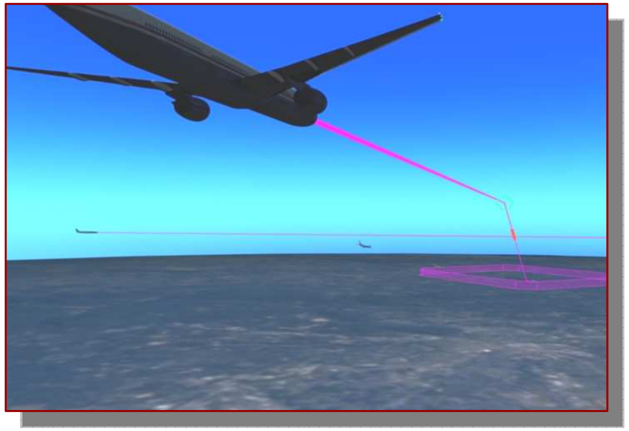
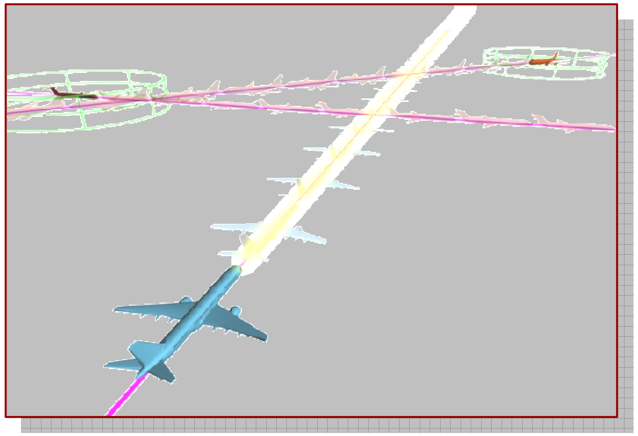
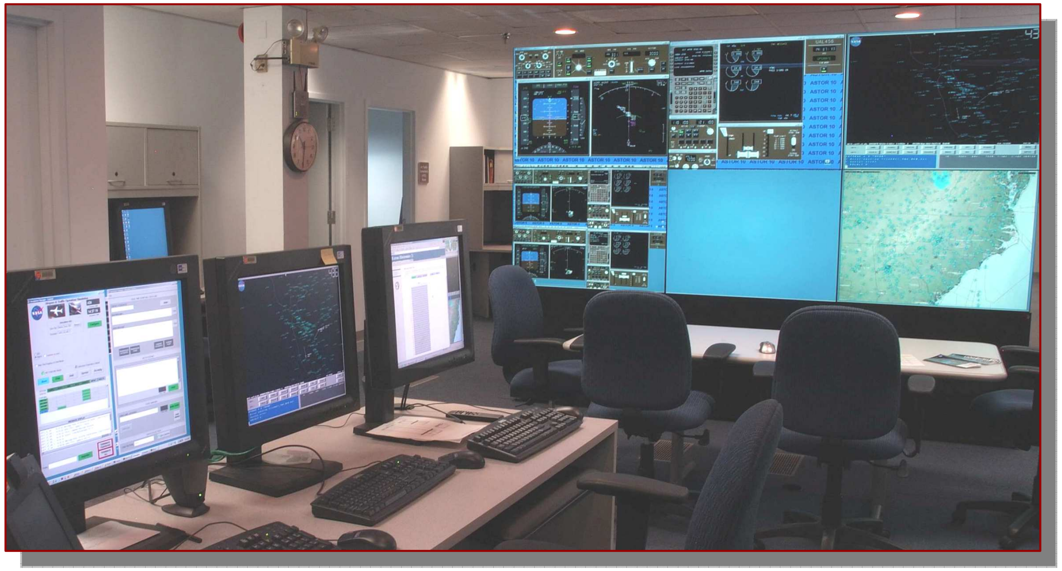
Self-Separation Research at NASA







Briefing to
iFLY Consortium

14 November 2007
David Wing, NASA

David.Wing@nasa.gov

Outline

- High-Level Concept
- Air Traffic Operations Lab
- Completed Research Review (1998-2006)
- New Research Activities (2007-2009)
  - Safety
  - Performance characterization
  - Traffic complexity prevention / mitigation
- Conclusions

- Announcement of special opportunity

Uncertainty of Future Demand Calls for a Scalable Solution

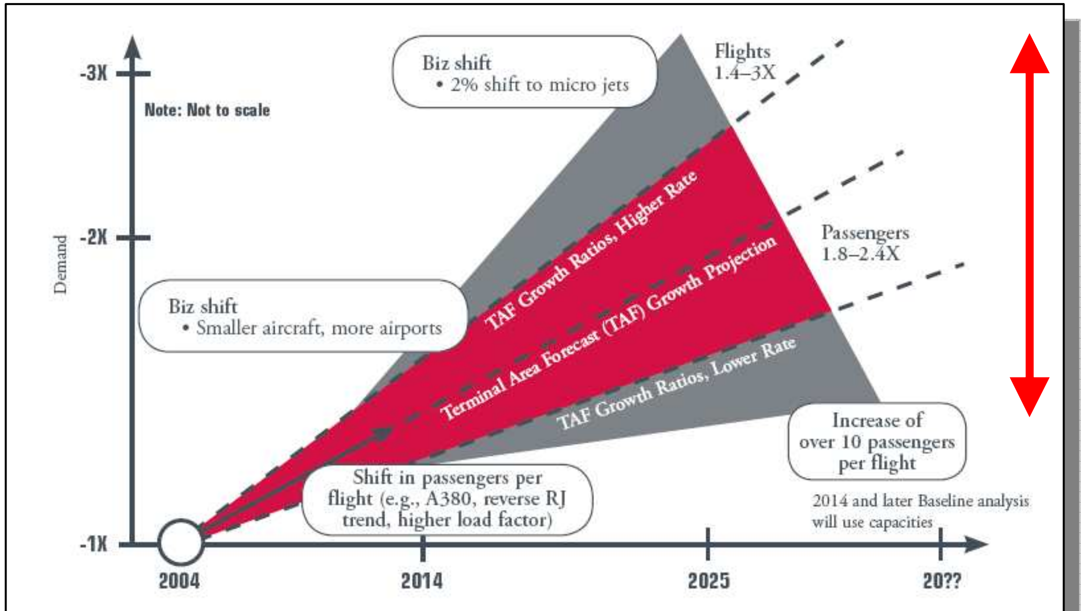


Figure 3. Planning for a Range of Futures

Goal for NextGen R&D:

Scalability

(demand-adaptive capacity)

"The uncertainties in the form of future demand call for a highly flexible solution to avoid over-building with the wrong infrastructure or under-building for the pace of expansion."

