

Overview of an Exploratory, Multi-Pilot Simulation Study of Early eVTOL Operations at Non-Towered Vertiports
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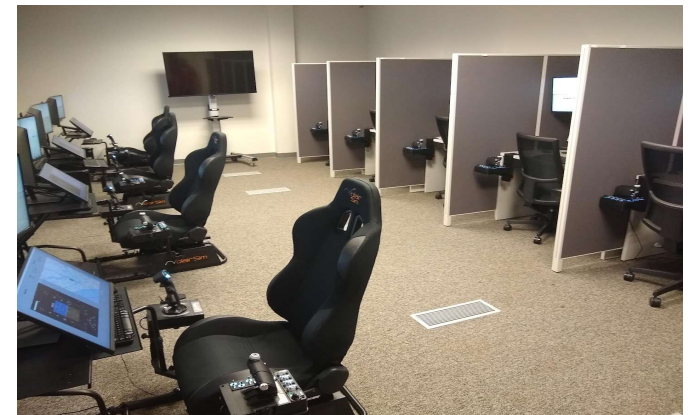
Goals and Objectives of Study

Assess early UAM Operations to inform future research

- Piloted UAM Maturity Level (UML)-2 ConOps Simulation, “PUCS”
- Baseline nontowered, VFR vertiport throughput under current rules & procedures
 - Class E & G airspace without positive control from ATC or cooperative, strategic scheduling services
- Identify bottlenecks and barriers to safe, scalable operations.
- Compliment other studies of entry into service
 - Typically focused on positively controlled, terminal airspace and controller workload

Initial evaluation of “UAM Flyers”, a real-time, many pilot simulation environment for rapid development/screening

- Low-cost, module hardware and software
 - Easily modified
- Non-proprietary, modifiable aircraft models, pilot displays, & interfaces





Bottom-Line Up Front

- *Note, initial exploration, not a formal experiment*
- Evaluation pilots assessed the Flyers as a useful compliment to typical single-aircraft development and research simulators
- Throughput of 72 vertiport operations / hour (operation = takeoff or landing)
 - Average of 30 second vertipad occupancy per “expeditated” takeoff
 - Average of 61 seconds vertipad occupancy per landing (from deceleration decision to vertipad exit)
- Pilots generally found flight operations had low overall workload
 - Suggestions for improving approach & landing task, assessing departure window, interval management



Outline

- Description of UAM Flyers
- Vertiport environment and flight procedures
- Evaluation pilots and training
- Evaluation scenario
- Results
- Summary



