



# Trajectory Specification for Terminal Air Traffic: Pairwise Conflict Detection and Resolution

Russ Paielli and Heinz Erzberger  
NASA Ames Research Center

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# Outline

- **Background**
- **Trajectory Specification**
- **Conflict detection**
- **Conflict resolution**
- **Pairwise conflict test method**
- **Results**
- **Concluding Remarks**

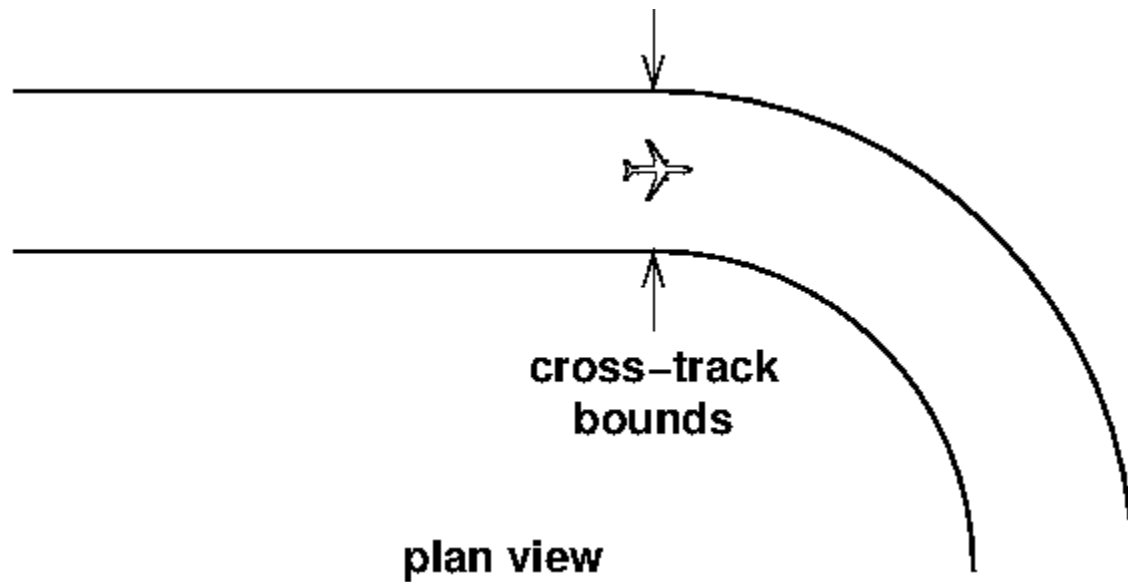
# Introduction

- NASA is developing the Advanced Airspace Concept (AAC) to automate ATC
  - Applies to both enroute and terminal airspace
  - Goes beyond decision support to enable eventual autonomy (little or no human intervention)
- Trajectory Specification is an enhancement of AAC
  - Has near-term application for trajectory prediction error modeling, but
  - Full concept is far-term because it requires new FMS (Flight Management System) standards

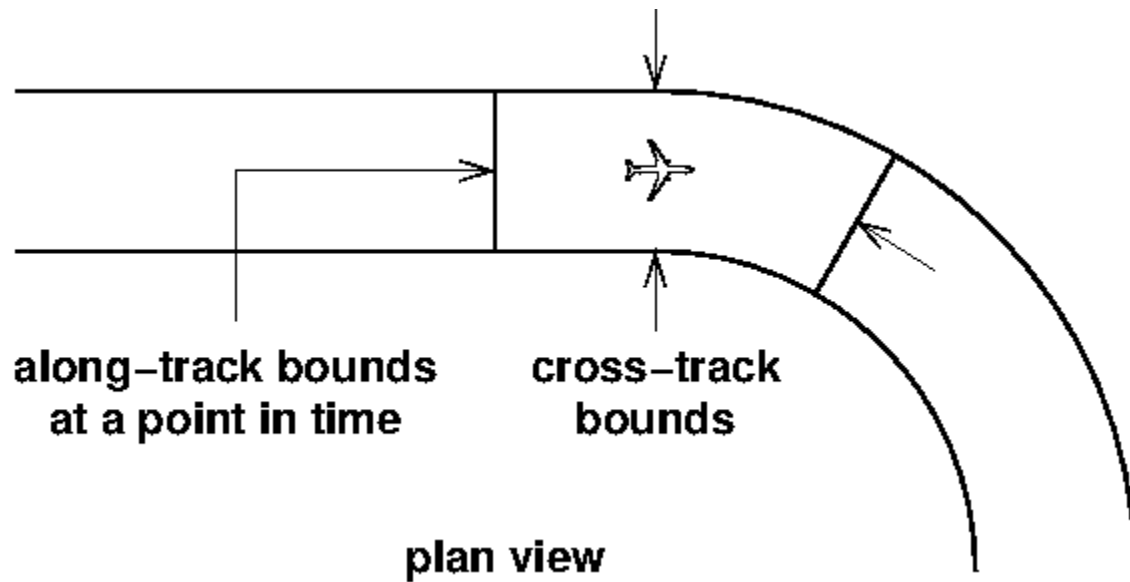
# Trajectory Specification: Dynamic “4D” RNP

- Required Navigation Performance (RNP) is based on published routes with fixed cross-track bounds and real-time conformance monitoring
- Trajectory Specification concept is dynamic and adds vertical and along-track (time-based) bounds

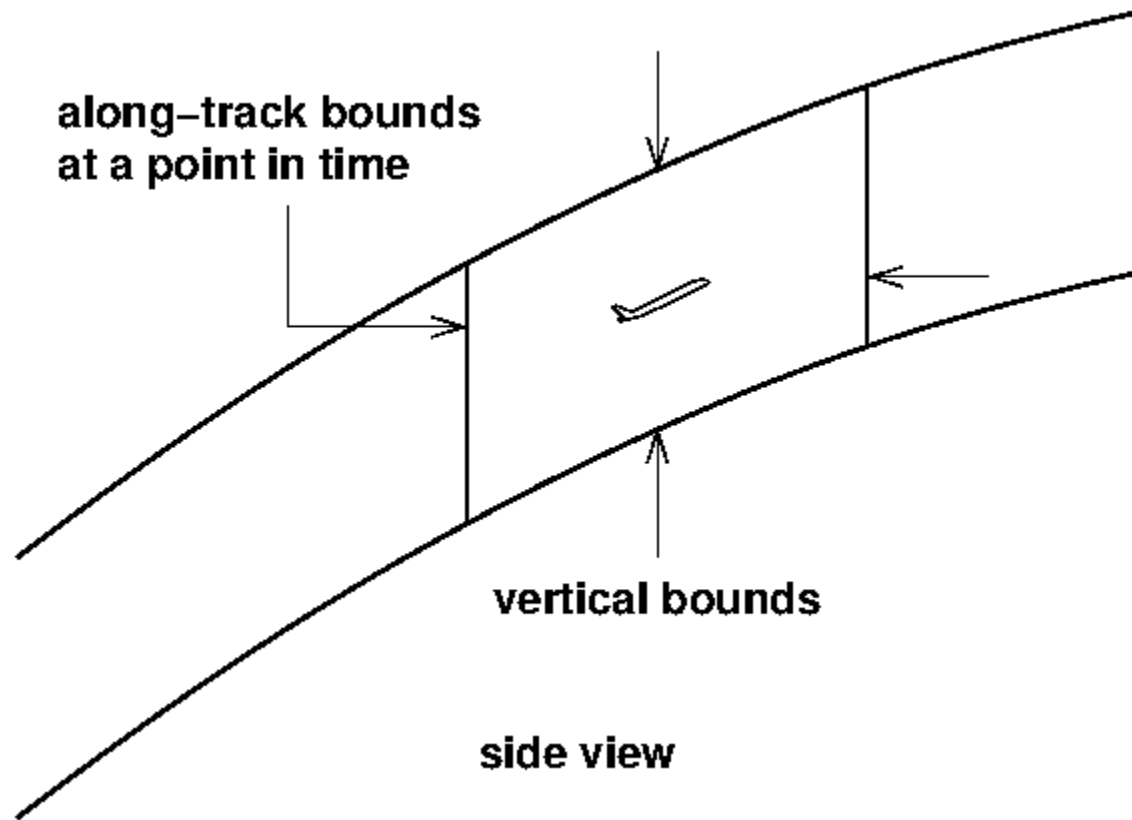
# Required Navigation Performance (RNP)



# Trajectory Specification: Horizontal Bounds



# Trajectory Specification: Vertical Bounds



# Related Concepts

- Joulia and Le Talle (2011-)
  - “4D” contract with elliptical tolerance “bubble”
  - Fixed tolerances too restrictive in light traffic
- Jackson, et al. (2009-)
  - “4D” trajectory datalink (4DTRAD)
  - Allows altitude bounds at several discrete points
  - Allows one required time of arrival (RTA)
  - Works with existing FMSs
  - Does not explicitly bound trajectory at any time

[Trajectory Specification should not be confused with another tube concept that implements “freeways in the sky”]



# Trajectory Specification Features

- Each aircraft constrained to a well defined volume of space at each point in time
- Bounds determined by tolerances relative to a reference “4D” trajectory (position as function of time)
- Tolerances can be piecewise linear function of distance along route (function fixed at time of assignment)
- Tolerances cannot be less than aircraft navigational capability allows but can be as large as current traffic situation permits (without a conflict)

# Challenges of Automation

- Failsafe operation required if automated system or datalink goes down (cannot depend on a human controller to take over)
- Trajectories with unbounded prediction errors cannot be guaranteed conflict-free for a sufficient period of time (depends on wind modeling error)

# Trajectory Specification Benefits

- Can guarantee conflict-free trajectories for a specified period of time (assuming conformance) -- facilitates failsafe operation
- Provides more reliable strategic planning and less reliance on tactical backup systems and tactical maneuvering during normal operation

# Basic Operational Concept

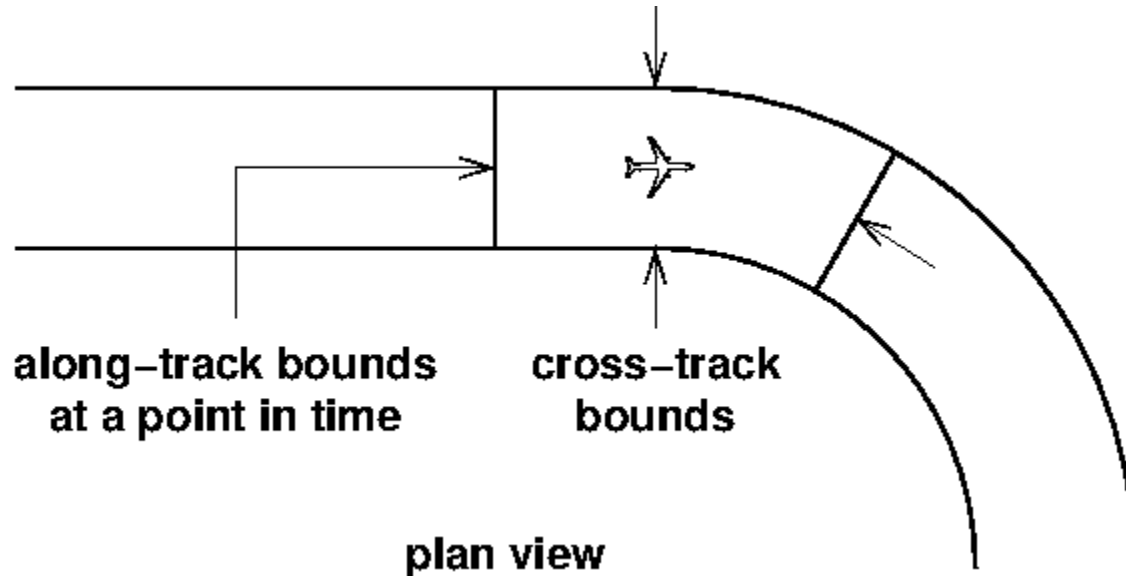
- Pilot enters route/intent into Flight Management System
- FMS computes “4D” trajectory prediction
- FMS downlinks predicted trajectory to ATC as request
- ATC assigns tolerances, checks for conflicts
- ATC modifies trajectory if necessary to resolve conflicts
- ATC uplinks assigned trajectory with tolerances
- FMS flies assigned trajectory to specified tolerances

Trajectory Specification Language (TSL) based on XML to be documented in a NASA Technical Memorandum

# Objective

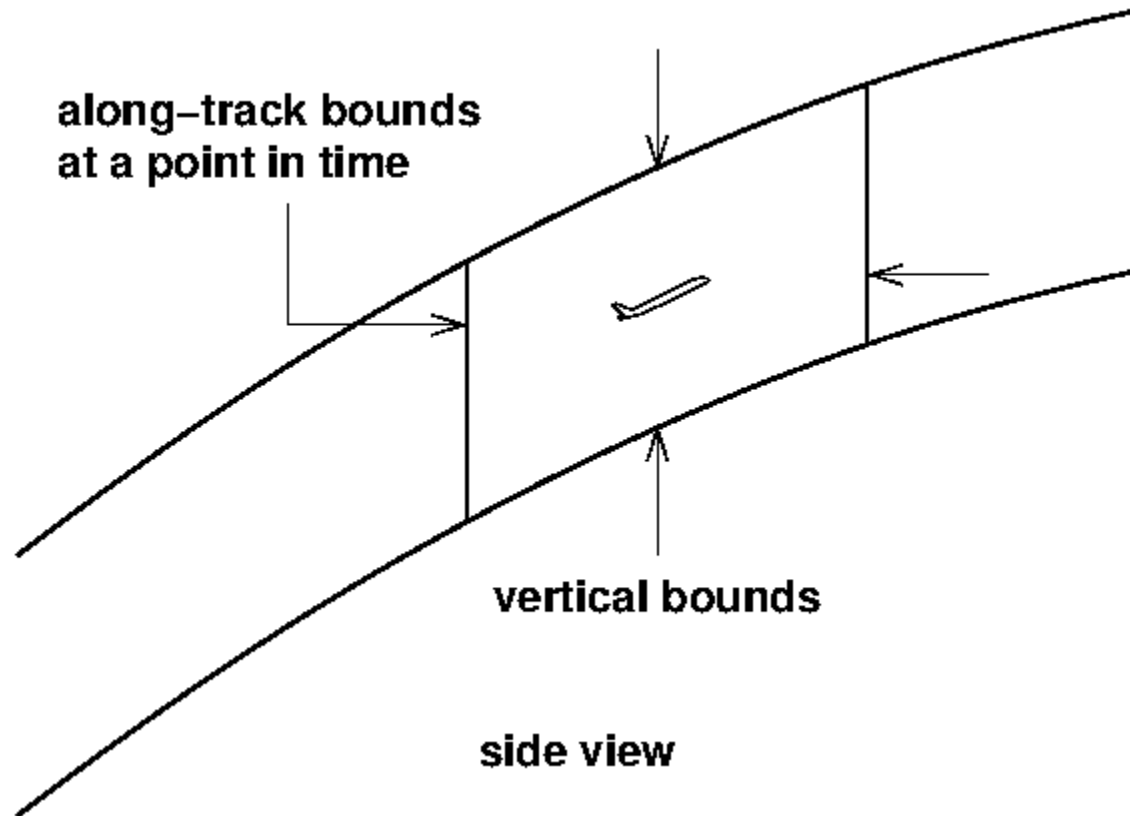
**To develop a research software prototype and demonstrate the computational feasibility of Trajectory Specification as applied to conflict detection and resolution for terminal air traffic**

# Conflict Detection



Anywhere within the bounding space, the aircraft should be sufficiently separated from all other flights (at any point in *their* bounding space).

