# Combining Strategic and Tactical Conflict Management in Urban Air Mobility Environments

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# Urban Air Mobility


Credit: NASA Air Mobility Pathfinders (AMP)

- Advanced Air Mobility (AAM) – air transportation systems that move people and cargo between local, regional, intraregional, and urban locations underserved by aviation, using innovative aircraft, technologies, infrastructure, and operations
- Urban Air Mobility (UAM) – subset of AAM that focuses on flight operations in and around urban areas

# Motivation

- There is a desire to increase the frequency of air operations
- Future concepts envision the use of Cooperative Areas (CAs) that leverage highly automated cooperative management approaches to safely enable higher operational tempos
- Approaches to be leveraged include:
  - Strategic conflict management (SCM) – pre-flight deconfliction of flight plans
  - Tactical conflict management (TCM) – resolving unexpected conflicts reactively during flight
- Previous studies in NYC Class B airspace showed SCM alone did not prevent all conflicts, so in this work, we combine SCM & TCM

# Research Questions

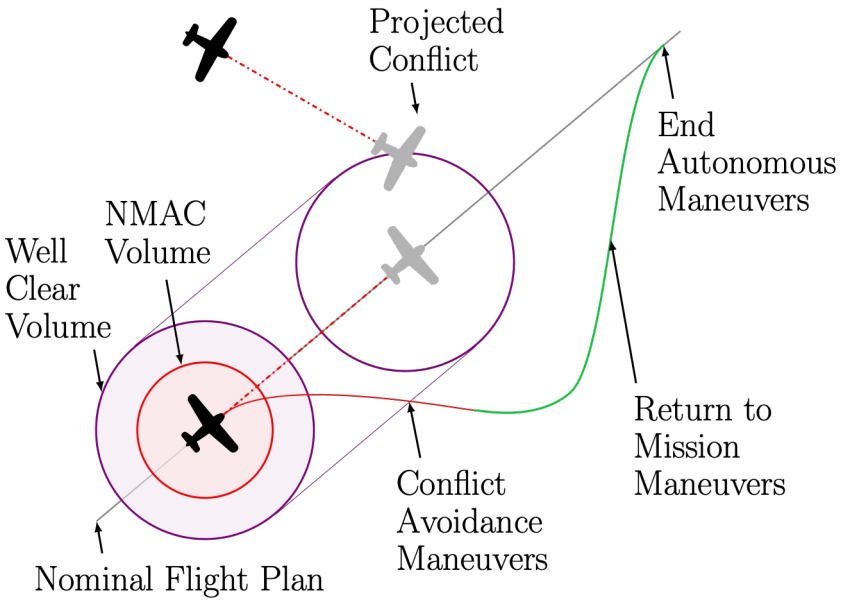
- In terms of maintaining safe separation, what does the addition of a TCM capability over SCM provide?
- What are the tradeoffs between more and less conservative parameters for the TCM capability?
- Are there specific locations or situations in which tactical conflicts tend to occur?
- How often do secondary conflicts arise when the TCM capability alters the course of an aircraft to avoid an initial conflict?

# General Definitions

- *Well clear* – the legal requirement for an aircraft to maintain a safe separation distance from other aircraft to avoid collision risks (14 CFR 91.111 and 91.113)
- *Detect-and-avoid (DAA) well clear* – a mathematical definition to support unmanned air system (UAS) operations (RTCA SC-228)
  - Relies on the concept of a *well-clear volume* (WCV) around an aircraft
  - WCV is parameterized by spatial and temporal thresholds with horizontal and vertical components
- *Loss of DAA well clear* (LoWC) – occurs when one aircraft occupies the WCV of another
- *Severity of Loss of DAA Well Clear* (SLoWC) – a metric that ranges from 0–100% that estimates the penetration into the WCV accounting for both horizontal and vertical separation
- *Conflict* – predicted future infringement of an aircraft's WCV based on current positions and velocities of the involved aircraft
- *Near mid-air collision* (NMAC) – when two aircraft are within 500 ft horizontally and 100 ft vertically of each other

