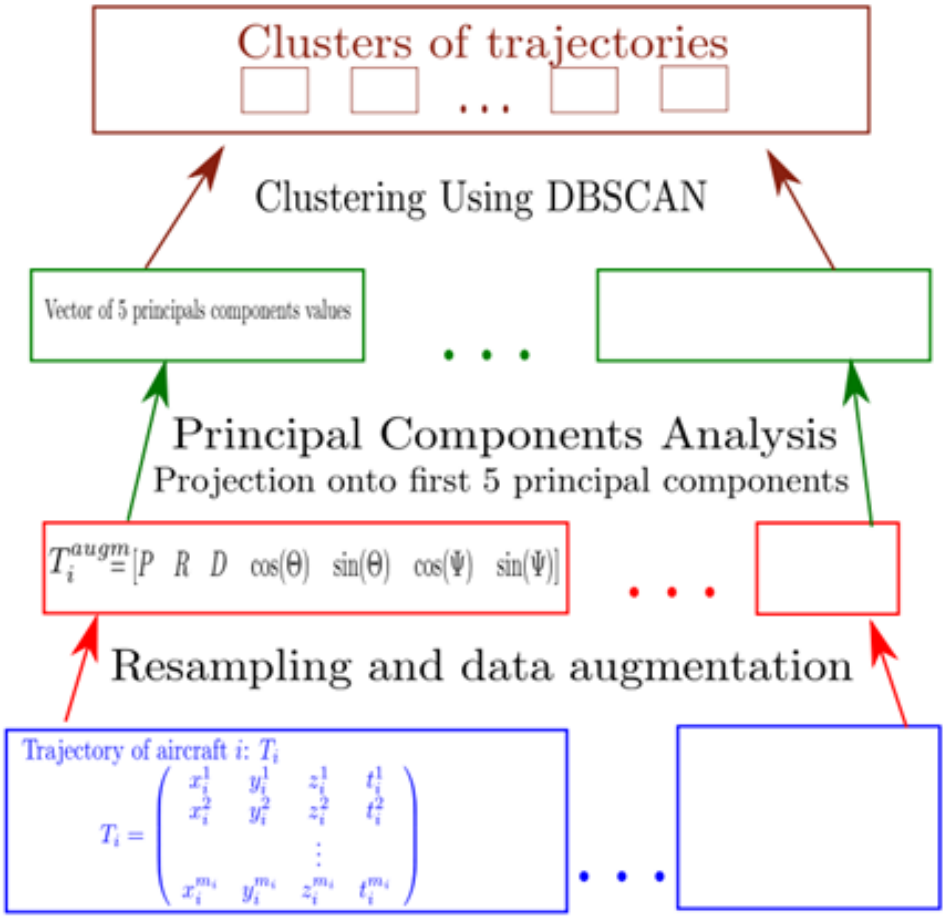
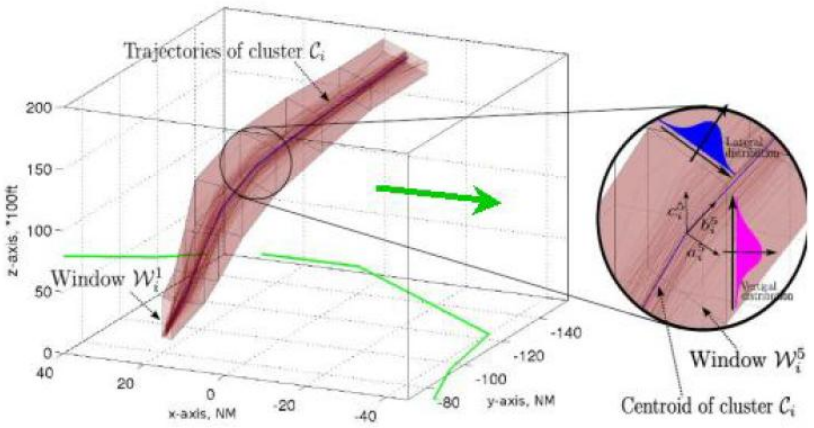
Introduction : Two Perspectives

