Pathfinding for Airspace with Autonomous Vehicles (PAAV) Overview for RTCA SC-228

April 30, 2024

Pathfinding for Airspace with Autonomous Vehicles (PAAV) Background

- PAAV sub-project started in 2021 under NASA’s Air Traffic Management – eXploration (ATM-X) project
  - ATM-X tasked with conducting research to support the growth of traditional aviation and new entrants

- Previous PAAV work included:
  - Concept development
  - Tabletop analyses, fast-time and human-in-the-loop simulation work
  - Development of a function allocation framework

- PAAV team expanded in 2023 to include research and flight test execution elements from NASA’s Advanced Air Mobility project
  - Included teams that worked on the 2023 Sikorsky flight test
  - Led to a shift toward the establishment of a flight test ecosystem and new partnerships

PAAV Organization Chart

Sub-Project Management Team


SPM
Arwa Aweiss


Deputy SPM
Matt Gregory


Acting ASPM
Raquel Redhouse


Tech Lead & DAA Lead
Conrad Rorie

External Engagement


Partnerships
Paul “Speedy” Fast


SDO Engagement
Andrew Guion

Research Leads


Traffic Pattern Integration
Tod Lewis

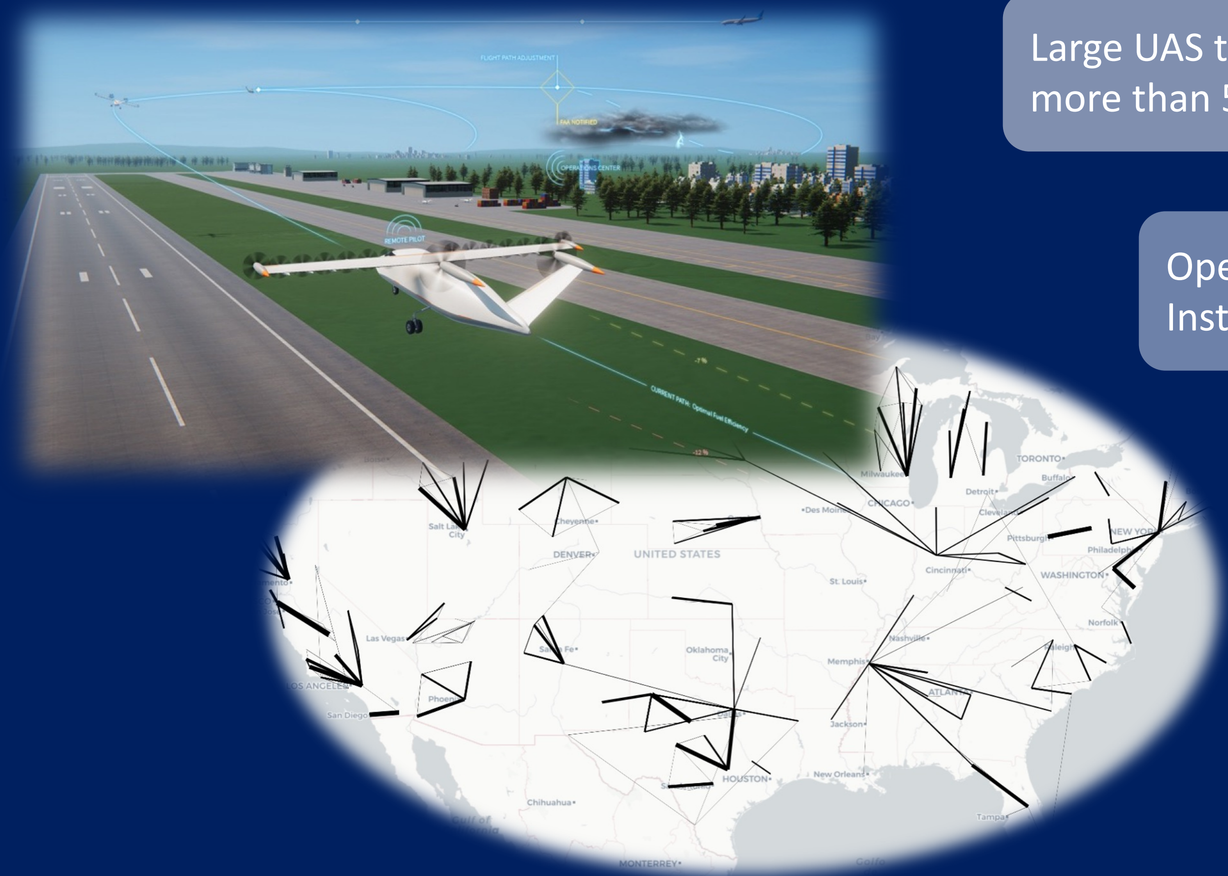
Dynamic Path Planning
David Wing


Contingency Management
Jordan Sakakeeny


A2A Comms
Casey Bakula

PAAV Scope & Assumptions

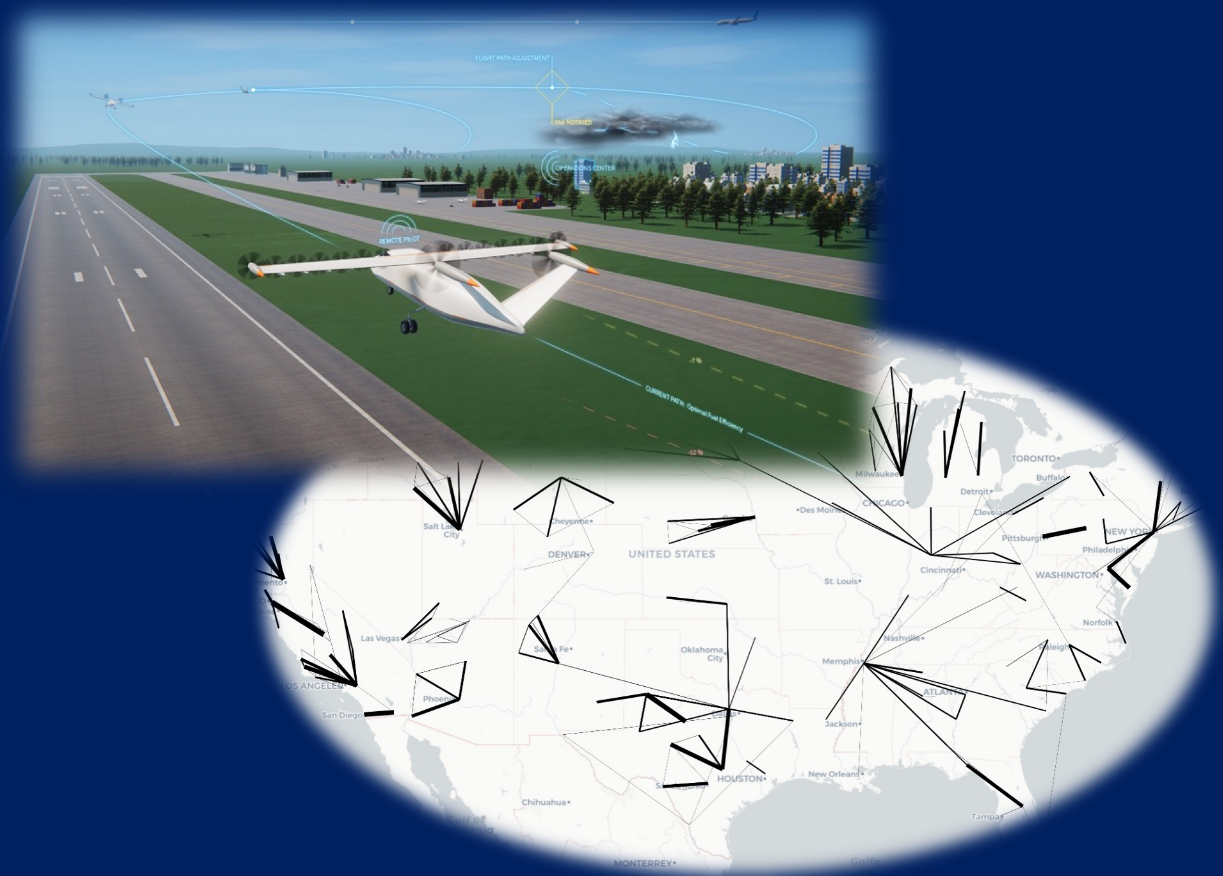
Enable scalable airspace integration of routine remotely piloted operations under Instrument Flight Rules



- Large UAS that weigh significantly more than 55 pounds
- Ecosystem approach that integrates airspace, infrastructure, and UAS automation
- Operations conducted under Instrument Flight Rules (IFR)
- Number of operations necessary to enable economically viable use cases
- At least one remote pilot per Uncrewed Aircraft
- Flight between conventional airports (all classes)
- Flight primarily in controlled airspace shared with conventional air traffic

