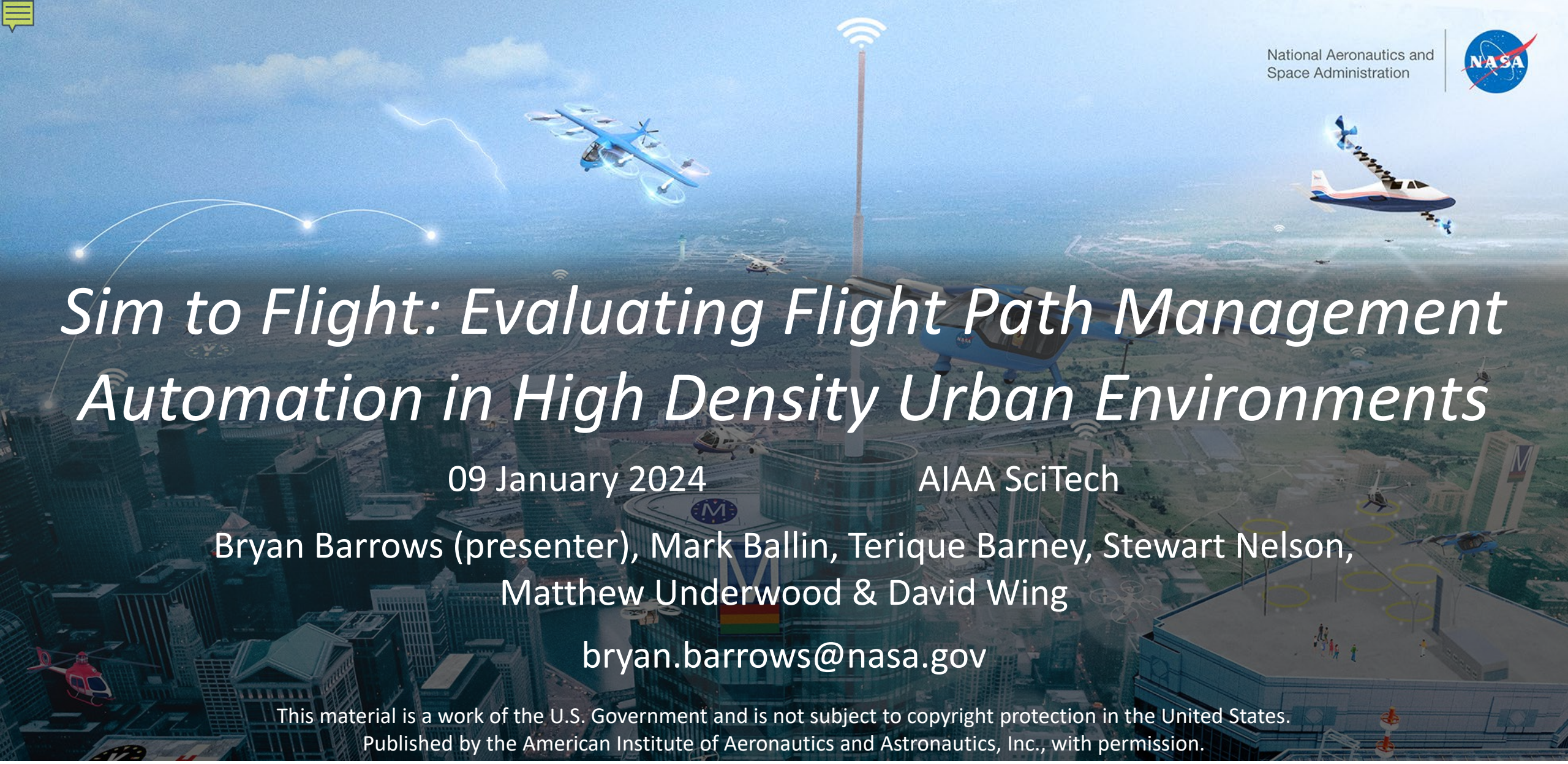


National Aeronautics and Space Administration

Sim to Flight: Evaluating Flight Path Management Automation in High Density Urban Environments