# Definitions Used in This Work

- *(Well-clear) encounter* – a pair-wise conflict between two aircraft
- *Conflict avoidance maneuver* – a maneuver designed to avoid a conflict
- *Return to mission maneuver* – a maneuver designed to return to the nominal flight plan after a conflict
- *Autonomous maneuver* – a sequence of conflict avoidance and return to mission maneuvers

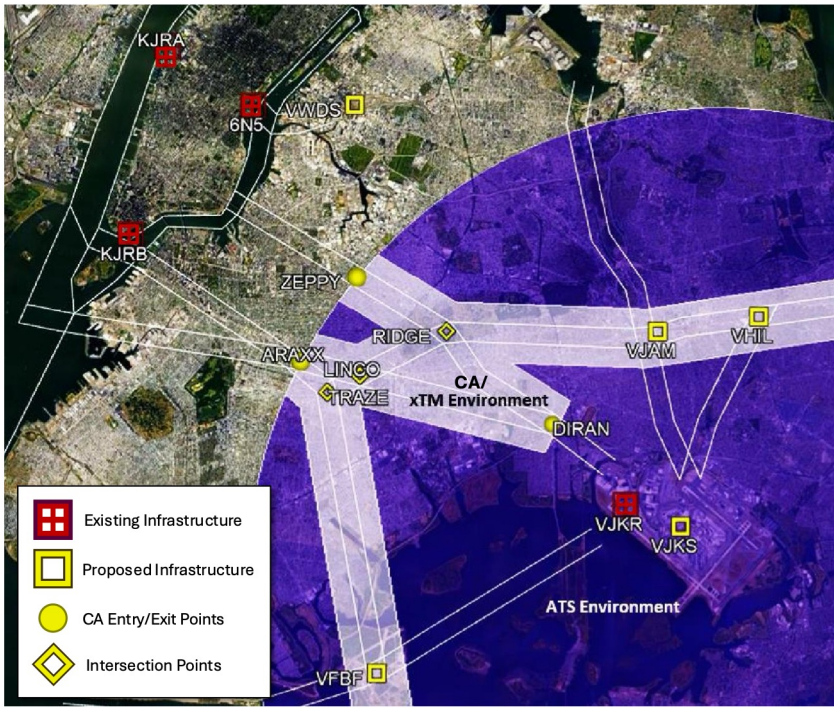


# Strategic Conflict Management Methods

- Two different SCM methods were developed on top of NASA's ATS-TIGAR mission planning service
- *Baseline SCM* – Deconflicts flight plans at vertiports
- *Enhanced SCM* – Additionally deconflicts flight plans at points where routes merge or cross

# Strategic Conflict Management Assumptions

- Vertiports are connected by pairs of uni-directional routes that satisfy a safe separation distance plus a buffer
- Part of the airspace is designed as a CA with labeled *CA entry/exit points* and *CA intersections*
- Each vertiport has some number of vertipads and optional parking spaces
- Some vertiports have a single-in/single-out (SISO) restriction (no simultaneous operations allowed across vertipads)
- Some vertipads are dedicated to takeoffs or landings only
- Fixed amounts of time are required for takeoff and landing operations, including time to move to/from a parking space or between takeoff/landing-only vertipads
- There are fleets of aircraft with different performance characteristics and run by different operators
  - Customers make trip requests to a specific operator that are fulfilled on a first-come, first-served basis
  - Sometimes *clearing* and *repositioning* flights are needed
  - Some s*taging vertiports* are dedicated to these flights