PAAV Objectives

Enable scalable airspace integration of routine remotely piloted operations under Instrument Flight Rules



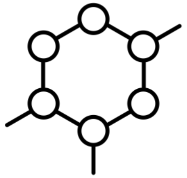
Concept and Architecture
Develop Concept of use and an integrated vehicle, airspace, and infrastructure automation architecture

Conflict and Contingency Management Automation and Interoperability
Develop and test robust contingency and conflict management systems that include interoperable strategic and tactical technologies to enable routine, scalable operations for large UAS

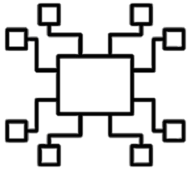
Integrated Ecosystem Flight Tests
Catalyze an ecosystem for routine large UAS operations by testing the integration of surveillance and communication services with UAS automation

PAAV Objectives

Concept and Architecture

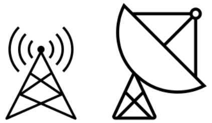


Concept

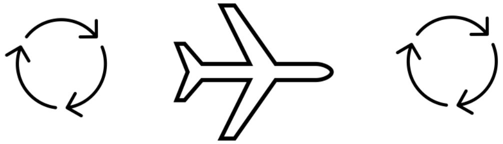


Integrated Air-Ground Architecture

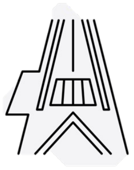
Ecosystem Assessment



Infrastructure as a Service

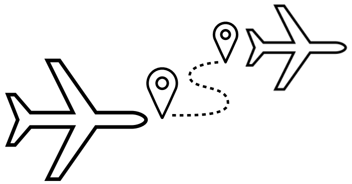


Industry UAS Automation

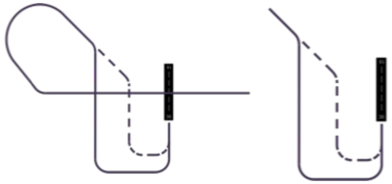


Surface Operations & Autonomous Capabilities

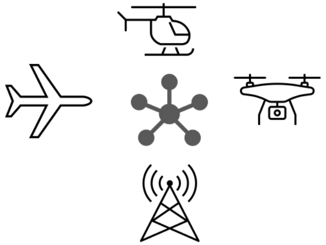
Conflict and Contingency Management Automation and Interoperability



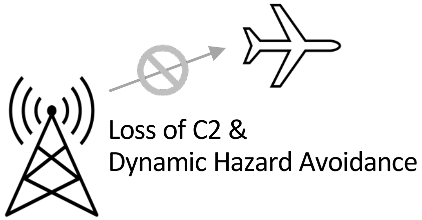
DAA and Dynamic Path Planning (DPP)



Traffic Pattern Integration



Aircraft-to-Aircraft (A2A) Communications



Contingency Management

Purpose of Today's Presentation

- Get feedback on the various areas PAAV is tasked in:
  - Creation of a flight test ecosystem in Northern California
  - DAA research topics
  - Development of a Traffic Pattern Integration Prototype
  - Work on aircraft-to-aircraft (A2A) communications
  - Conceptual work & research into contingency management
    - Impact of different contingency procedures on the NAS
    - Dynamic hazard avoidance using Dynamic Path Planning (DPP)

- Current iteration of sub-project extends through FY26
  - Planning for consistent engagement with RTCA & FAA to refine research questions and approach over the next several years

Ecosystem Approach

- **Goal: catalyze an ecosystem for recurring large UAS flight test activities**
- Near term focus is using the ecosystem to collect operational data to inform standards and exercise DAA, CNS, and other UAS automation capabilities
  - PAAV is primarily targeting IFR 'auto-cargo'-type large UAS operations but PAAV will not be the only user of the ecosystem
  - Will eventually support higher levels of automation and advanced airspace concepts (e.g., PSUs)
- Working to include aircraft designers/operators, surveillance infrastructure, and other third-party service providers
- NASA's Live, Virtual, & Constructive (LVC) sim capabilities will be leveraged as needed – e.g., provide confederate air traffic controllers, traffic, etc.
  - NASA concept development and research/simulations will be used to inform the scenarios flown in the ecosystem and associated performance metrics

Ecosystem Status

- Currently working with a vehicle partner as a risk-reduction activity and with a contractor to deploy a ground-based surveillance system
    - Activities being conducted in the NASA Ames area
    - Aim to characterize installed GBSS performance and compare against DO-381 requirements
    - Will provide partners an opportunity to work with contractor and enable terminal area flight test objectives

- Visualization center being built at NASA Ames to support flight test operations in the ecosystem
    - Will also integrate other NASA projects and capabilities (e.g., Digital Information Platform [DIP])

Partnership Efforts

- RFI notice released (closed on April 26)
  - Partnerships desired by end of FY24 & intent to fly in FY25-26
- Areas of interest referenced in the RFI:
  - DAA/ACAS Xr & non-cooperative surveillance
  - Airspace & ATC interactions
  - A2X
  - Surface operations
  - Contingency management
- Requested industry perspective on key barriers to IFR UAS ops
  - Data collection intended to feed technology maturation and standards development

Detect and Avoid

- PAAV is planning to support SC-228/SC-147 where needed
  - E.g., document revision, sim data to address gaps

- Near-term emphasis on simulations and flight test activities that support ACAS Xr (modified for fixed-wing large UAS) development
  - Assess Xr v4 (when released) in a real-time HITL simulation setting with NASA test pilots
  - Focus on operations within, and transiting into/out of, terminal area
  - Flight tests in ~FY25 with industry partners in ecosystem environment
    - Non-cooperative sensors in the loop (e.g., ATAR, GBSS)

Detect and Avoid

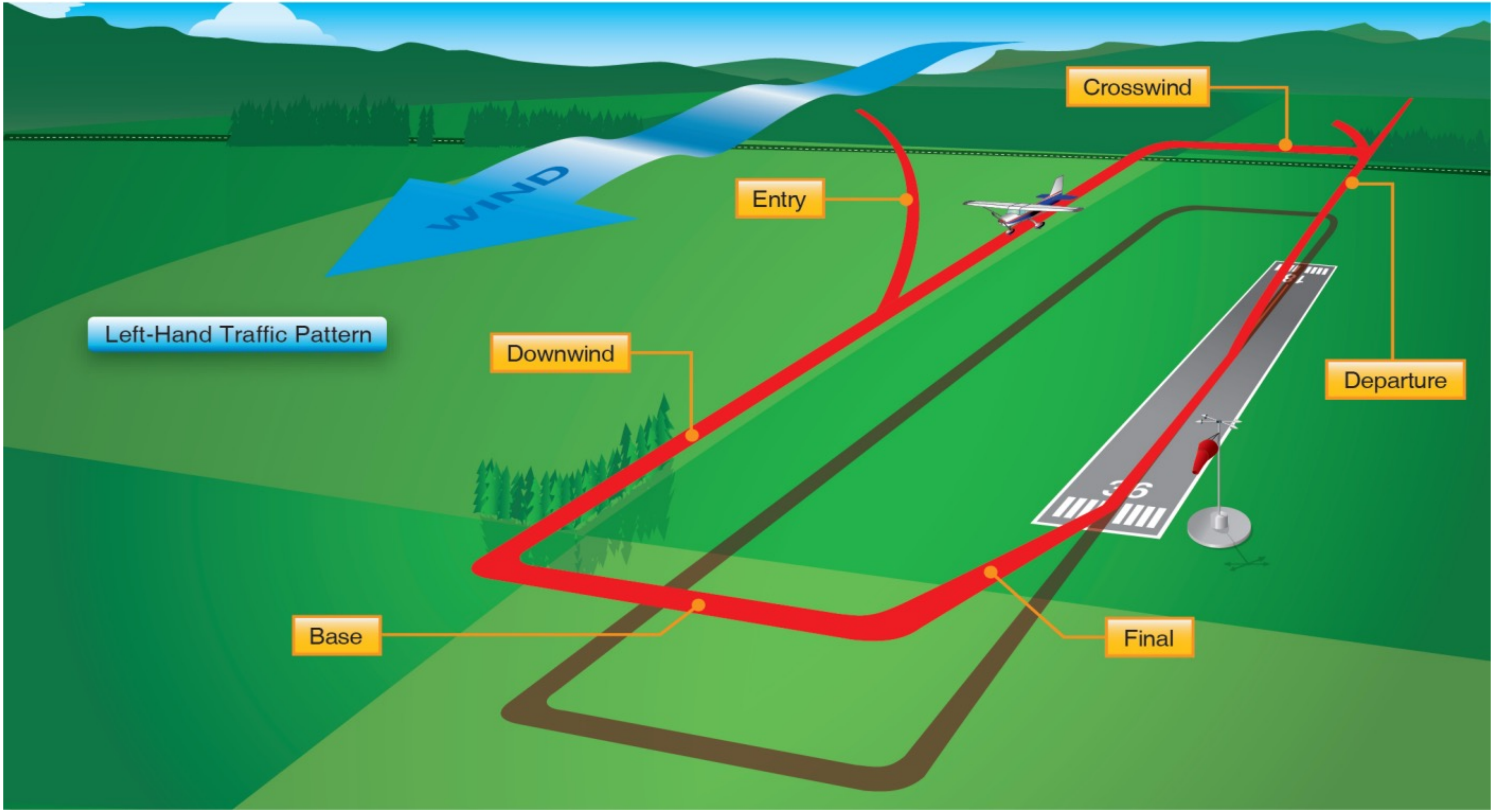
- Additional PAAV focus on interoperability between DAA and other PAAV systems
  - E.g., Dynamic Path Planning, Traffic Pattern Integration
  - DAIDALUS & ACAS Xr algorithms are expected to be part of testing