JPDO, Next Generation Air Transportation System Integrated Plan, Dec. 2004

4D-ASAS Trajectory Management

Research Premise

Scalability achieved by applying two significant innovations to ATM:

Automation

Relieve human workload bottleneck
Increase 4D trajectory precision
Change nature of “complexity”
Enable function distribution

Distribution

Retain human active involvement (air/ground)
Involve aircraft in achieving ATM objectives
Build in safety through redundancy
Scale up and down with demand

Human Functions (Decision Making)

Establishing goals and preferences
Selecting between alternatives
Applying human judgment

Service Provider Functions (*Strategic TM*)

Allocating limited system resources
Generating trajectory constraints
Controlling unequipped aircraft

Automation Functions (Information processing)

Monitoring for conditions & events
Computing alternatives & optimums
Doing routine & predictable tasks

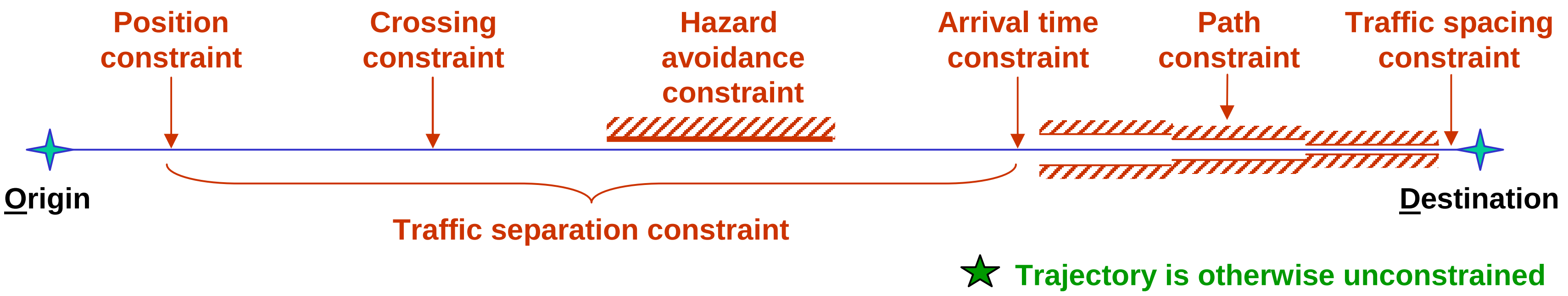
Aircraft Operator Functions (*Local TM*)

Managing trajectory to constraints
Adjusting trajectory for safety
Optimizing where flexibility permits

4D - Four Dimensional
ASAS - Airborne Separation Assistance System
TM – Trajectory Management

4D-ASAS Trajectory Management

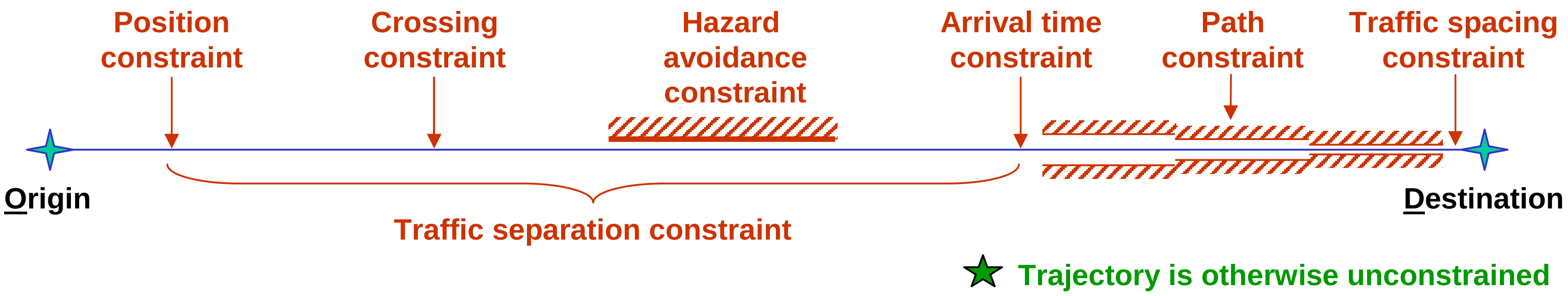
Concept for Performance-Based Operations



- **The basic idea**
  - **Instead of ATSP specifying the actual trajectory, they specify trajectory *constraints*, driven by ATM objectives**
  - **Aircraft use performance-based capabilities to meet each type of constraint**
- **ATSP benefits**
  - **ATM objectives are met, if constraints are properly specified and met**
  - **System performance predictability is increased, aircraft-by-aircraft**
- **User benefits**
  - **Priority handling for equipping**
  - **Flexibility to self-optimize trajectories, operations**

