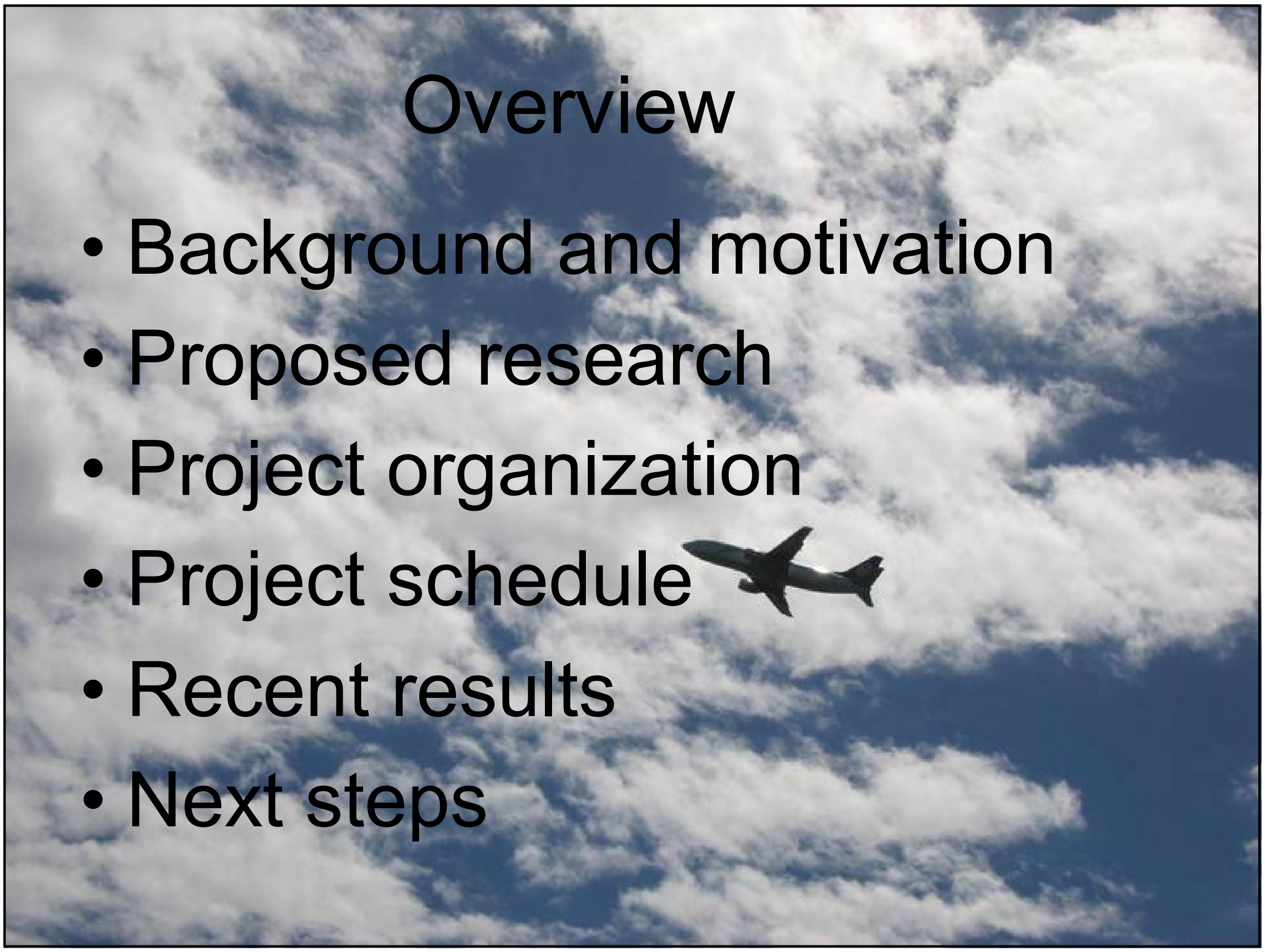
ADVANCED STOCHASTIC NETWORK QUEUING MODELS OF THE IMPACT OF 4D TRAJECTORY PRECISION