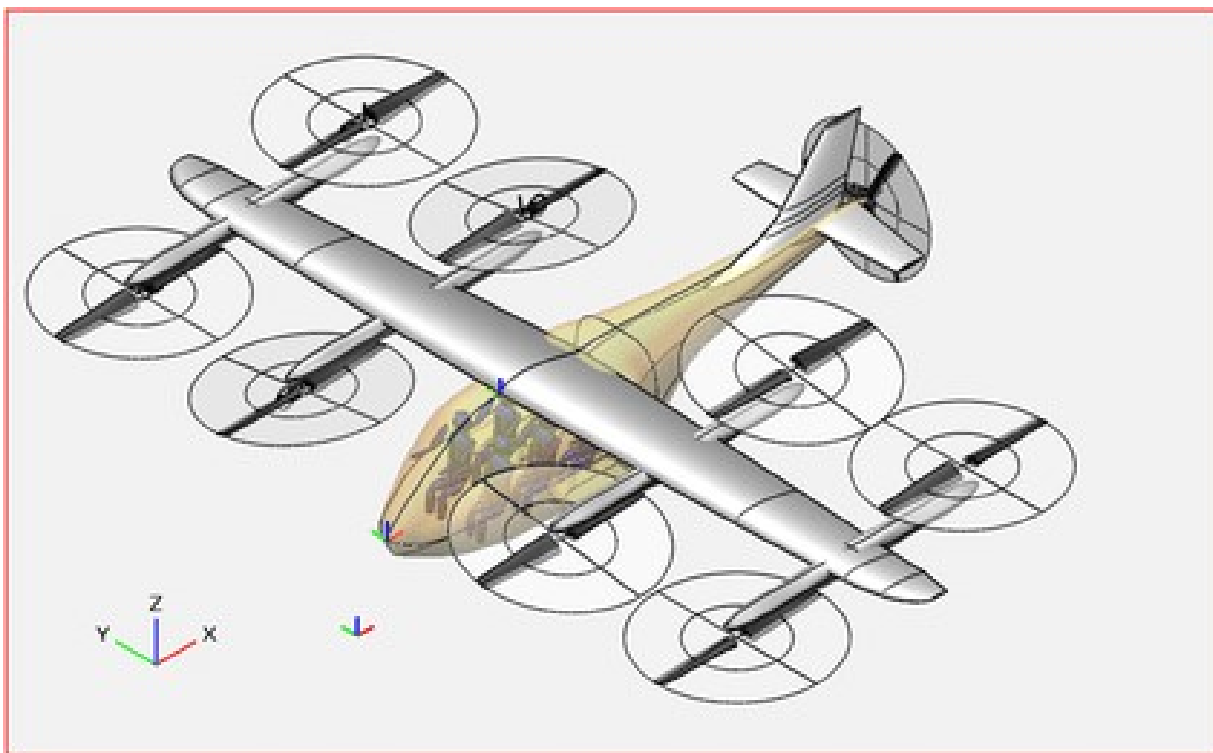
UAM Flyer Lab



- Networked pilot stations
 - 10 used for PUCS, but easily expanded
 - Stand-alone for PUCS but also integrates with fleet and airspace management tools at NASA & FAA
 - Aircraft models based on NASA reference configurations
 - Includes flight control system
 - Gaming-quality pilot inceptors
 - Cockpit displays are programmed in-house
 - X-Plane used to render external visuals
 - Can edit/add elements as needed



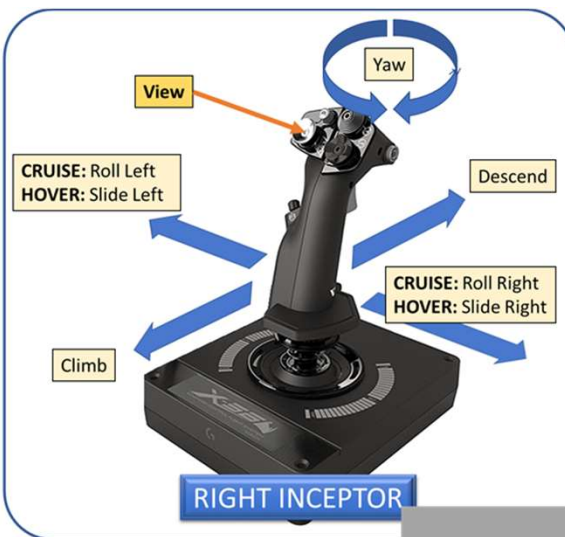
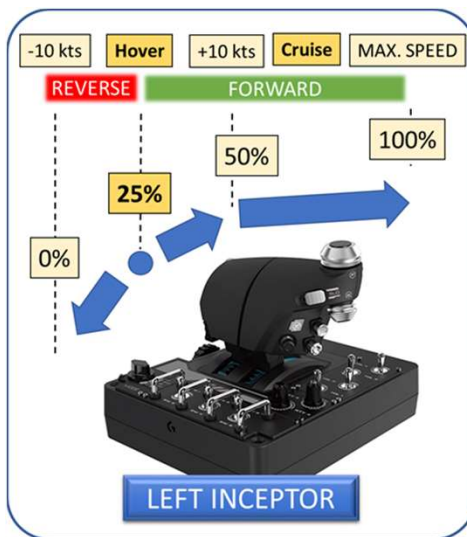
Reference “Lift + Cruise” eVTOL Configuration



- Modified version of Revolutionary Vertical Lift (RVLT) Project Lift + Cruise
 - Motor torques increased for satisfactory handling
- Full-authority flight control system similar to “Unified” concept
 - Automated transition between powered-lift & wing-borne flight
 - ~70 knot transition speed
- 120 kt cruise, 130 kt max
- Battery modeling not a factor for PUCS, but pilots instructed to minimize use of power-lift



Pilot Control Inceptors and Aircraft Response



Primary Controls—Full Authority FBW

- Controls trajectory & speed, not attitude and power
 - Pitch + Power = Performance habits aren't applicable
 - Two inceptor mapping regimes: Hover (≤ 10 kts) & Cruise (> 10 kts)
 - Below ~ 70 kts, lift from rotors, > 70 kts lift from wing
- Lefthand sets Speed Command (SC): set it & monitor
 - Other than landing & taxi, generally set SC & monitor result (note, occasionally SC creeps; monitor it too)
- FPM on external display useful for path management
 - Since flightpath angle is a function of Speed and vertical speed, use coordinated inputs during landing approach to keep FPM on target

Display information

The touchscreen button between PFD and map toggles between the map-display and a downward looking camera view useful for landing

Note, in the sim, Bader Field's elevation is 1' so for practical purposes MSL and AGL at Bader are the same. If during practice you want to land on an elevated vertiport, there is a digital radar altitude (RA) readout below the altitude tape.