# Conflict Detection



# Conflict Detection

- Need to ensure minimum required separation for entire bounding space at each point in time
- Much more computation than simple pointwise separation calculations
- Use coarse checks and large time steps to avoid detailed computation when separation is large
- Horizontal separation of bounding areas can be calculated using polygon approximation
- When horizontal separation of bounding areas is insufficient, use gridded sampling method



# Definition of Separation Ratio

Minimum separation standard:

3 nmi horizontal or  
1,000 ft (1 kft) vertical

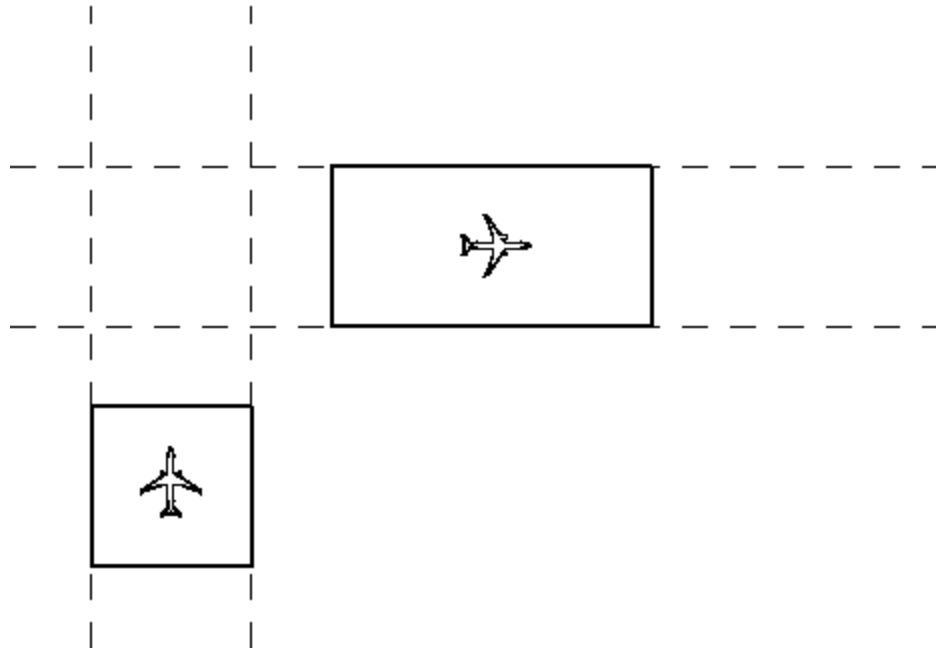
horiz sep ratio = horiz sep / 3 nmi

vert sep ratio = vert sep / 1000 ft

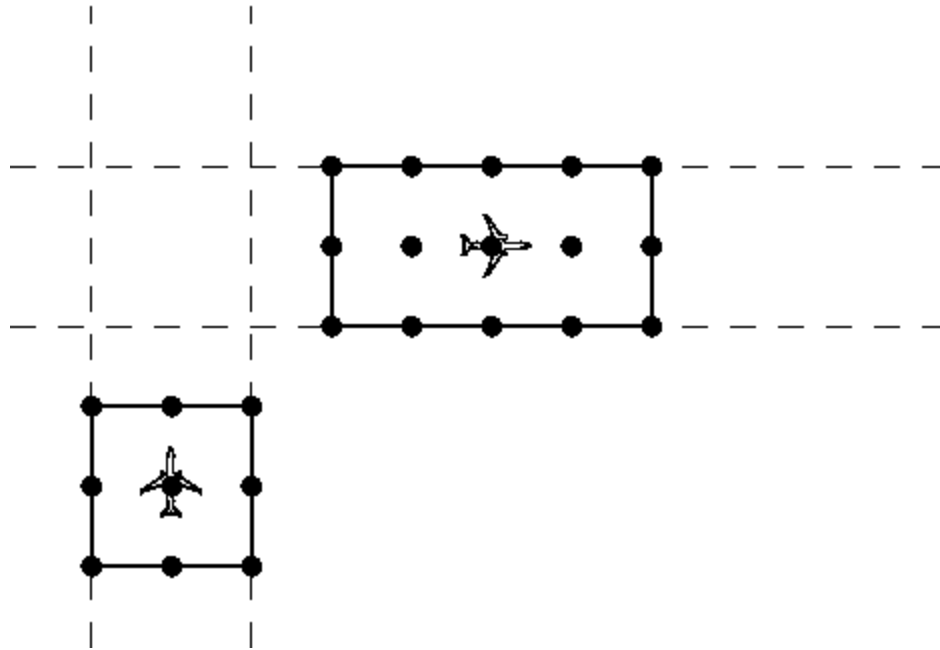
separation ratio = max(horiz, vert) sep ratio

< 1.0 means less than separation standard

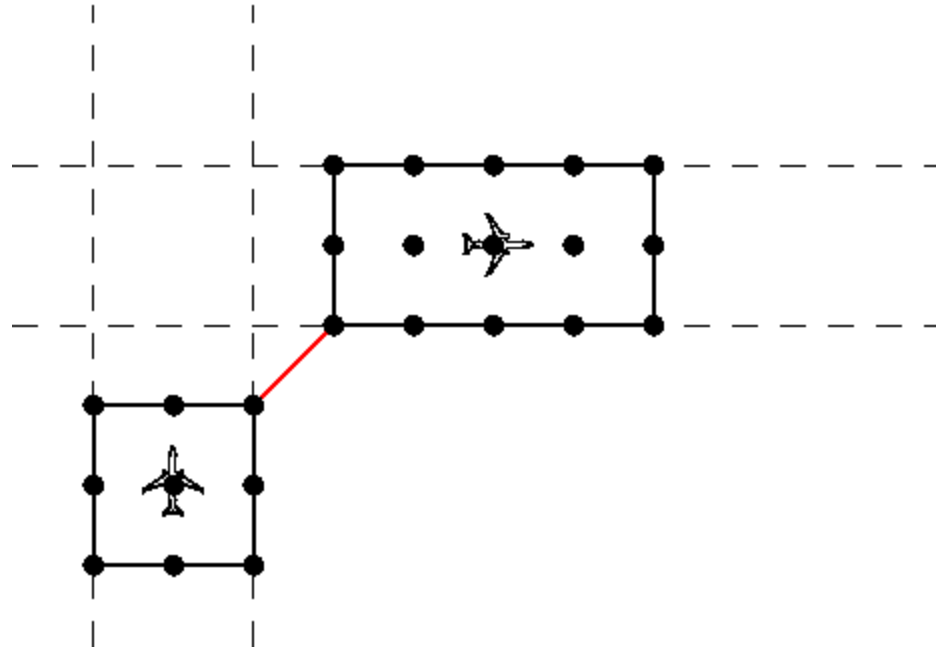
Combines horizontal and vertical separation into a single scalar metric (for comparison, ranking, ordering)



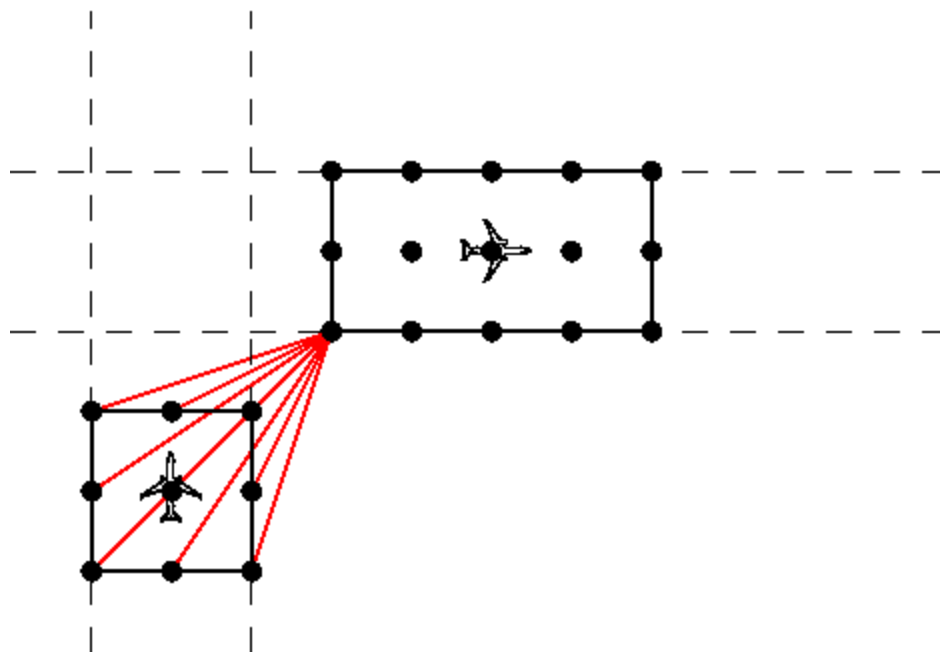
Plan view of bounding spaces at a point in time

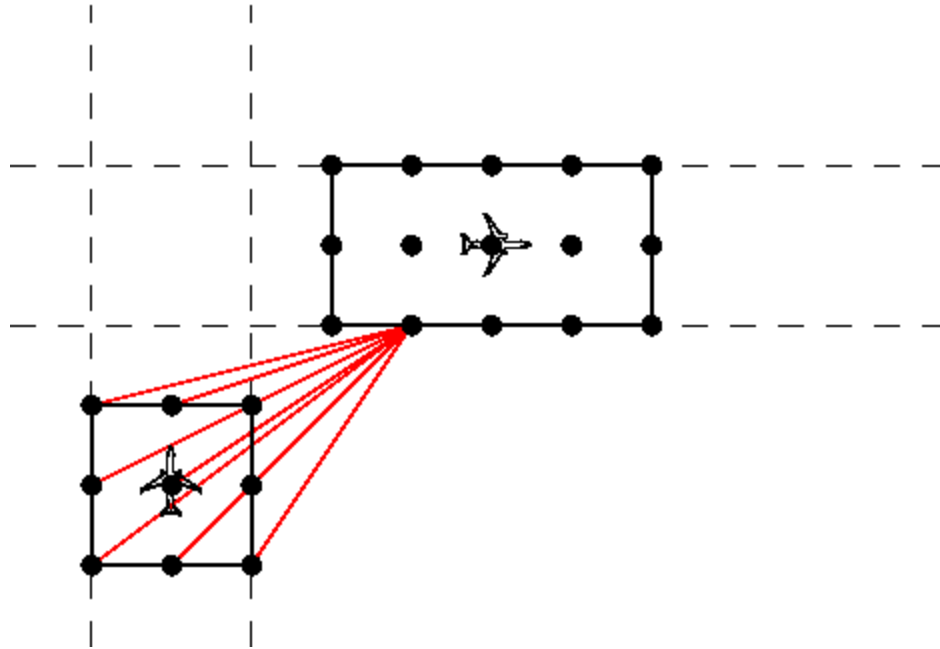


[Each grid point has an altitude range]