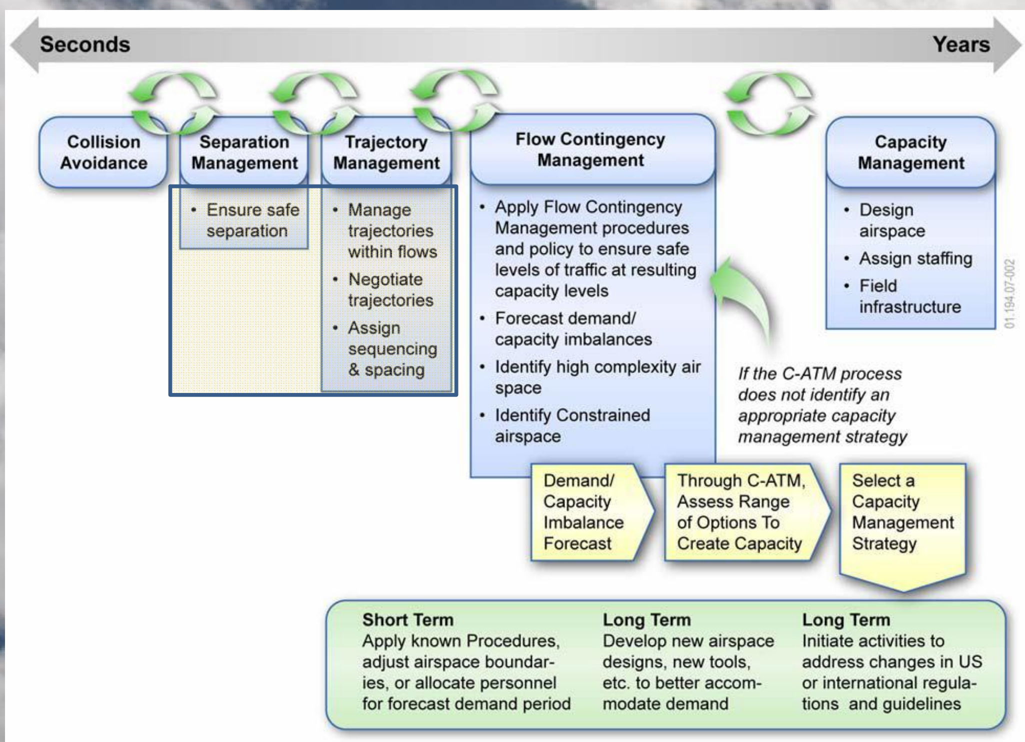
Mark Hansen, Principal Investigator

Amedeo Odoni, David Lovell,

Vikram Manikonda, Alex Bayen, Co-investigators


Overview
• Background and motivation
• Proposed research
• Project organization
• Project schedule
• Recent results
• Next steps

ATM Decisions in NextGen



Managed Airspace under NextGen

	Current System	NextGen
Trajectory-Based Operations	• Flights are managed via verbal delivery of clearances and vectors. • Time-based metering is used in some localities to improve predictability and throughput. • Required navigation performance (RNP) operations are used initially to manage complexity and increase capacity.	• Flights are managed through use of 4DTs that specify accurate current and future aircraft position. • Metering, controlled time of arrival (CTA) exchange, and more flight-specific adjustments increase overall throughput and operator efficiency. • Safety, security, and environmental considerations are integrated in TBO. • Flight crew–initiated, dynamic trajectory adjustment is possible with ATM and airport operations center (AOC) collaboration.

Research Questions

- What are the delay reduction benefits from 4DT precision?
- What benefit mechanisms from 4DT precision are the most important (e.g. reduced service times vs reduced inter-arrival times?)
- How do benefits vary with the level of precision?