Digital readout of SC set by LH inceptor

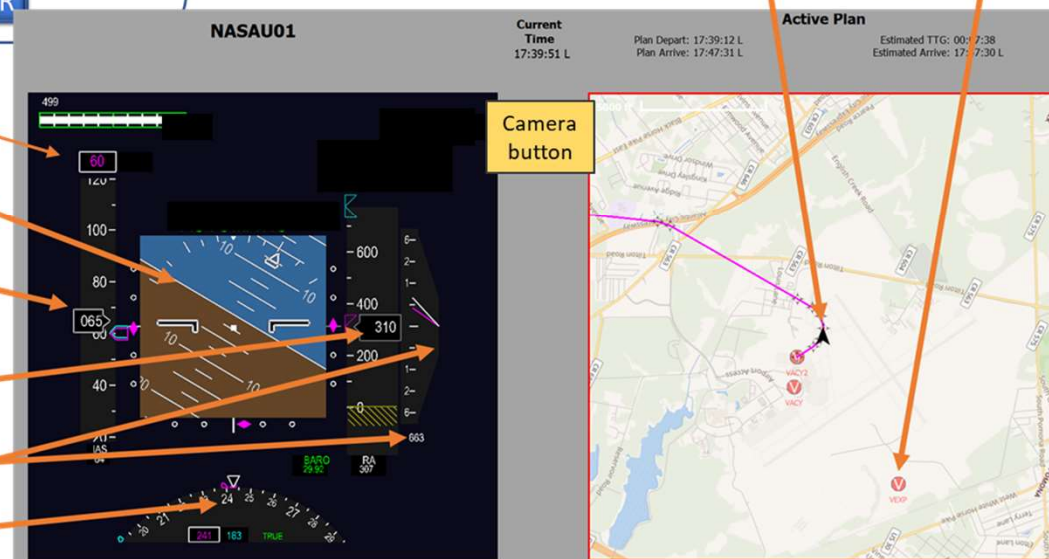
ATTITUDE

SPEED

ALTITUDE

VERTICAL RATE

HEADING





External and Cockpit Displays



External display

- 34", 21:9 aspect ratio
- 3-arc minute per pixel
- View swivelable via hat-switch on side-stick
- Some heads-up display like symbology overlaid

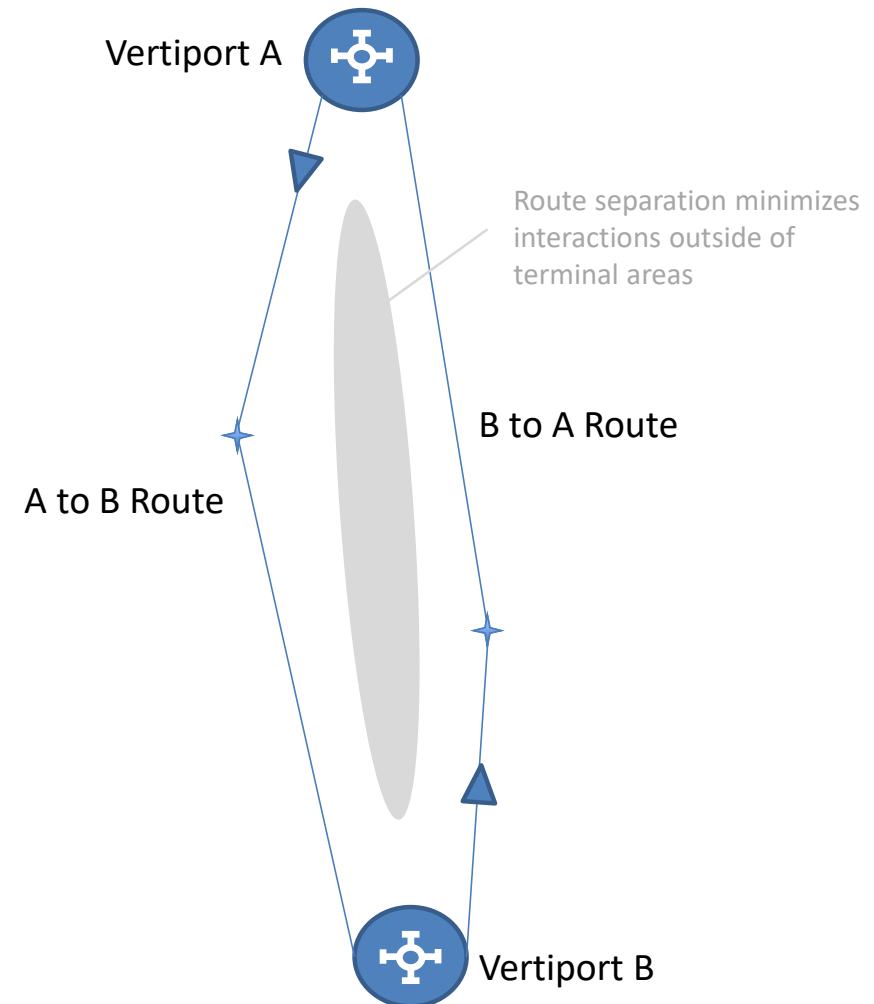
“Cockpit” displays

- Primary flight display
 - Mostly used to monitor command and performance parameters
- Multifunction display
 - Track-up moving map
 - Local flight procedures
 - Location of ADS-B equipped traffic
 - Switchable to downward looking camera for landing