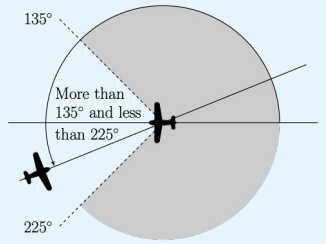
# Strategic Conflict Management

- For each flight, the mission planner generates a kinematically feasible flight plan as a 4D trajectory encoded in NASA's Efficient Universal Trajectory Language (EUTL)
- Baseline SCM:
  - Models time windows around takeoff and landing operations
  - Checks for time window overlaps (accounting for whether a vertiport has a SISO restriction)
  - When a new flight plan is generated, takeoff is delayed until all overlaps are resolved
- Enhanced SCM:
  - Additionally deconflicts flight plans at CA crossing and merging points
  - Calculates a time window to clear each point based on worst-case WCV and route geometry
  - For each flight plan, calculates an ETA and clearing window for the aircraft at each point
  - When a new flight plan is generated, takeoff is delayed until there are no clearing window overlaps

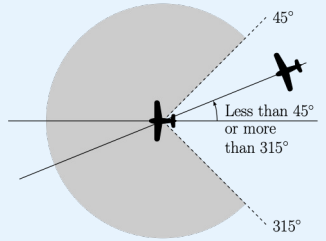
# Tactical Conflict Management

- Leverages NASA's Detect and AvoID Alerting Logic for Unmanned Systems (DAIDALUS*)
  - Reference implementation of RTCA DAA Minimum Operational Performance Standards for UAS (DO-365)
  - Checks for conflicts between *ownship* and *intruders* based on current velocity vectors and configurable WCV, aircraft performance parameters, alerting time
  - Computes maneuver guidance as ranges or *bands* of heading, airspeed, vertical speed, and altitude values that would avoid either cause, resolve, or avoid conflicts with intruders
- Classify conflicts to determine which aircraft has *right of way (RoW)*, inspired by ICAO Document 4444 "Procedures for Air Navigation Services"
  - *Vertical encounter* – Aircraft have more than 300 ft vertical separation; lower aircraft has RoW
  - *Head-on (horizontal) encounter* – 135° to 225° angular distance between tracks; slower aircraft has RoW
  - *Same-track (horizontal) encounter* – <45° or >315° angular distance between tracks; leading aircraft has RoW
  - *Crossing (horizontal) encounter* – all other angles; aircraft to the right has RoW