Queuing network models

- Huge number of important applications
- Results are approximate in the absolute sense, but capture both the magnitude and time profile of delays and congestion
- Very powerful in quantifying relative change (i.e., change relative to a baseline) and in identifying promising directions in which to move
- Extensive project team experience in queuing models of all flavors, including theoretical development, numerical solution procedures, and empirical validation

Queuing Models and Simulation

- When used properly, queuing and simulation models are strongly synergistic
- Queuing models require little input preparation and run very quickly; can explore a wide range of options and alternatives; do not require statistical analysis of results (e.g., estimation of confidence intervals)
- Simulation models can capture far higher levels of detail and accuracy
- Simulation models can be used to validate queuing models and vice versa

Challenges of Queuing Models

- Queuing models necessarily involve approximations and simplification of reality
- Classical queuing theory provides many closed-form results which are essentially limited to long-term equilibrium conditions ("steady state") and to non-time-varying demand rates and service rates
- However, such equilibrium conditions and absence of time variation very rarely apply to airport and ATM operations
- Thus, the classical results are of limited usefulness in ATM and airport congestion analyses
- Numerical approaches are almost always necessary when it comes to systems with time-varying demand rates and service rates
- Such numerical solutions are increasingly viable and efficient computationally – and will be one of the principal foci of our

Proposed Research

- Objectives
- Technical Approach and Methodology
  - Low Precision Case
  - High Precision Case
  - Intermediate Precision Case
  - Simulation and Validation

Objectives

- Develop Queuing Models that Predict Benefit of Increased Trajectory Precision
  - Reduced inter-arrival time
  - Reduced variation in inter-arrival time
  - Reduced service time
  - Reduced variation in service time
  - Increased number of servers
- Develop Modeling and Visualization Environment to Allow
  - Validation of Queuing Model Results Against Simulation
  - Visualization of Benefit Mechanisms
- Validate Proposed Queuing Models
- Apply Validated Models to NGATS Concepts

Low Precision Case

- Captures present-day system
- Arrivals are time-dependent Poisson process
- Service times are time-dependent Erlang *k* process
- Assume *n* servers
- Kendall notation: $(M(t)/E_k(t)/n)$
- Employ previously developed DELAYS & AND models

Features of Low Precision Models

- DELAYS and AND include an important simplification made in the interest of speed, ease-of-use and minimizing input requirements:
  - Poisson demands ($M(t)/E_k(t)/n$)
- But the models can address the impacts on airport congestion of four of the five types of benefits obtainable through 4 DTP, identified earlier:
  - Reduced expected times between successive demands (smaller expected inter-arrival times) ($M(t)/E_k(t)/n$)
  - Higher expected service rates (capacity) ($M(t)/E_k(t)/n$)
  - Smaller variability of service rates (less variable capacity) ($M(t)/E_k(t)/n$)
  - More runways ($M(t)/E_k(t)/n$)
- Cannot (so far) capture reduced variability of inter-arrival times ($M(t)/E_k(t)/n$)
- Both models are stochastic and dynamic

High Precision Case

- Deterministic Queuing Models
- Given
  - Arrival schedule (aggregate or disaggregate)
  - Capacity or deterministic minimum headways
- Construct cumulative arrival and departure curves to obtain
  - Delay and queue length by time of day
  - Average and total delay
- Aggregate Version
  - Aircraft assumed to arrival at uniform rate within a given time period
  - No delay so long as arrival rate does not exceed service rate
  - Departure curves translate to downstream arrival curves
- Disaggregate Version
  - Aircraft metered to avoid excessive bunching
  - High precision allows “perfect” metering
  - Robust scheduling to coordinate downstream arrivals

Robust scheduling as a link between queues

- Multiple inputs, single (or multiple) output(s)
- Shortest travel time from one queue to another
- Actuation in the “in between queues” space in the form of delay
- Classical scheduling performs optimal assignment of arrivals into the next queue
- Robust scheduling assumes the margins (travel time and actuation) are only known within specific bounds.
- Output of the method will be algorithmic, i.e.:
  - Will take any flow input from a set of queues’ outflows
  - Will schedule the corresponding aircraft
    - Optimally (or suboptimally if NP-hard)
    - Deterministically
    - Robust (will give worst case scenario)
  - Will thus prescribe inflows into the next queue according to (or as close as possible to) queue specs

