Universities Space Research Association

Simulations of Urban Air Mobility Operations

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Overview

- X2 Simulation Experiment
  - Describe simulation experiment to evaluate the integration of UAM operations with existing and future airspace operations with NASA services and technologies working alongside partner services and technologies

- FY2020 Autonomy API Research
  - Describe simulation experiment to determine the information exchange requirements and protocols needed for UAM airspace management services to interact and support scalable operations

X2 SIMULATION EXPERIMENT

* The slides in this section are based on Verma, S., et al., “Lessons Learned: Using UTM paradigm for Urban Air Mobility operations,” 39th Digital Avionics Systems Conference (DASC), Virtual Conference, Oct. 2020.

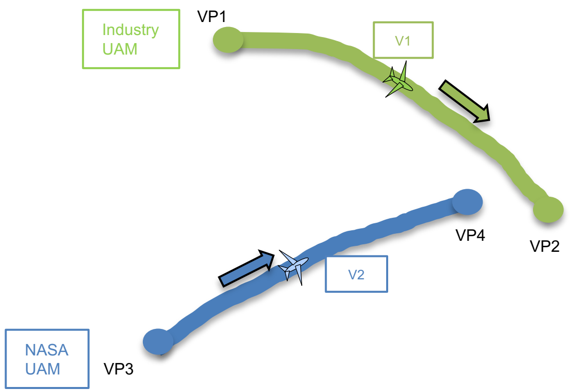
X2 Simulation Experiment Overview

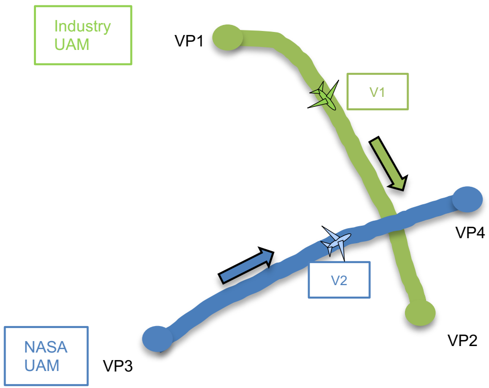
Goal: Determine if the X2 UAM airspace system can enable the information exchange required between simultaneous high-tempo UAM operations by multiple operators in shared airspace

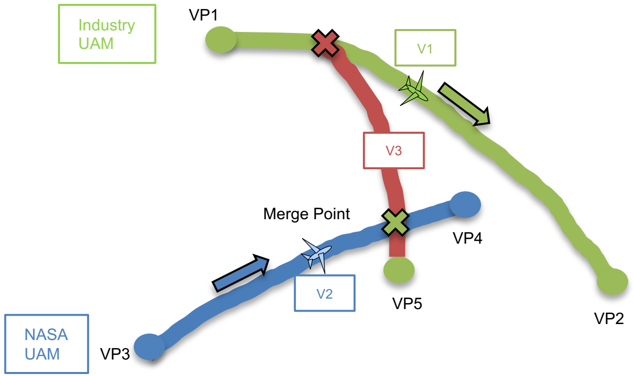
Approach: Conduct lab evaluation with industry partner using the X2 UAM airspace system

- Two UAM operators in the same airspace, each aware of the other
- UAM services connected to a common simulation environment to investigate information exchange requirements
  - Examples of services used: MACS (flight simulator), Network Scheduler (NS), Autoresolver (AR), Fleet Operator
- Route network designed to test use cases and exercise strategic scheduling and tactical separation algorithms

Simulation Use Cases







Use Case A

- Multiple UAM operators in shared airspace managing to separate constrained resources

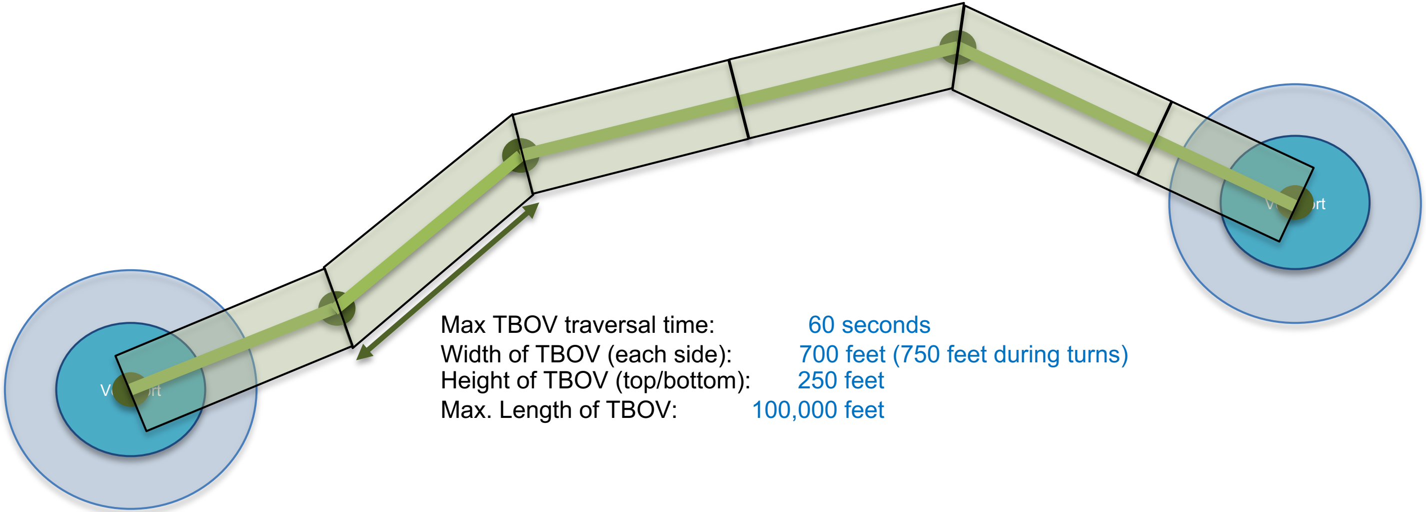
Use Case B

- Multiple UAM operators in shared airspace managing to the same constrained resources in strategic timeframe

Use Case C

- Multiple UAM operators in shared airspace managing to the same constrained resources in a tactical timeframe due to contingency

Transit-Based Operational Volumes (TBOVs)



- Transit-based Operation Volumes (TBOV) are Operation Volumes that are based on a known route or flight profile, where lateral and vertical boundaries are built around a centerline. The TBOV includes any geographical buffer required to account for the UAS' ability to maintain flight along the centerline (navigation performance capabilities, environmental factors, etc.)