09 January 2024 AIAA SciTech

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Overview

- Multi-year, multi-study research on dynamic Flight Path Management (FPM) automation for immersion into complex, high density, future Urban Air Mobility (UAM) operations

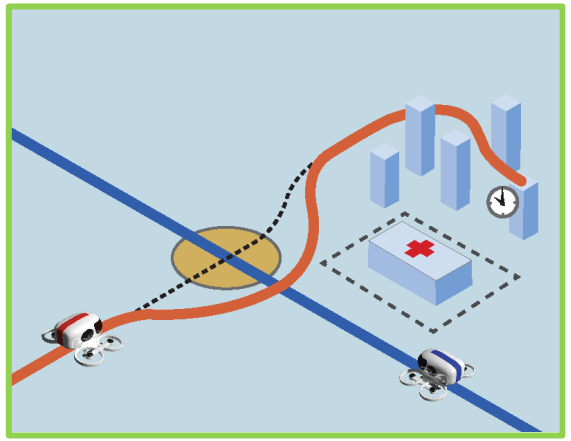
- Conducted in three phases: Constructive (batch simulations), Virtual-Constructive (batch and pilot simulations) and Live-Virtual-Constructive (flight testing) of a reference FPM automation prototype

- Assessed the technical performance of FPM functionality under highly complex conditions

Outline

- Background: Flight Path Management Automation Concept
- Sim-to-Flight Methodology
- FPM-1 Simulation Study
- FPM-2 Simulation Study with Pilot Assessment
- FPM Flight Testing
- Flight Test Preliminary Results
- Conclusion

Flight Path Management Automation Concept (FPM)



FPM: In-flight autonomy in shared airspace

- Continuous replanning to safely achieve mission objectives in the presence of traffic, flow restrictions, and weather

Goal:

- A safe and operationally acceptable flight path is available to airspace users and aircraft systems throughout the flight

FPM Objectives: Create | Monitor | Evaluate | Revise | Coordinate the flight path to have:

Five Qualities:

- **Feasible** – Conforms to aircraft performance and range; Complies with airspace structure, rules, and constraints
- **Deconflicted** – Avoids unsafe proximity to known traffic, terrain, obstacles, weather, and airspace hazards
- **Harmonized** – Follows cooperative rules and procedures to be compatible with other airspace users & systems
- **Flexible** – Provides adequate degrees of freedom to enable future flight path changes
- **Optimal** – Achieves business objectives and preferences of the pilot and fleet operator