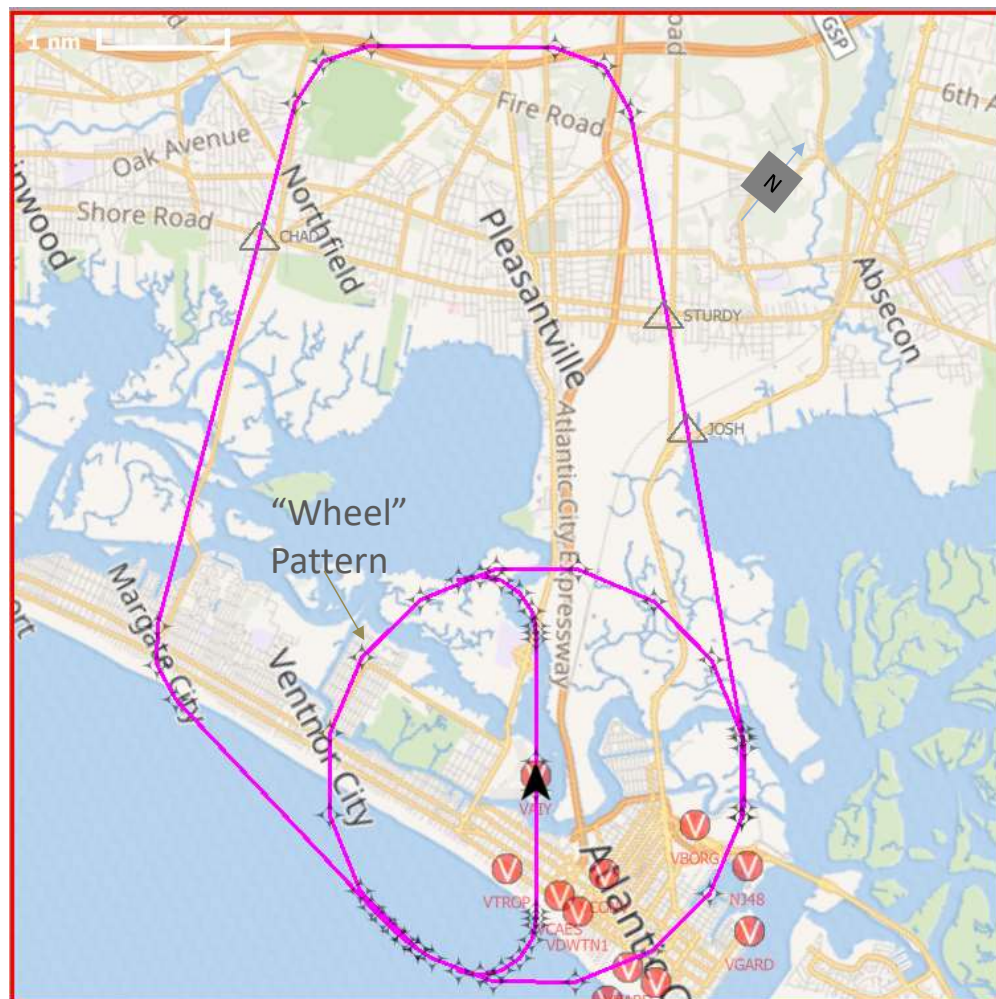
Background Context, Early Shuttle Service Between Vertiport Pair

- Bi-directional, “ring-route” between 2 vertiports (e.g. connecting city center & airport)
 - UAM traffic follows “advisory” UAM routes
 - UAM Routes have no regulatory recognition, but operators and ATC use them as a cooperative operating practice
 - UAM routes add predictability to UAM operations
 - UAM aircraft must detect & avoid non-participating VFR traffic (not present in this initial study)
 - Away from vertiports, routes for opposing traffic flows are separated and don’t routinely interact
 - Homogenous aircraft representing a single-fleet operator
 - Matched cruise & approach speeds simplified operations
 - Separation between ports for early network ~10-25 nm to allow for nominal reserve endurance/range
 - Note, for these simple networks, flight planning/dispatch of individual flights is mostly repetitive and wasn’t considered in this study
 - *This study used closed-circuit between a single vertiport to increase traffic density for given number of pilots*