- Goal : Optimize aircraft routing to reduce congestion and delays, while allowing more aircraft in an airspace and ensuring high safety levels
- Centralized approach to simulate realistic traffic through an airspace
- Decentralized approach to identify and forecast systemic congestion and delays caused by local interactions and strategies of aircraft

Graph Abstraction : From Trajectories to Flows





Trajectory Clustering Process (Salaun et al. 2011)

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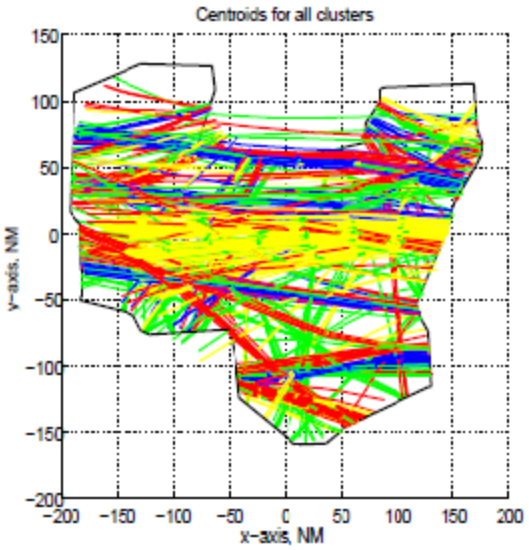
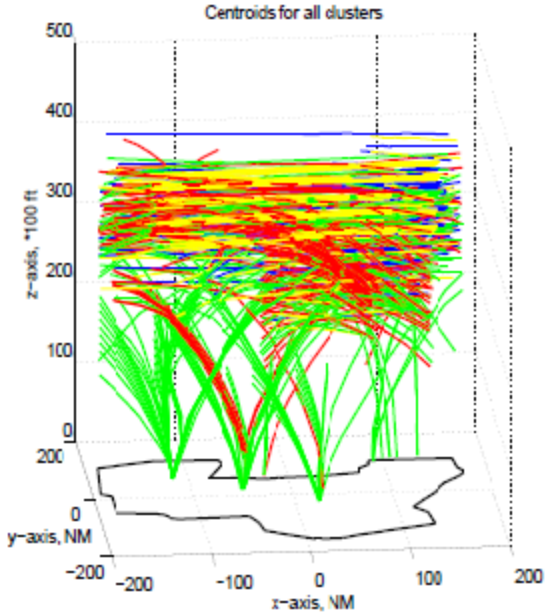
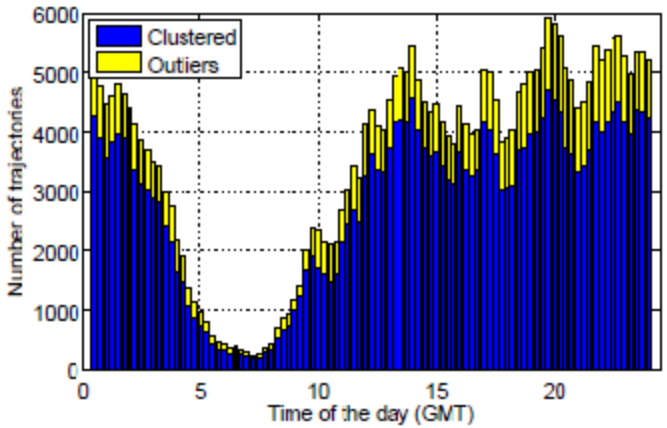
Graph Abstraction : From Trajectories to Flows