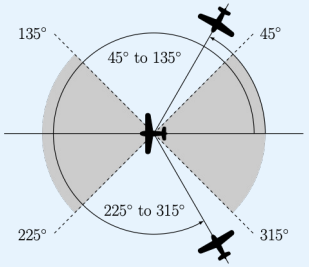
* https://github.com/nasa/daidalus




Head-on horizontal encounter




Same-track horizontal encounter




Crossing horizontal encounter

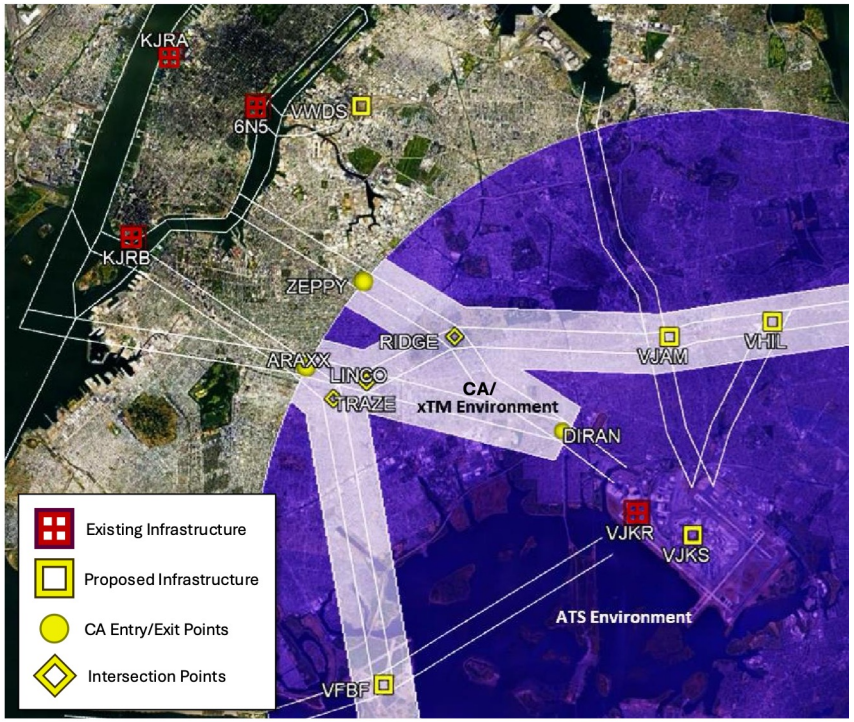
# Tactical Conflict Management

- Run DAIDALUS at 1 Hz
- If there is a conflict and the ownship has RoW:
  - The ownship continues on its current velocity vector for 3 seconds
  - The ownship no longer assumes it has RoW if there is still a conflict after 3 seconds
- If there is a conflict and the ownship does not have RoW, it follows the value from a DAIDALUS band that is closest to the current ownship state
  - Vertical encounter – band preference is vertical speed > heading > airspeed
  - Head-on encounter – band preference is heading > vertical speed
  - Crossing encounter – band preference is heading > airspeed > vertical speed
- If a loss of separation has occurred, chose the maneuver that achieves the greatest separation in the least amount of time
- If there are simultaneous conflicts:
  - Classify the conflict according to the one that will happen first to choose which band to use
  - DAIDALUS considers conflicts with all intruders, so if any bands exist, they solve all conflicts
- Execute return to mission maneuvers once there are no more conflicts and required maneuvers would not cross any unsafe DAIDALUS bands

# Simulation Study – Airspace

- Nine vertiports
  - KJRA, 6N5, VJAM – SISO restriction
  - VFBF, VWSD – dedicated vertipads for takeoff and landing
  - VFBF, VWSD, VHIL – staging vertiports
- Uni-directional routes ~2000 ft apart at 900 ft MSL cruising altitude
- CA with three entry/exit points and three intersections

| Location | Vertiport | ID | Vertipads | Parking |
|---|---|---|---|---|
| Downtown | East River | 6N5 | 4 | 0 |
| | Hudson River | KJRA | 6 | 0 |
| | Wall Street | KJRB | 1 | 13 |
| | Woodside | VWSD | 2 | 20 |
| Off Airport (CA/xTM) | Jamaica Station | VJAM | 4 | 0 |
| | Floyd Bennet Field | VFBF | 2 | 20 |
| | Hillside | VHIL | 10 | 0 |
| On Airport (ATS) | Rampside | VJKR | 1 | 4 |
| | Streetside | VJKS | 2 | 0 |



# Simulation Study – Framework

- Fast-time simulations were run using NASA's Simulation Infrastructure for Research on Interoperating Unmanned Systems (SIRIUS)
  - Takes SCM-scheduled flight plans as inputs
  - Connects to an eVTOL dynamics model for each aircraft with:
    - Simple first-order dynamics for airspeed, vertical speed, and bank angle
    - Limits on the magnitude of these values and their derivatives
  - Connects to each aircraft's decision-making and control module
  - At every time step:
    - Calls decision and control module to compute airspeed, vertical speed, and heading commands
    - Calls eVTOL model to update the aircraft's state in response
- Decision and control modules implemented using NASA's Independent Configurable Architecture for Reliable Operation of Unmanned Systems (ICAROUS*)
  - Provides algorithms to support robust autonomous UAS operations (including DAIDALUS)
  - Provides a framework that allows users to specify *triggers* that activate user-defined *behaviors*

* https://github.com/nasa/icarous

# Simulation Study – Decision and Control Module

- Decision and control module triggers and behaviors:
  - Flight start → Fly the nominal flight plan
  - Aircraft reaches the flight plan's top of climb → Enable TCM
  - TCM detects a conflict → TCM performs conflict avoidance maneuvers
  - TCM detects that a conflict is over → TCM performs return to mission maneuvers
  - Aircraft reaches the flight plan's top of descent while there are no conflicts → Disable TCM
  - During a conflict, the aircraft reaches the closest waypoint in the nominal flight plan outside a 500 m horizontal ring around the landing site → Make an emergency landing
  - No other conditions apply → Fly the nominal flight plan
- Basic control laws to fly the nominal plan and return to mission are detailed in the paper
  - There is no wind in our simulations, so ground speed is equivalent to airspeed
  - Desired airspeed is adjusted to account how far ahead or behind schedule the aircraft is (within limits)
  - Desired altitude is synchronized to desired horizontal position for segments with low slope