- Able to incorporate other key research questions identified by RTCA and industry partners
  - Integrating terrain and obstacle data
  - Automating DAA/remain well clear
  - Auto-DAA/RA during lost C2 link scenarios
  - Non-cooperative intruder symbology

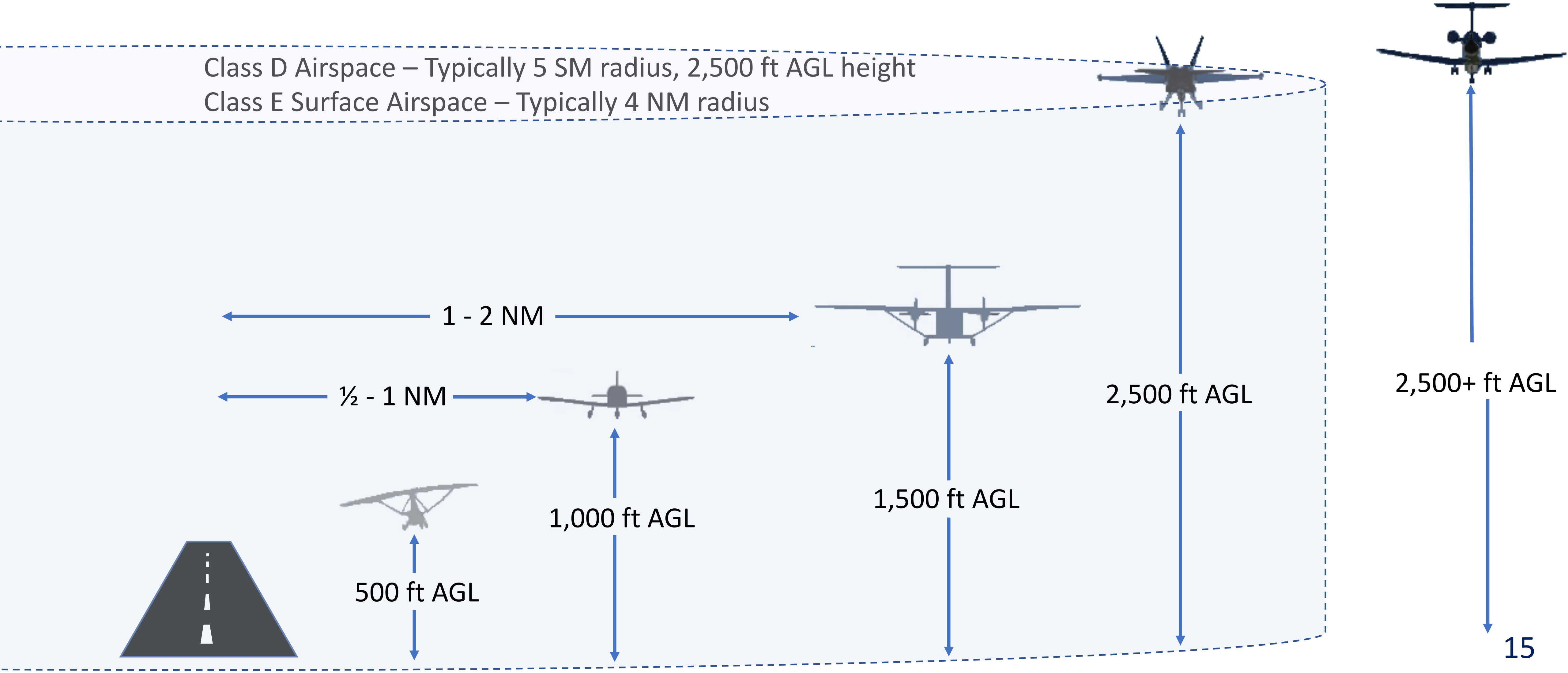
Traffic Pattern Integration

- Airport Traffic Pattern
- Background
- Traffic Pattern Integration Planner (TPIP)
  - Purpose
  - General Operational Concept
  - Research