Assumed for this research: An FPM system is located onboard each aircraft

Urban Air Mobility at Scale

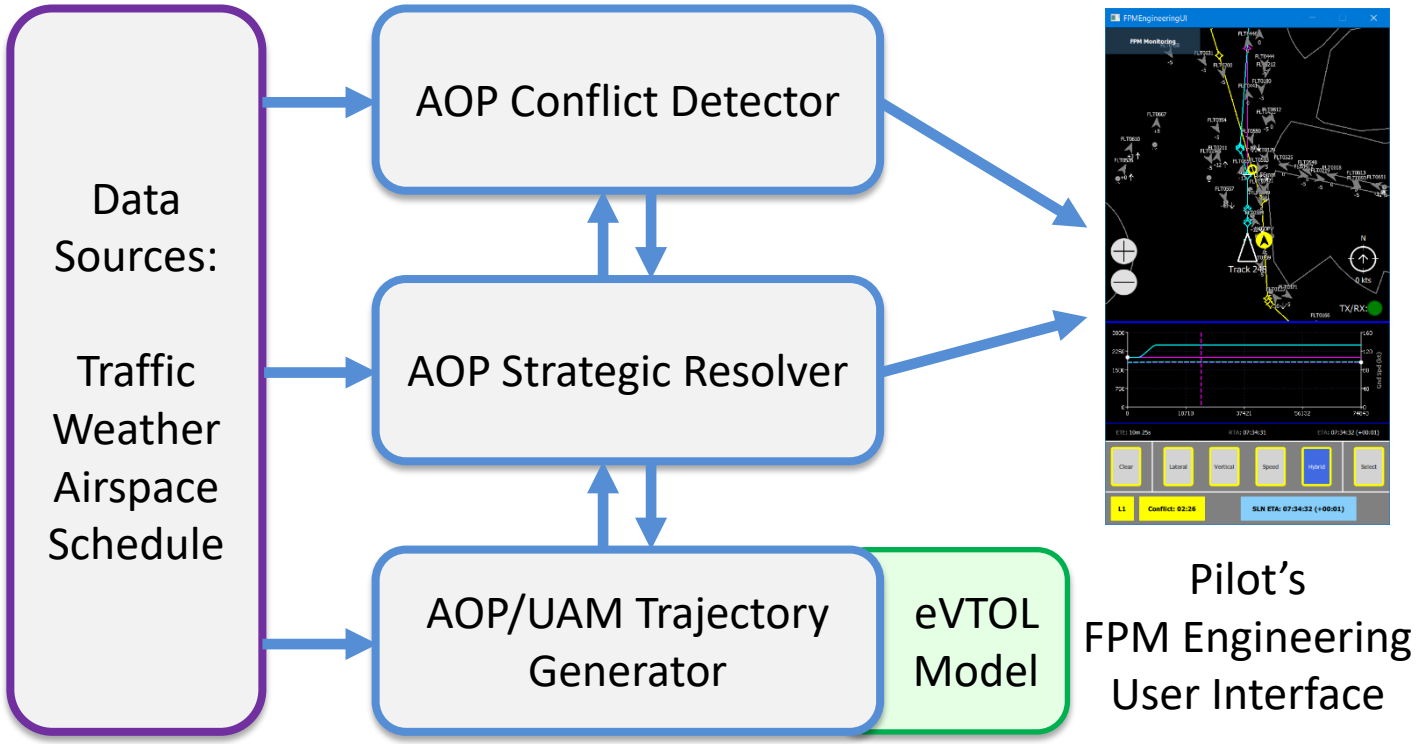
Urban Air Mobility (UAM) – a vision for a future transportation system that provides economical high-access air travel within urban environments.

- UAM Maturity Level 4 (UML-4)
  - Comparable to FAA's UAM Mature Operational Stage
  - Hundreds of aircraft serving a metropolitan area
  - Dozens of vertiports, restricted airspace volumes, and corridors
- The need for FPM automation:
  - Human-centric flight path management may not be feasible at UML-4 traffic complexity
  - Increasingly dense and complex operations with closer separation
  - Safe and assured operations
- Our Assumptions for UML-4
  - Future eVTOL vehicles with low margin for contingencies
  - Short flight durations (0.5 hr or less); continuous 4D trajectory conformance
  - 1500 ft (~0.25 NM) lateral and 450 ft vertical assumed separation
  - Short time constraints and strategic look-ahead (3 minutes)

Autonomous Operations Planner (AOP)

Reference implementation role:

- Platform for assessing FPM system requirements
- Advanced algorithms for complex FPM operations
- Supporting NASA autonomy R&D for 20+ years



Pilot's FPM Engineering User Interface

AOP Implementation for UAM R&D

AOP core functionality:

- Generates the flight path
- Monitors the flight path and the factors which may impact it
- Evaluates ongoing acceptability of the flight path and proposed changes
- Revises the flight path, as needed, to sustain the desired qualities
- Coordinates the flight path with other airspace users and service providers

Karr, D. A., Sturdy, J. L., Barrows, B. A., and Ballin, M. G., *"An Experimental System for Strategic Flight Path Management in Urban Air Mobility,"* AIAA SciTech, January 2024.