4D-ASAS Trajectory Management

Concept for Performance-Based Operations



Position constraint

Crossing constraint

Hazard avoidance constraint

Arrival time constraint

Path constraint

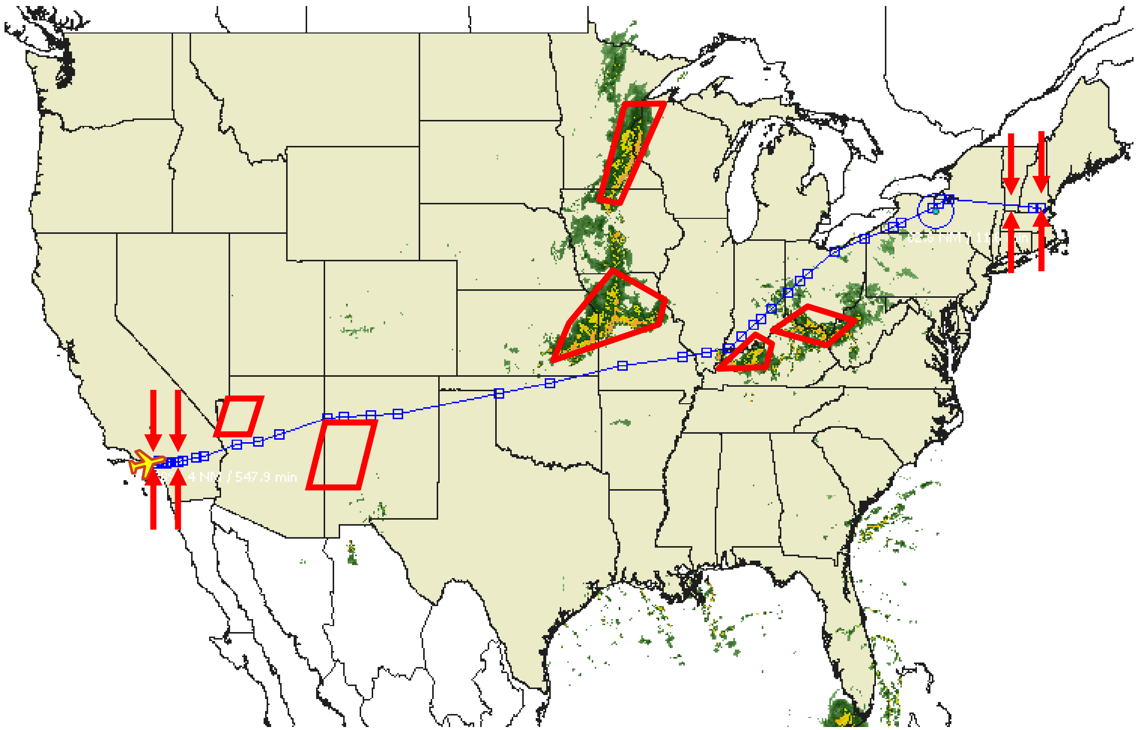
Traffic spacing constraint

Origin

Destination

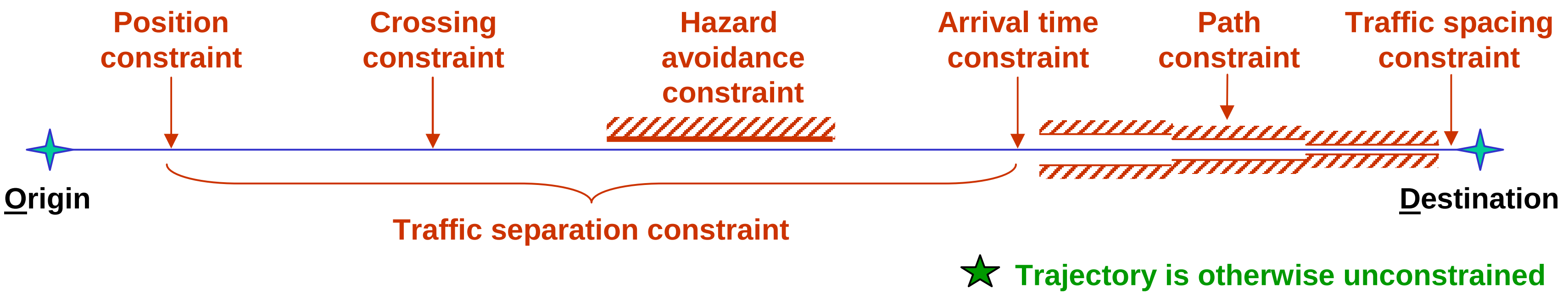
Traffic separation constraint

★ Trajectory is otherwise unconstrained



4D-ASAS Trajectory Management

Relationship Between Air and Ground

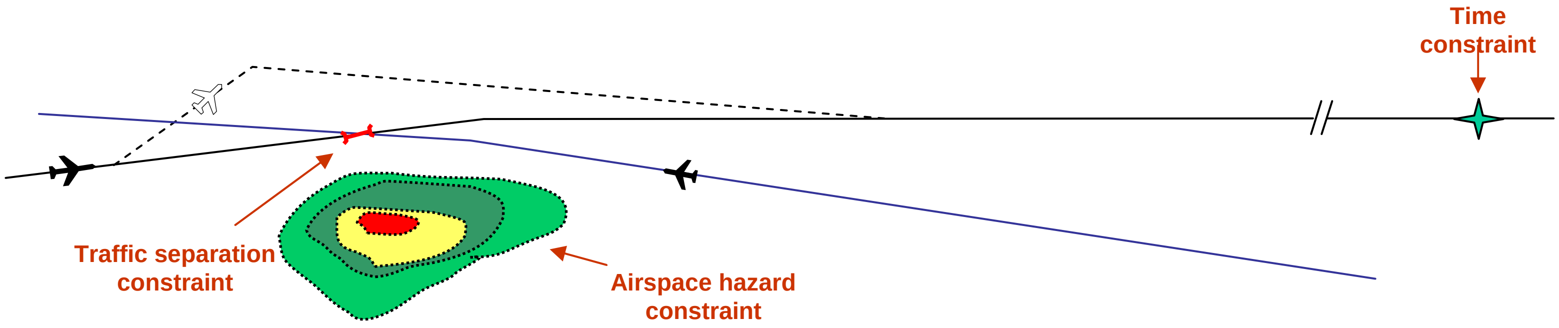


Clear and efficient air/ground trajectory management roles:

ATSP/AOC establish strategic trajectory constraints

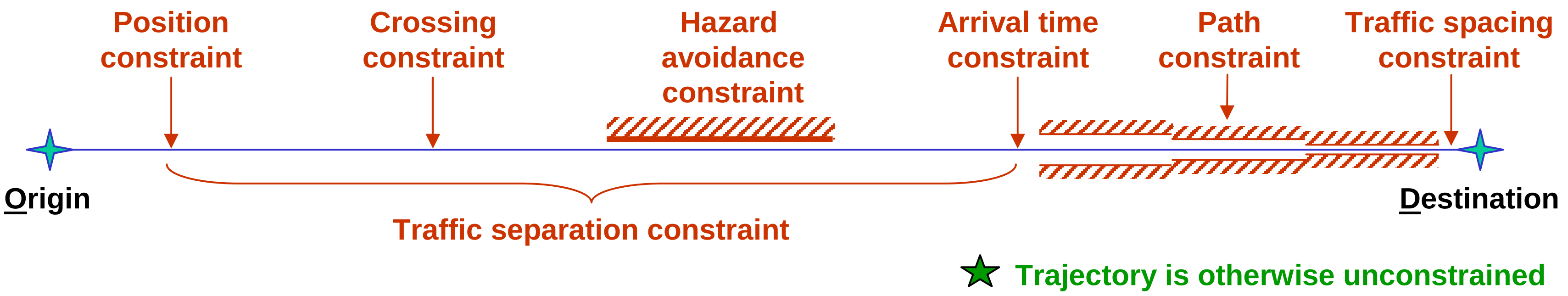
Aircraft manages trajectory to meet the constraints

- Coordination and negotiation occurs on the constraints
- Negotiation (if needed) involves changing, relaxing, or exchanging constraints