X2 Services: Autoresolver (AR) and Network Scheduler (NS)

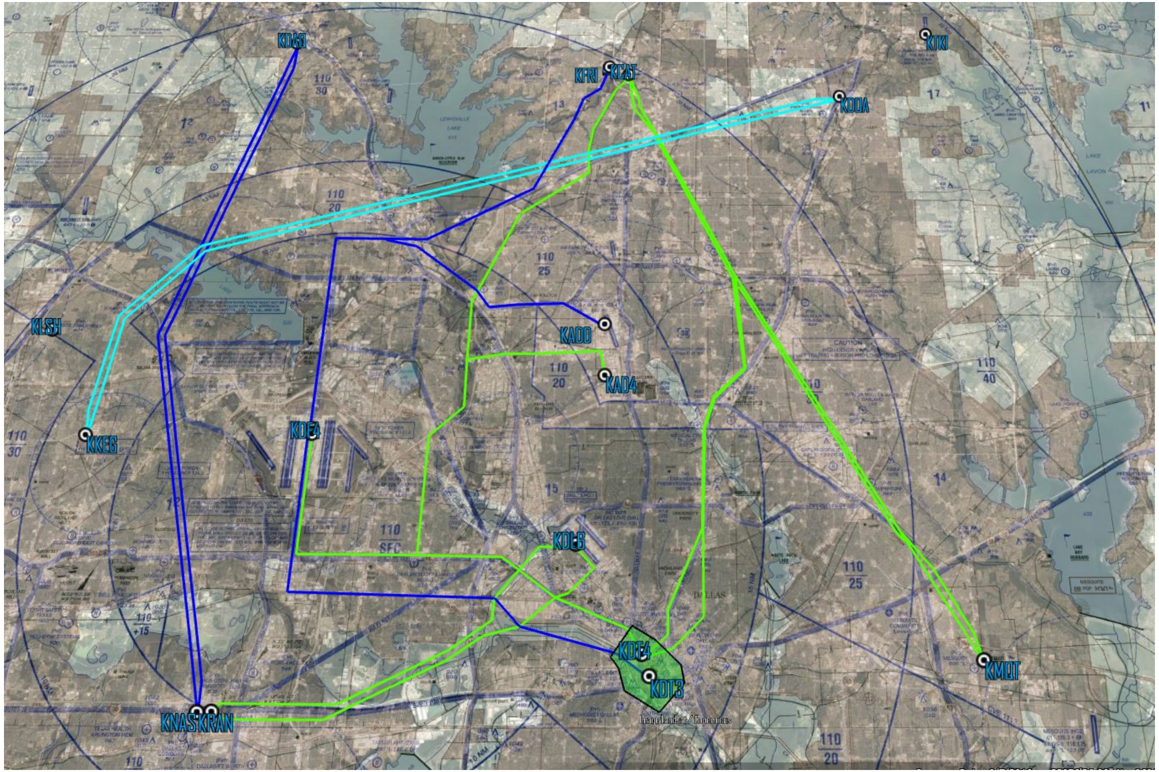
Autoresolver (tactical conflict detection and resolution service)

- Maneuver NASA flights to satisfy spatial separation constraints using
  - Ground delay
  - Speed control
  - Path stretch
  - Altitude changes
- NASA-to-NASA conflicts:
  Based on flight track information
- NASA-to-Uber conflicts:
  Based on flight track for NASA flight and TBOV for Uber flight

Network Scheduler (strategic scheduling service)

- Assign ground delay to NASA flights to satisfy temporal separation constraints
- NASA-to-NASA temporal separation:
  Based on estimated time of arrival at vertiports or waypoints
- NASA-to-Uber temporal separation:
  Based on Uber TBOVs

X2 Route Network



Routes:

- Uber: all use cases
  5 routes
- NASA: all use cases
  9 routes
- NASA: use cases B&C
  2 routes

Simulation Scenarios and Data Collection

Services	Use Case A		Use Case B		Use Case C	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Baseline (unconstrained and with no services)	✓	✓	✓	✓	✓	Deferred
Network Scheduler (strategic)	✓	✓	✓	✓	Deferred	Deferred
Auto Resolver (tactical)	✓	✓	✓	✓	✓	✓
Network Scheduler and Auto Resolver	Deferred	Deferred	✓	✓	✓	✓

- Traffic scenarios define the level of both simulated non-UAM and UAM traffic
  - UAM traffic interacts with non-UAM flights obtained from historical data

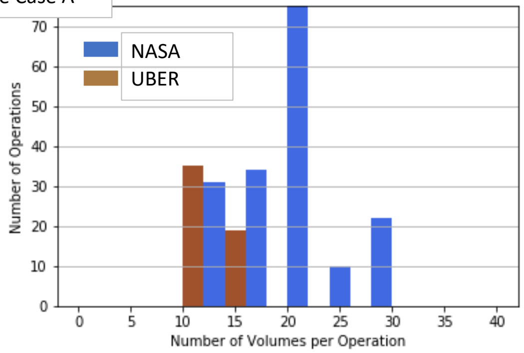
Metrics

Scalability (C-2)	# of operations, # of routes, throughput on routes	**Fleet operator's exchange ledger** – timestamp, gufi, acid, route, takeoff time **Fleet operator's state ledger** – timestamp, gufi, acid, state information
Flexibility (C-3)	TBOV temporal sizes and volumes, flight paths	**Operations** (NASA and Uber) – gufi, flight geography description **Volumes** (NASA and Uber) – gufi, ordinal, time begin and end, max and min altitude, latitude and longitude
Information Exchange (C-4)	Message latency, message response time, message integrity	**uss_exchange** – storage time, exchange data, request time, response time **nasa_requests, uber_requests** (files from Uber)
Safety (C-7)	Spatial and temporal loss of separation, ground delay	**Positions** (NASA and Uber) – gufi, timestamps, latitude, longitude, altitude **Fleet operator's exchange ledger** – scheduled takeoff time, original takeoff time, message published time

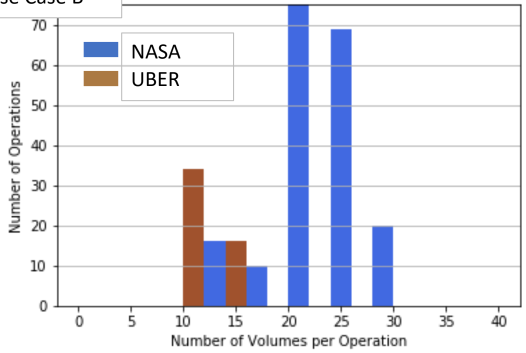
Number of Volumes per Operation for Baseline Case