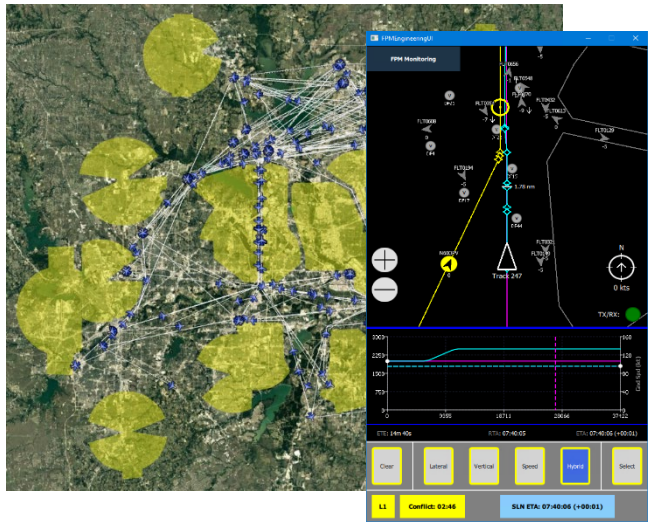
Sim-to-Flight Methodology

FPM-1 Sim Study (2021)



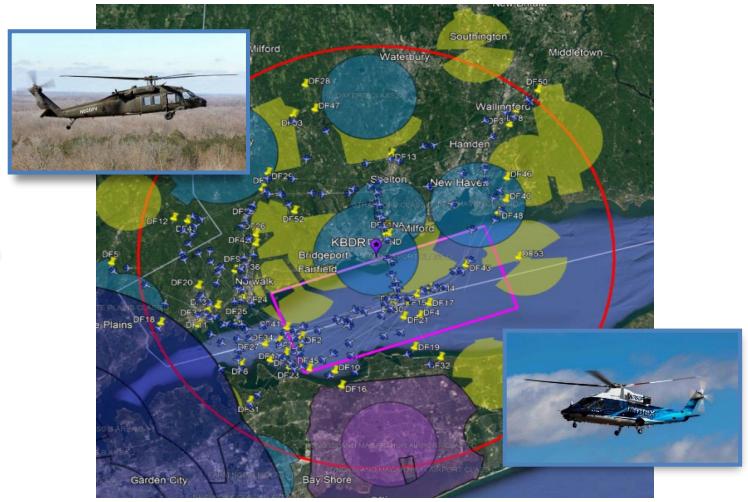
- ***Constructive*** UAM Dallas Fort Worth (DFW) Airspace
- Batch simulation for initial evaluation of the FPM automation concept
- Involved 150+ simultaneous operations (all FPM-equipped)

FPM-2 Sim Study (2022)



- ***Virtual-Constructive*** batch plus human-in-the-loop (HITL) acceptance testing
- AOP feature additions and function refinement
- Preparation for flight testing

Flight Test (2023)