Calculate separation ratio for each pair of grid points and record minimum



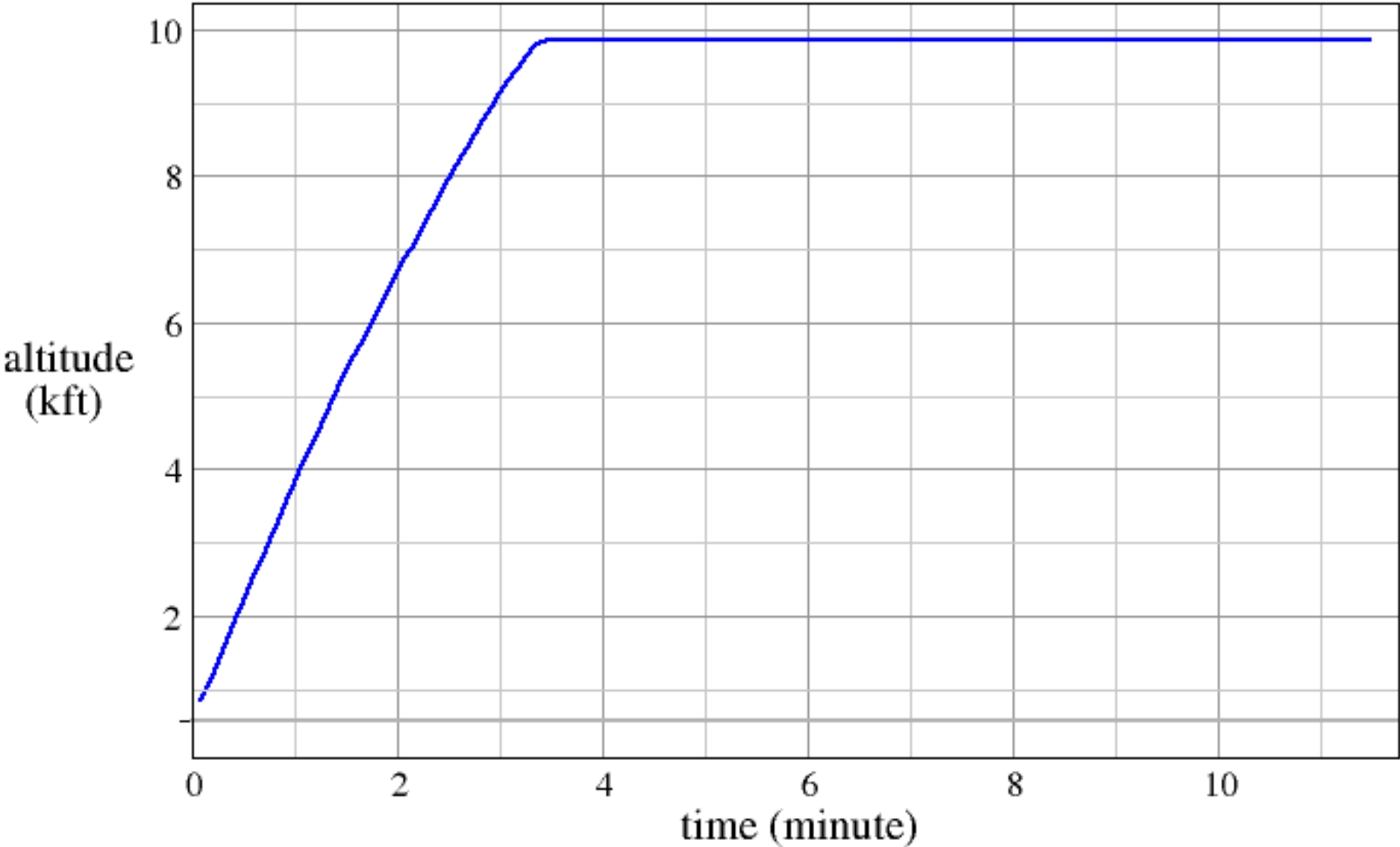


# Conflict Resolution Maneuver Types

- Temporary Altitude
- Speed Reduction
- Reroute
- Takeoff Delay
- Other

# Altitude Profile

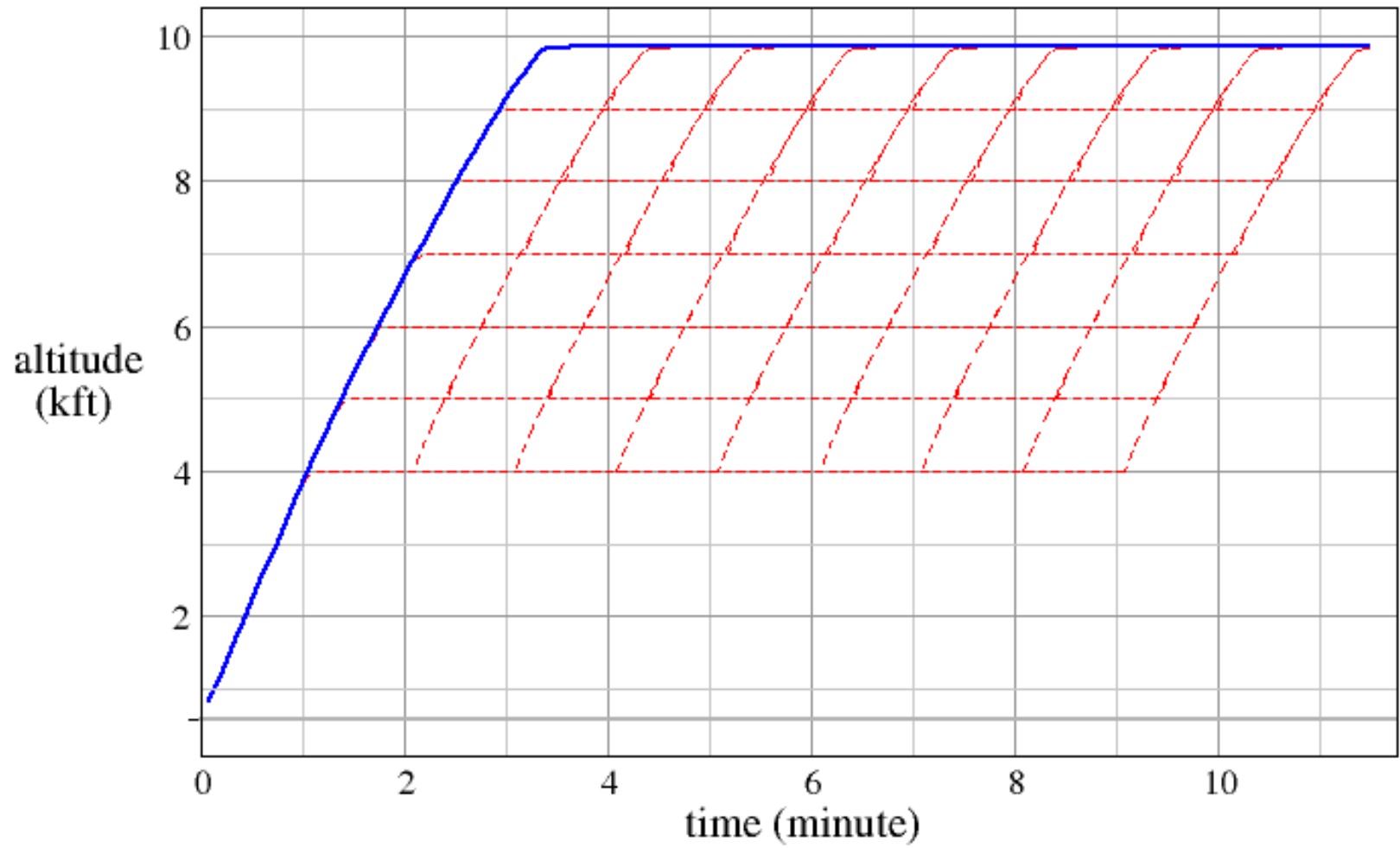
A319 Departure



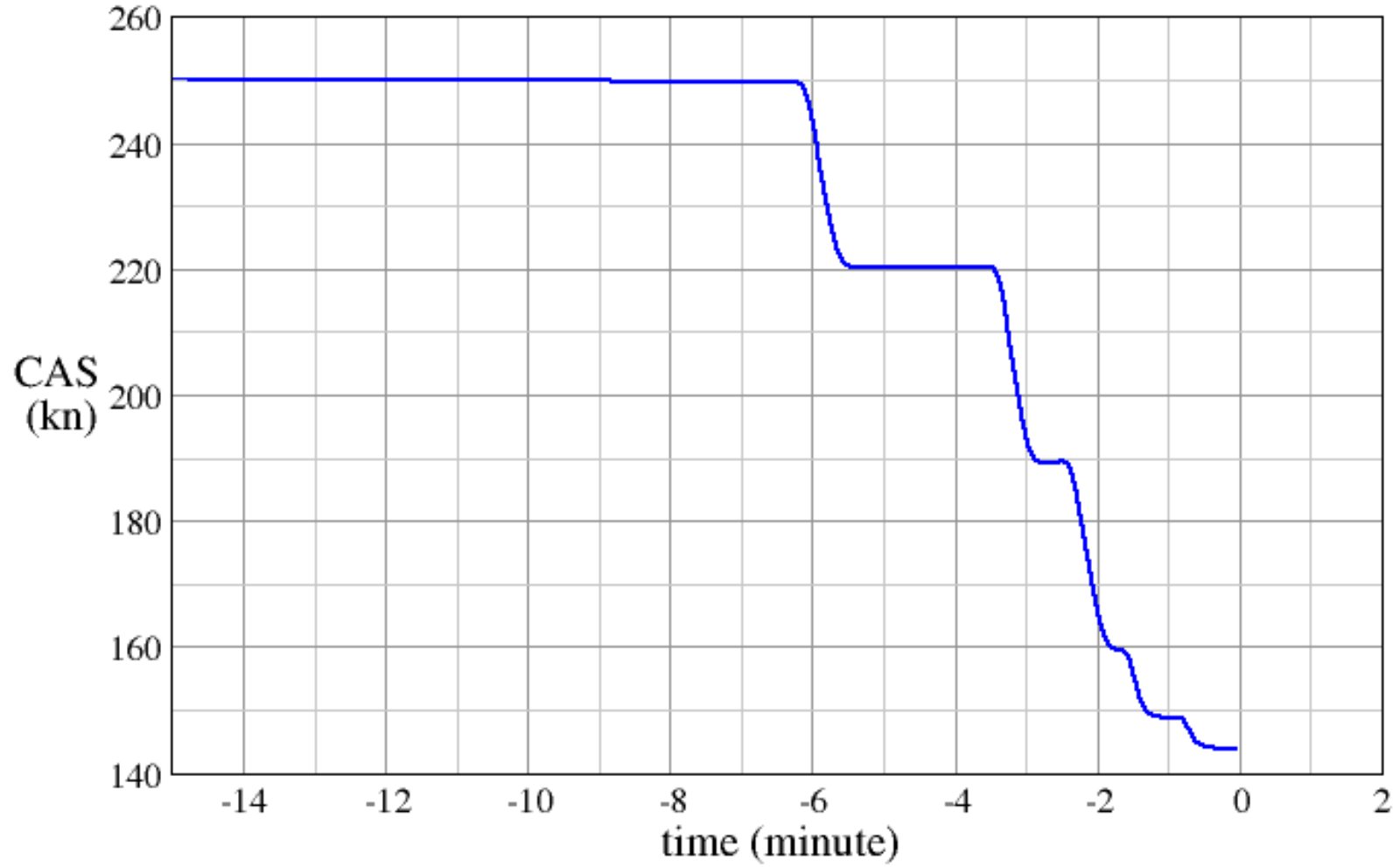


# Temporary Altitude Candidates

A319 Departure

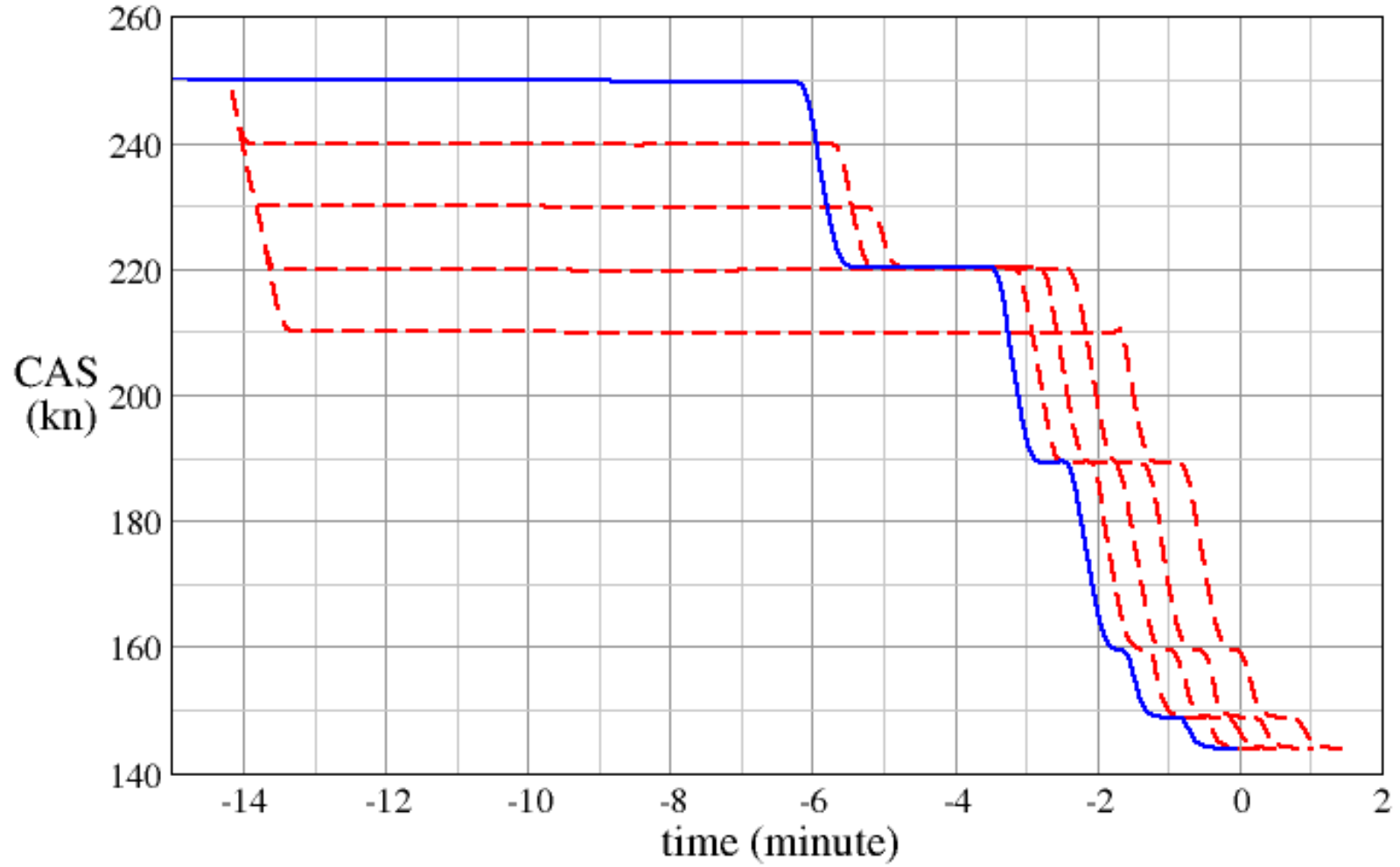


## Descent CAS Airspeed Profile B738 Arrival

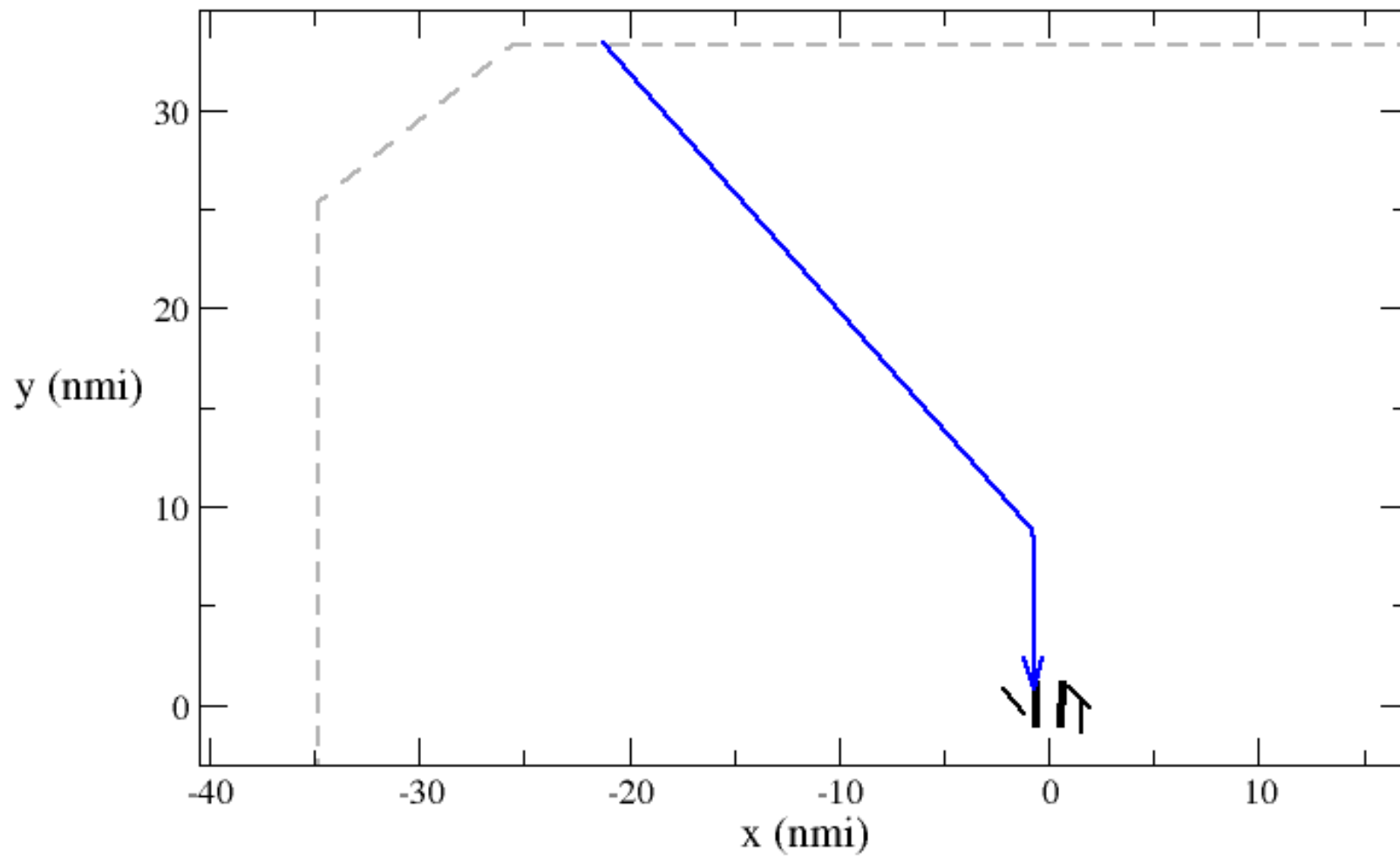


# Speed Reduction Candidates

## B738 Arrival

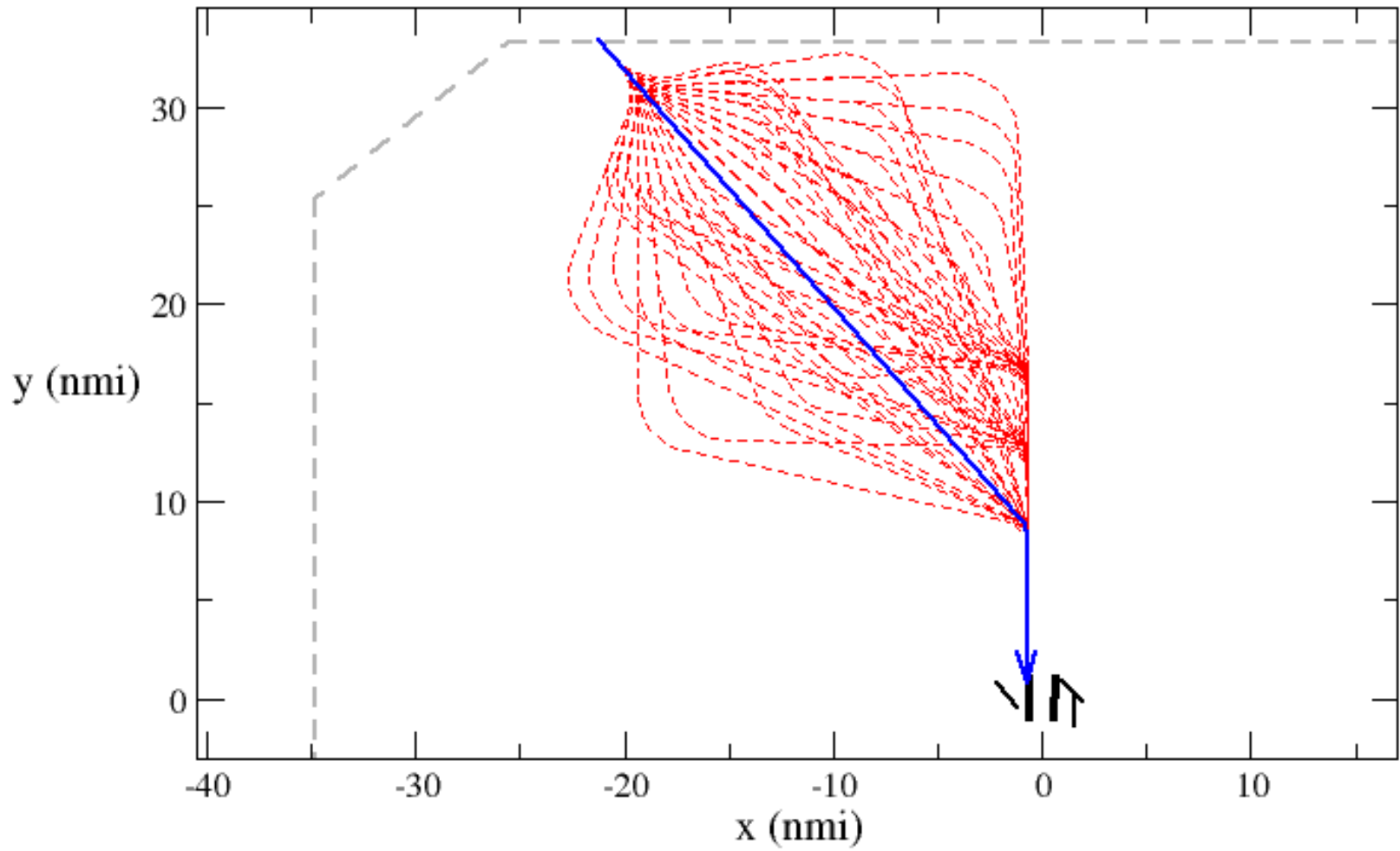


# Arrival Route DFW/18R



# Arrival Reroute Candidates

DFW/18R (53 candidates)