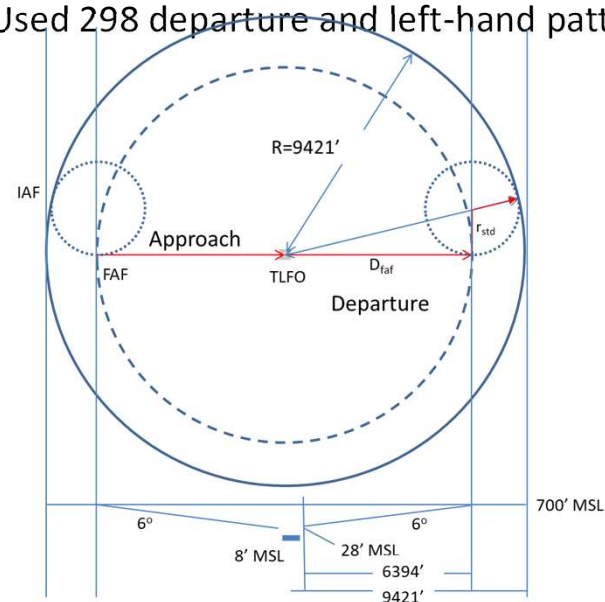




Vertiport Environment and Flight Procedures



- No winds or weather in this study
- Only vertiport located on Bader Field used in data scenarios (i.e. pad, centered in "wheel").
 - Other vertiports used during individual familiarization and practice
- "Deproach" directions of 298 & 118 degrees
 - Used 298 departure and left-hand pattern



Details of wheel pattern & deproach procedures



Surface Operations

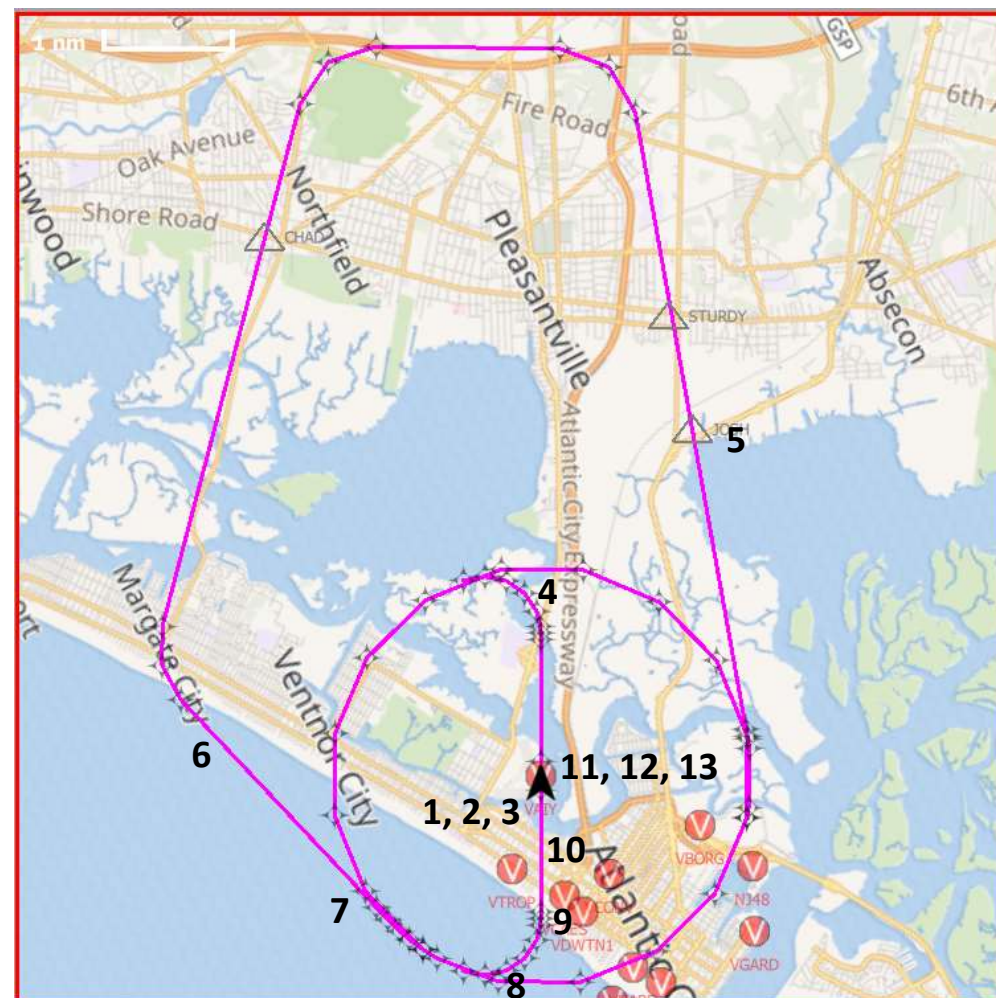
- Single 50' x 50' vertipad for takeoffs and landings
- Departing aircraft queue behind hold-short line
- Taxi line provided guidance to/from vertipad and departure queue.