- NASA TBOVs were designed with time windows of roughly 60 seconds, shorter between crossing waypoints, and longer at ascent and descent
- Uber TBOVs were designed to cover straight segments of routes in a single TBOV, thus Uber fights have fewer TBOVs per flight

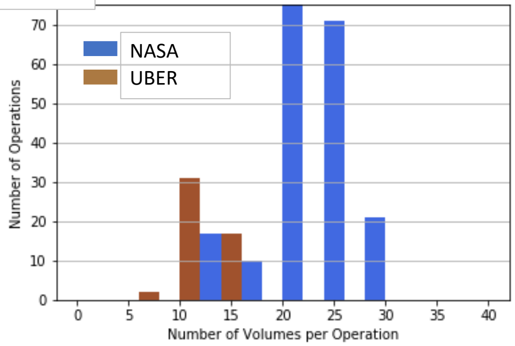
Use Case A



Use Case B

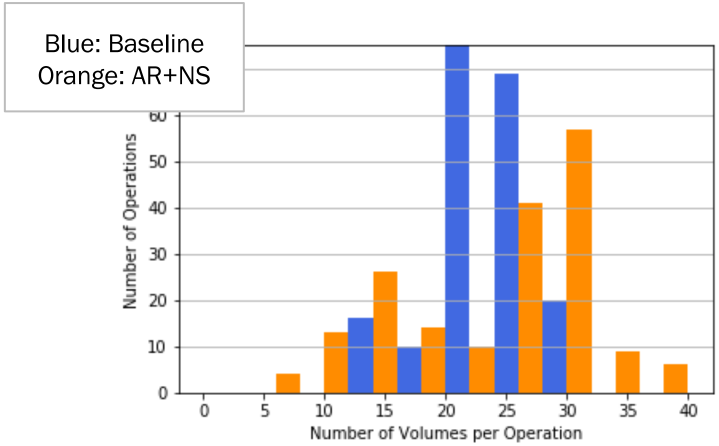


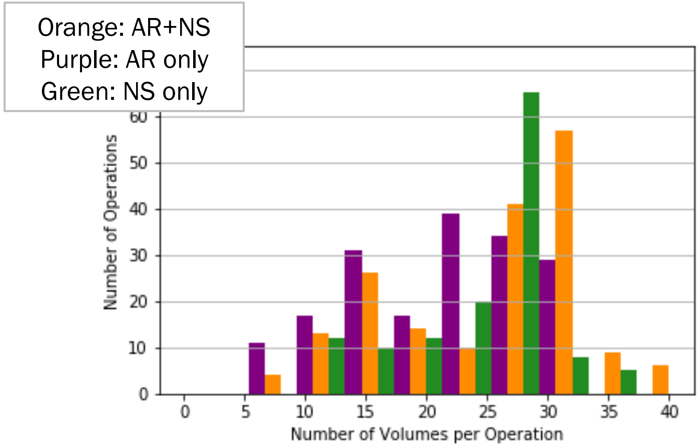
Use Case C



Number of Volumes per Operation with Advanced Services

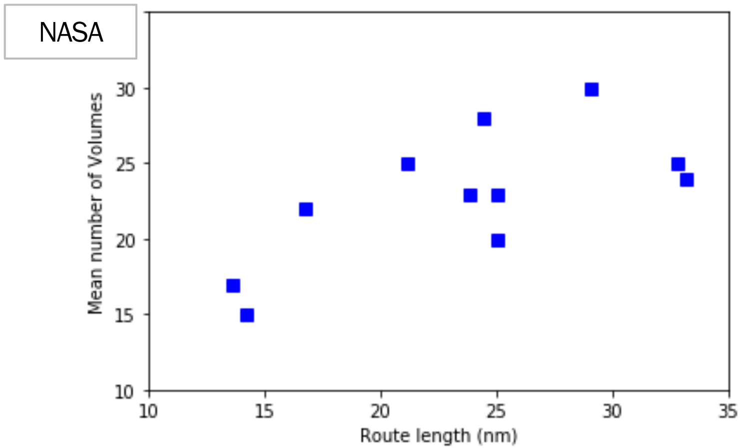
- Higher number of TBOVs are generated because the advanced services tend to modify trajectories leading to extra waypoints, around which extra volumes may be generated
  - This effect is particularly pronounced when the strategic *Scheduling Service* (NS) is utilized
- Advanced services should be designed keeping the design for the generation of TBOVs in mind, since they impact the number of TBOVs per operation

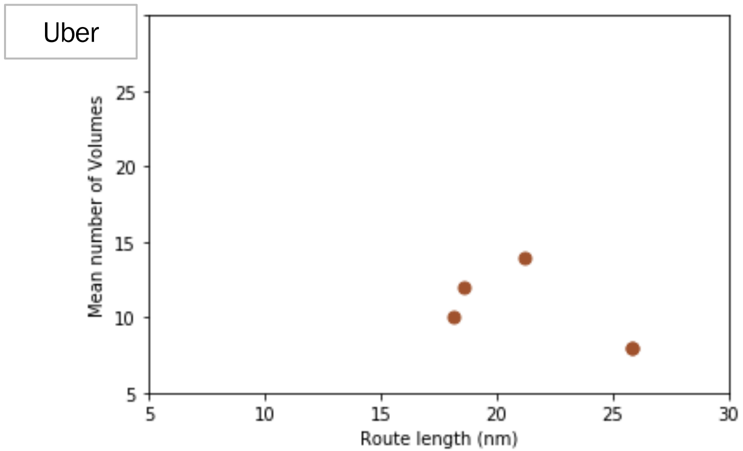




Number of Volumes per Route

- Number of volumes per operation per route is proportional to the length of the route
    - A route with more turns is likely to have a larger number of waypoints and thus larger number of TBOVs generated around those waypoints
- Higher number of volumes generally means that the volumes sizes are smaller and that conformance to the volumes can be a challenge for the overall system





Number of POSITION Messages per Operation

- Investigation of number of messages exchanged is used to measure metrics such as message latency, message response time, etc.
- With advanced services, the total number of messages exchanged is expected to increase
- POSITION messages are recorded at 1 hertz and are based on UTM TCL-4 implementation
- Table shows average number of POSITION messages per nautical mile for all three Use Cases for Baseline scenario

Use Case	NASA	Uber
A	621	552
B	700	669
C	654	492

Takeaway Messages

- The airspace system architecture and the implementation of services has a considerable impact on the efficiency of the system.
- Increase in number of volumes per operation, or their size, has an effect on density of flights.
- Increase in number of position messages being exchanged is likely to stress the system and add to the message latency.
- Strategic deconfliction and tactical separation services were able to suitably manage de-confliction of flights even in high traffic scenarios.