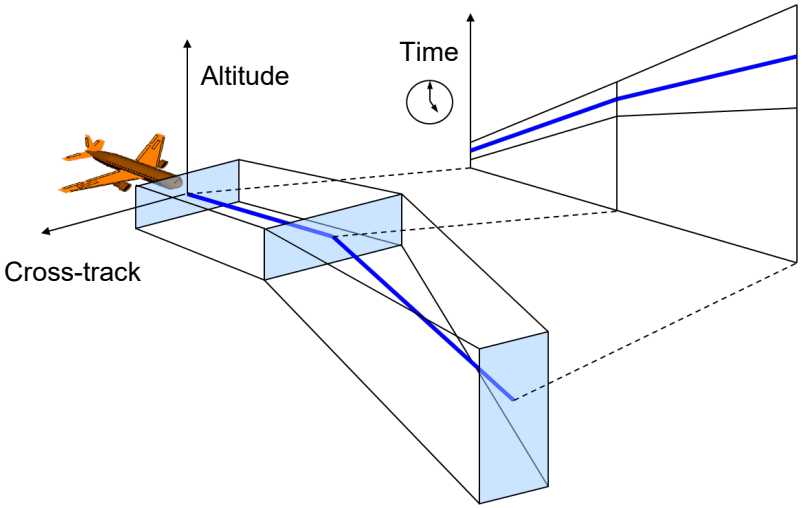


- ***Live-Virtual-Constructive*** *(LVC)* system integration and operation over Long Island Sound
  - First-ever in-flight execution of strategic airborne self-separation
- FPM concept technical feasibility assessment and advancement
- Validation of simulation results

FPM-1 Batch Simulation

- Batch data accumulated: 50,963 flights across 72 scenarios; full **high fidelity AOP** on every vehicle
- Five independent variables: traffic demand level, arrival schedule shift, wind error, traffic intent sharing, resolution type availability
- FPM-1 separation criteria:
  - 1500 ft lateral and 250 ft vertical separation minima
  - Trajectory Prediction Uncertainty Bounds (TPUBs) of ±150 ft lateral, ±25 ft vertical and 2 seconds along-path additional separation
- Primary performance metrics: Loss of Separation (LOS) and required time of arrival (RTA) conformance:
  - Most significant variables impacting LOS count: **Traffic intent and traffic demand**
  - Most significant variables impacting RTA conformance: **arrival schedule shift and resolution type availability**



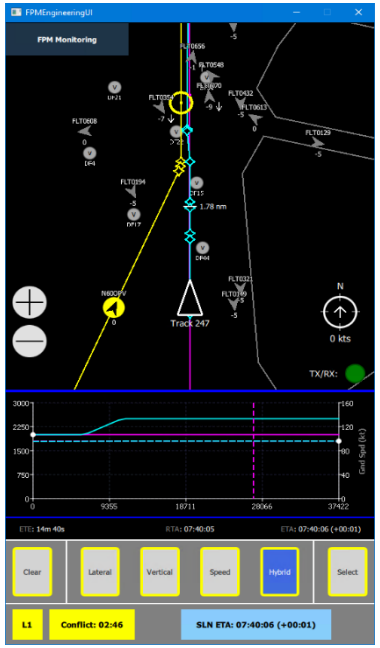


TPUBs protection envelope

FPM-2 Batch/HITL Simulation

- Batch data accumulated: 127,224 flights across 216 scenarios; all flights equipped with AOP
- Wind error and TPUBs were not independent variables of study. Additional metrics studied after FPM-1
- FPM-2 separation criteria:
  - 1500 ft lateral and 450 ft vertical separation minima (increased from 250 ft)
  - TPUBs of ±150 ft lateral, ±25 ft vertical and 3 seconds along-path (increased from 2 seconds) additional separation
- Consistent trends with FPM-1:
  - Enabling traffic intent sharing was needed in flight to achieving desired AOP performance
  - Magnitude of RTA delays and resolution availability expected to significantly contribute to RTA conformance in flight
- Strategic deconfliction performed well. Technology deemed ready for flight testing