- Data set of 338,060 trajectories
- 80% of traffic clustered into 690 flows

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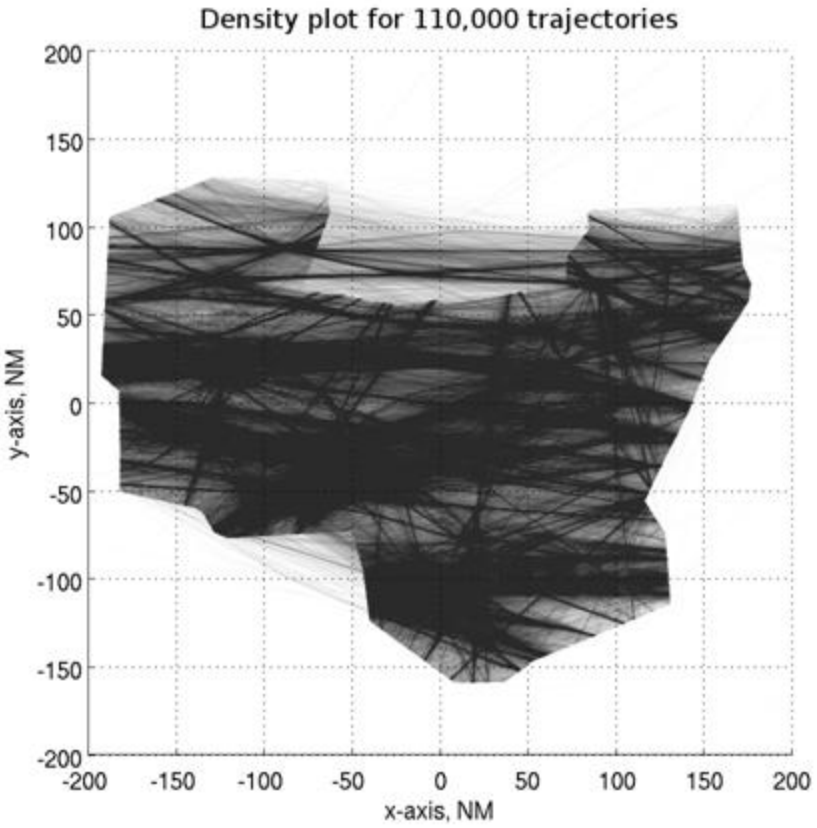
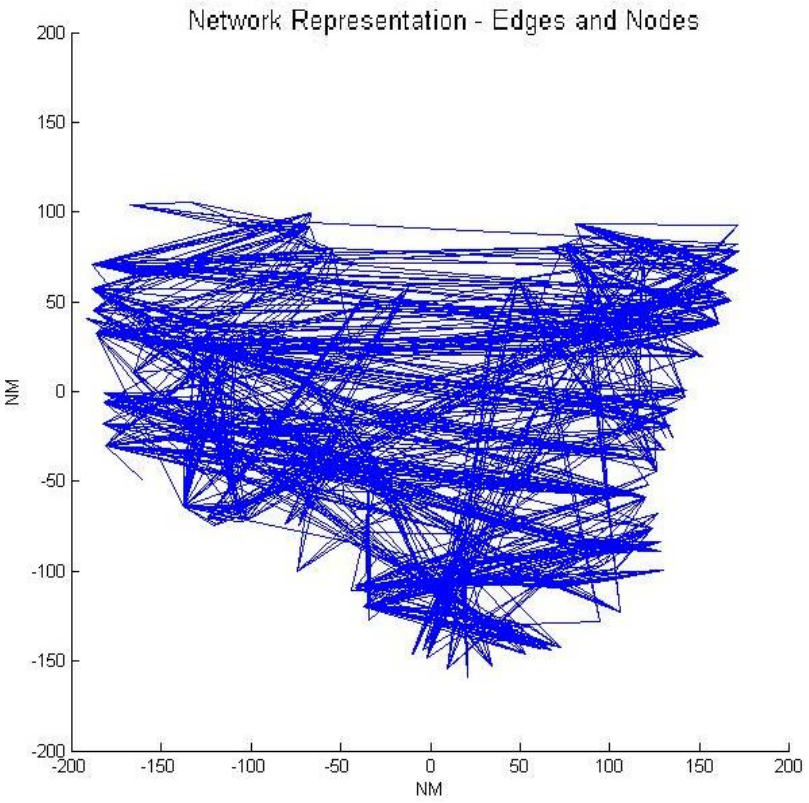
Graph Abstraction : From Flows to a directed Network

- Locate spatial areas common to different flows, and identify the ones suitable for rerouting -> 1198 inside nodes
- Define entry and exit nodes of the airspace, using k-means clustering -> 90 nodes
- Create the edges that link the nodes along the flows -> 3085 edges
- Extract the 218 origin-destination pairs inside the network from data -> 90% of traffic travels on 40% of the OD pairs

Graph Abstraction : From Flows to a directed Network





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Centralized approach : TFM on the network & Linear Formulation