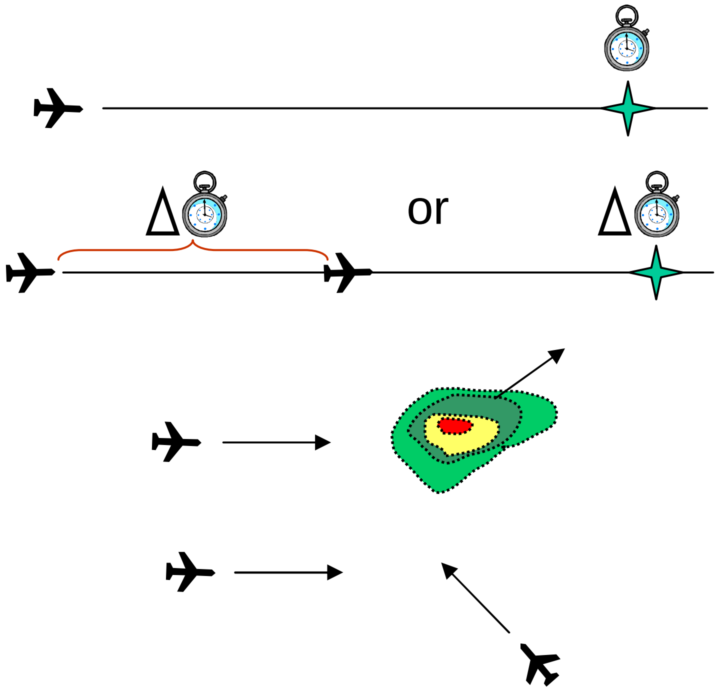
4D-ASAS Trajectory Management

Enabling ASAS Performance Capabilities



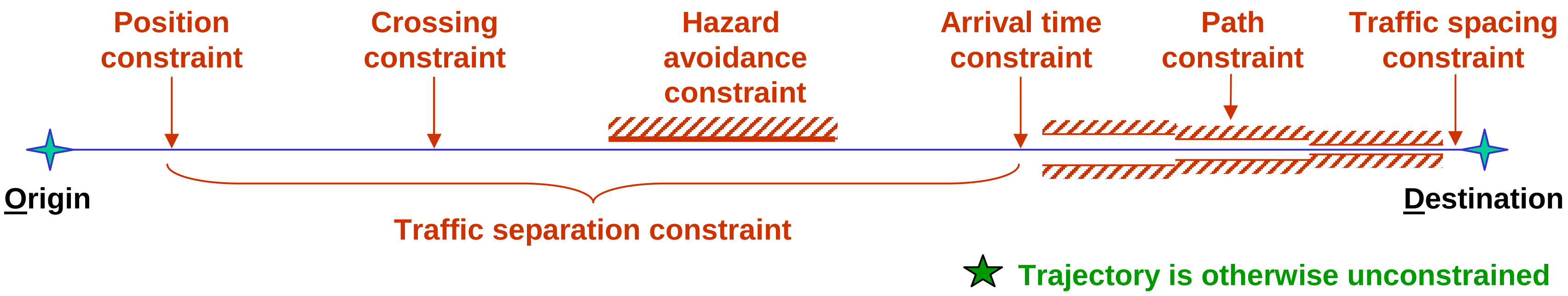
***Approach*: Expand RNP concept with new performance-based functions**

- **Precision time of arrival**
  (4th D, fixed frame)
- **Interval management**
  (4th D, relative frame)
- **Hazard separation**
  (4D, relative frame, slow moving hazards)
- **Traffic separation**
  (4D, relative frame, fast moving hazards)



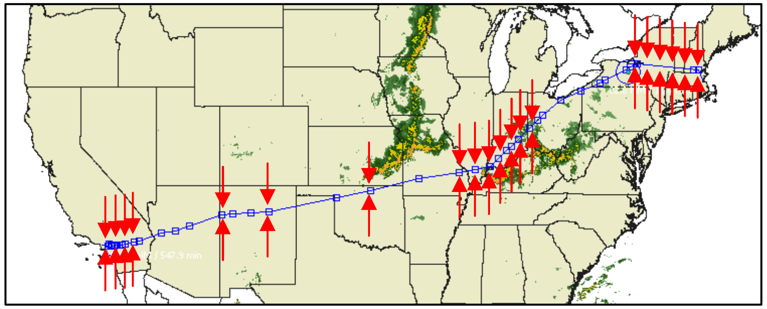
4D-ASAS Trajectory Management

Defining Trajectory Constraints Properly



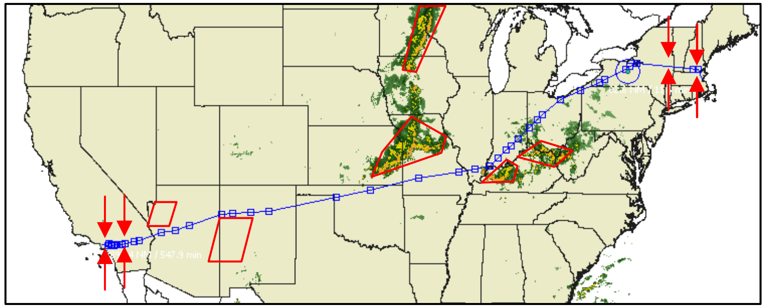
Restricts trajectory only where needed to meet specific objectives:

Excessively constrained trajectory



- Excessive constraints lead to over-controlling the trajectory
- Inflexible to changing conditions and unforeseen events
- Inefficient use of resources

Correctly constrained trajectory



- Constraints directly linked to hazards or ATM objectives
- More trajectory solutions available when constraints are minimized
- Flexibility is used by operators for self-optimization

Macro Performance Levels

Performance category	Communications method	Communication object	Loop closure	ATM “friendliness”	Burden on ground system
4D ASAS A/C	Constraint exchange Intent broadcast	The constraints	Dynamic RNP on constraints	↑	↓
4D Managed A/C	Trajectory exchange	The 4D trajectory	4D RNP RNAV on trajectory		
2D-3D Classic A/C	Voice comm	Flight instructions	Follow the instructions		

Airborne Trajectory & Separation Mgmt

Key ATM Research Challenges at Multiple Levels

Meta-level challenge: Accomplishing huge paradigm shifts

- From airspace-based operations to ***trajectory-based operations***
- From equipage-based capabilities to ***performance-based operations***
- From human-only control to ***automation-dominated trajectory management***
- From centralized-only architecture to ***centralized/distributed hybrid architecture***

Metrics of success

- Demand-adaptive capacity (“scalability”)
- Quantifiable safety
- Behavioral stability and robustness
- System performance predictability
- User operational flexibility & equity

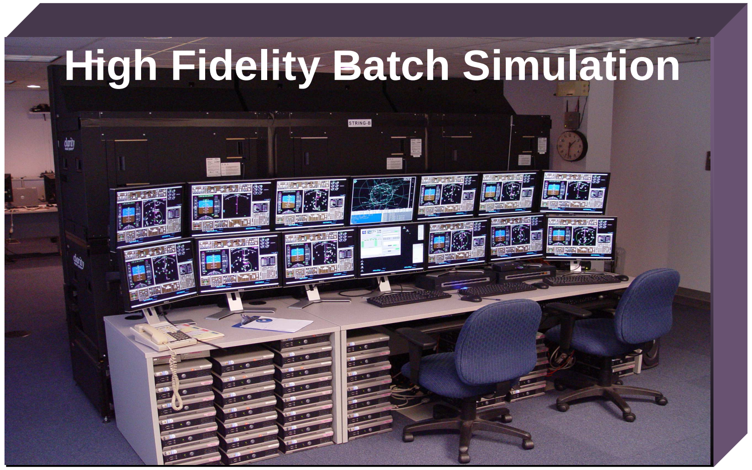
Micro-level challenge: Traffic complexity control within new paradigm

- Redefining complexity and preventing automation from exceeding limits
- Double challenge: Applying this in a distributed architecture!