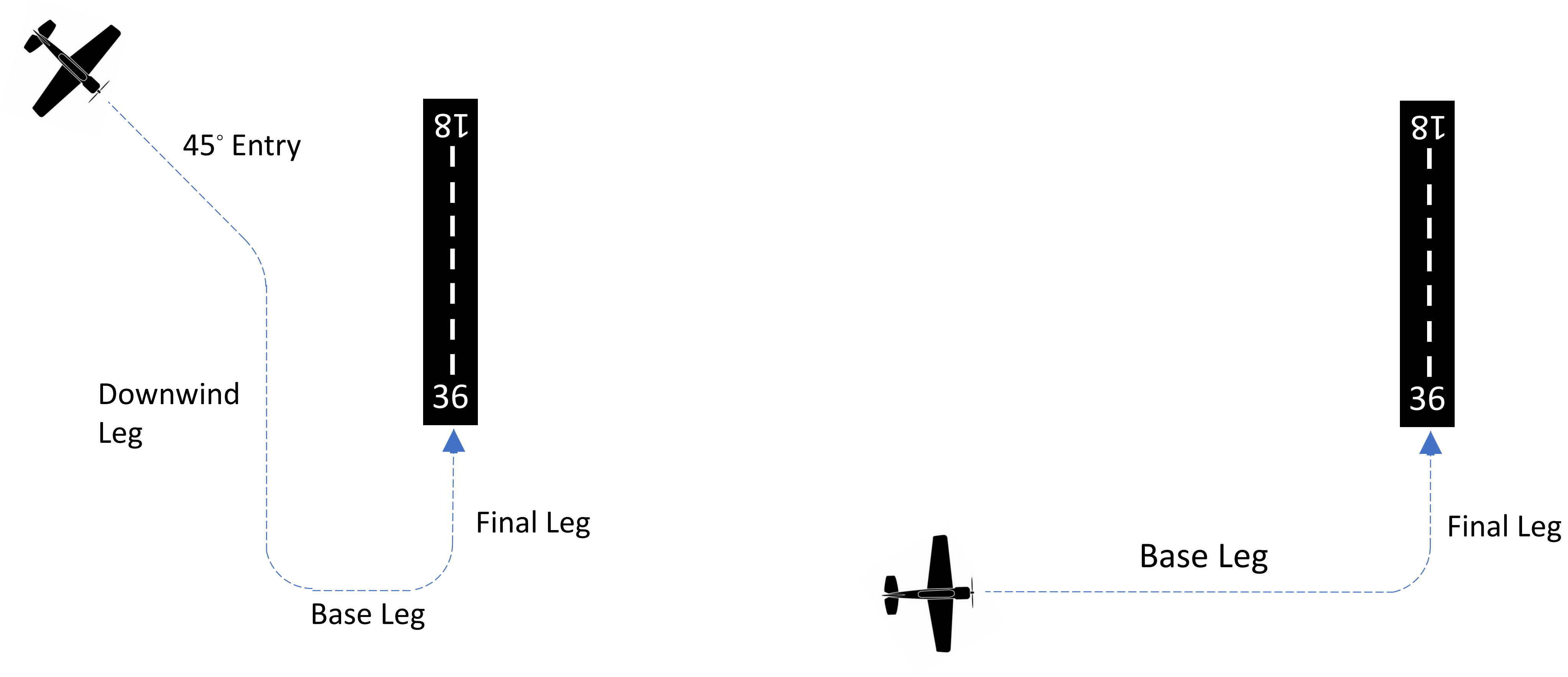
Airport Traffic Pattern



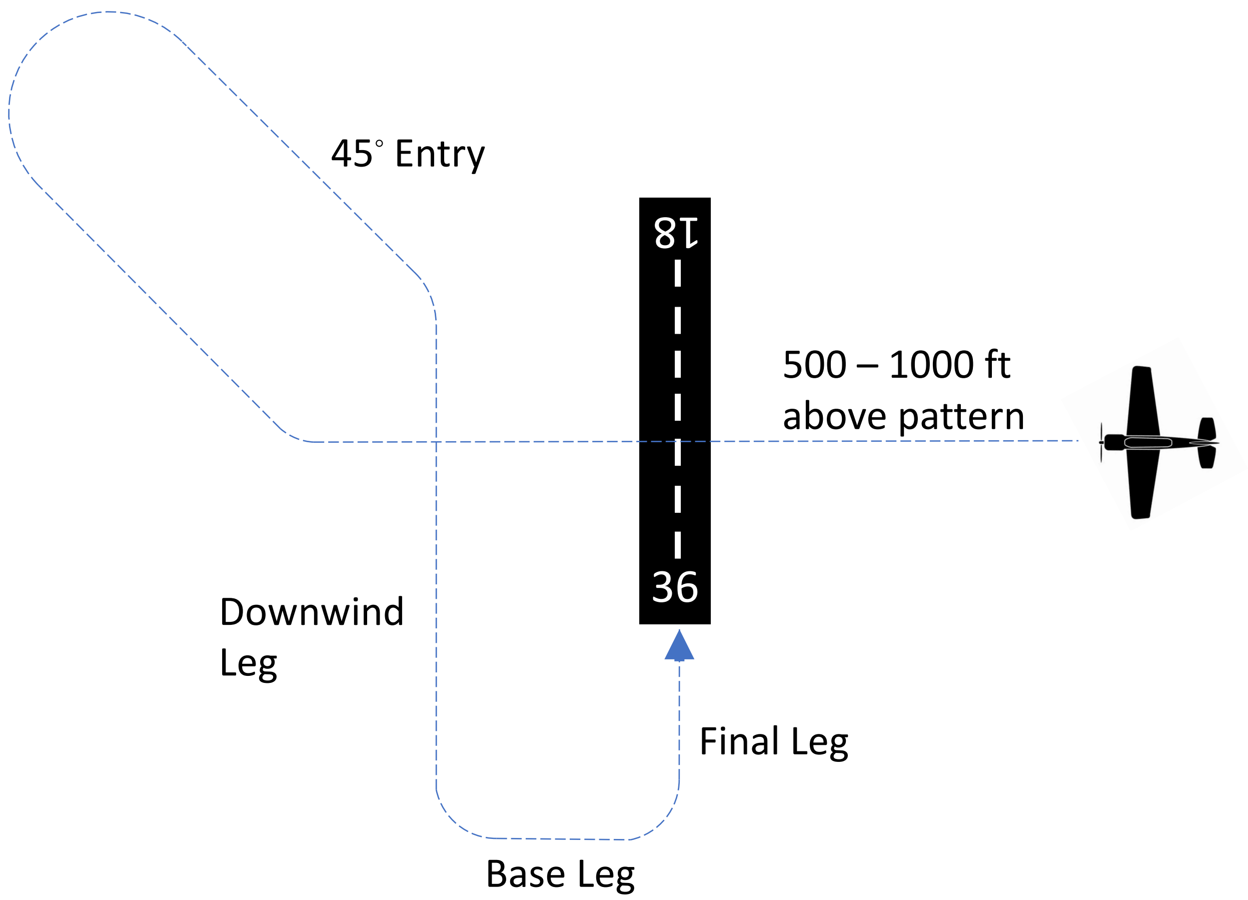
Airport Traffic Pattern Dimensions



Traffic Pattern Entries

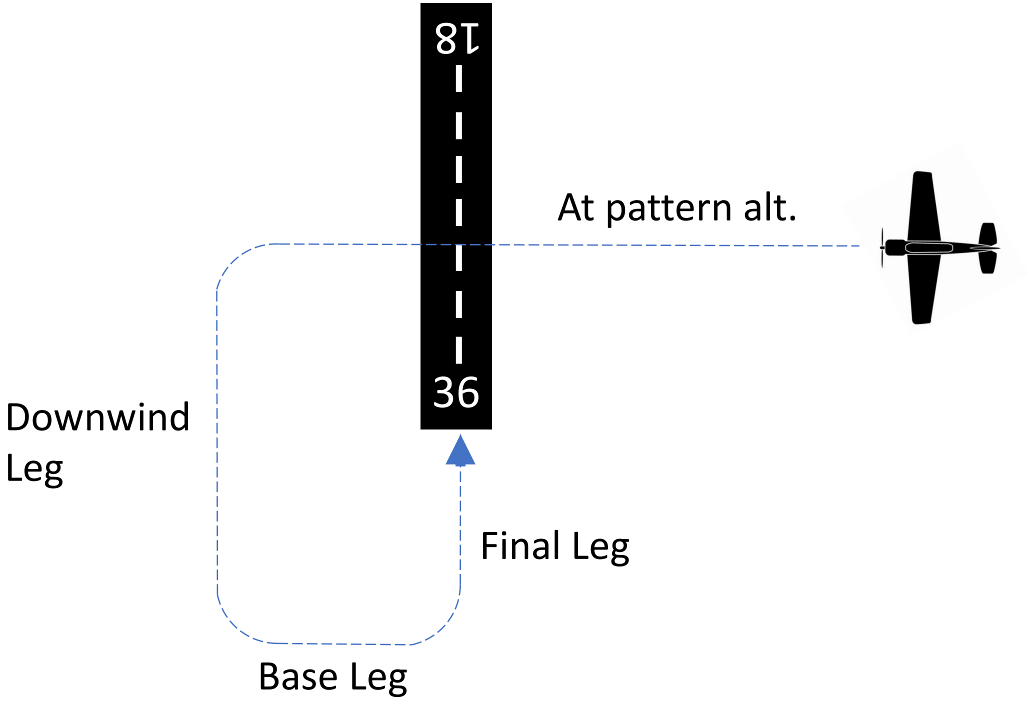


Preferred Midfield Entry



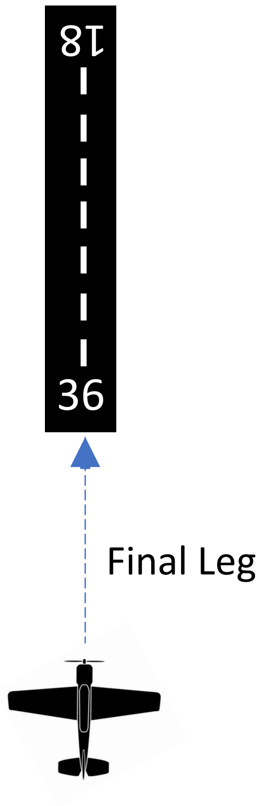
- Cross midfield 500-1000 ft above pattern altitude and fly clear of traffic pattern (approx. 2 NM).
- Enter downwind leg at pattern altitude

Alternate Midfield Entry



- Cross midfield at pattern altitude while yielding to traffic on the downwind or about to enter the downwind from the 45 deg entry.

Straight-In Entry



AIM 4-3-3:
NOTE-

Pilots are encouraged to use the standard traffic pattern. However, those pilots who choose to execute a straight-in approach, maneuvering for and execution of the approach should not disrupt the flow of arriving and departing traffic. Likewise, pilots operating in the traffic pattern should be alert at all times for aircraft executing straight-in approaches.