“Bookend” Modeling Strategy

- Compare results of three models
  - MIT Stochastic Queuing Model (DELAYS)
  - Deterministic Queuing Model
  - High Fidelity Simulation (ACES)
- Consider ACES results to represent “truth”
- Begin with extremely simple scenarios and gradually increase complexity
- Initiate comparisons with real-world data in next phase

Intermediate Case

- State space dynamics are impossible to describe exactly (i.e., Chapman-Kolmogorov equations cannot be written)
- Case is important when considering propagation of uncertainty
- In networks, outputs and downstream inputs are coupled
- Resultant need to condition on all upstream possibilities explodes the state space
- Typically resort to some kind of approximation:
  - Heuristic adaptation of low precision models
  - Fluid approximation
  - Diffusion methods
  - Robust scheduling adaptation

Diffusion approximation

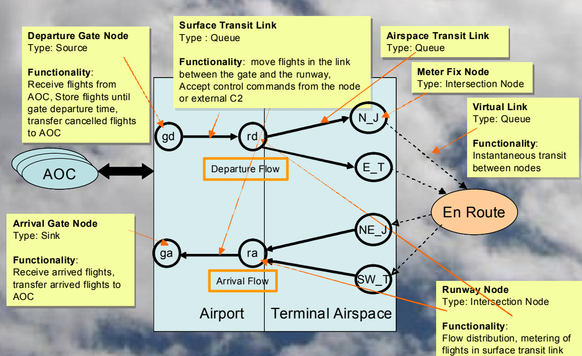
- Dynamics of joint probability density functions are analogous to dynamics of physical flows or other density problems
- Continuous approximations using systems of coupled partial differential equations
- Because derivatives of probability density functions are modeled, they can be integrated to produce moment estimates
- Exploit fast numerical solvers

Simulation and Validation

- Develop a queuing network representation of NAS network consisting of the busiest airports and their associated traffic

Local Representation

Develop a queuing network representation of each airport and its corresponding traffic.



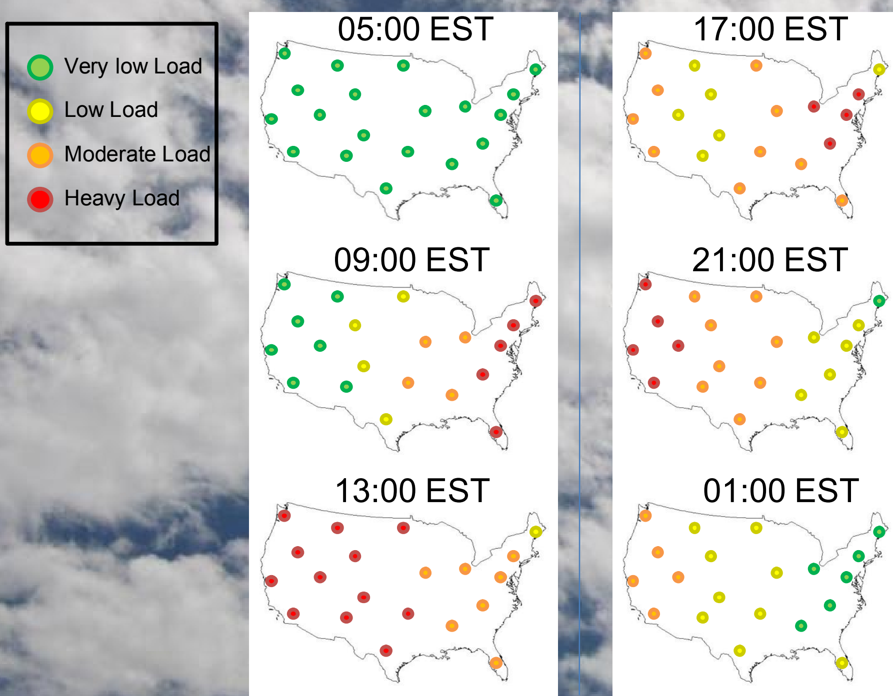
National Representation

Develop a queuing network representation of the NAS consisting of the busiest airports and their associated traffic.