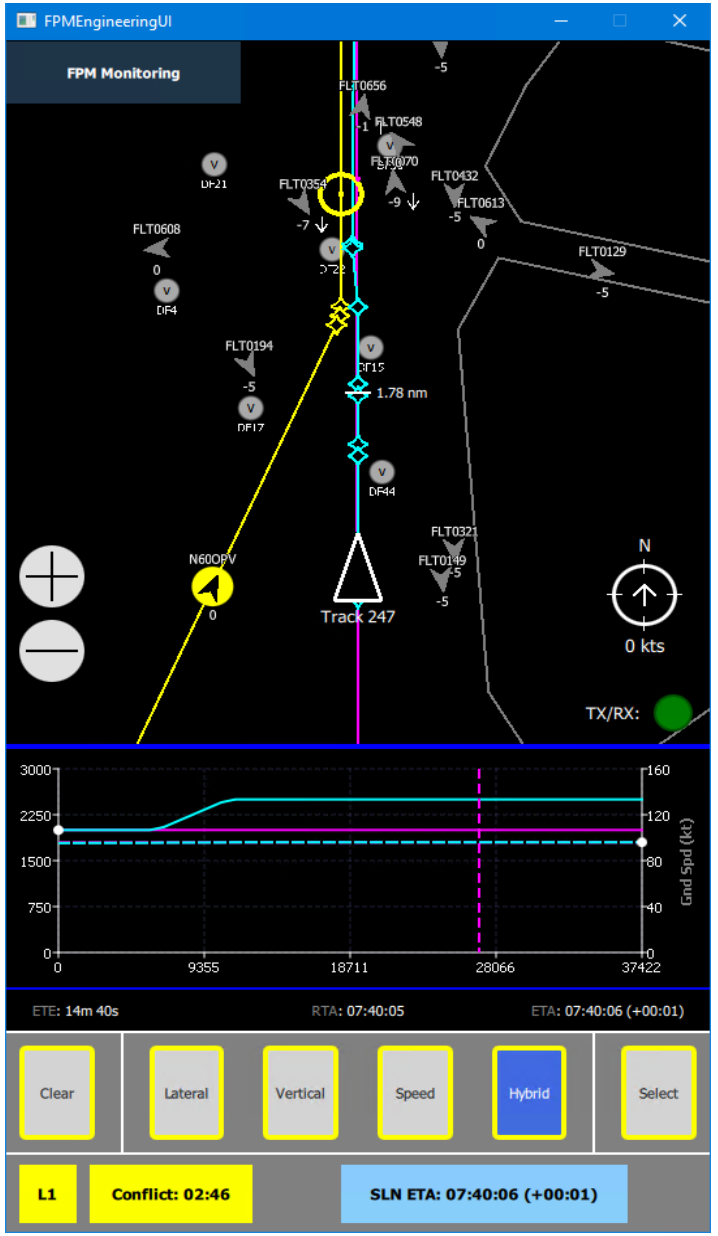




FPM-2 Batch/HITL Simulation (cont.)

- Additional pilot usability/acceptance testing via an engineering user-interface





- Scenario configuration which most closely resembled scenario/environment configuration for the flight test
  - 12 scenario replicates to assess variance

FPM Flight Testing: Integration of Automated Systems 1 (IAS-1)

- Total of 34 test points collected across 8 maneuver group types

- Helicopters used as surrogates for future eVTOLs aircraft.
- LVC environment:
  - SARA (Ownship): with AOP
  - OPV (Intruder): without AOP
  - Virtual background traffic (250-330 simultaneously): recorded AOP