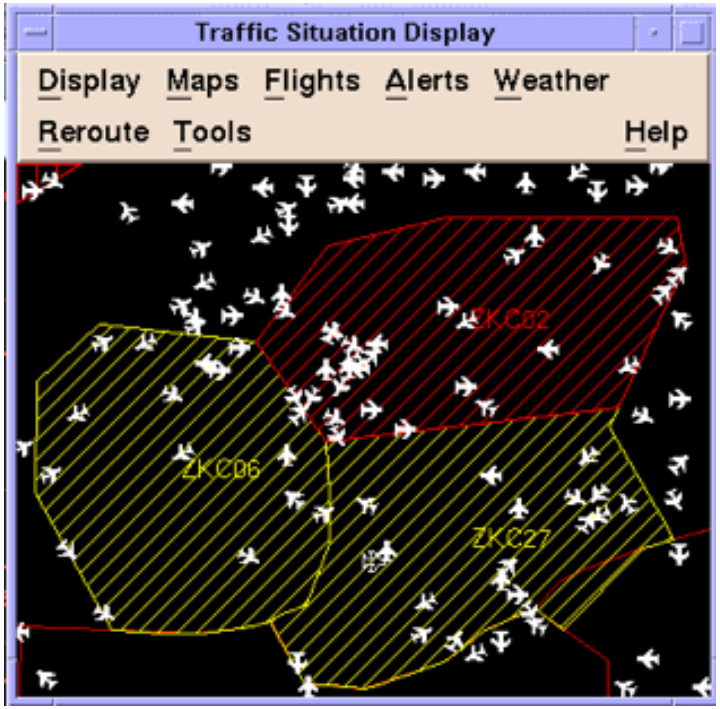
- Linear Programming Approach :

$$max\ H$$
$$subject\ to:$$
$$flow\ constraints$$
$$sector\ constraints$$

- All problems solved using CPLEX solver.
- Flow constraints : local and global conservation of flow, flow rate limited on each edge
- Linear Formulation for the Flow Constraints of about 273,000 lines.

TFM on the network : Linear Formulation & Controller Taskload

- Monitor Alert Parameter : # of aircraft allowed in a sector at any time. Approximates average workload limit of controllers
- Complexity measures provide a better indication of controller workload (e.g. Dynamic Density)
- Network formulation allows consideration of complexity



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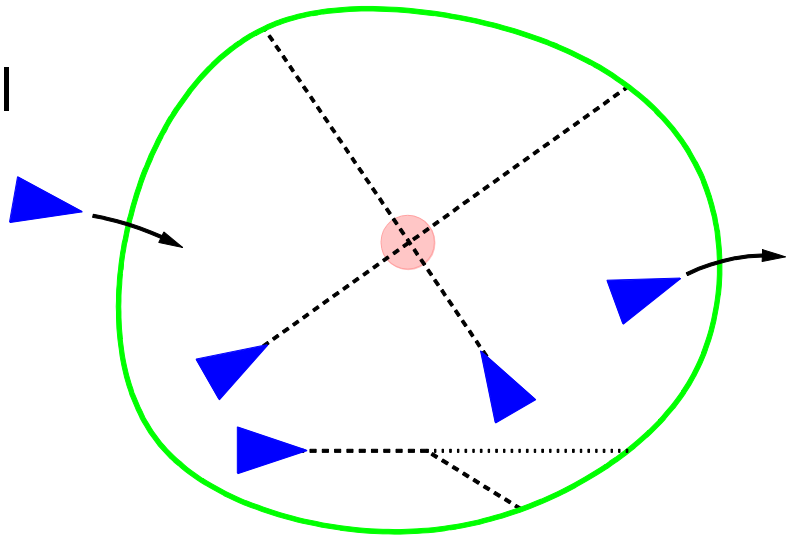
TFM on the network : Linear Formulation & Controller Taskload

- Controller Taskload Approach
  - Arrival Acknowledgements
    - Ascending/Descending/Level
  - Departure Hand-offs
  - Turning aircraft flows
  - Potential conflicts at Merges/crossings/intersections