Air Traffic Operations Lab (ATOL)

Airspace and Traffic Operations Simulation

Filled a gap for modeling future ATM concepts at medium/high fidelity
Originally designed to assess feasibility of distributed ATM concepts



High Fidelity Batch Simulation

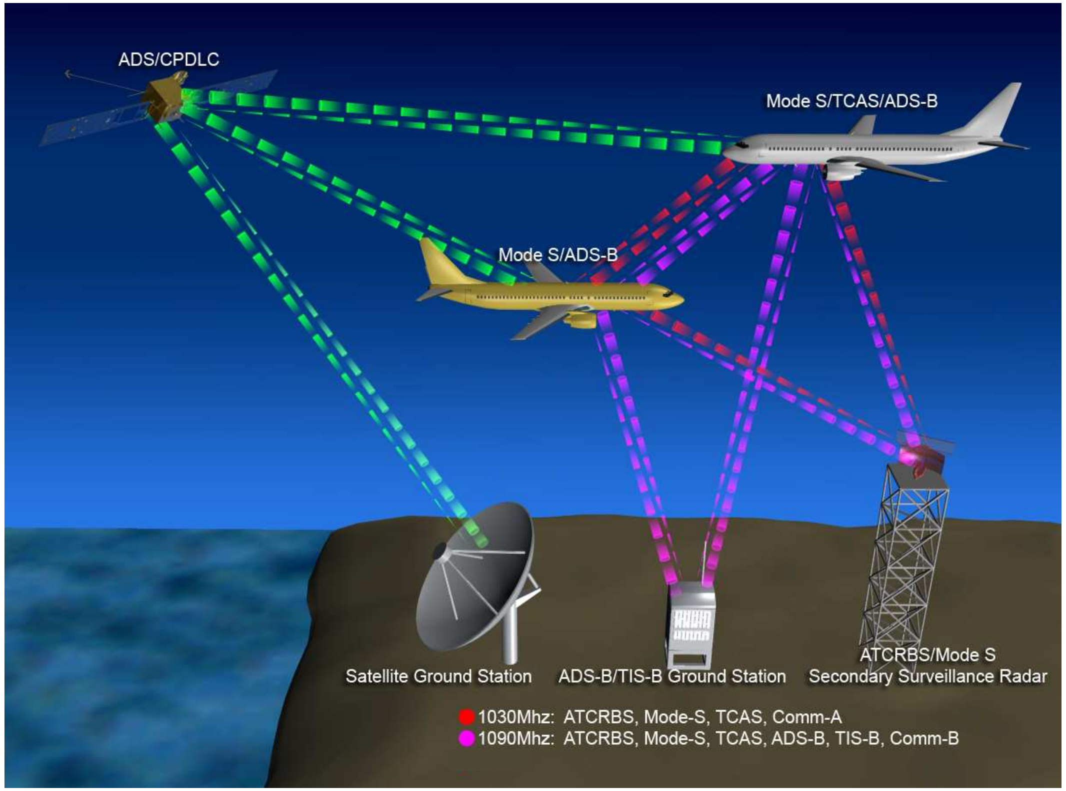
Multi-Aircraft Pilot-in-the-Loop Simulation

- Concept level operations research
- Rapid prototyping of flight deck automation capabilities (ASAS)
- Initial flight deck interfaces and procedures development
- Technology / concept performance assessment
- Concept-level safety assessment
- Future CNS requirements evaluation

- Multi-fidelity modeling of airborne systems and CNS infrastructure
- Multiple strings on HLA network
- 96 a/c for batch simulation
- 21 a/c for interactive piloted tests
- Leverages NLR TMX simulation
- Specialization on airborne side
- Connects easily to other simulation facilities (e.g. ground-side)

Air Traffic Operations Lab

ADS-B Simulation (1090 MHz)



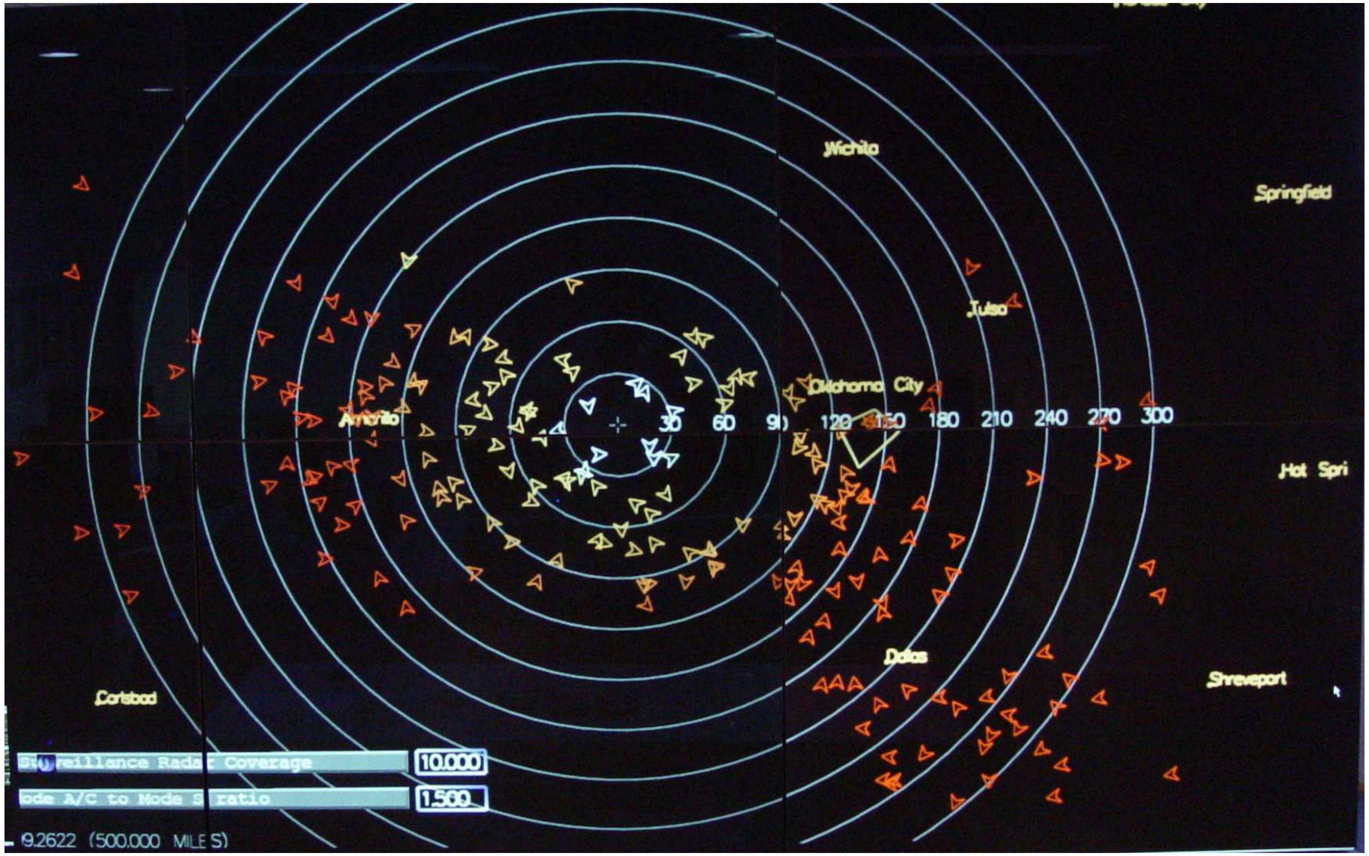
- Messages and information elements as defined in industry standard (RTCA/DO-242A)
- ADS-B performance model based on RTCA/DO-260A:
  - Range
  - Probability of reception based on interference from various sources:
    - Mode S and Mode A/C radar replies
    - TCAS messages
    - Other ADS-B and TIS-B messages

- Modular architecture allows incorporation of new performance models or message information elements.
- Can incorporate all ADS-B or mixed ADS-B/TIS-B/radar environment.