# Simulation Study – Conditions

- Two SCM conditions
  - SCM1 – Baseline
  - SCM2 – Enhanced
- Two sets of TCM parameters
  - WCV1 – 1500 x 450 ft volume
  - WCV2 – 800 x 300 ft volume
- Four total combinations of SCM and TCM
- Also evaluate SCM conditions without TCM
- 128 random trip requests over two hours
  - 64 in the first hour
  - 64 in the second
- SCM plans and deconflicts all routes (including clearing and staging routes) <1 minute
- Simulations run in ~15 minutes with data logging, ~6 minutes without data logging
- Compute metrics *in the CA* over an hour starting 30 minutes into the simulation

# Simulation Study Results – Active Flights

| Simulation Condition | Avg, Max, Total Flights Active (no TCM) | Avg, Max, Total Flights Active |
|---|---|---|
| SCM1+WCV1 | 2.7, 7, 74 | 2.8, 7, 75 |
| SCM1+WCV2 | 2.5, 7, 68 | 2.7, 7, 70 |
| SCM2+WCV1 | 2.7, 6, 74 | 2.7, 6, 75 |
| SCM2+WCV2 | 2.6, 6, 70 | 2.6, 6, 71 |

# Simulation Study Results – Alerts

- A *nuisance alert* is one that does not result in a LoWC when no conflict avoidance maneuver is made
- TCM always maneuvers, so nuisance alerts do not apply to TCM conditions
- In SCM-only conditions, WCV2 produces fewer alerts than WCV1
- In conditions with TCM:
  - Total alerts tend to go up
  - More alerts for WC1 than WCV2

| Simulation Condition | SCM Nuisance Alerts / SCM Total Alerts | TCM Total Alerts |
|---|---|---|
| SCM1+WCV1 | 27/43 | 66 |
| SCM1+WCV2 | 35/36 | 66 |
| SCM2+WCV1 | 1/13 | 18 |
| SCM2+WCV2 | 3/5 | 5 |

# Simulation Study Results – Maximum Deviations

- Arrivals are measured according to when an aircraft reaches the *top of descent* (TOD) phase of its flight plan
- Maximum deviation values in SCM1 conditions are higher than SCM2
- Maximum deviation values for WCV1 are a bit higher than WCV2

| Simulation Condition | Max Cross-Track Deviation | Max Vertical Deviation | Max TOD Arrival Delay |
|---|---|---|---|
| SCM1+WCV1 | 9007 ft | 323 ft | 481 s |
| SCM1+WCV2 | 8827 ft | 99 ft | 341 s |
| SCM2+WCV1 | 1377 ft | 6 ft | 118 s |
| SCM2+WCV2 | 79 ft | 6 ft | 9 s |