Operational Procedures

1. Hold short line
2. Taxi to pad
3. Takeoff and departure
4. Cruise transition
5. Cruise
6. Arrival transition
7. Pattern entry
8. Turn to final
9. Final approach
10. Deceleration decision point, DDP (Alt = 300')
 - a. Go-around
 - b. Deceleration to powered-lift
11. Translational hover to pad
12. Set down
13. Taxi to departure queue





Communication—Recommended Self-Announcements

- Common Traffic Advisory Frequency (CTAF) announcements based on FAA Advisory Circular for Non-Towered Airports
- Radio not simulated; pilots simply spoke loud enough to be heard across room
- Standard CTAF self-announcements:

Outbound:

1. Before taxiing onto the vertipad: “Bader traffic, NASA 4 , entering vertipad, Bader”
2. At takeoff: “Bader traffic, NASA 4 , departing vertipad, Bader”

Inbound

3. Entering the pattern from the cruise-route (e.g. analogous to entering downwind): “Bader traffic, NASA 4 , entering pattern, Bader”
4. Rolled out on final: “Bader traffic, NASA 4 , on final, Bader” (Note: aircraft announcing on final has priority until landing complete or go-around performed)
5. Taxiing clear of the vertipad (beyond the hold-short line): “Bader traffic, NASA 4 , clear of vertipad, Bader”

In addition to standard inbound & outbound calls, self-announce anytime there is a potential deconfliction issue or other hazard.