# Pairwise Conflict Resolution

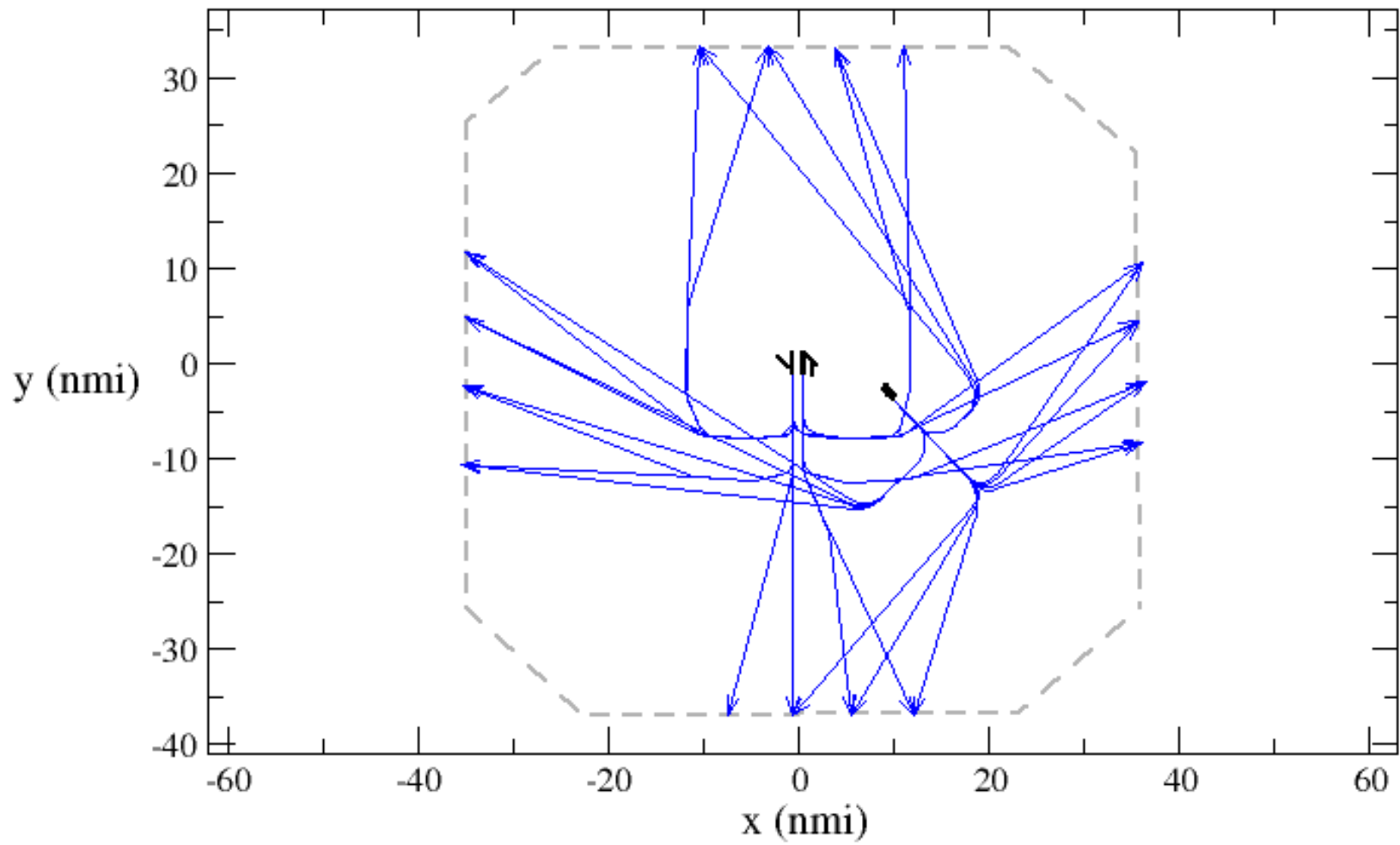
- Conflict resolution must avoid conflicts with all traffic
- Pairwise conflict resolution is simpler but is a logical first step
- This paper is limited to pairwise conflict resolution, but a future paper will address general conflict resolution in realistic traffic

# Test Environment

- Trajectories generated using NASA simulators:
  - Airspace Concepts Evaluation System (ACES)
  - Kinematic Trajectory Generator (KTG)
- One full day of (unresolved) trajectories generated for DFW and DAL airports
  - DFW arrivals routed direct to final approach
  - Default tolerances applied
- Trajectories modified to simulate maneuvers for resolving conflicts