Background

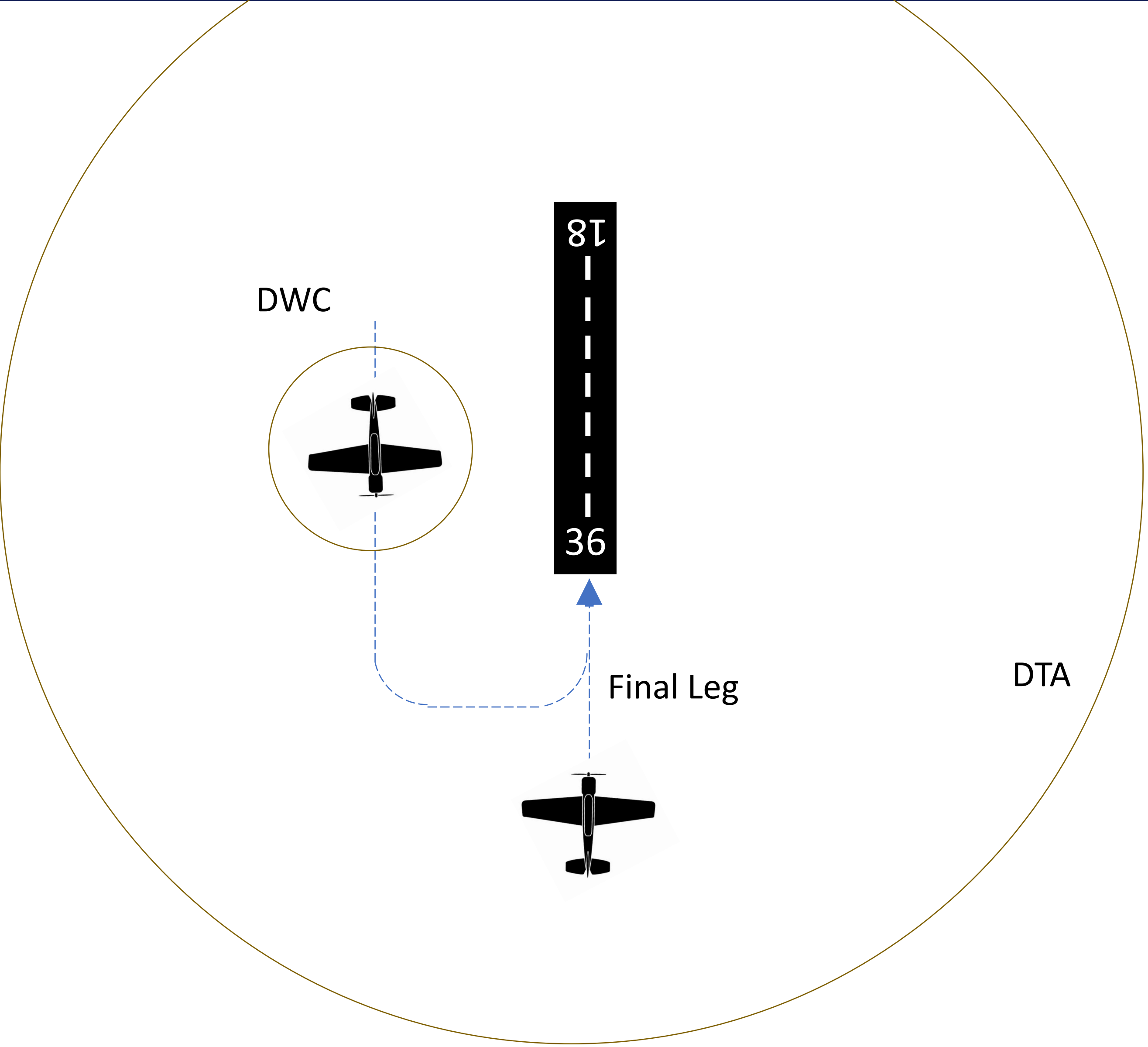
Detect and Avoid:

- DAA OSED (DO-398): The pattern and landing phase includes flight in the airport traffic pattern and descent from the last altitude in an instrument approach to the landing surface. It is not in scope for MOPS DAA functions.
- DAA OSED (DO-398), ASSUMP-OSED.2:
  - DAA systems will not be used to fly in a VFR traffic pattern or a circling approach
  - DAA systems will be used to fly departure procedures and instrument approach procedures at airports in Class C, D, E, or G airspace.
- Detect and Avoid (DAA) MOPS assumes that a UA will land straight-in
- DAA alert results in the UA performing an IFR missed approach
- 1500 ft Terminal DAA Well Clear radius is not designed, nor sufficient, for spacing behind landing traffic

Traffic Pattern Operations:

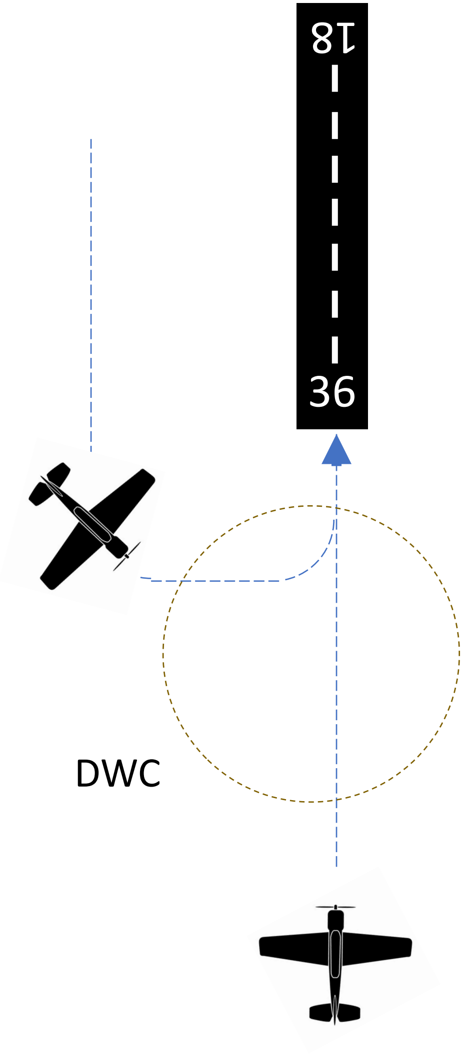
- Non-Towered Airports:
  - Pilots (and UAs) are responsible for self-sequencing and spacing
  - Straight-in arrivals do not necessarily have priority over aircraft in the traffic pattern
- Towered Airports:
  - Tower controllers will typically sequence traffic in the pattern to allow IFR straight-in arrivals to continue the approach
  - ATC is responsible for sequencing aircraft, pilots (and UAs) are responsible for spacing with VFR traffic
  - ATC is responsible for separation of IFR traffic from other IFR traffic

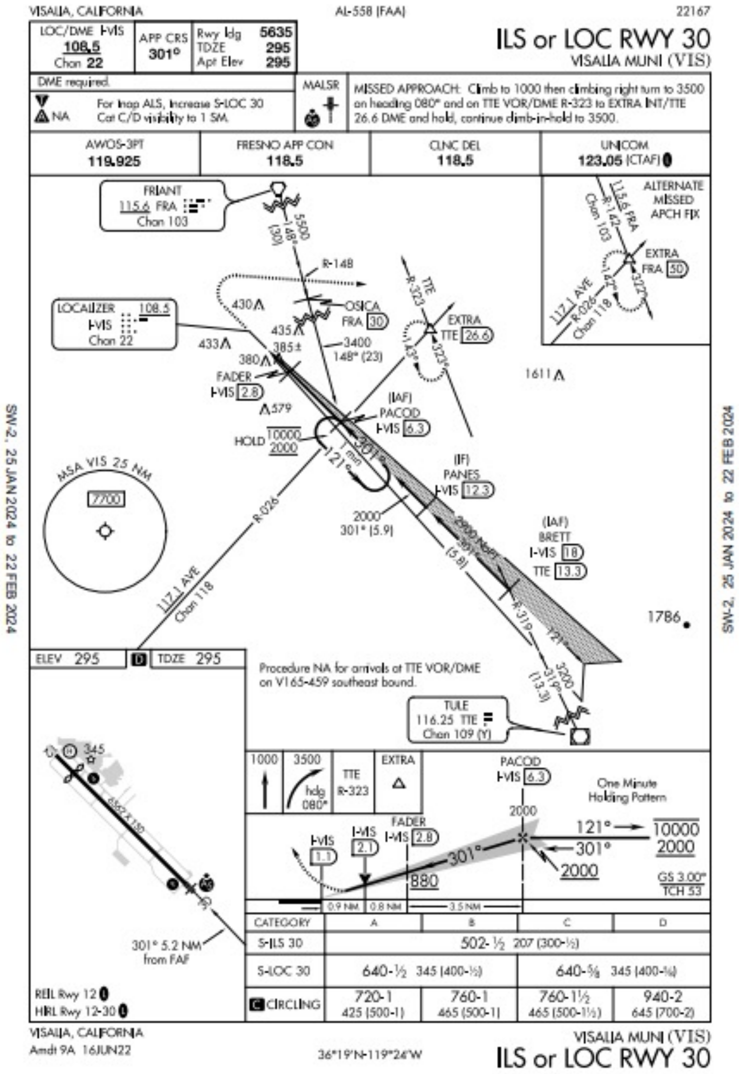
Terminal DAA Well Clear



- DWC: 1500 ft radius, +/- 450 ft height
- Terminal DAA Well Clear (DWC) applicable to traffic aircraft that are within an active DAA Terminal Area (DTA)
- A DTA is active for runways intended to be used by the UA for takeoff or landing

DAA Alert





- A DAA alert will result in the UA having to fly the IFR missed approach
- Performing a go-around, then entering the pattern is not allowed at present