- Taskload complexity sum the expected effort required to manage the airspace.
- Sector Constraint: $C^{total} \leq C^{allowed}$
- $C^{allowed}$: Maximum stead-state time effort of controller – 50%

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TFM on the network : Influence of sector constraints

$max \sum_{k \in \mathbf{C}} s_k$
$subject\ to:$
$flow\ constraints$

$max \sum_{k \in \mathbf{C}} s_k$
$subject\ to:$
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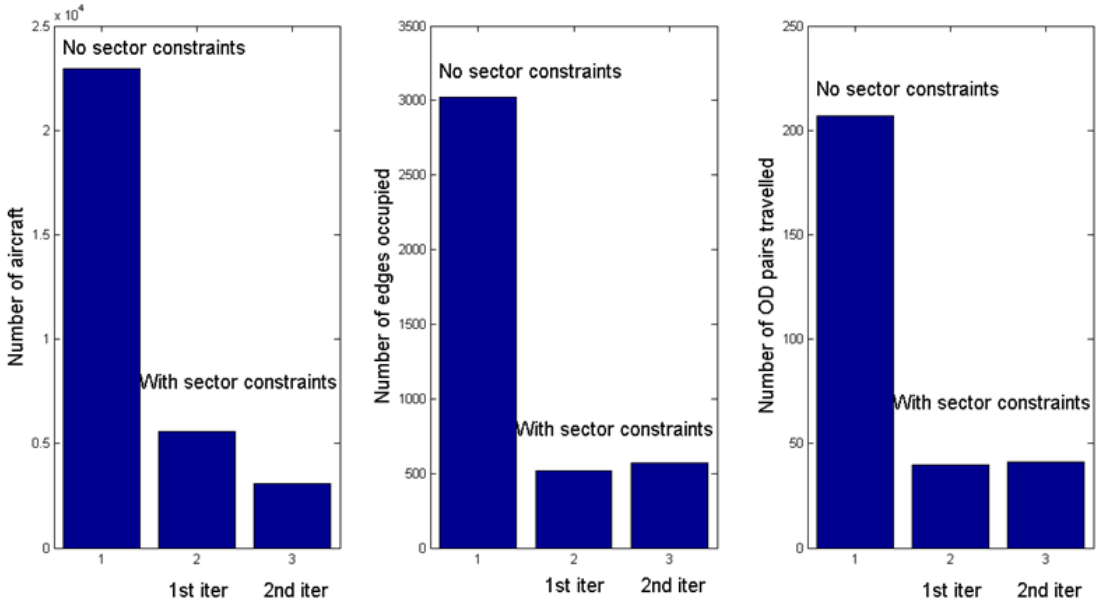

- Sector constraints limit the throughput.
- With sector constraints, the main routes only are travelled.
- When accounting for conflicts, spreading on the edges.
- Results obtained : bounds, no realistic demand pattern.

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TFM on the network : Throughput & Demand patterns

- Constriction of the throughput by demand patterns, that may or may not be accommodated
- Identification of nominal networks by data-mining
- Comparison with airspace state under weather perturbations
- Evaluation of re-routing costs
- Definition of "best routes"

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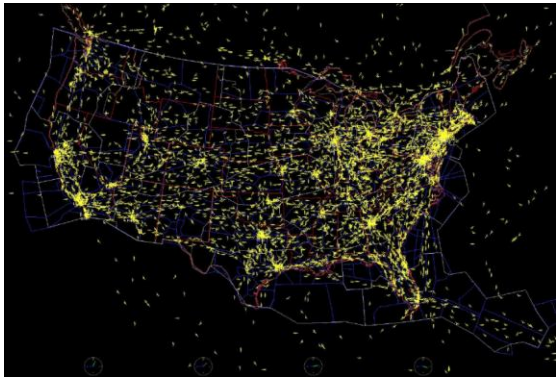
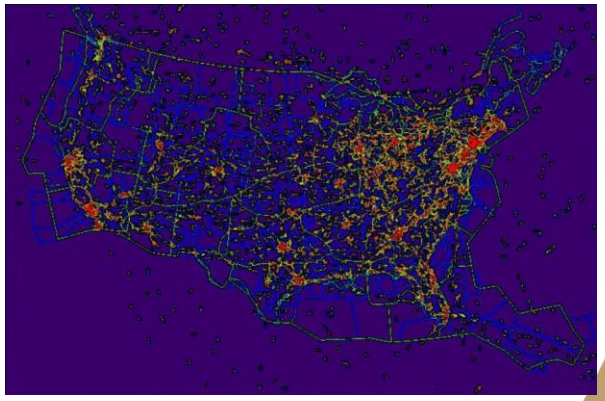
Decentralized Approach : Mean Field Games