# Departure Routes

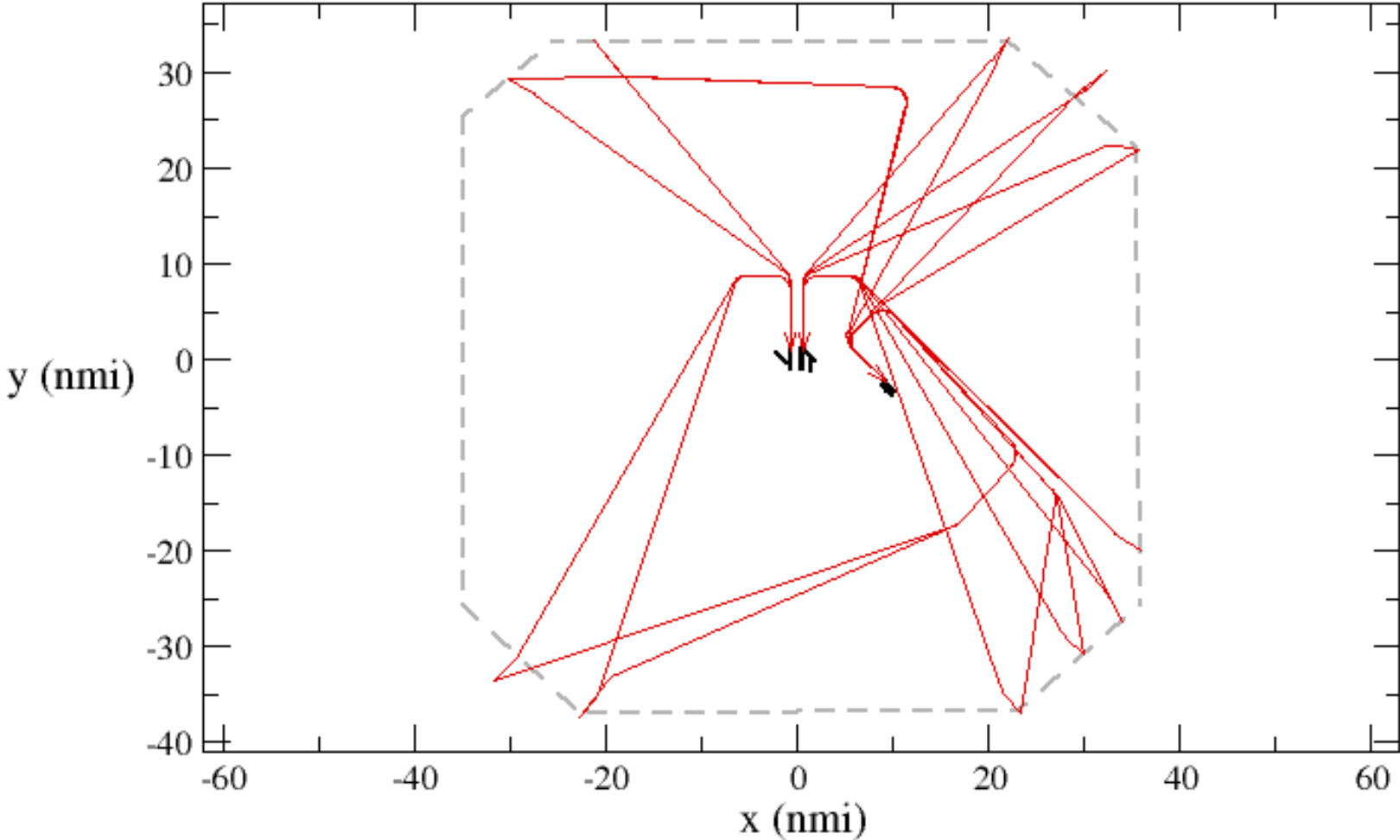
30 Unique Routes





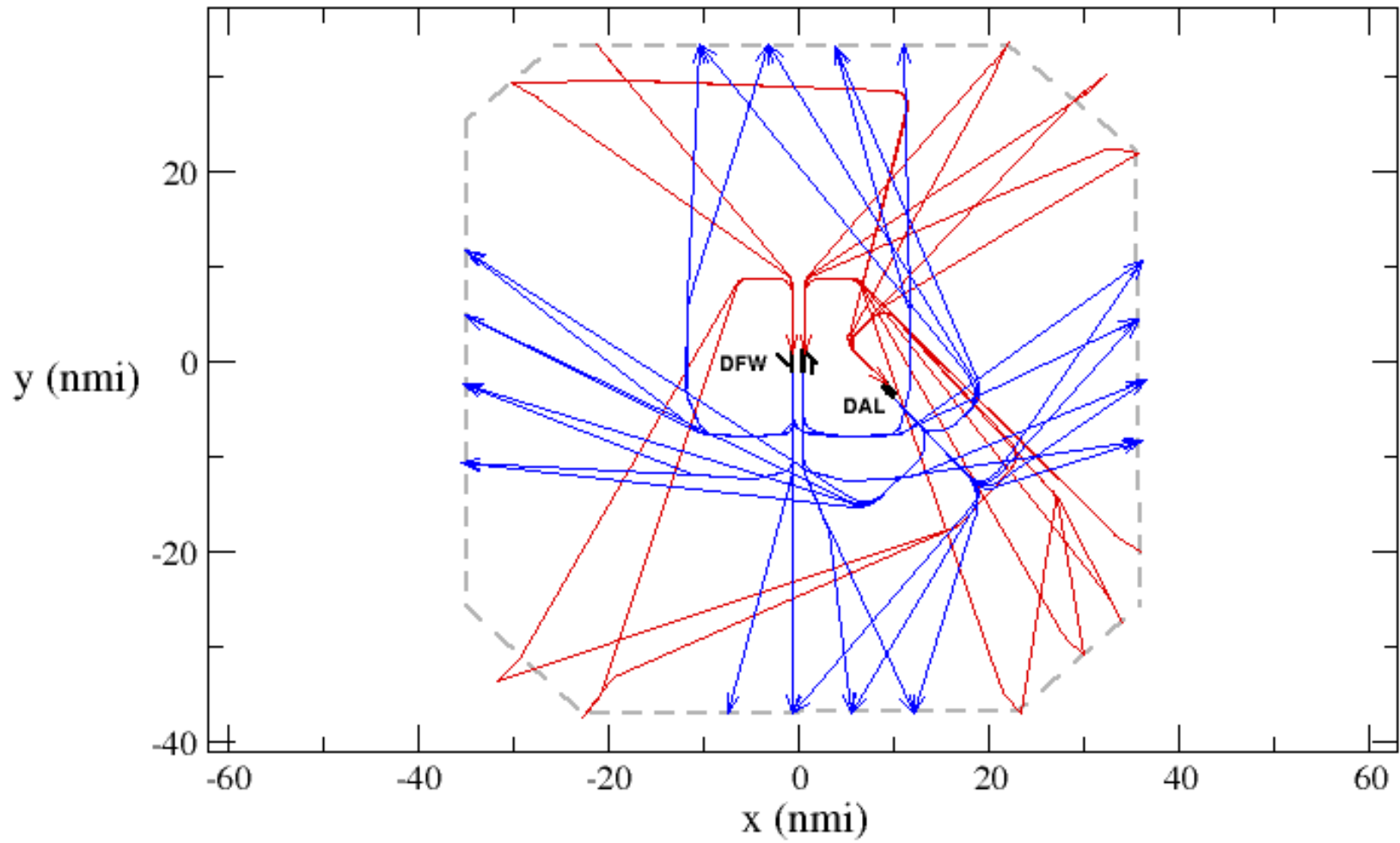
# Arrival Routes

22 Unique Routes



# Arrival and Departure Routes

52 Unique Routes: 30 departure, 22 arrival

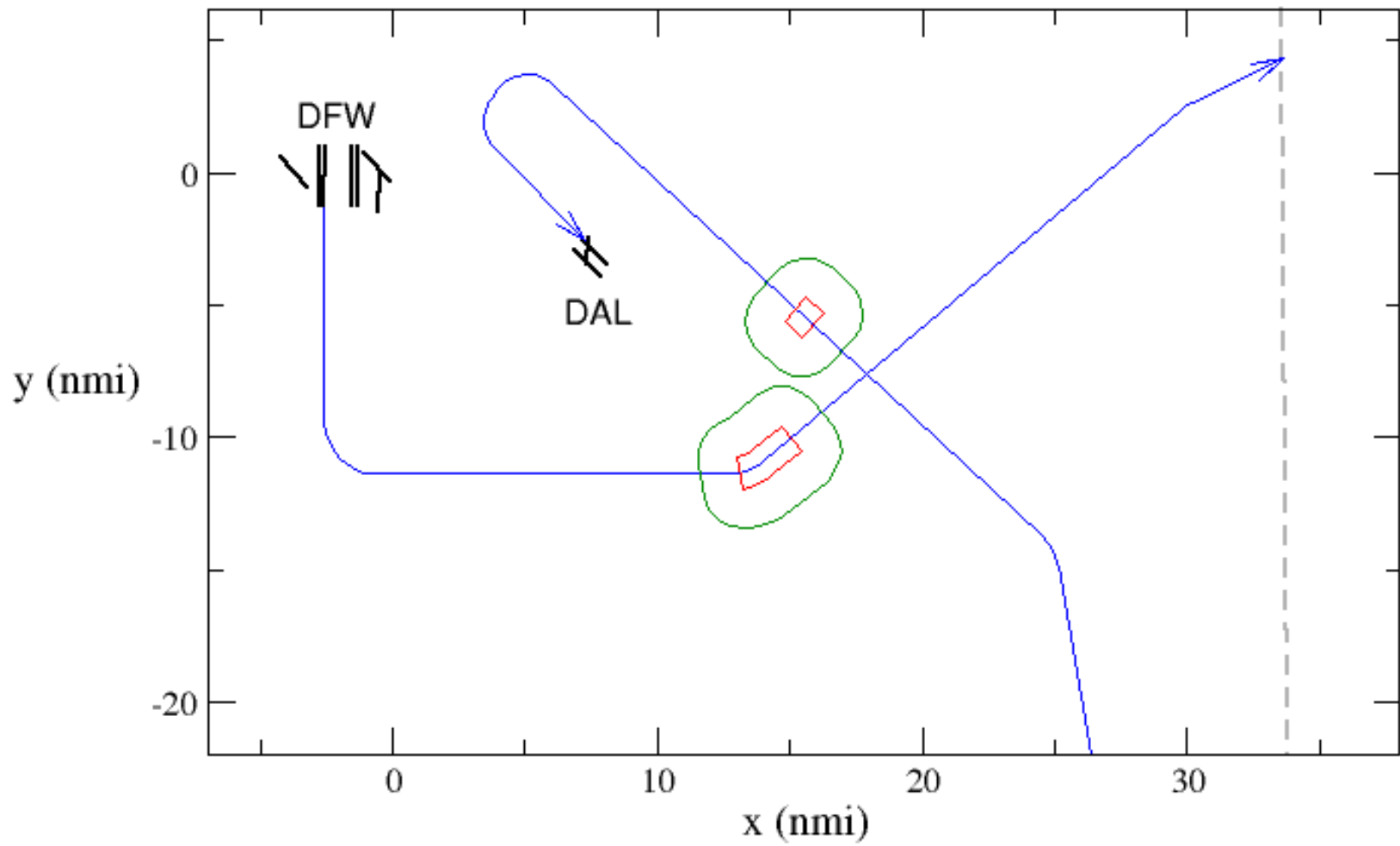


# Pairwise Resolution Tests

- 52 unique routes (30 departure, 22 arrival)
- One trajectory to represent each route
- $52 \times 51 / 2 = 1326$  trajectory pairs
- Each pair time shifted in steps of 30 sec
- 1325 pairwise conflicts resulted
- One flight maneuvered per conflict
  
- **All conflicts successfully resolved**
- Run time < 1 sec per pairwise conflict  
(with parallel processing on an Intel 32-core processor)

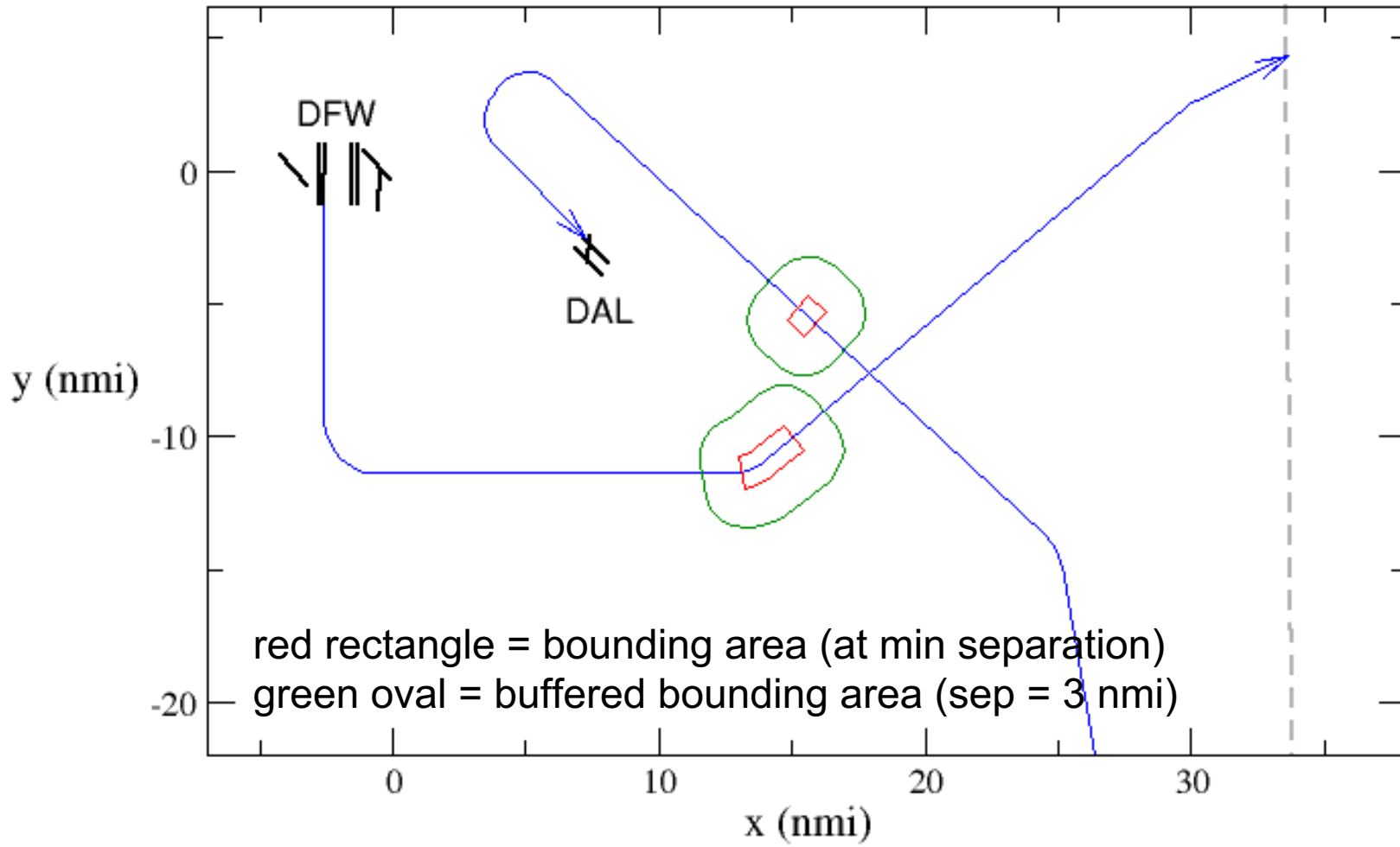
## Departure Reroute Example

separation ratio: 0.657->1.150 depart reroute 12 nmi, 0 deg, 16 nmi (+102 s)



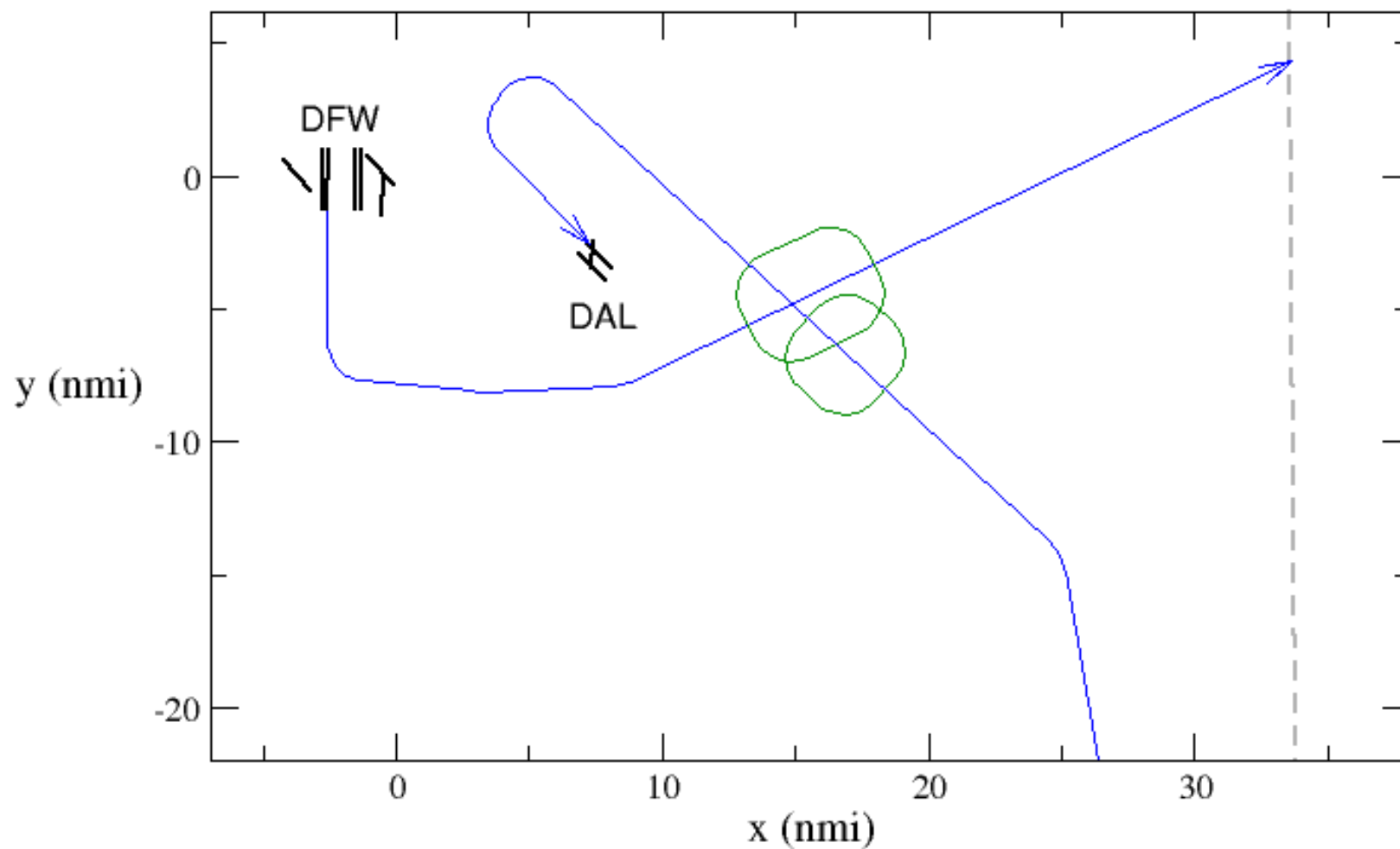
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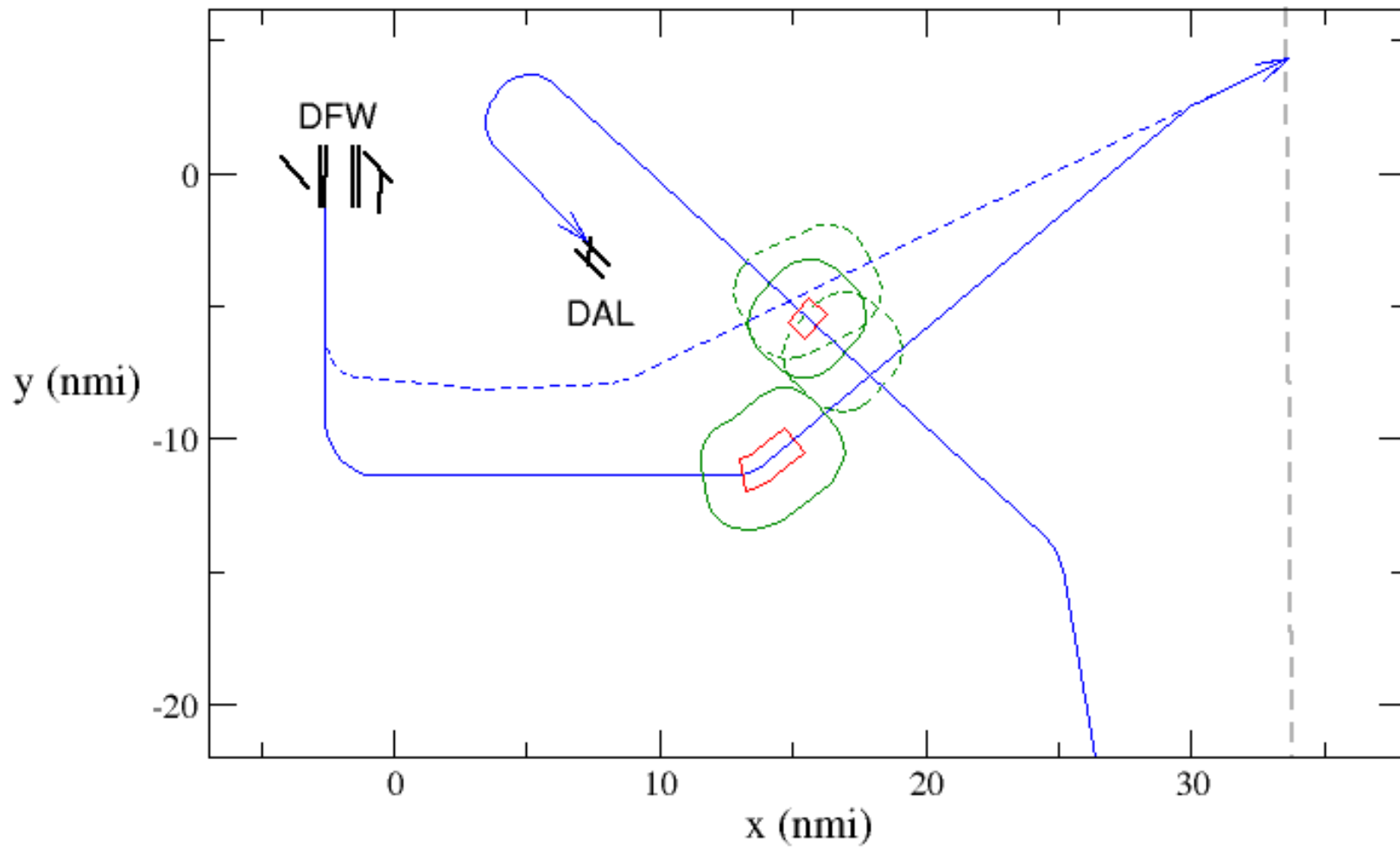
# Conflict Planview for Departure Reroute Example