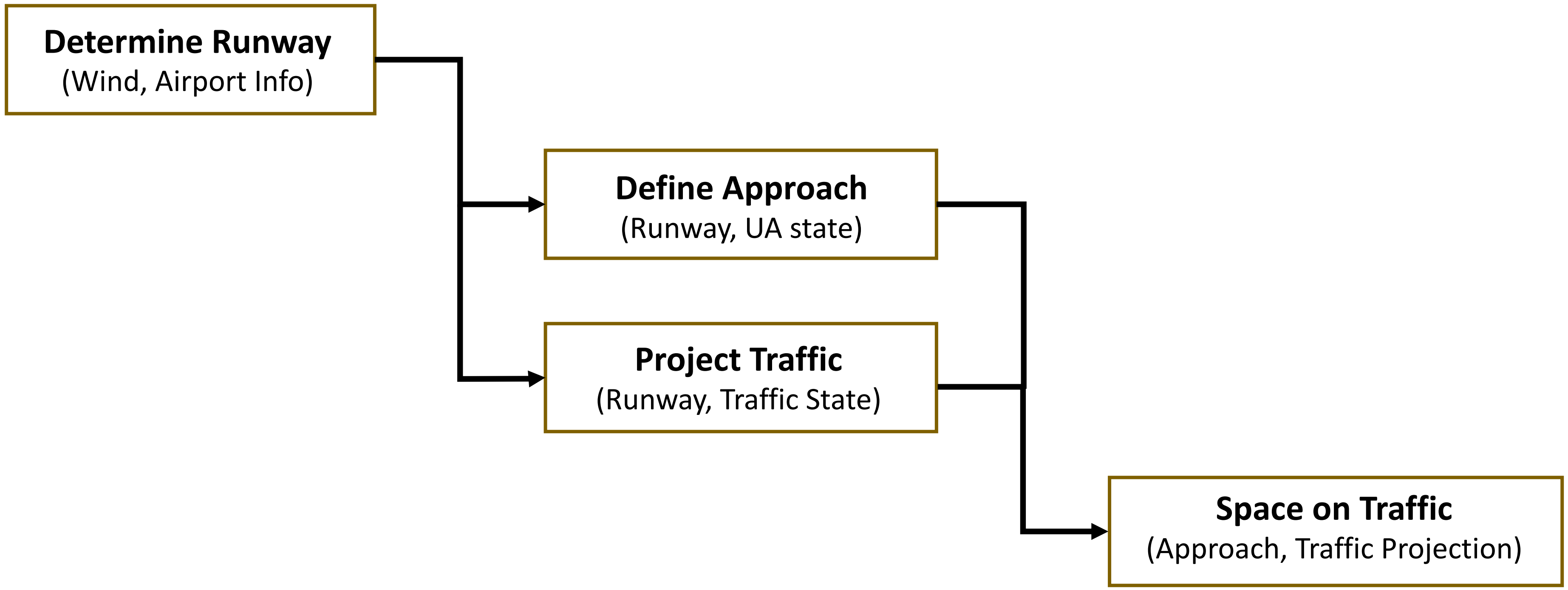
Traffic Pattern Integration Planner (TPIP)

- TPIP purposes:
  - Provide a near-term capability to help remote pilots meet their responsibility for spacing on VFR traffic (regardless of whether the UA is landing straight-in or using the traffic pattern)
  - Enable UA to fly to airports that do not have a straight-in instrument approach
    - Enable UA to fly to airports that do not have an instrument approach to the runway favored by current winds
  - Enable UA to enter and fly the traffic pattern
  - Enable go-arounds and avoid having to fly the IFR missed approach
  - Improve operational efficiency
    - Save time, fuel
  - Ultimately enable autonomous use of the traffic pattern with predictable UA behavior

General Operational Concept

- Assumptions:
  - UA is flying IFR with nominal C2 link
  - UA destination is a non-towered airport
  - TPIP designed for automatic operation with RP supervision
    - Anticipate that initial TPIP operation would involve an RP in-the-loop using TPIP for guidance
  - UA is equipped with all surveillance technology required by the DAA MOPS
  - TPIP provided with runway, traffic pattern direction, wind, and other airport information
  - UA broadcasts typical position and intent information over the CTAF
- Operation:
  - UA has a continuous route to a destination runway programmed into its Flight Management System (FMS) before departure
  - In the vicinity of the destination airport, TPIP surveils traffic aircraft and predicts their possible flight paths and threshold crossing time using the airport traffic pattern as a reference
  - TPIP determines an arrival runway based on wind and traffic information
  - TPIP determines an approach path to be consistent with typical arrival operations at a non-towered airport
  - TPIP maintains spacing on traffic aircraft

Key Traffic Pattern Integration Planner (TPIP) Functions



Research Plan through FY26

- Evaluate TPIP performance given known traffic trajectories (12/31/24)
  - Develop TPIP concept and software
  - Perform batch simulation to evaluate TPIP performance
    - Gather anecdotal conflicts between TPIP guidance and DAA alerts
- Evaluate TPIP performance with predicted traffic trajectories (6/30/26)
  - Develop and integrate traffic prediction capability
  - Perform batch simulation to evaluate TPIP performance
- Trade simulation to investigate impact of air and ground radar surveillance limitations on TPIP performance (9/30/26)
  - Perform batch simulation to evaluate TPIP performance with:
    - Lower frequency surveillance data
    - Radar range and field of regard limitations
    - Sensor uncertainty

Research Plan through FY26, Continued

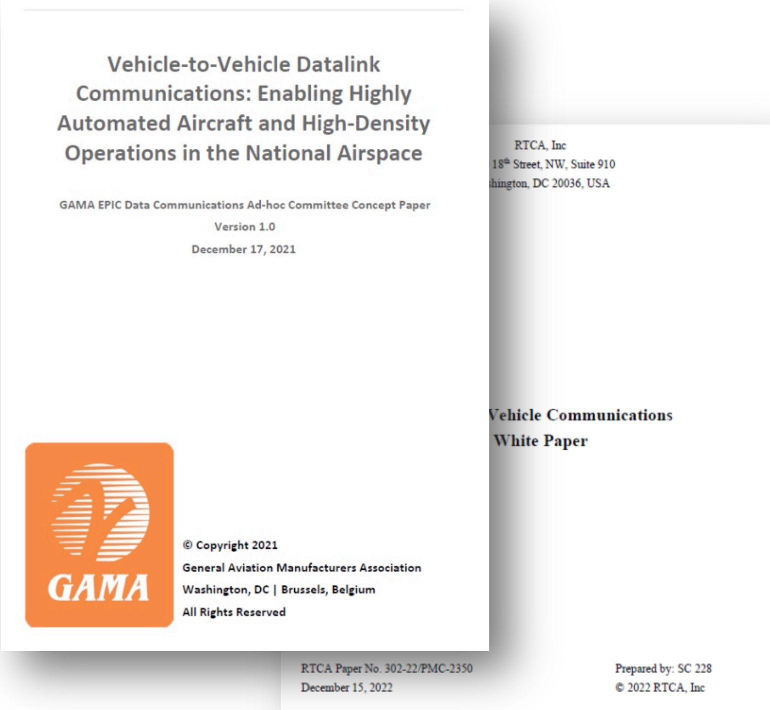
- Natural Language Processing of Traffic Radio Calls (6/30/25)
  - Determine the feasibility of using natural language processing to gather intent information from CTAF voice communications and quantify benefits/performance
  - Potential benefits include:
    - Determination of the existence of un-surveilled non-cooperative traffic and approximate location
    - Identification of runway intended to be used by arriving traffic aircraft
    - Improvement of TPIP traffic intent prediction
    - Determination that traffic has entered the runway for departure
    - Determination that traffic has exited the runway after landing
  - Develop natural language translator architecture and software/hardware to support future simulations.

Potential Research Post FY26

- TPIP/DAA Interoperability
  - Under certain circumstances, a DAA alert is temporary and should not be followed. Under other circumstances it should be followed.
  - Is the current Terminal DWC suitable when the UA is entering and flying the traffic pattern?
  - Investigate potential changes to TPIP and/or Terminal DAA to support interoperability

- Potential Activities for Interoperability Evaluation
  - Develop appropriate encounter set
  - Agree on safety metric (risk ratio using NMAC many not be suitable for the traffic pattern)
  - Define and evaluate alerting/guidance, including alert levels and timing
  - Perform end-to-end fast-time simulation to showcase safety thresholds

Aircraft-to-Aircraft (A2A) Communication for Conflict Mgmt. in PAAV


Vehicle-to-Vehicle Datalink Communications: Enabling Highly Automated Aircraft and High-Density Operations in the National Airspace

GAMA EPIC Data Communications Ad-hoc Committee Concept Paper

Version 1.0

December 17, 2021

GAMA

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Vehicle Communications

White Paper

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Findings from recent A2A-related working groups:

- A2A communication services are necessary and enabling for scalable UAS operations
- Lack of spectrum dedicated for A2A services is a primary challenge
- NASA should play an integral role in the definition, development, and standardization of these services
- Interoperability between UAS operators is required for these services to be most effective
- Existing technologies will not meet mid- and long-term needs
- Uncertainty regarding a profitable business model for A2A services outside of initial hardware sales

NASA's A2A research under PAAV is a new-start activity in FY24 with the objective of developing an A2A communications concept to meet PAAV conflict management requirements

Integrated A2A Communications Concept

A2A research in PAAV combined with Aircraft-to-Ground (A2G) research in NASA's Air Mobility Pathfinders (AMP) project to result in an Aircraft-to-Anything (A2X) concept architecture for UAS

5G NR selected as the first air interface for consideration due to:

- Sidelink integration with support for both standalone and network-assist modes of operation
- Spectral efficiency of the waveforms
- Maturity of the 3GPP standards
- Ability to leverage massive cellular industry investments

Integrated A2X Concept:

- Private 5G NR-based network tailored for UAS communications
- Candidate Network Supported Service (NSS) technology in accordance with the C-Band NPRM
  - Experimental C-Band license application pending
  - Would like to explore Block A-D (10 MHz each) use and block aggregation
- Utilizes Mode 1 and 2 sidelinks to achieve A2A communications
- Exploring data services including but not limited to C2
  - Planning Workshop at Glenn Research Center on this topic

Data Service Considerations:

- Coop. deconfliction
- Coop. collision avoidance
- Command
- Telemetry
- Voice
- Contingency services
- Passenger welfare
- Aircraft security
- Pre- and post-flight surface comm.