FY2020 AUTONOMY API RESEARCH

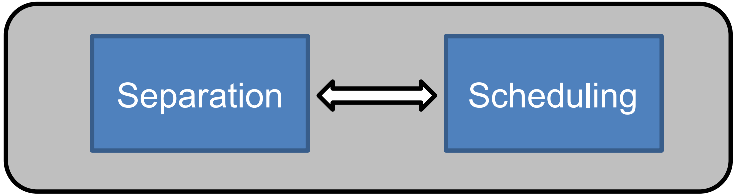
* The slides in this section are based on the final presentation to the UAM SPM on FY2020 research on 09/16/2020

Research Overview

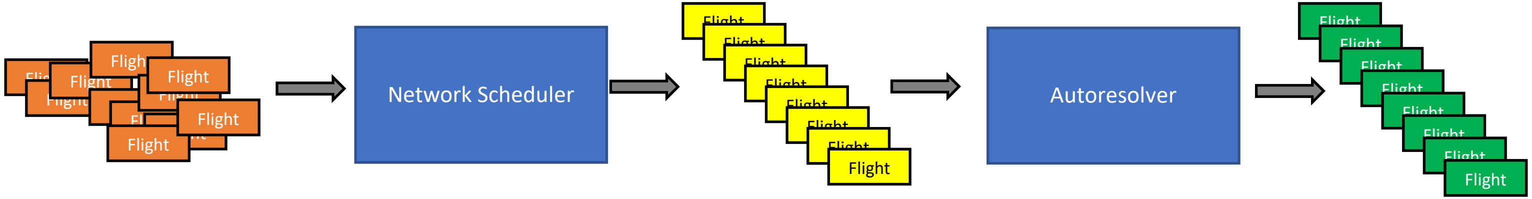
- FY2020 research tasks included integration of Autoresolver (AR) and Network Scheduler (NS) services to gain initial understanding of interaction of complex services in high throughput operations [UAM Research Objectives FY20 1, 2, 6]

- **Green Success Criteria:** "Conduct simulation using a highly automated airspace management system towards developing the requirements for using increasingly autonomous systems in a service-oriented architecture for a specific scenario."

- 3-step approach:
  - Integrate two services contributing to autonomous operations together in the same simulation environment
  - Simulate high-density operations in increasingly complex situations
  - Analyze different approaches to integration including communication and performance requirements for different concepts of operations

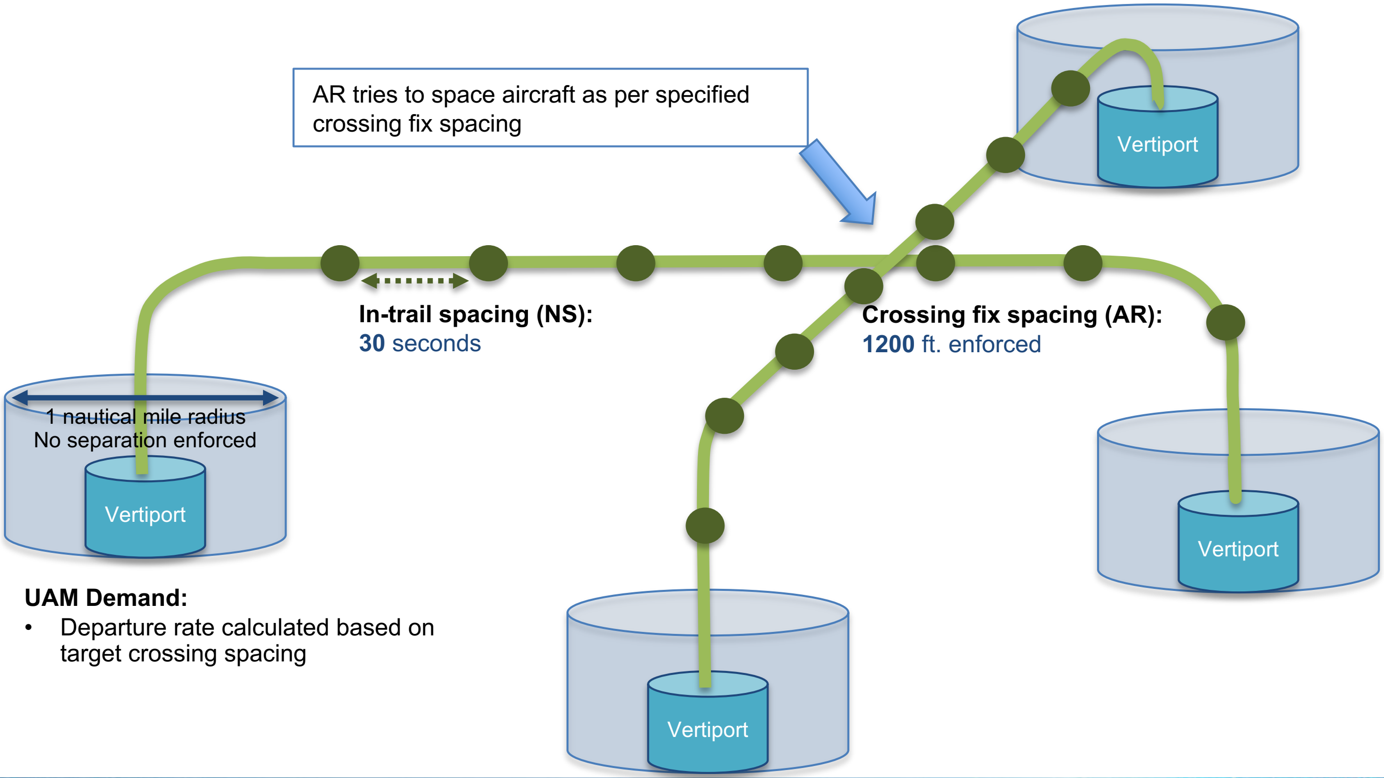


Interaction of Autonomous Services



- Network Scheduler (NS):
  - Takes a complex input demand set and attempts to match that demand to the resource availability throughout the network
  - Generally satisfies time-based separation requirements
- Autoresolver (AR):
  - Monitors the aircraft during flight to ensure that safe separation is maintained
  - Concerned with spatial separation requirements