Air Traffic Operations Lab

ADS-B Simulation (1090 MHz)

ADS-B Visualization Tool Shows Reception Probability



Surveillance Radar Coverage 10.000

ode A/C to Mode S ratio 1.500

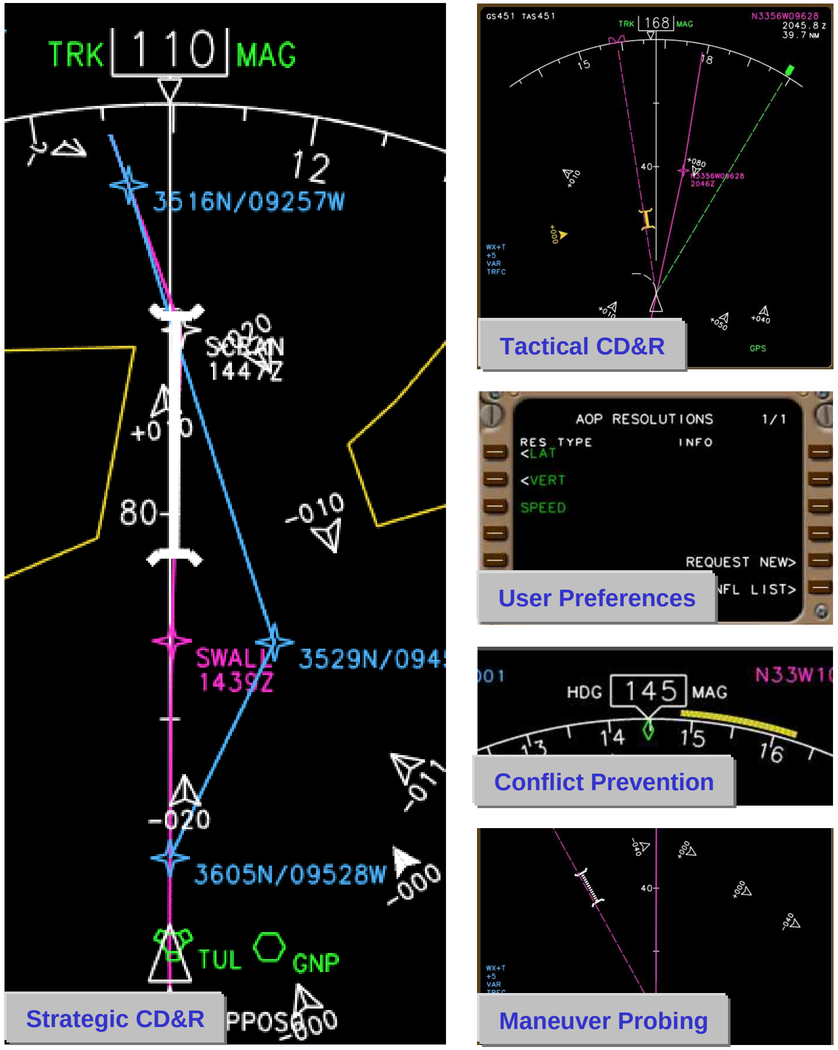
9.2622 (500.000 MILES)

Airborne Automation Technology for SSEP

Autonomous Operations Planner

- Working software prototype: “AOP”
  - ARINC 429 data-bus & 702a FMS integration
- Meets traffic, airspace, user, and flow management constraints
- Conflict management consistent with RTCA standards
  - DO-263, SC186 ACM-WG
- Includes additional functionality
  - Conflict prevention tools
  - Right-of-way scheme
  - Trajectory prediction uncertainty
- Tested in simulations with
  - Flow and airspace constraints
  - Cruise and descent flight
  - Pop-up traffic
  - Aircraft blunders
  - Reduced separation scenarios

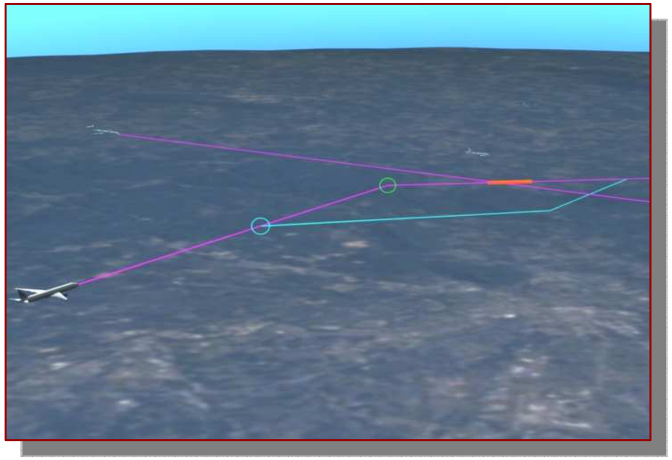
Prototype Conflict Management Capabilities



CD&R - Conflict Detection and Resolution

Status of Research in Self Separation

Overview



Research Focus Areas (1997-2006)

- Feasibility of distributed control
- Safety of distributed control
- Potential for scalable capacity

- Track-constrained operations (different concept)

Results presented in 2-chart format

- First chart: Accomplishments
- Second chart: Research findings and unresolved issues

Simulation experiments and modeling activities

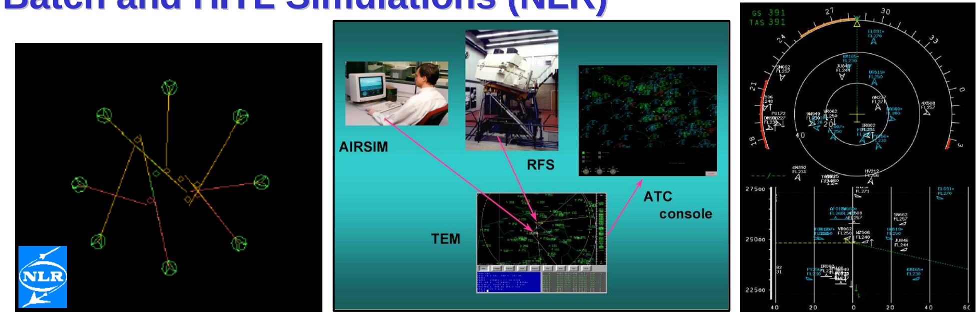
- NLR batch simulations – evaluation of algorithms
- NLR phase I, II, III HITL sims – evaluation of procedures and scenarios
- Langley 2001 piloted sim – comparison of strategic and tactical trajectory management
- NLR/EU 2002 fast-time simulation
- Langley 2002 piloted sim – safety hazard scenario evaluations
- NASA 2003 demand / capacity modeling
- NASA 2003 controller performance modeling
- Langley 2004 batch sim – initial ‘sidewalk’ scenario research
- NASA 2004 integrated air/ground simulation – mixed operations w/ flow constraints