A2A Research in PAAV: Approach

A2A Team Focus Areas:
- Air interface
- Spectrum

Required Input:
- Conflict Mgmt. Use Cases
- Airspace Assumptions
- ConOps

PAAV Input → A2A/A2X Concept Definition ↔ RTCA Support

A2A/A2X Concept Definition ⇄ Prototyping and Validation

- Utilization of Open Source 5G Implementations
- Reconfigurable Radio Platforms
- Potential Use of C-Band (5030-5091 MHz)

AEROSPACE COMMUNICATIONS FACILITY
ACF

A2A Research in PAAV: Challenges/Future Work

- Spectrum availability: Chicken and egg problem. How much? Where?
- No viable technology candidates available, but there several “80%” solutions (e.g., 5G, 802.11p)
  - How do these technologies need to be adapted to meet AAM requirements?
- Can we reconcile differing requirements and design objectives between sUAS, large UAS, and piloted aircraft to develop a common A2A solution? (SAIC recommendation 5.4.5)
- How do we design A2A systems for scalability? (SAIC recommendation 5.1.8)
- How do we safely test A2A systems while still maintaining operational fidelity? What does an A2A test capability look like?

Contingency Management

- What is contingency management?
  - Contingency: off-nominals (e.g., loss of C2 link [LC2L], lost comms, divert)
  - Management: the preemptive planning for and reactive response to
- What contingencies affect UAS?
  - Normative aircraft contingencies (e.g., lost comms, divert, fuel issues)
  - Normative contingencies that are different for UAS (e.g., lost comms, divert)
  - UAS-unique contingencies (e.g., LC2L, DAA failure)
- Why focus on LC2L?
  - Unique to UAS
  - Risk in all phases of operation; cross-cutting contingency
  - Pathfinder to higher levels of autonomy
  - Note: PAAV is not excluding other contingencies from its research

Lost Command and Control Link

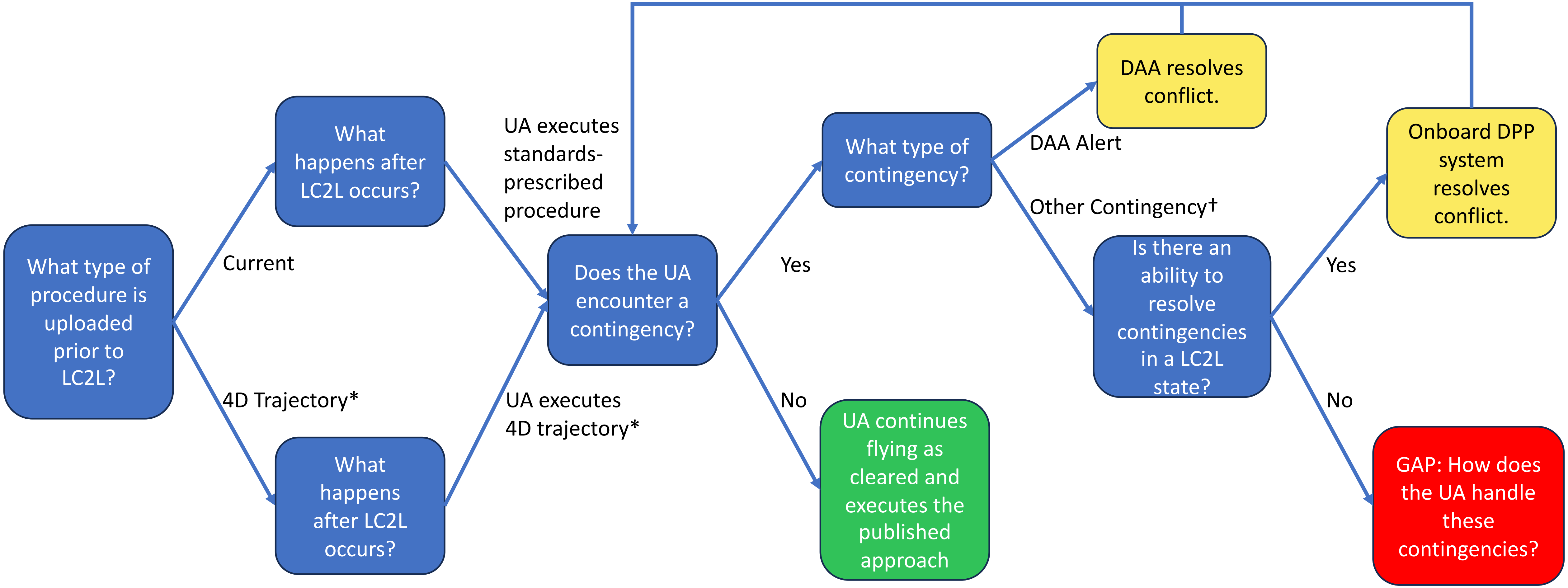
- Select previous work:
  - NASA HITL (Fern, Rorie, and Shively 2014) showed that dealing with a single UAS LC2L event was not problematic (within the limits of the study)
    - Only looked at airspace that was relatively conflict free
    - No VFR
    - Highly-skilled controllers
  - ATCO, pilot SMEs at NASA PAAV tabletops (Wolter, Davikoff, and Rorie 2023) largely echoed the sentiment, though pointed out potential areas of workload overload, namely:
    - As operations scale
    - Deviation during a LC2L event (e.g., the UAS needs to reroute for weather under LC2L)
    - Multiple concurrent LC2L events
- Existing standards:
  - ICAO Remotely Piloted Aircraft Systems Panel WP-15 “Progress on Lost C2 Link and Detect and Avoid (DAA) Procedures”
  - RTCA SC-228 DO-400 “Standardized Lost C2 Link Procedures for Uncrewed Aircraft Systems”

Lost Command and Control Link

- What gaps were identified?
  - LC2L procedure and trajectory requirements
  - Communication and coordination of LC2L actions
  - Avoidance of hazards when in LC2L state
  - Automation needed to support LC2L state
  - Training and simulator requirements
- What are some additional gaps?
  - Procedures for deconfliction of multiple concurrent LC2L events
  - Measurement of impact of LC2L procedures on other airspace users (e.g., ATC, other UAS, other pilots)
- **Are there conditions under which current LC2L procedures are not sufficient?**

Possible LC2L Procedure Types

When is the LC2L procedure updated?	Does not use DPP	Uses DPP
Pre-LC2L but not Post-LC2L	Type I	Type II
Pre- and Post-LC2L	N/A	Type III



*4D trajectory should consider weather, traffic, etc. up to time of LC2L and be conflict-free for a period after LC2L

†Any contingency that causes the standards-prescribed procedure to not be sufficient (e.g., weather, airport flow change, divert, etc.)