separation ratio: 0.657



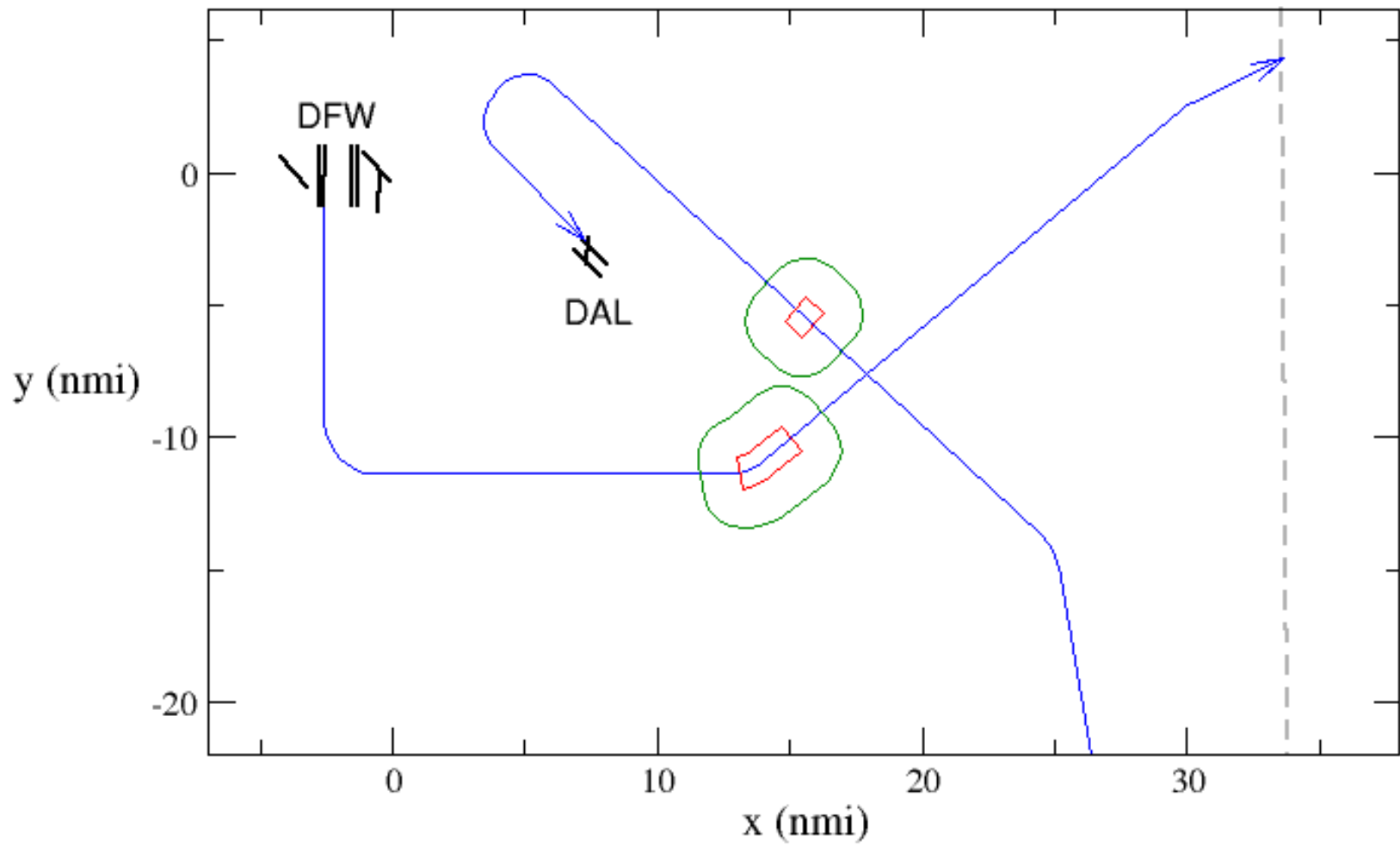
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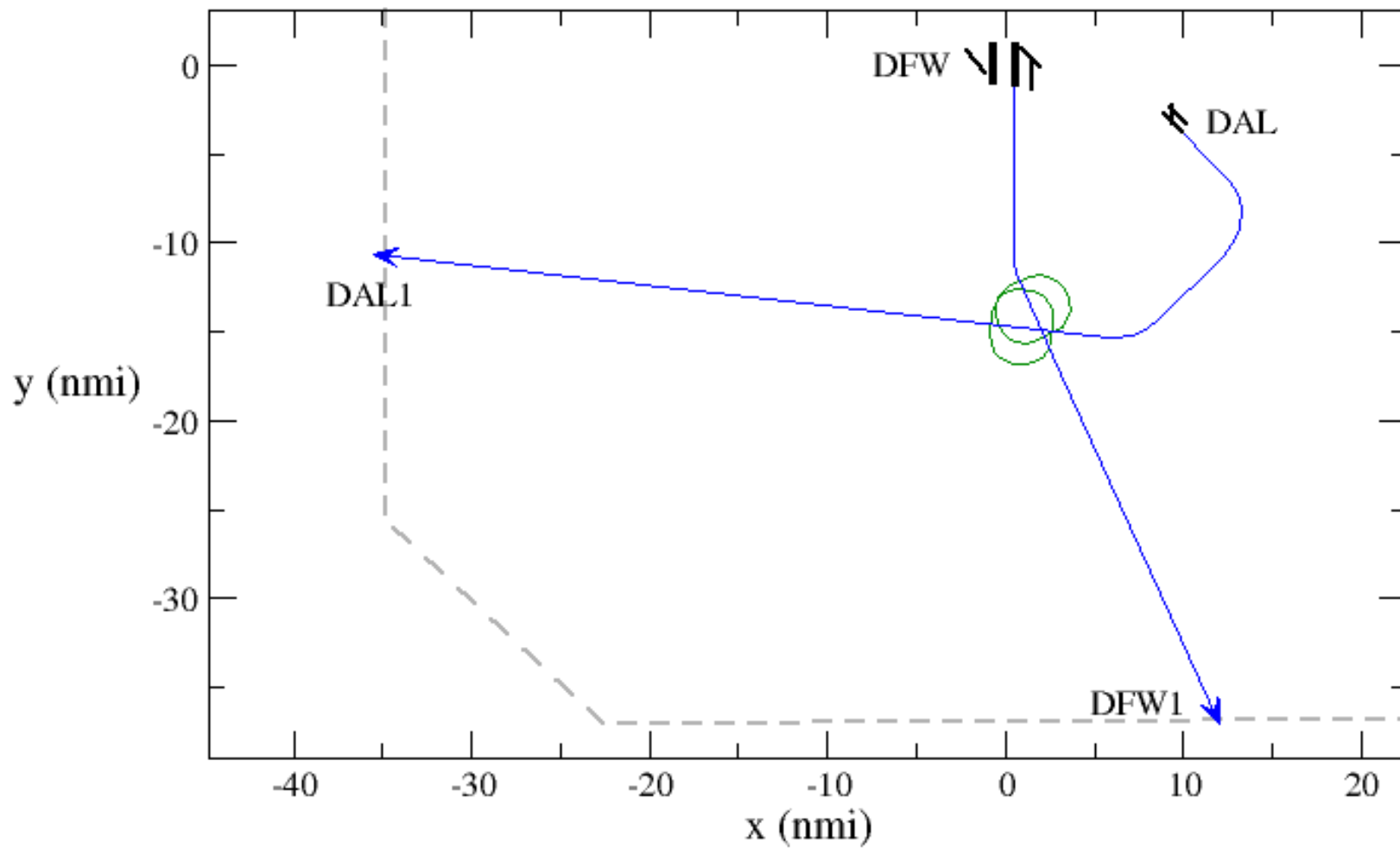
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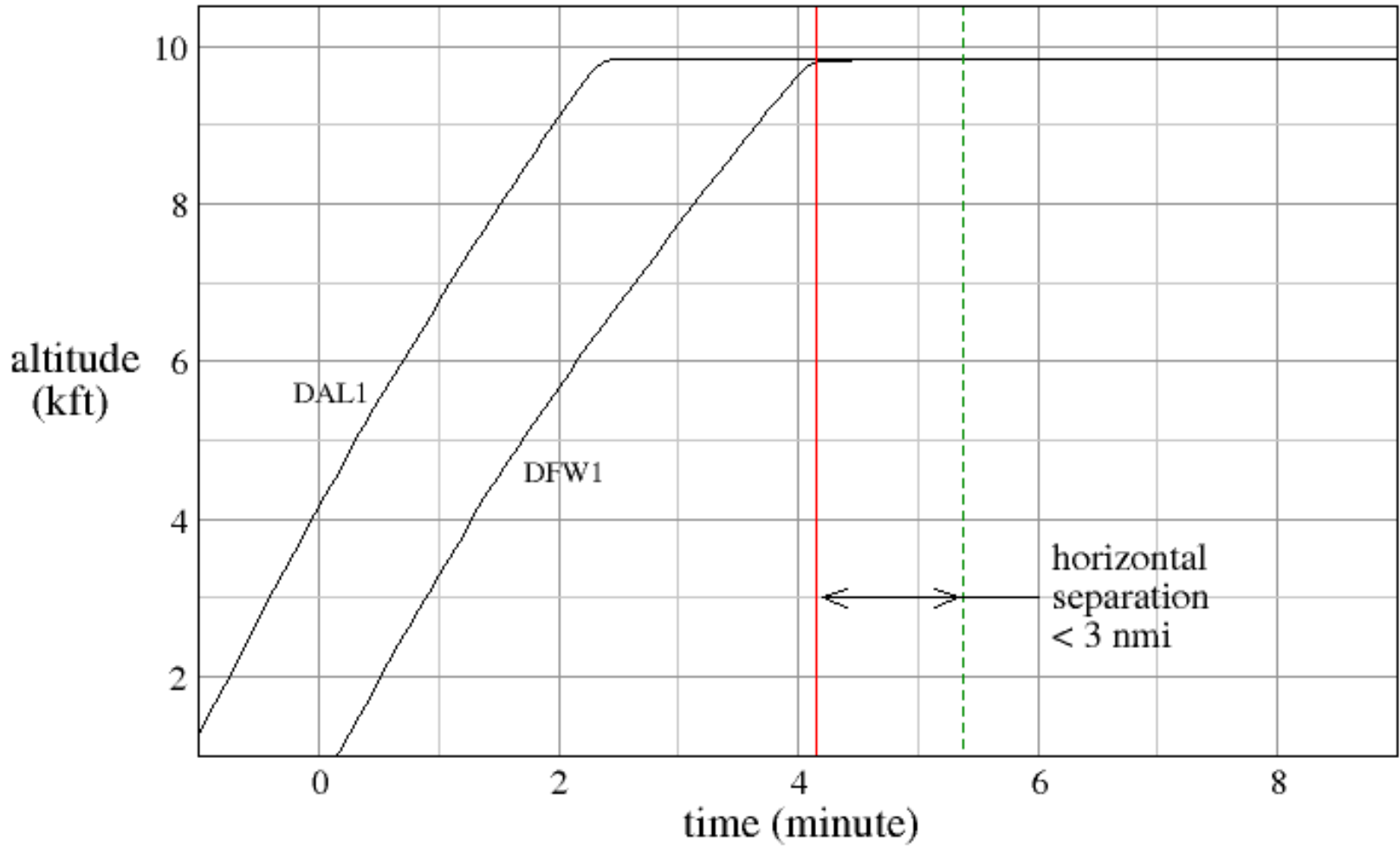
# Conflict Planview