Status of Research in Self Separation
Feasibility of Distributed Control

Accomplishments

- Developed simulation platform suited for design/testing of distributed ATM operations
- Prototyped high-fidelity airborne automation, procedures, concept details
- Tested large variety of scenarios with pilots and controllers
  - Unconstrained cruise
  - Restricted-airspace cruise
  - Flow-constrained cruise/descents
  - Hazard scenarios
  - Mixed-equipage operations
- Resolved many latent design & feasibility issues from previous “Free Flight” research

Batch and HITL Simulations (NLR)



Piloted Simulations (NASA)

Integrated Air-Ground HITL Simulation (NASA)

Status of Research in Self Separation

Feasibility of Distributed Control

Metrics for assessing feasibility

- – Automation functionality achieves objectives in challenging scenarios with real-world system limitations
- – Achieved or attainable ATM goals in simulation:
  traffic separation, conformance to airspace / flow constraints
- – Favorable pilot & controller ratings on feasibility
- – Problems solved or achievable solution approach identified

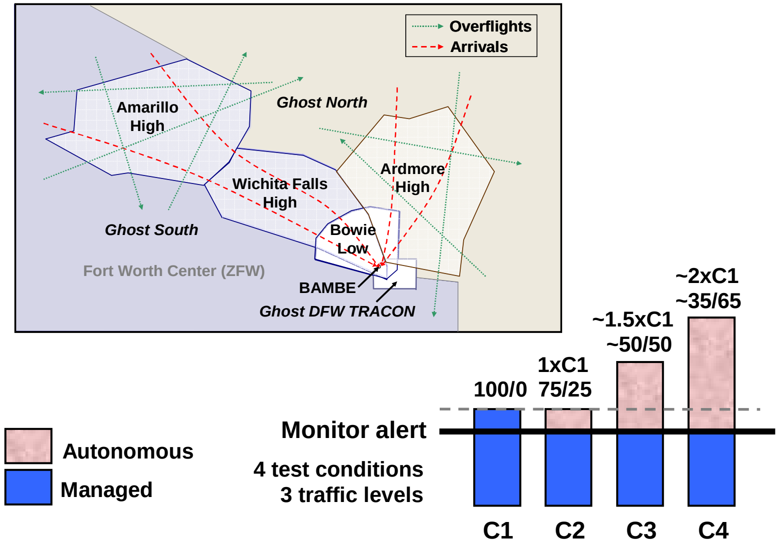
Research Findings

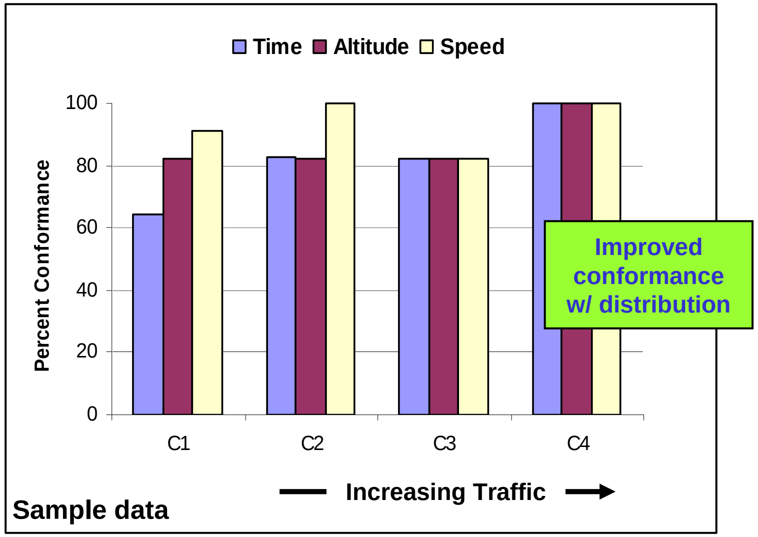
- Airborne-only operations
  - – Feasible to at least 3X current traffic (pilot HITL) and 10X (batch simulations – traffic constraints only)
  - – Feasible under simultaneous metering, airspace, and traffic constraints to at least 3X current traffic
  - – Reaches a limit in post-descent close to merge points, requiring additional tools designed to support merging
- Mixed airborne / controller-ground-based operations
  - – Feasible to at least 2X current traffic (max of experiment data)
  - – Feasible in cruise and descent-transition airspace with dynamic metering and delay absorption (see chart)

Unresolved Issues

- ✰ Upper limit of manageable complexity and whether centralized oversight is required to prevent reaching limit
- Extended climbs, interaction with dynamic weather, and transitioning to terminal merging and spacing
- Optimal approach to air/ground coordination in short-notice mixed-control conflicts (controller safety concerns)
- Integration with fully-automated ground-based operations

NASA Integrated Air-Ground HITL Simulation





Sample data

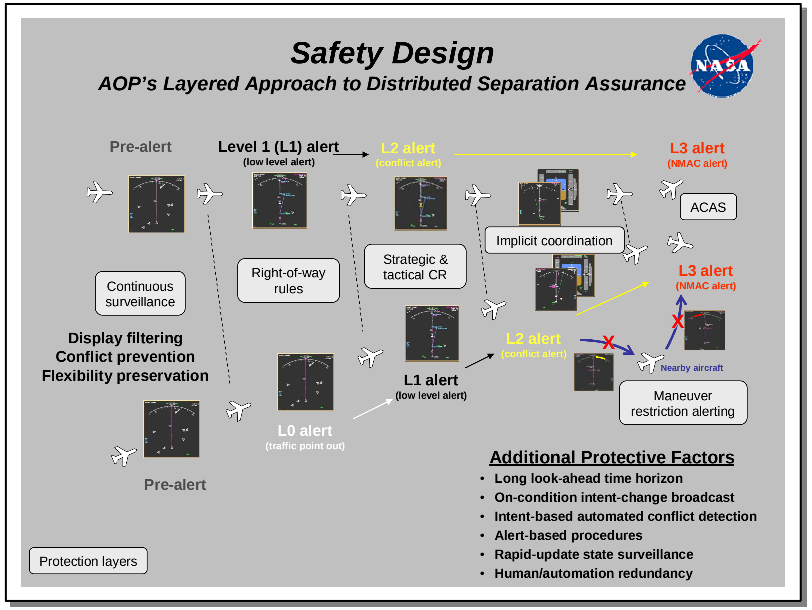
Status of Research in Self Separation

Safety of Distributed Control

Accomplishments

- Qualitatively compared current system and proposed system concept
- Designed and prototyped safety controls in airborne automation
- Eliminated conflict domino effect
- Collected pilot-HITL sim data on blunders, pop-ups, over-constrained conflicts, reduced separation standard, no ATC backup
- Analyzed feasibility of pilot responsibilities in airborne separation