Visualization

Develop an interactive tool to facilitate visualization of the ways that trajectory uncertainty propagates.

Visualization of the Time-Evolution of the Load on the National Airspace



Project Schedule

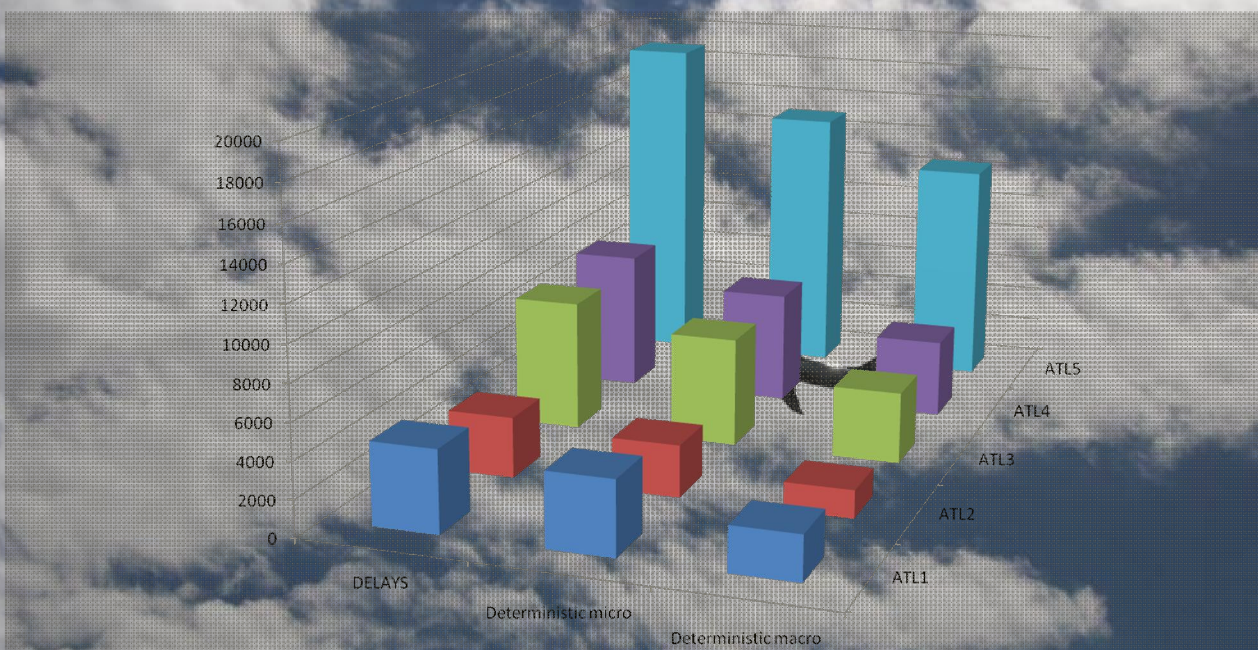
	FY 2008				FY 2009			
Task	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Low precision case	■	■	■	■				
High precision case		■	■	■	■			
Robust scheduling		■	■	■	■	■		
Intermediate precision case					■	■	■	■
Simulation and validation	■	■	■	■	■	■	■	■
Applications							■	■

Application to ATL

- ACES Simulation for 5/17/2002
- No capacity constraints
- Resulting unconstrained arrival times at ATL serve as demands for queuing models
- Demand is run against representative capacity profiles for ATL using both queuing models
- Results are compared

Example Simulation Results

Example Simulation Results



Results to Date

- Stochastic delay model predicts higher average delays
  - 11%-25% higher
  - Differences generally greater on low capacity days
  - Greater differences in peak delays
- Delay build-ups predicted by deterministic model lag delay build-ups predicted by stochastic model

Immediate Next Steps

- Ensure results of queuing models are fully comparable w/r to how delay profile is constructed
- Run ACES with arrival capacity constraints
- Increase complexity of ACES runs
  - Departure capacity constraints
  - En route capacity constraints
  - Network effects