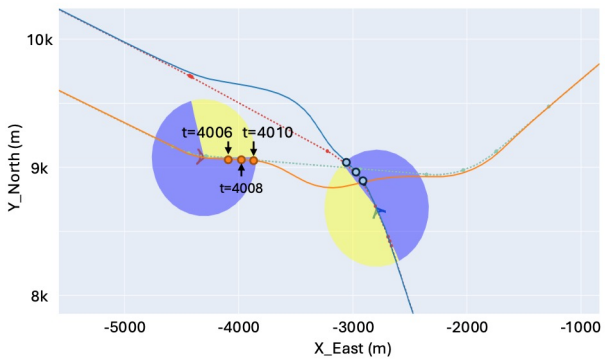
# Simulation Study Results – LoWC

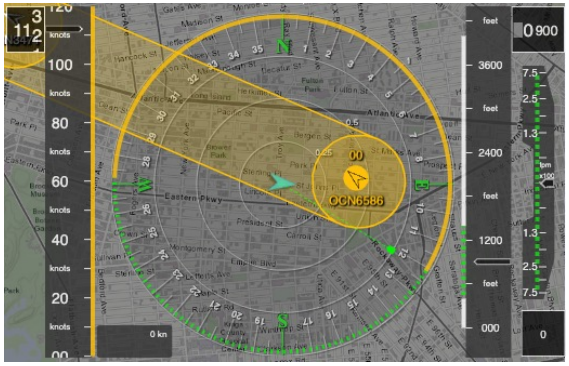
- SCM2 has fewer LoWC events than SCM1
- TCM both reduces the total number and severity of LoWC events and increases minimum DCPA
  - Under TCM, all losses are minimal
- Note that the number of LoWC events is counted per aircraft
  - Usually the number is even, since most events involve two aircraft
  - When the number is odd, encounters have more than two aircraft or one aircraft is not in the CA
- No secondary (sequential) conflicts occurred in TCM conditions

| **Simulation Condition** | **SCM LoWC** Total (Minimal, Minor, Major, Hazardous, Catastrophic) | **SCM+TCM LoWC** Total (Minimal, Minor, Major, Hazardous, Catastrophic) |
|---|---|---|
| SCM1+WCV1 | 16 (0, 0, 4, 6, 6)<br>Min DCPA: 130 ft | 6 (6, 0, 0, 0, 0)<br>Min DCPA: 1370 ft |
| SCM1+WCV2 | 0 (0, 0, 0, 0, 0)<br>Min DCPA: N/A | 0 (0, 0, 0, 0, 0)<br>Min DCPA: N/A |
| SCM2+WCV1 | 12 (6, 4, 0, 2, 0)<br>Min DCPA: 130 ft | 3 (3, 0, 0, 0, 0)<br>Min DCPA: 706 ft |
| SCM2+WCV2 | 2 (0, 0, 0, 0, 2)<br>Min DCPA: 5 ft | 0 (0, 0, 0, 0, 0)<br>Min DCPA: N/A |

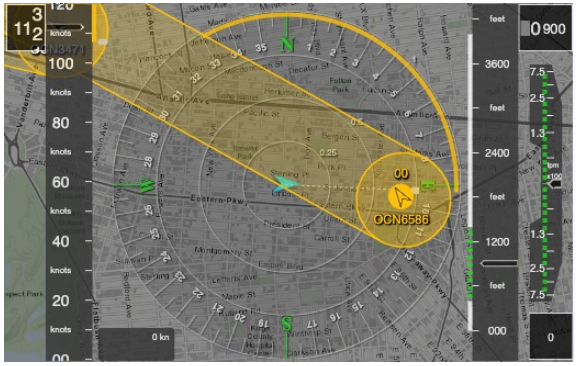
# LoWC Events

- With TCM enabled, LoWC events all occurred at intersections and were due to one of two causes
- One was due to an encounter changing classification in the middle of conflict avoidance maneuvers
- All others had maneuvers that were turns in the direction opposite to the aircraft's current turn
  - DAIDALUS assumes bank angle rate is unlimited
  - eVTOL models assume bank angle rate is limited




t = 4006 s




t = 4010 s

# Findings

- The addition of TCM does in fact reduce the number of and severity of LoWC events
- A larger WCV results in:
  - Higher numbers of alerts
  - Higher ratios of nuisance alerts
  - Larger resolution maneuvers, but also a larger minimum DCPA between aircraft
- Conflicts tend to occur near intersections
- Secondary conflicts due to the TCM were not observed
- Given this TCM implementation, LoWC events in the CA can occur due to:
  - Changing encounter classification in the middle of conflict avoidance maneuvers
  - Different assumptions on turn rates in conflict avoidance maneuver logic vs. aircraft dynamics models
- Outside of the CA, there were some LoWC events due to TCM not being enabled during takeoff
  - Higher RoW aircraft delays its response to aircraft that is taking off
  - SIRIUS framework would need to be modified in order for aircraft to communicate TCM status

# Questions?