Lost Command and Control Link

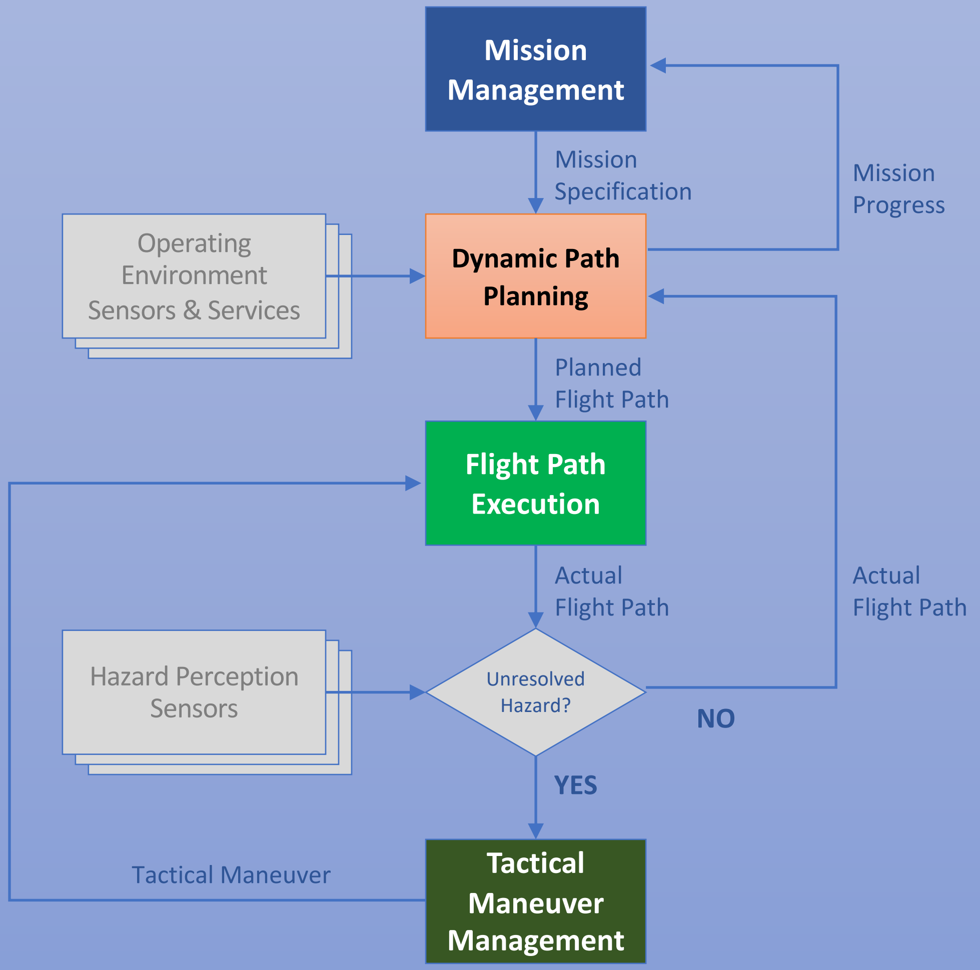
- Research questions:
  - What is the most important gap in the current procedures?
  - How big of a concern is LC2L expected to be? Can we quantify this concern?
  - Can we quantify if/when a procedure will not be sufficient?
  - Can we quantify the impacts LC2L events will have on the NAS/airspace users?
  - Are there additional mitigations that need to be enacted to lessen the impacts?
  - How do we determine the best course of action during LC2L events?
  - How do we balance predictability and robustness?
- Approach:
  - Apply DO-377 MASPS to expect regional air cargo traffic
  - Develop metrics for assessment and framework for use of metrics to create test cases
  - Perform fast-time sims to quantify impacts
  - Apply test cases in higher-fidelity environments (e.g., HITL, flight test)
  - Maintain feedback/engagement loop with stakeholders

Dynamic Path Planning (DPP) Automation Concept for AAM

Background

Operational Context

SCOPE



Mission Management is concerned with real-time decision-making about the mission goals and objectives

Dynamic Path Planning supports flight path decision-making within the boundaries of established and potentially evolving mission parameters

Flight Path Execution addresses the execution of the planned flight path but not its generation or modification

Tactical Maneuver Management is an independent layer of safety designed to detect and respond to imminent unresolved hazards

DPP Automation Concept for AAM

System Overview

System Objectives

WHAT

GOAL

Ensure that a safe and operationally acceptable flight path is available to the users throughout the flight

FLIGHT PATH QUALITIES

AUTOMATION TASKS

CREATE | MONITOR | EVALUATE | REVISE | COORDINATE

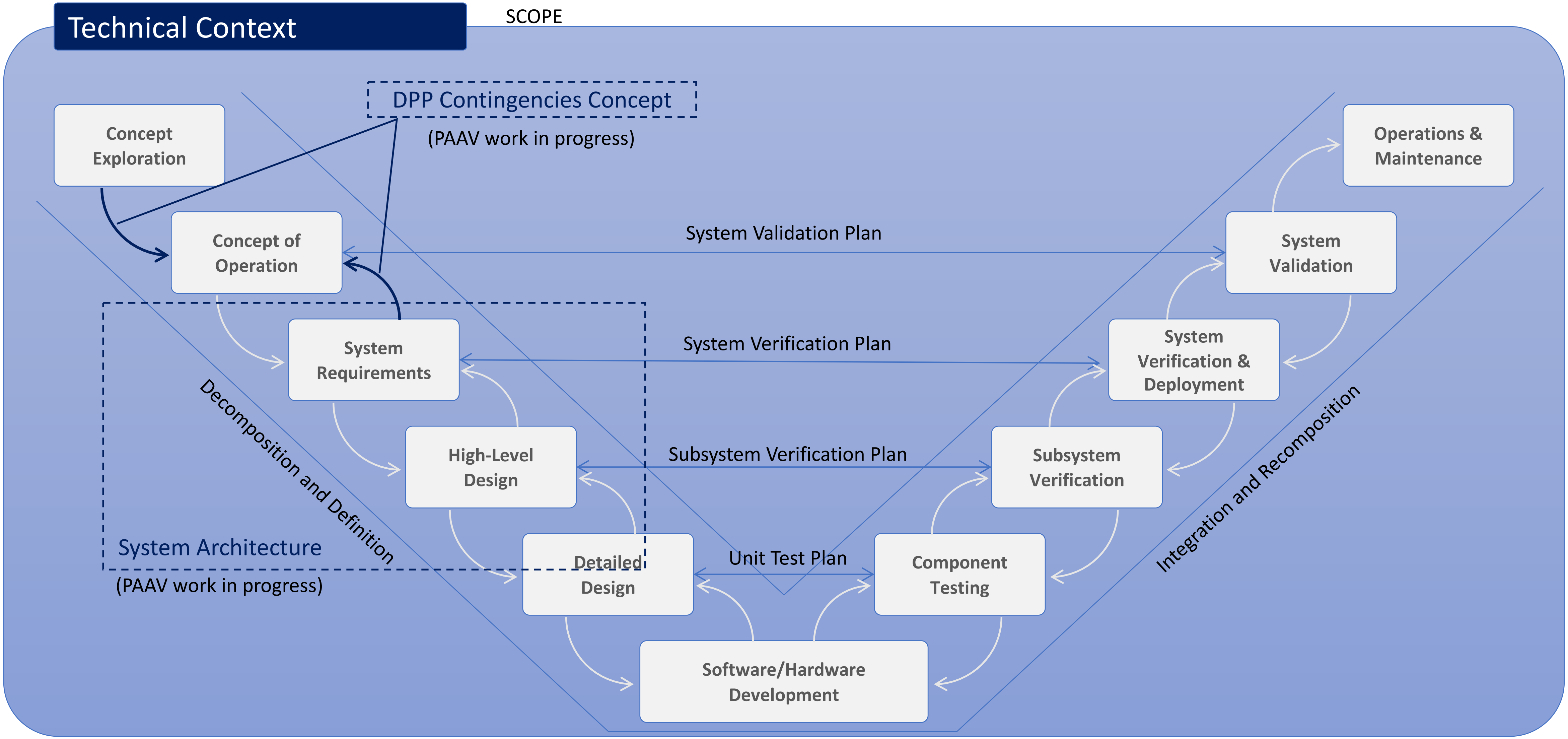
Feasible	Path conforms to the aircraft performance and range capabilities; complies with the airspace structure, rules, and constraints; avoids the terrain and charted obstacles; and meets the arrival constraints
Deconflicted	Path avoids unsafe proximity to known aircraft, dynamic obstacles, inclement weather, and other emergent airspace hazards
Harmonized	Path follows cooperative rules and procedures to ensure that the use of the airspace is coordinated with other airspace users
Flexible	Path provides adequate maneuverability to ensure future flight path changes, if needed, are available and feasible
Optimal	Path best achieves the operator’s business objectives for the specific flight

OBJECTIVES

Construct **and** maintain a flight path with five principal qualities: feasibility, deconfliction, harmonization, flexibility, optimality

DPP Automation Concept for AAM

PAAV



Partner Opportunities in Dynamic Path Planning

- DPP system concept and architecture modeling
- Use of DPP for dynamic hazard avoidance during LC2L
- Considering the merits of developing DPP industry standards (e.g., for LC2L)
- System concepts development of DPP-adjacent systems

Concept Research

- Simulation experiment planning (test cases, performance targets, etc.)
- Ecosystem area testing of industry DPP systems

Applied Research

Wrap Up

- PAAV team will refine specific approach and research questions based on feedback from stakeholders
  - RTCA
  - FAA RTT
  - Partner/industry collaboration

- Timeline
  - RFI closed April 26
  - Aiming to establish partnership(s) and start flying in FY25
  - PAAV concept paper due in FY24
  - Several batch studies planned for FY24