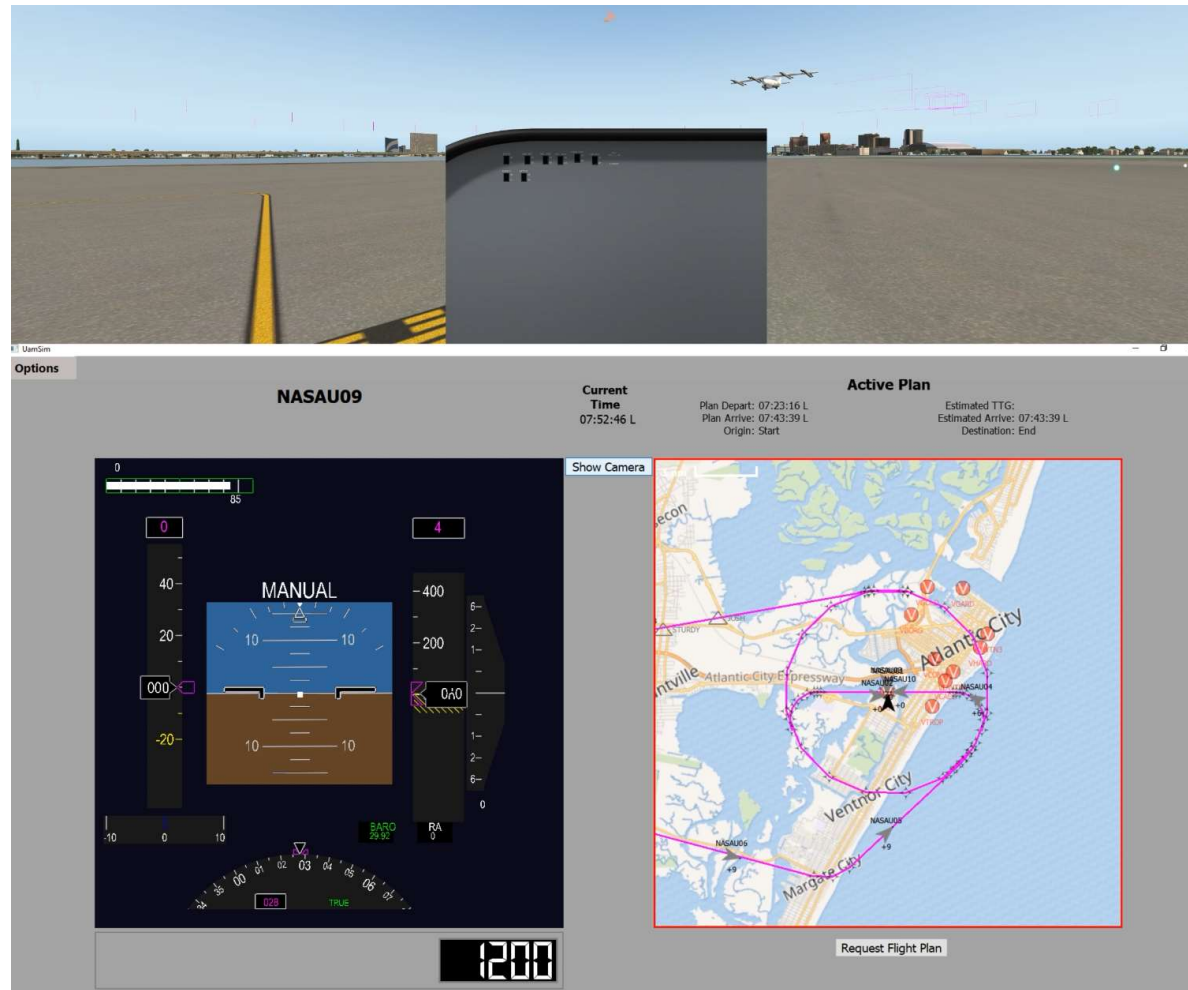


Evaluation Pilots and Training

- Evaluation pilots recruited from NASA workforce
 - 5 NASA research / test pilots from Ames, Armstrong, and Langley
 - 1 Commercial rated pilot (not employed as professional pilot)
 - 2 private pilots
 - 2 Part 107 sUAS remote pilots
- Preparation of subjects consisted of at least 1 practice session and the final data collection session
 - Practice sessions involved at least 5 pilots
 - Divided into familiarization and practice with individual aircraft and group conduct of vertiport operations
 - Multiple early practice sessions conducted with local pilots/volunteers to develop proposed procedures and scenario timing
 - Final practice session used to finalize operational and evaluation procedures (afternoon before data collection session)
 - Data collection
 - Single 3-hour simulation session, followed by 1-hour group exit interview / discussion
 - First opportunity to run with all 10 cockpits occupied