- Mean field games refine Eulerian flow models
  - Agent preferences & strategies
  - Agent expectations (information)
  - Mixed population
- Suitable to model numerous agents with marginal influence
- Continuous density approximation





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Decentralized Approach : Mean Field Games

- Feedback coupling
  - Agent strategies vs population dynamics
  - Strategy (HJB) backward in time
  - Dynamics (FP) forward in time

- Microscopic rational agents anticipate macroscopic system dynamics
- Agents develop strategies depending on their preferences and cost
- Preferences : destination, routings
- Cost: fuel, aversion to congestion /delays

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Application of MFG to the network

- Explicit formulations in the paper
  - Quadratic cost function

$$J = \int_t^T \left[\int_\Omega \left(\frac{{\alpha_s}^2}{2} {m_s}^\beta + \lambda d^2(x, x_{gc}) \right) dm_s \right] e^{-rs} ds$$

    - Congestion aversion
    - Deviations from preferred routings
    - Discount factor
- Discretization scheme is essential
  - Semi-implicit discretization scheme
- Numerical complexity
  - Forward-backward coupling
  - Parabolic equations

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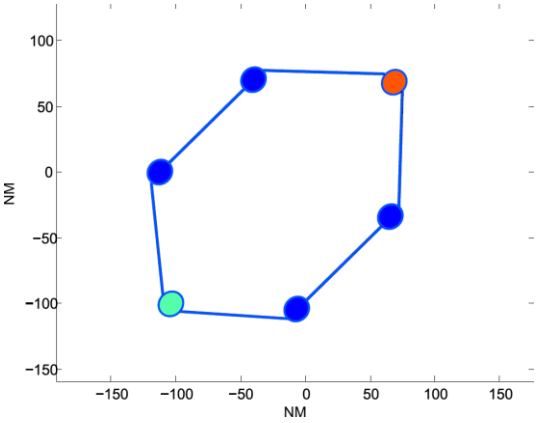
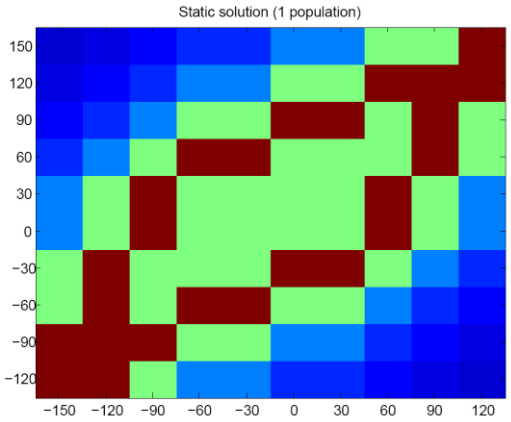
Application of MFG to the network : Simulation

- A basic case
  - Very simple flow graph
  - 2 ways to go from source to destination
  - Look for static distribution of aircraft
  - Trust-region dogleg algorithm
- Static solution
  - Higher density along graph edges
  - Lower density away – but not 0!
  - Demonstrates the method





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Conclusion & Future Work

- Data-based methodology for modeling an airspace as a flow network
- Centralized & Decentralized approaches with same goals : simulate realistic traffic, predict congestion, mitigate its effects, both under nominal and perturbed conditions
- Next steps :
  - Refine the models
  - Incorporate perturbations
  - Compare the performances of both models

Acknowledgments

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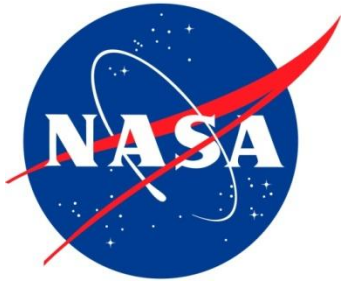

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