separation ratio: 0.037



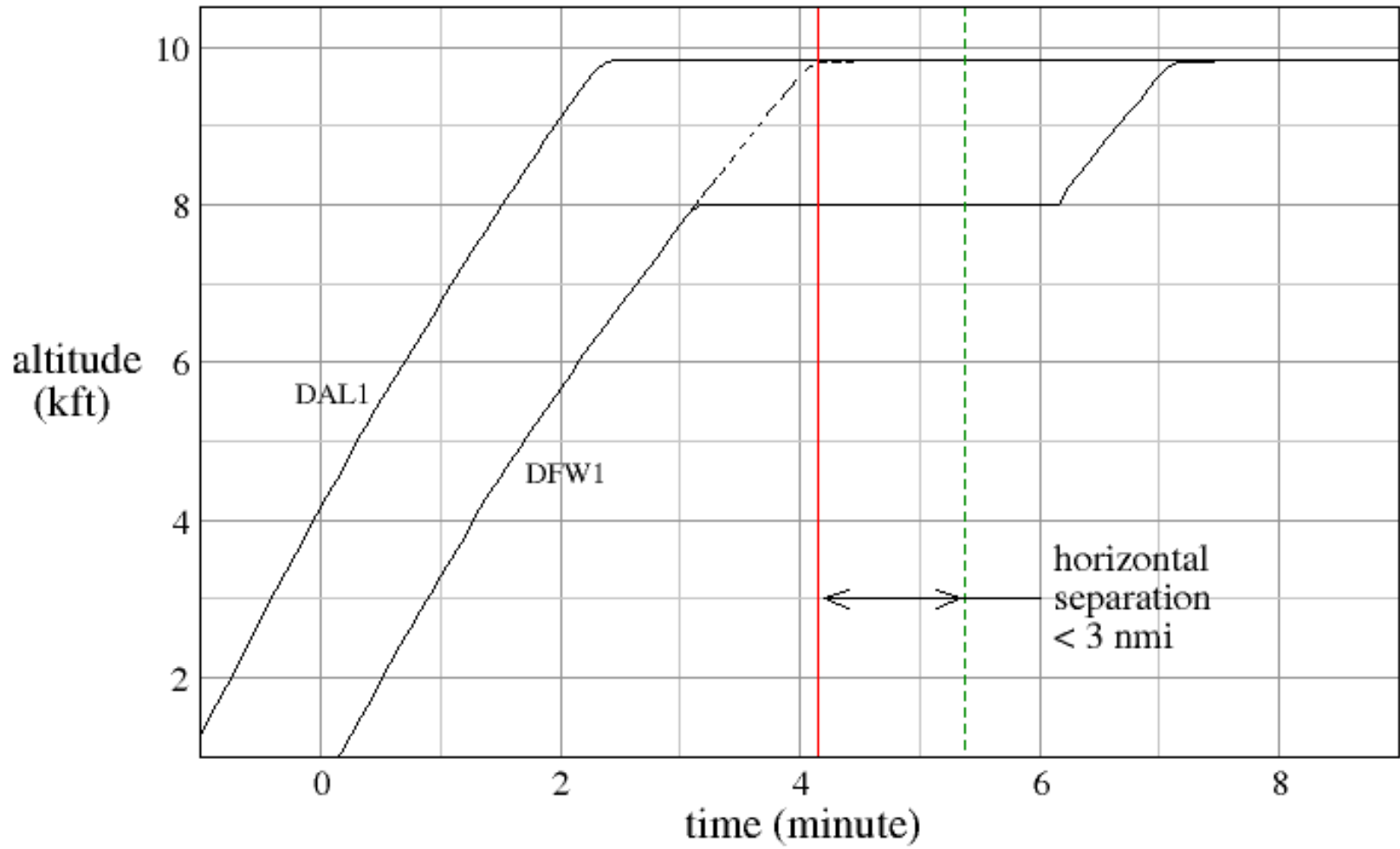
# Conflict Altitude Profiles

separation ratio: 0.037



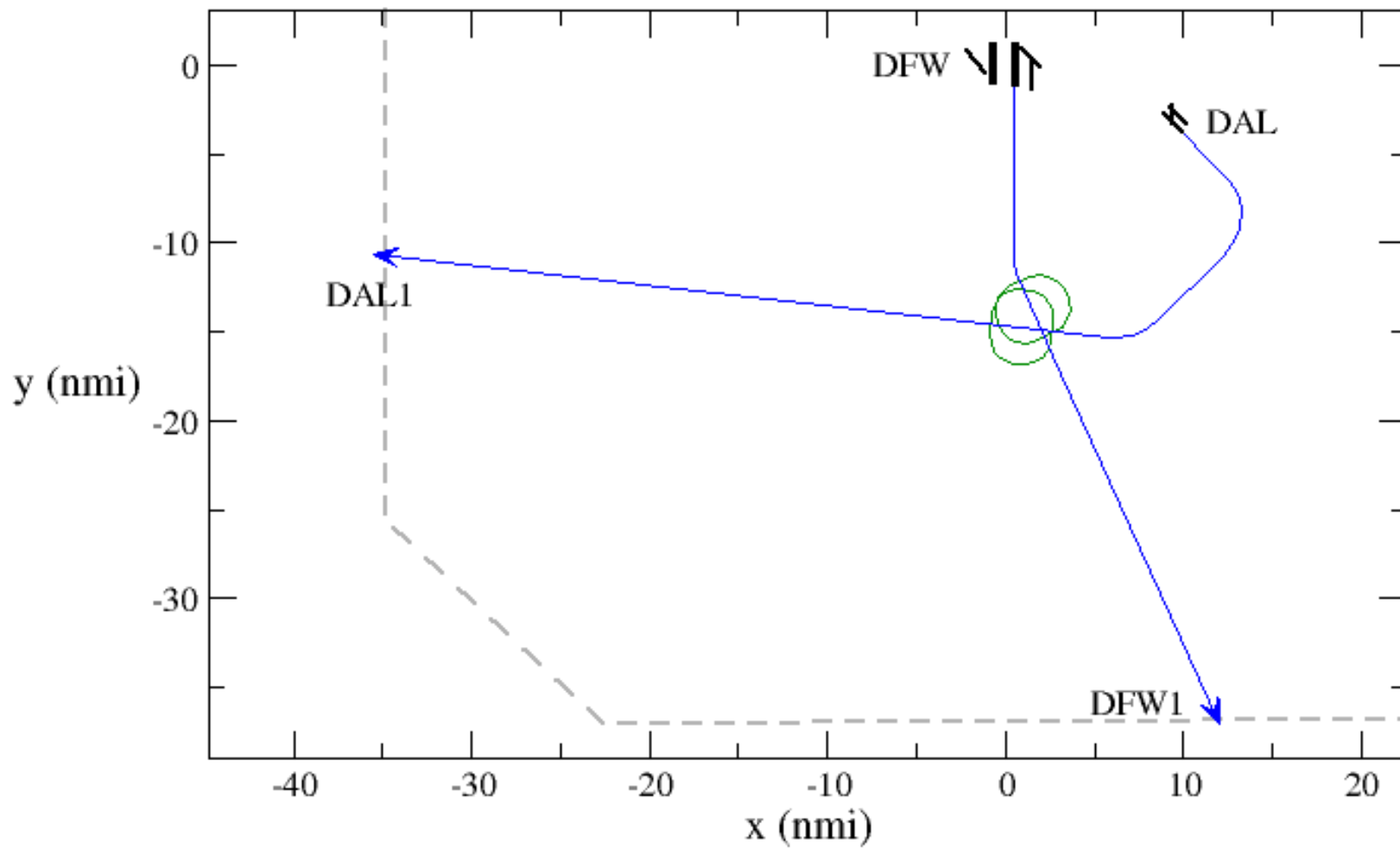
# Temporary Altitude Maneuver

DFW1 temp alt 8.0 kft, 3.0 min, separation ratio: 1.50



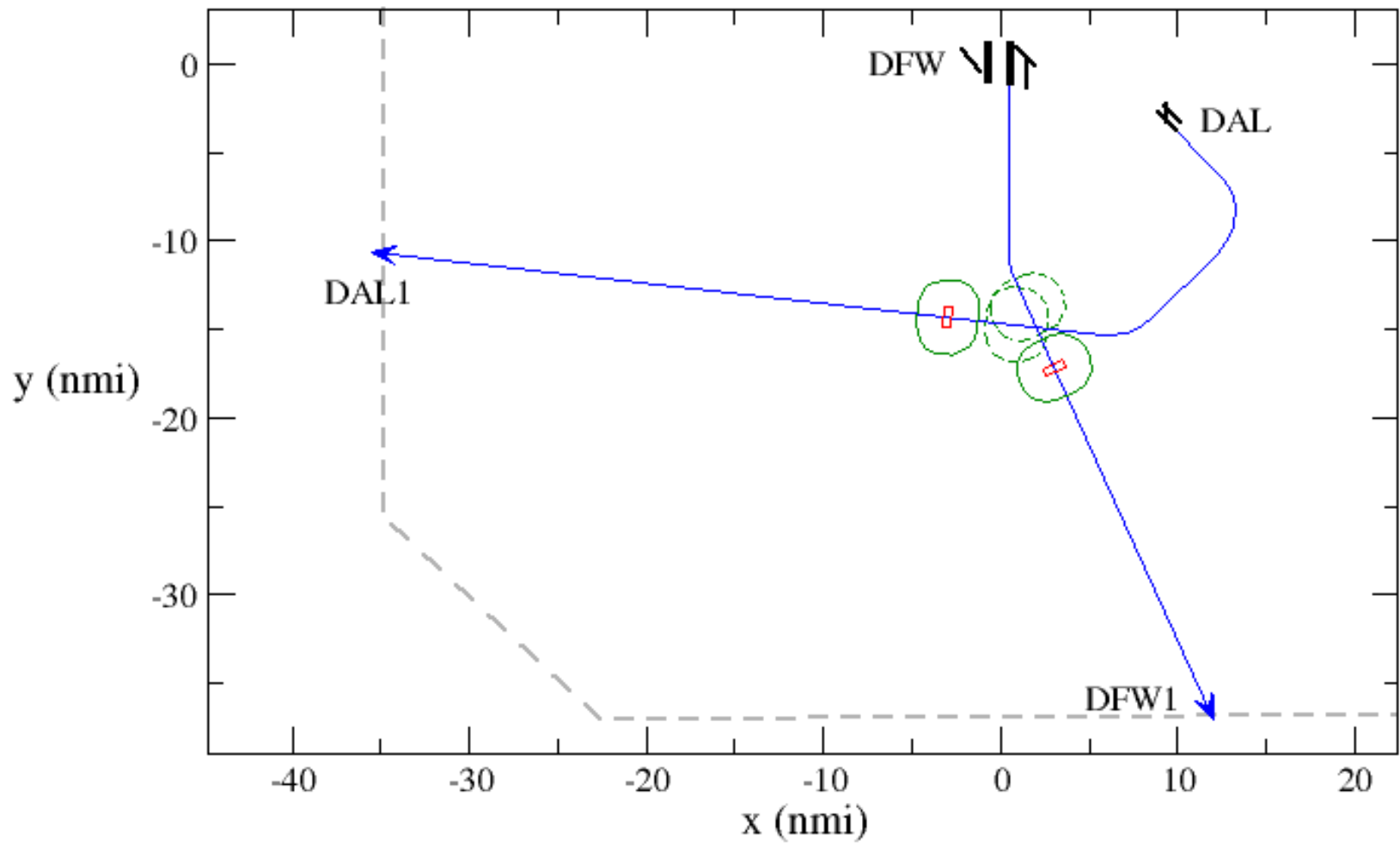
# Conflict Planview

separation ratio: 0.037



# Temporary Altitude Maneuver Planview

DFW1 temp alt 8.0 kft, 3.0 min, separation ratio: 1.50



# Concluding Remarks

- Trajectory Specification is dynamic “4D” RNP (Required Navigation Performance)
- Each flight constrained to a well-defined volume of space at each point in time
- Tolerances can be as large as current traffic situation permits (without a conflict)
- Makes ATC more failsafe and less dependent on backup systems and tactical maneuvers
- Computational feasibility of pairwise conflict detection and resolution demonstrated



# Questions?

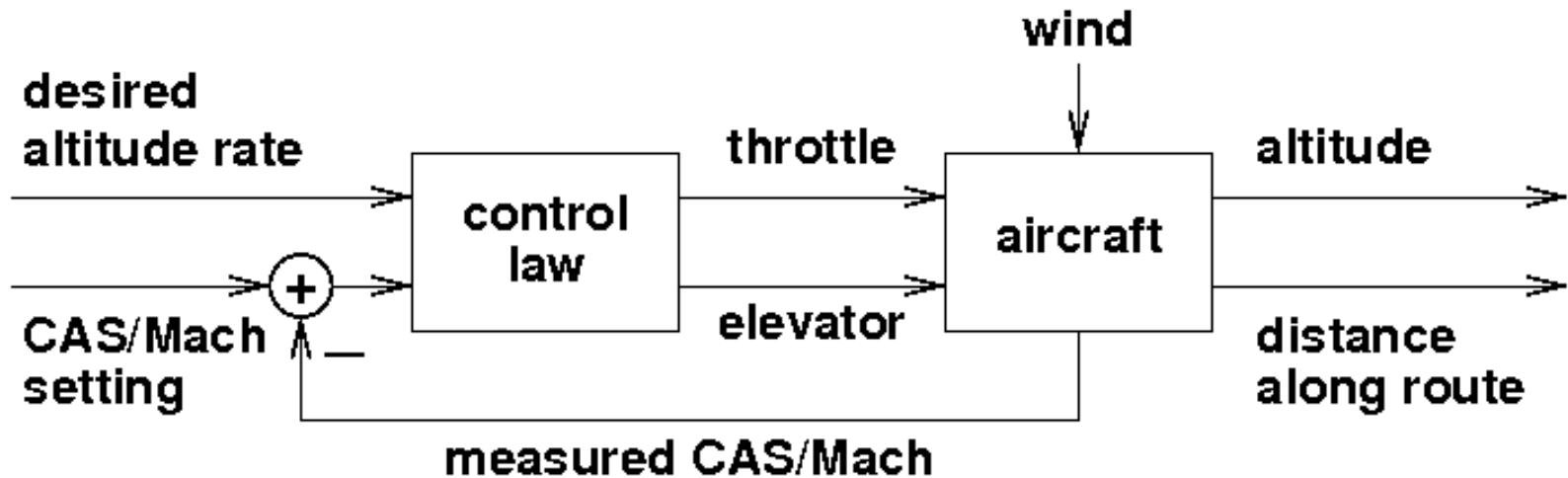
**[Russ.Paielli@nasa.gov](mailto:Russ.Paielli@nasa.gov)**