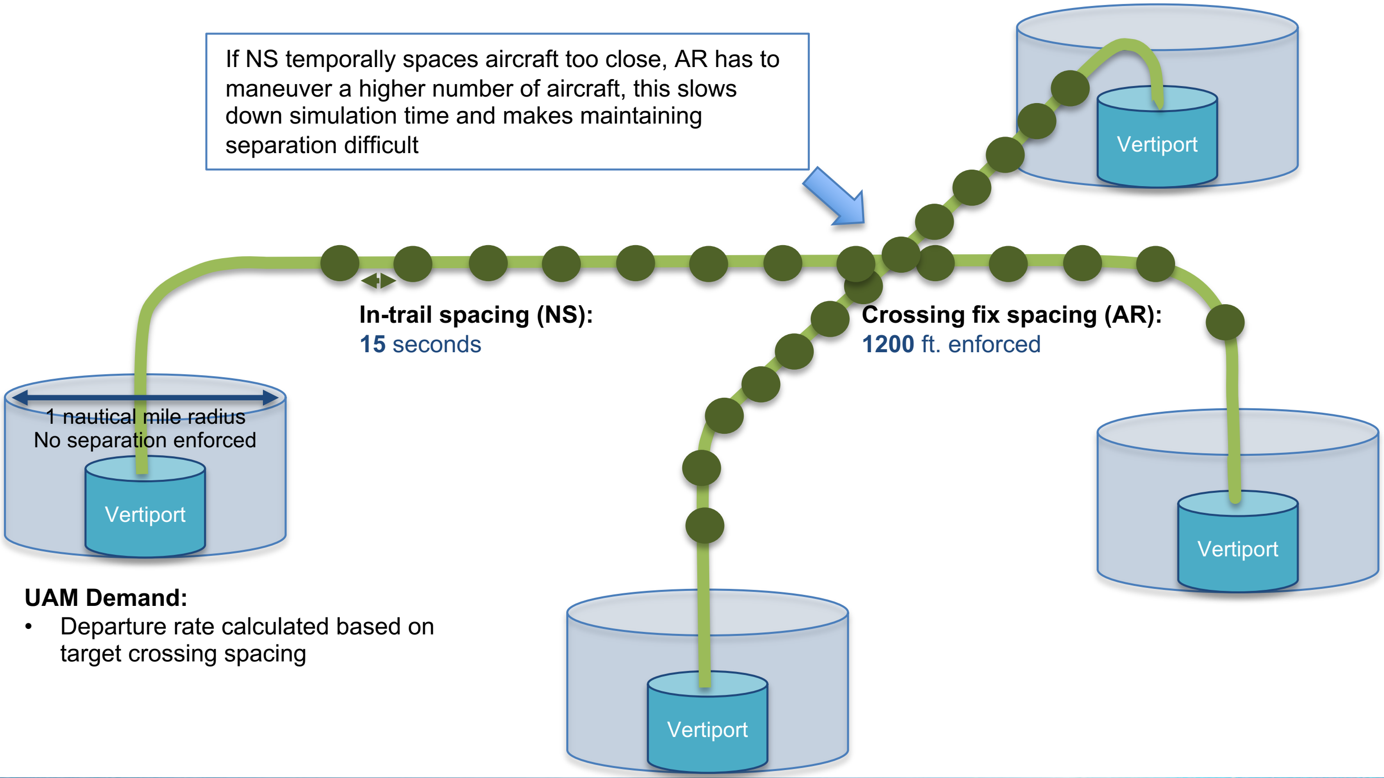
AR Response to Fixed NS Temporal Separation



UAM Demand:

- Departure rate calculated based on target crossing spacing

AR Response to Fixed NS Temporal Separation

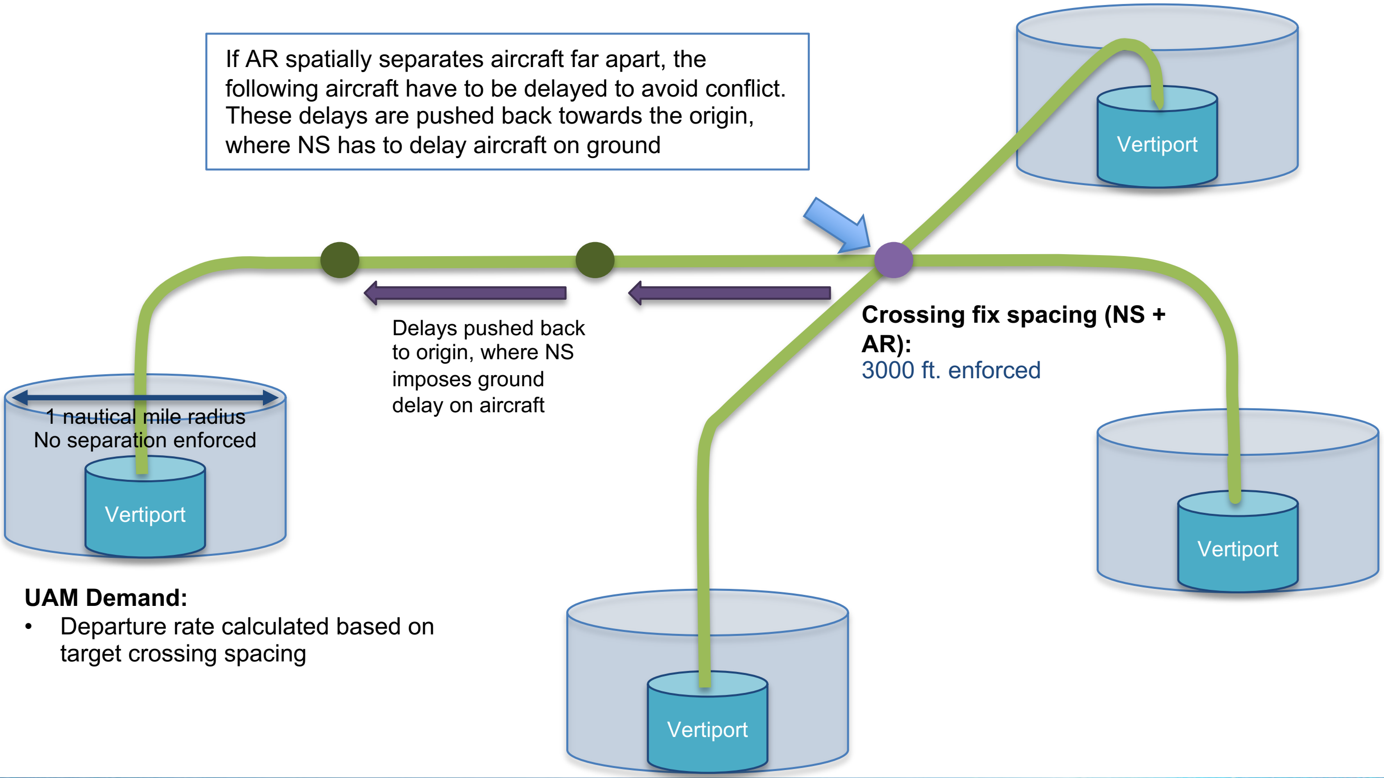


UAM Demand:

- Departure rate calculated based on target crossing spacing

NS Response to Fixed AR Spatial Separation

If AR spatially separates aircraft far apart, the following aircraft have to be delayed to avoid conflict. These delays are pushed back towards the origin, where NS has to delay aircraft on ground



UAM Demand:

- Departure rate calculated based on target crossing spacing

Studying Effects of Variation of Separation Requirements

How can Scheduling and Separation function together in a complex UAM network under ideal conditions?

- Investigate how Scheduling and Separation work together in a complex UAM network under ideal conditions
  - Currently, temporal and spatial separation values are fixed; want to evaluate how changes in these values affect system performance

- Results will develop requirements for the relationship between the spatial separation and temporal separation values used by the algorithms when they are working collaboratively in the same simulation environment

Experiment Setup

- Simulate scenarios of varying demand level and separation requirements
  - Fixed network with two intersecting routes
  - Active services: NS and AR. We run scenarios with no services, NS-only, and AR-only to establish baselines.
  - Vary traffic level; demand is modeled as uniformly spaced flight request events
    - NS controls *inter-departure separation* at departure vertiports to control amount of traffic in the network
  - Vary temporal and spatial separation values and observe system performance

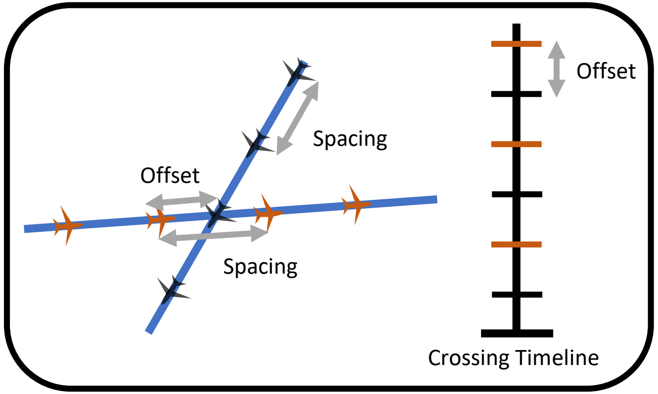
Factor	Levels	Comments
Interoperability level	Level 1	There is no communication between NS and AR
Services	AR-only, NS-only, AR+NS	
Traffic level Inter-departure spacings	14 seconds	Constant on both routes
AR spatial separation	1200 ft., 2000 ft.	
NS departure temporal separation	Range from 30 seconds to 18 seconds	These are values at the departure vertiports

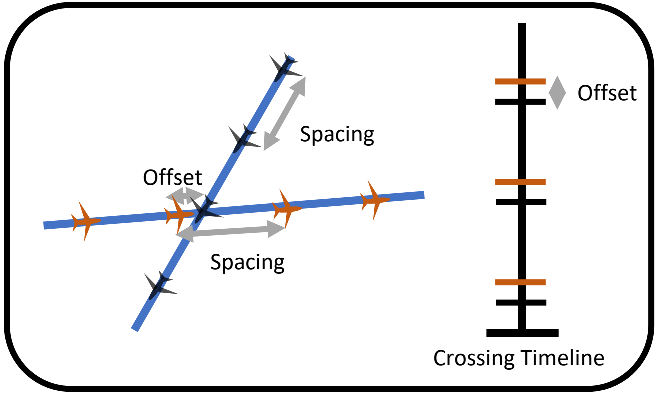
Expected Outcomes and Metrics

- Desired / expected behaviors:
  - With low temporal separation: AR maneuvers many aircraft, and may still result in many LOS
  - With large spatial separation: NS adds large delays on ground, which reduces traffic throughput

- Metrics:
  - Safety
    - Total Loss of Separation (LOS)
    - Total number of aircraft that encounter LOS
  - Efficiency
    - Flight delay (total, by route, per flight)
  - NS scheduling
    - NS iteration length
    - NS ground delay
  - AR maneuvers (total, by maneuver type)
    - Speed change
    - Path stretch
    - Total maneuver counts

Separation Between Airborne Aircraft at Crossings





Generally, aircraft on the same route are arranged with equal spacing (offset = spacing / 2)

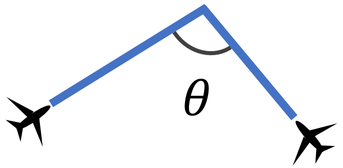
We will also specify the offset between minimum crossing times between aircraft on different routes (offset < spacing / 2)

Theoretical Separation at Crossings

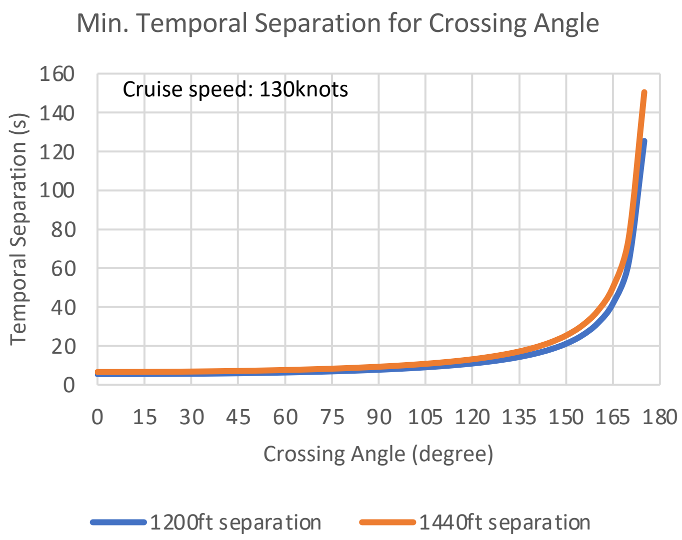
- Minimum temporal separation required at a crossing waypoint is given by

$$temporalSep_{min} = \frac{spatialSep}{speed * \cos(\frac{\theta}{2})}$$

where *spatialSep* is the desired spatial separation, *speed* is the speed of aircraft, and θ is the crossing angle