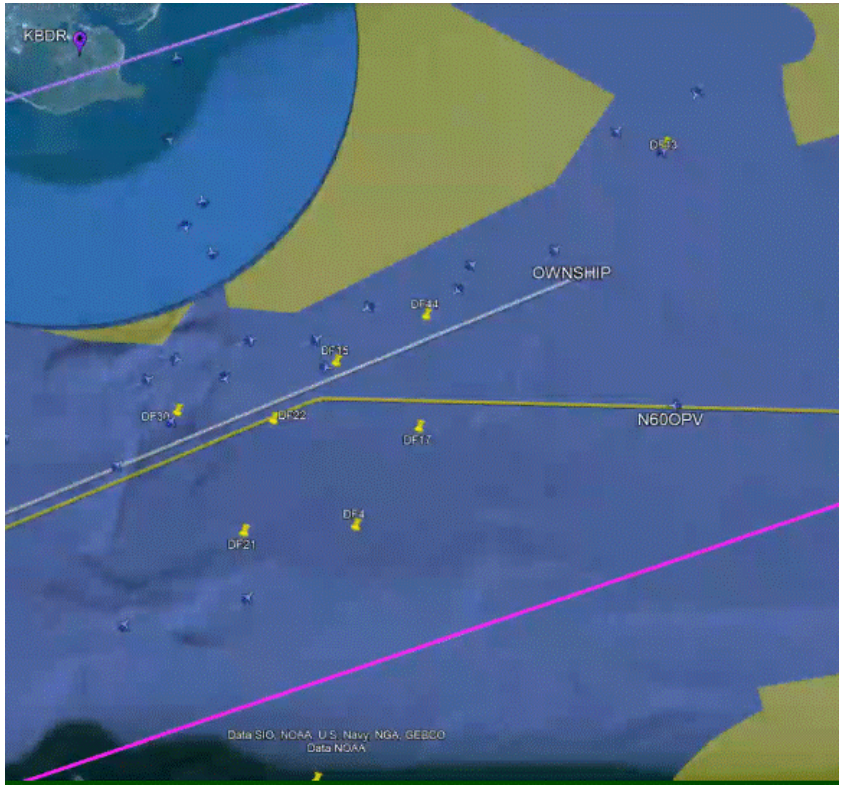
- Systems Integration Laboratory (SIL) setup using flight test hardware and software for testing.

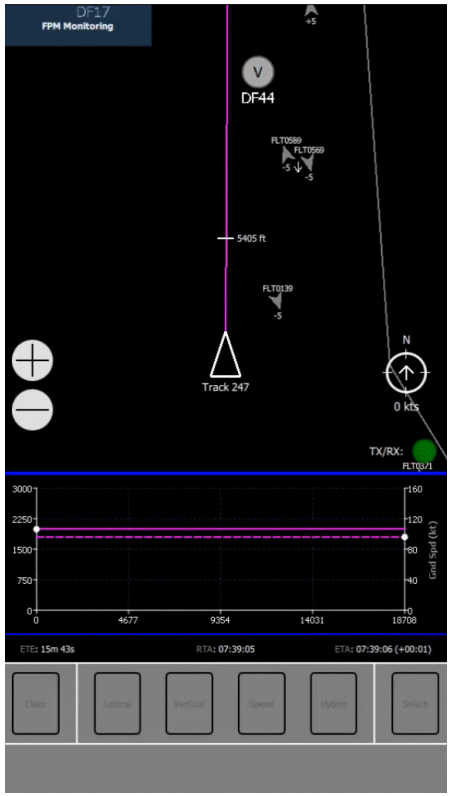


Intruder: Sikorsky S-70 Optionally Piloted Vehicle (OPV)



Ownship: Sikorsky Autonomy Research Aircraft (SARA) S-76B





FPM Flight Test Preliminary Results

- FPM technology performed as expected and achieved full mission success

- Flight test summary across all 34 acquired test points:
  - 41 traffic conflicts and RTA change events detected
  - 34 traffic conflicts (3 w/background)
  - 7 RTA change events
  - 478 total unique conflict resolutions produced by AOP
  - 24 total pilot-executed conflict resolutions

- Takeaways
  - AOP successfully deconflicted with known traffic conflicts and resolved RTA change events
  - Flight testing mirrored the behaviors and results found in SIL testing and past simulations
  - 1500 ft lateral and 450 ft vertical separation minima posed no issue toward UML-4
  - Pilots felt adequately “in-the-loop” of FPM; although, desired more time to evaluate AOP generated resolutions