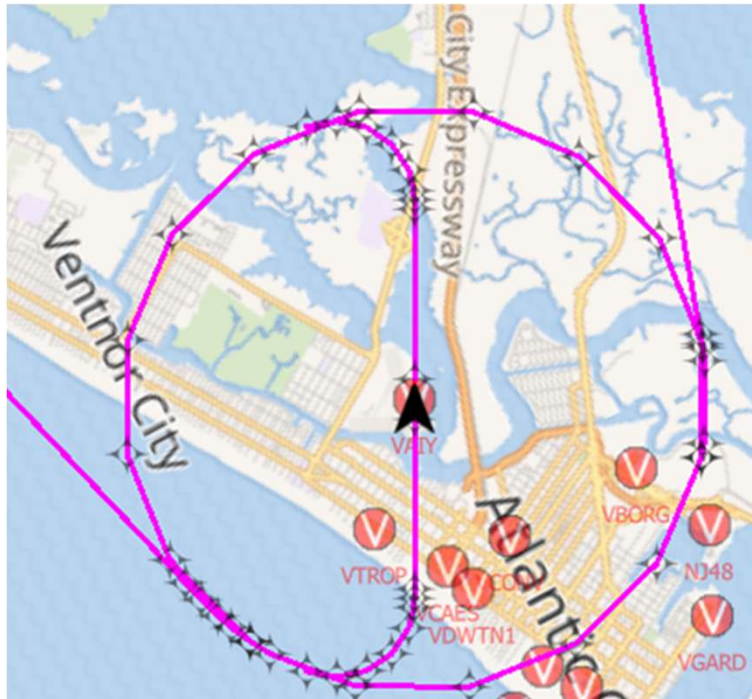


Video





Summary of All Vertiport Operations

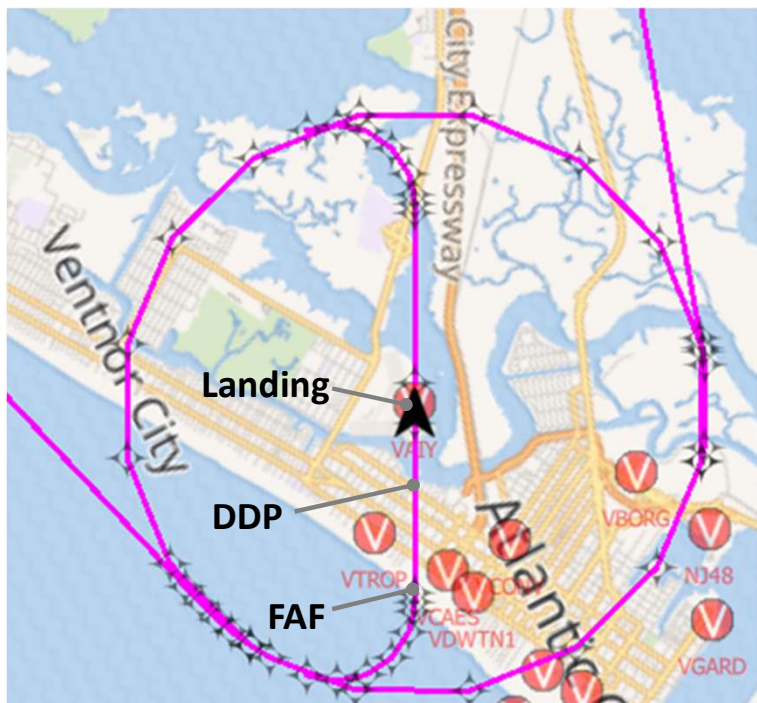


Operation Number	Event Type	Aircraft Tail Number	Time (secs.)	Delta Time (secs.)	Notes
1	Landing	1	642	NA	
2	Takeoff	8	673	31	
3	Landing	2	739	66	
4	Takeoff	9	765	26	
...	...	...	...	...	...
...	...	...	...	...	...
34	Takeoff	10	2301	47	
35	Takeoff	5	2354	53	
36	Takeoff	6	2382	28	
37	Landing	9	2439	57	
Average time per operation (secs.)				50	
Average tempo, operations per hour				72	

Average time per operation: 50 secs
Average tempo, operations per hour: 72



Summary of Landing Operations



DDP (deceleration decision point)
FAF (final approach fix)

Operation Number	Aircraft Tail Number	Final Approach		Deceleration		Landing Time (sec.)	Time from final fix to landing (sec.)	Time from Deceleration to Landing (sec.)	Time from prior landing (sec.)	Notes
		Fix Time (sec.)	Decision Altitude (feet)	Decision Time (sec.)	Time (sec.)					
1	1	549	320	566	642	93	76	NA		
3	2	641	330	661	739	98	78	97		
5	3	738	300	757	817	79	60	78		
7	4	830	260	852	923	93	71	106		
9	5	920	320	941	981	61	40	58		2-stage deceleration at DDA, hard touchdown
11	6	1018	240	1042	1087	69	45	106		
13	7	1126	290	1148	1196	70	48	109		
15	8	1197	230	1222	1271	74	49	75		
17	9	1301	290	1323	1384	83	61	113		
NA	10	1394	400	1416	Go around after DAA	NA	NA	NA		Go around due to unstable approach
...	...	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...
31	7	2083	240	2114	2168	85	54	55		Final flown at 77 kts for spacing, 4 still on pad after
33	8	2188	160	2218	2254	66	36	86		Slow deceleration prior to DDA for spacing (initiated at
37	9	2353	330	2372	2439	86	67	185		Relative slow deceleration at DDA, drawn out landing
Aggregate Performance					Average time	83	61	89		
					Standard deviation	12	14	32		
					Minimum time	61	40	34		
					Maximum time	104	87	185		

Average time from DDP to Landing, 61 seconds
Standard deviation, 14 seconds
Minimum time, 40 seconds
Maximum time, 87 seconds



Summary of Takeoff Operations



Nominal taxi
distance, 150'

Operation Number	Aircraft Tail Number	Previous Pad Usage	Time pressure to depart	Taxi Time (secs.)	Takeoff time (secs.)	Elapsed Time (secs.)	Notes
2	8	Landing #1	High	645	673	28	
4	9	Landing #2	High	740	765	25	
6	10	Landing #3	High	818	857	39	
8	1	Landing #4	High	922	957	35	
...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...
32	3	Landing #7	-	2171	2204	33	
34	10	Landing #8	-	2254	2301	47	
35	5	Takeoff #10	-	2304	2354	50	
36	6	Takeoff #5	High	2355	2382	27	
Average time for expedited takeoff						30	
Average time for nonexpedited takeoff						40	

Average time for *expedited* takeoffs, **30 seconds**



Post Simulation Debrief

Approach and Landing

- Highest workload phase of flight
 - But, not objectionable. (Overall workload was low)
- Automation aids for decel desired
 - Reduce workload, time, variability

Interval management

- Decision aids to better judge time and distance in-trail, particularly when speeds are off nominal

Departure

- Developed references to judge status of arriving aircraft, but these limitations
- Decision aids desired to mitigate self-pressure to go
- Questioned need to ground taxi to vertipad

Other

- Flight procedures and their depiction on displays created hybrid of VFR and IFR
 - Observation not criticism
 - Structure can enable automation support
- Wheel pattern and mechanism for late spacing adjustments



Summary

- Conducted study of piloted, VFR flight operations at a nontowered vertiport to establish throughput baseline, identify bottlenecks, and inform research
- Overall, pilots found operations reasonable with low to moderate workload
 - Demonstrated safe management of vertipad conflicts
- Tempo of 72 operations per hour with single vertipad
 - Average occupancy for landings, 61 seconds
 - Average occupancy for expedited takeoffs, 30 seconds
 - Suggestions for aircraft technologies and procedures that may reduce these times and associated variability
- UAM Flyers currently being used to support other NASA and FAA UAM airspace integration activities.