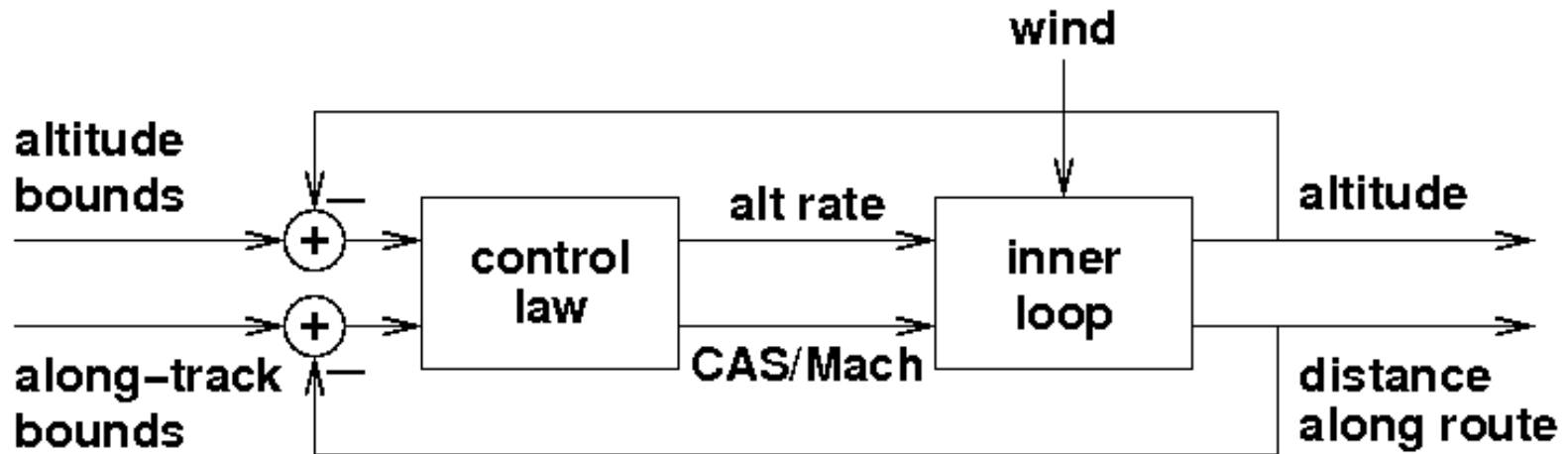
# Backup Slides



# Simplified Longitudinal Flight Control

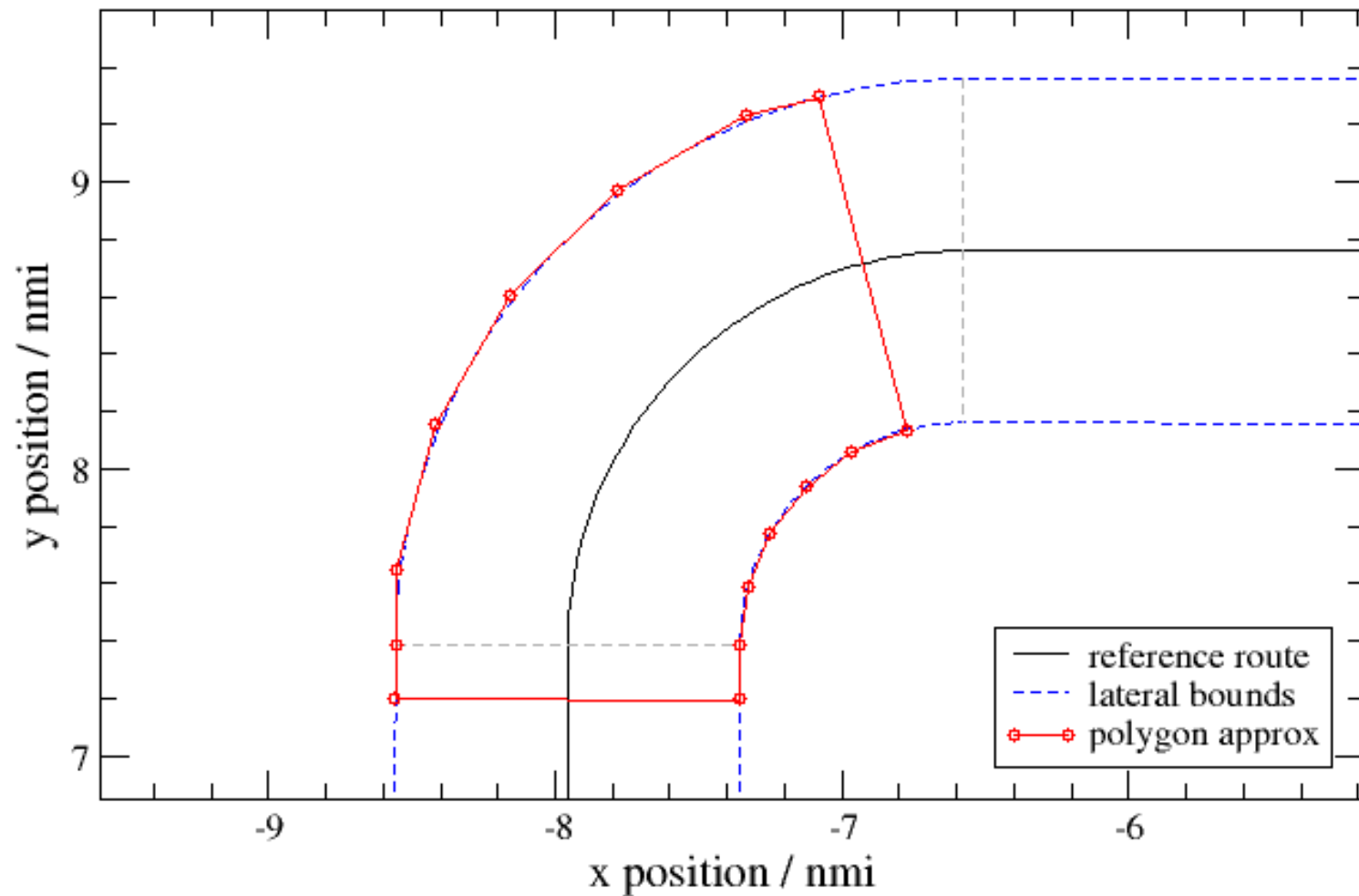


# Enhanced Longitudinal Flight Control

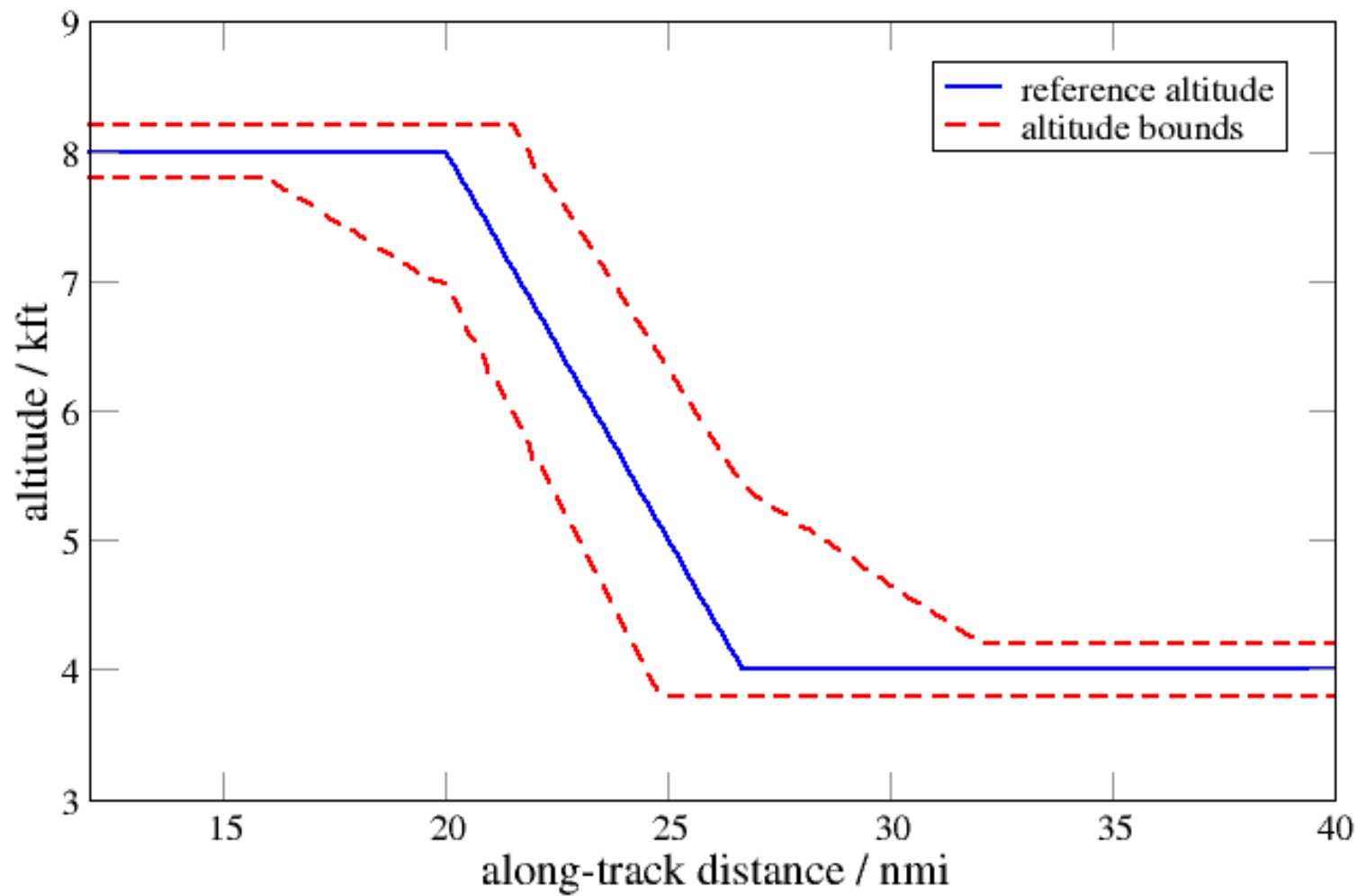


# Polygon Approximation of Bounding Area

## 90 deg turn to base



## Altitude Bounds Example



# Terminal Area Spacing and Separation Requirements

- Terminal areas (airspace within ~40 nmi of a major airport) requires both
  - In-trail spacing for wake vortex (3 – 6 nmi) and
  - general separation (3 nmi lateral or 1000 ft vertical)
- Delay maneuvers for wake vortex spacing also resolve most general separation conflicts
- A proven strategy is to first delay for the necessary arrival spacing, then apply other maneuvers when necessary to achieve general separation

# Default Tolerances

- Cross-track: 0.6 nmi constant
- Vertical:
  - Departures: 500 ft constant
  - Arrivals: 500 increasing to 800 ft
- Along-track:
  - Departures: 0.2 increasing to 1.0 nmi
  - Arrivals: 1.0 decreasing to 0.2 nmi

# Terminal Areas

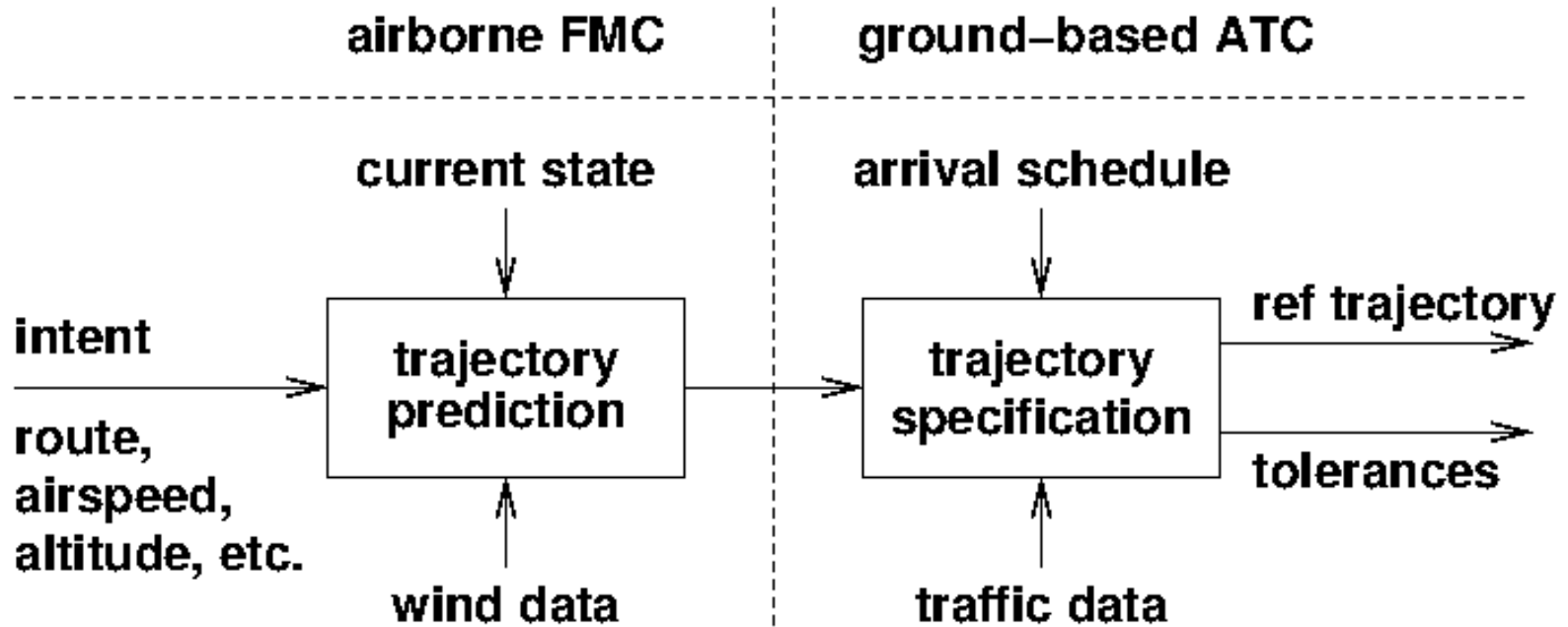
- Class B airspace within approximately 40 n. miles (nmi) of a major airport
- Managed in US by Terminal Radar Approach Control facilities (TRACONs)
- Minimum separation standard: 3 nmi horizontally or 1,000 ft vertically
- Have more constraints than enroute airspace and have more and larger turns
- Terminal ATC is currently very tactical, with many heading vectors and speed/altitude clearances
- Throughput limited mainly by wake-vortex spacing requirements (3-6 nmi, depending on weight classes)

# Background

- Air Traffic Control (ATC) is currently done by human controllers with radar displays and voice communication
- Controllers are human and make mistakes (over 1,800 operational errors in one recent year, including 55 serious cases)
- Automation can reduce human error and increase airspace capacity but is difficult due to complexity and safety criticality



# Trajectory Prediction and Specification



# Maneuver Type Counts

maneuvered: other:	arr arr	arr dep	dep dep	dep arr	sum
temp alt	11	245	311	282	849
speed dec	173	0	2	0	175
reroute	55	3	27	79	164
new level alt	5	22	53	11	91
takeoff delay	0	0	40	6	46