Conclusion

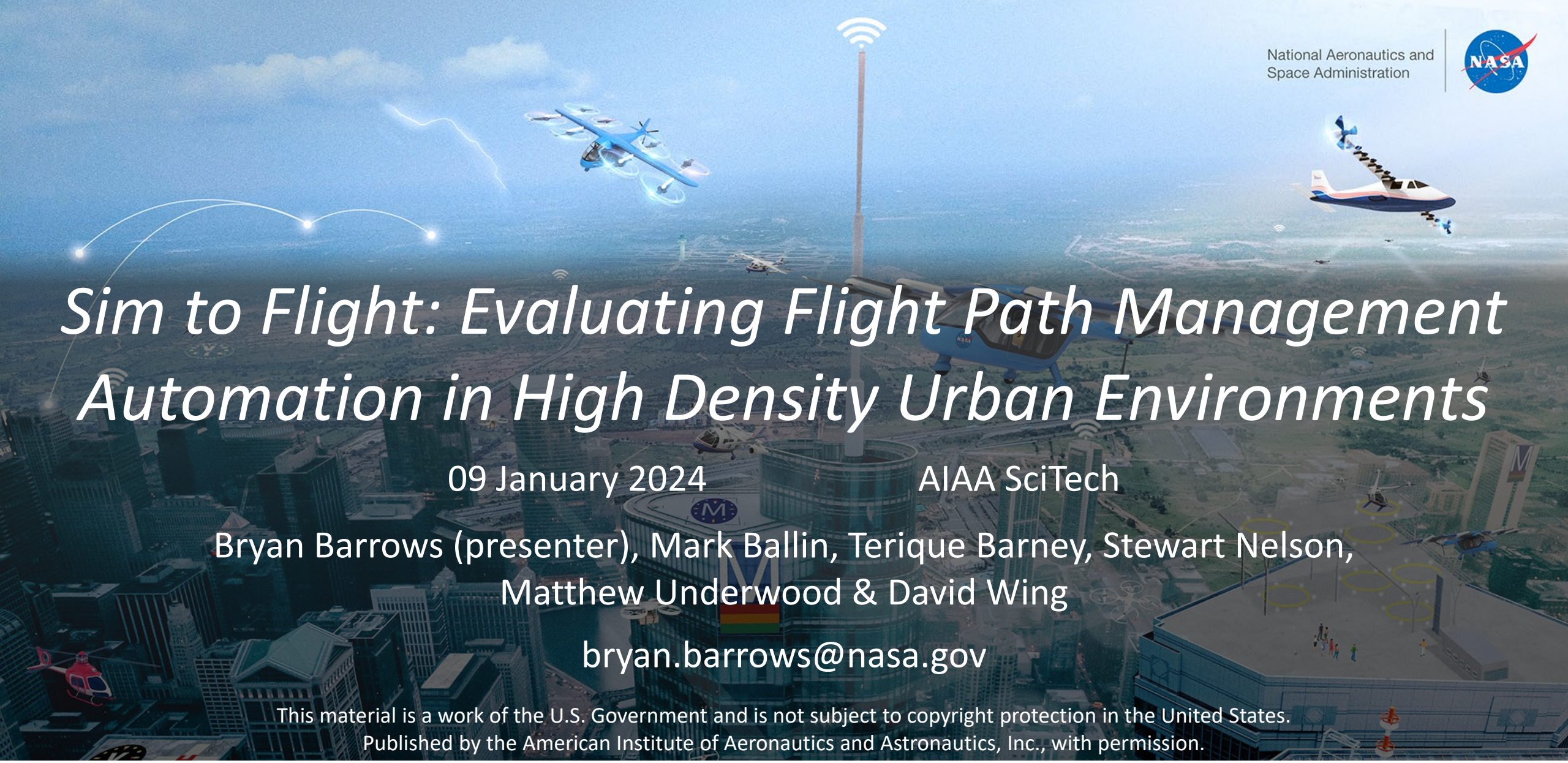
- First pass of iterative Sim-to-Flight technology progression
- Sim-to-Flight LVC build-up approach provided important benefits
- We better understand the research and data needs from simulation and flight testing, individually, to further address open-ended research questions

Planned work:

- Expanded data analysis on flight test results, including simulation validation
- Conduct more SIL testing and batch simulation for flight test data comparison
- Improve existing features of AOP and address uncovered defects

Future work needed:

- More iterations of sim-to-flight research
- Human factors and certification



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