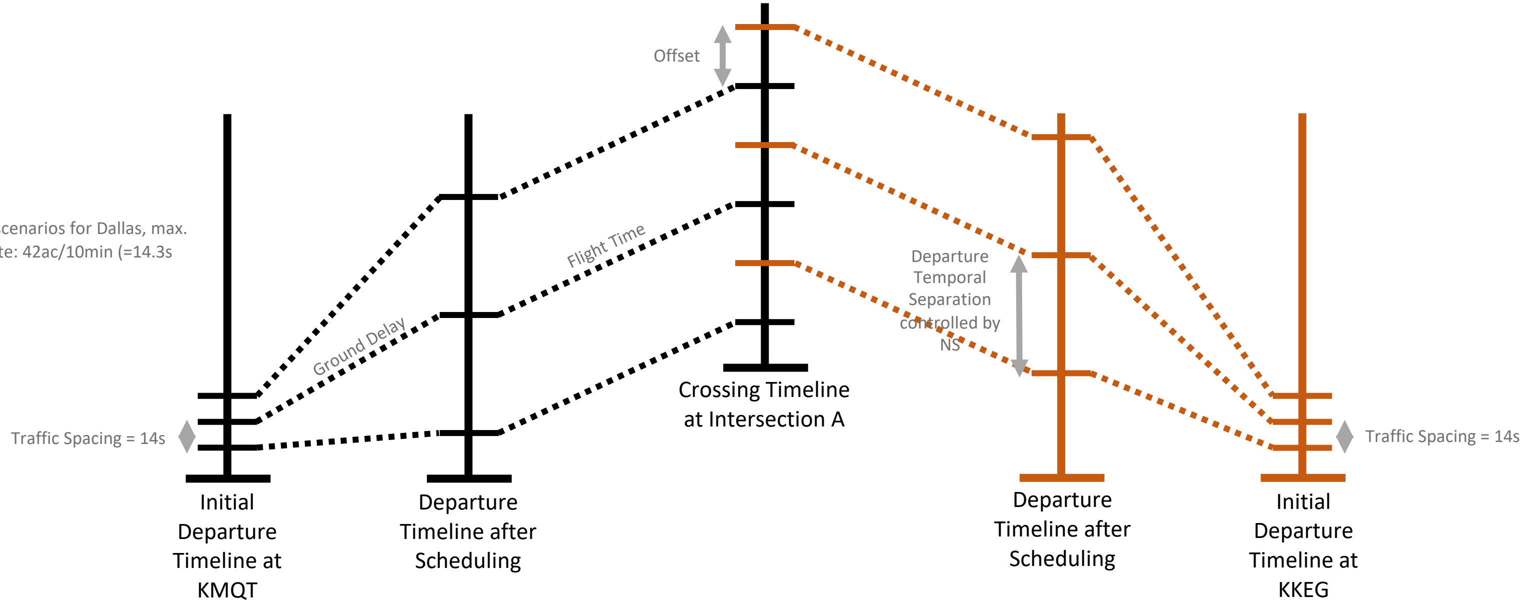


Spatial Separation	Separation when θ=101°	Separation when θ=130°
1,200 ft	8.60 sec	12.94 sec
1,440 ft	10.32 sec	15.53 sec

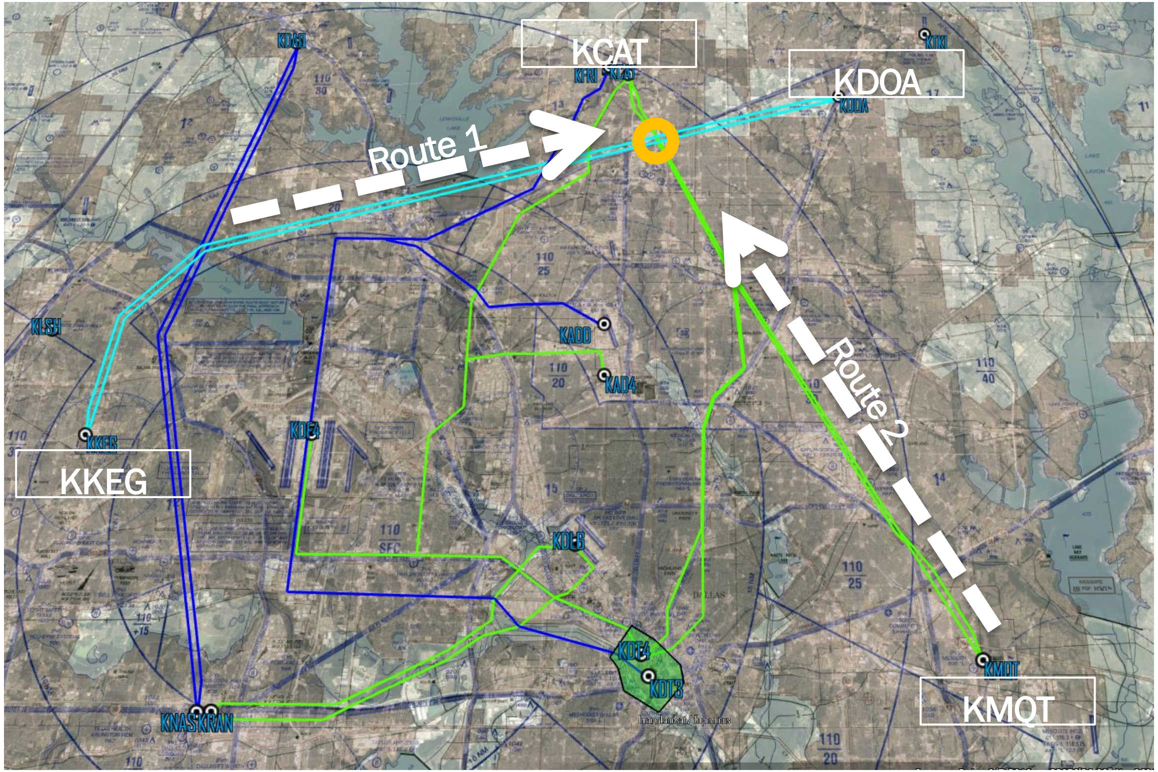


Scheduling Inter-departure Spacings

Reference
In VT traffic scenarios for Dallas, max. departure rate: 42ac/10min (=14.3s spacing)



Experiment Route Network



Routes:

KKEG … KDOA

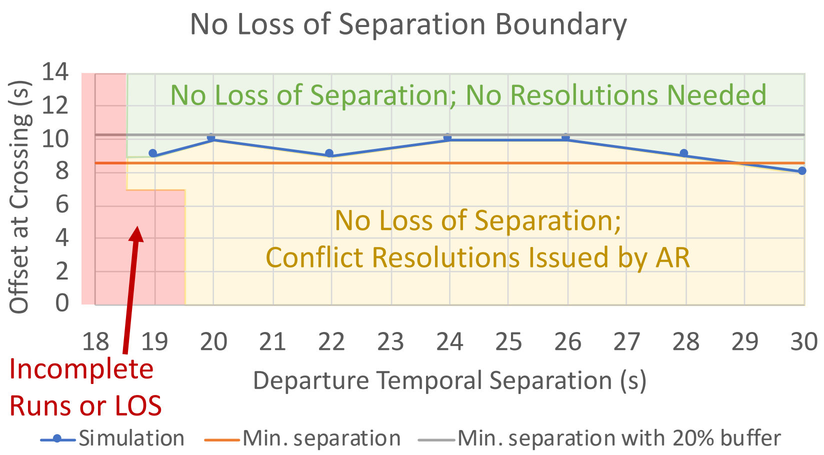
KMQT … KCAT

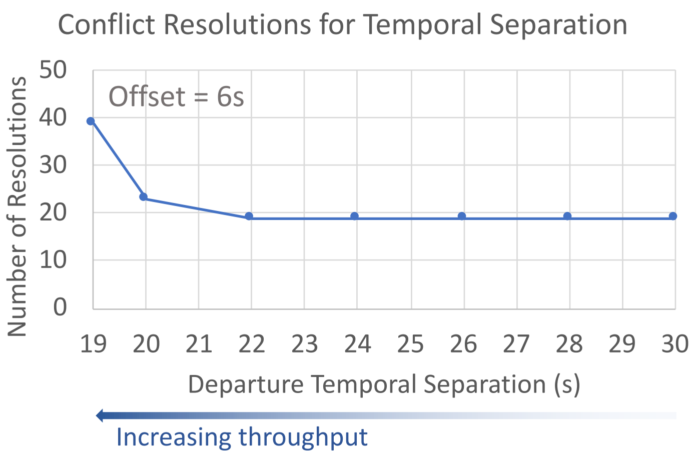
Constraint Points:

ZBX01 (crossing, at 1100 ft. AGL)

Conflict Resolutions for Varying Separations

- As offset is close to theoretical minimum separation at crossing, AR issues conflict resolutions to avoid Loss of Separation (LOS).
- The number of resolutions increases as the temporal separation decreases.
- NS and AR together can increase throughput by reducing departure separation and providing conflict resolutions





Takeaway Messages

- The minimum temporal separation between crossing flights depends heavily on the inbound crossing angle, i.e., increases non-linearly as a function of crossing angle.

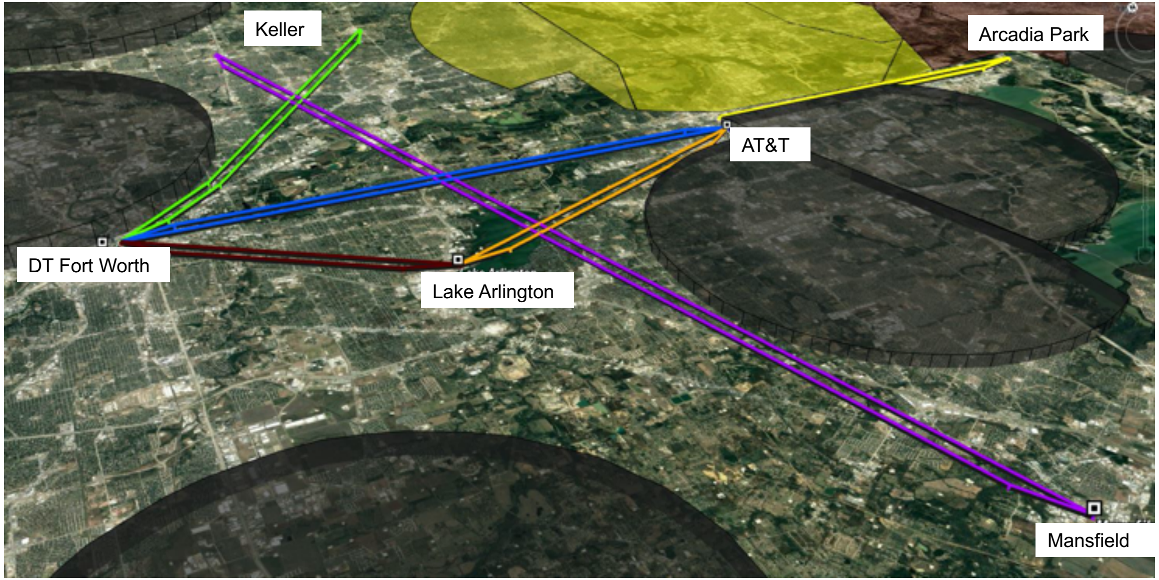
- Scheduling and separation services working together can handle heavy traffic scenarios in which LOS would happen without these services (e.g., when offset is below theoretical minimum separation), leading to increased throughput.

- Throughput at a crossing waypoint can be increased by scheduling flights to the crossing waypoint compared to setting flow rates.

- The number of conflict resolutions from a separation service increases as the departure temporal separation in a scheduling service decreases.

BACKUP

X2 Airspace



- All routes for X2 Engineering Evaluation are in Class G airspace
- The routes are direct
- Flights in opposite directions are laterally separated by 1400 ft
- UAMs will fly at 500 ft AGL
- No vertical separation is assumed to keep them in Class G
- Vertiports are assumed at busy city landmarks such as Cowboy Stadium

X2 Scope and Assumptions

- Airspace
  - Scope of X2 is Class G airspace
  - UAM are VFR; ATC contact not required
  - All routes GPS navigational, not solely relying on visual reference
  - UAM-UAM separation minima: 1400 ft horizontally, 500 ft vertically
  - UAM-UAM scheduling minimum: 60 seconds

- Roles and Responsibilities
  - Users and third parties will submit operational volumes for approval and manage their own aircraft

X2 Traffic Scenarios

- UAM Routes in Class G airspace
  - Direct routes but can cross each other
  - Bi-directional: laterally separated by 1400 ft
  - UAMs fly at 500 ft AGL

- IFR and VFR background traffic from: 12/21/2017

- UAM traffic simulation parameters:
  - 60 (+/-10) sec variation in departure times