Layered Safety Design of Airborne Automation



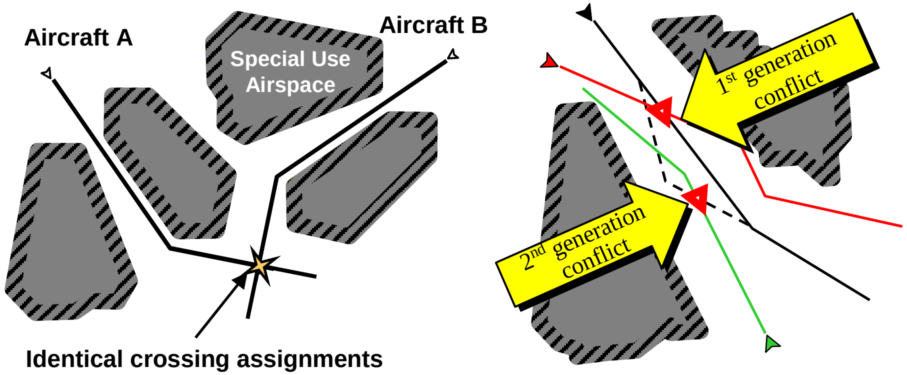
Safety Design

AOP's Layered Approach to Distributed Separation Assurance

Additional Protective Factors

- Long look-ahead time horizon
- On-condition intent-change broadcast
- Intent-based automated conflict detection
- Alert-based procedures
- Rapid-update state surveillance
- Human/automation redundancy

Hazard Scenarios from 2002 Piloted Sim



Identical crossing assignments

Status of Research in Self Separation

Safety of Distributed Control

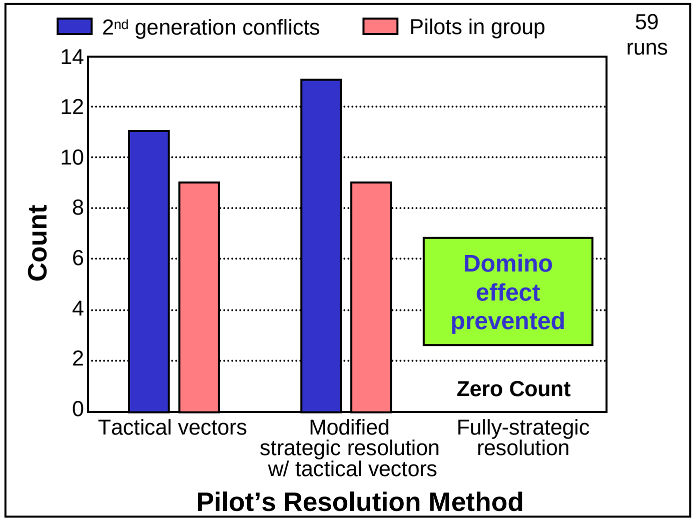
Research Findings

- Airborne separation has benefits in surveillance, human workload, and automation that provide the potential to be exceptionally safe
- Airborne separation can be implemented without ground-based backup or 'airborne ATC' pilot skills
- Coordination requirements
  - Domino behavior can be eliminated (see top chart)
  - Implicit coordination is sufficient and preferred over explicit coordination
  - Right-of-way rules (a.k.a. “priority rules”) reduce unnecessary maneuvering and increase predictability, but not shown to be safety critical (see bottom chart)
  - Staggering the conflict alerts is an effective approach to breaking synchronicity of decision-making (a.k.a. “sidewalk scenario”)
- Reducing lateral separation standards does not appear to increase operational risk in pop-up scenarios

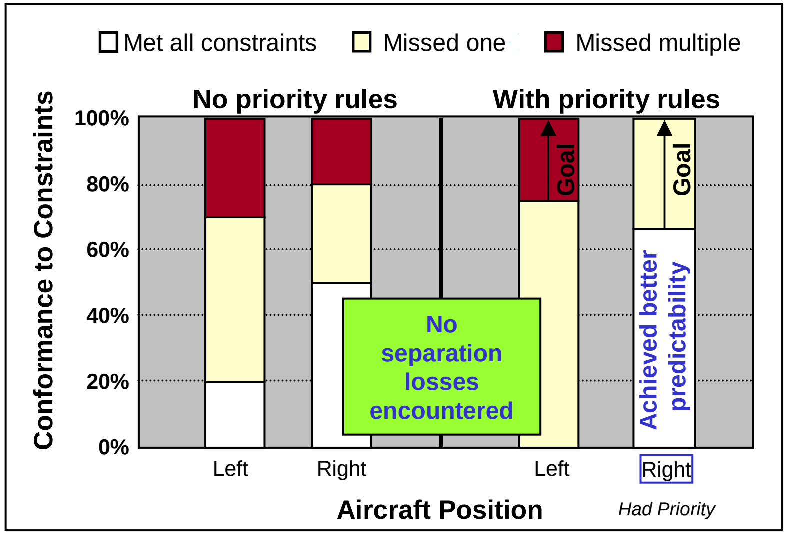
Unresolved Issues

- ☆ Quantified safety performance of airborne separation
- ☆ Frequency of “sidewalk scenario” and other conflicts and measured effectiveness of prevention methods
- Detailed airborne system design to achieve quantified safety targets (e.g., number of layers of redundancy)
- Safety impact of crew & environment factors
- Controller performance issues associated with mixed control and airborne separation awareness

2002 Sim Data on Domino Behavior



2002 Sim Data on Priority Rules



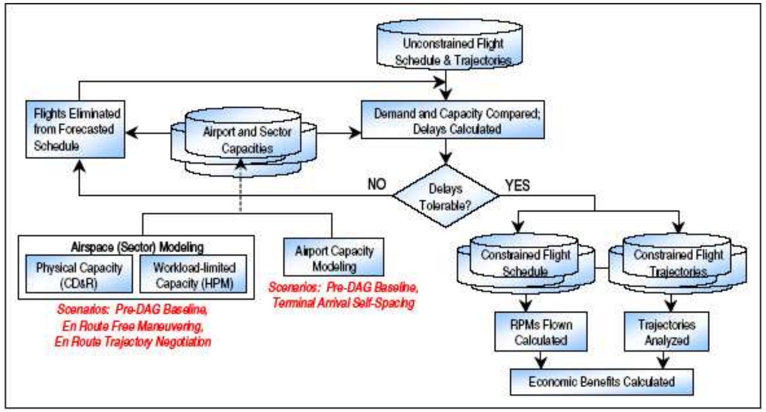
Status of Research in Self Separation

Potential for Scalable Capacity

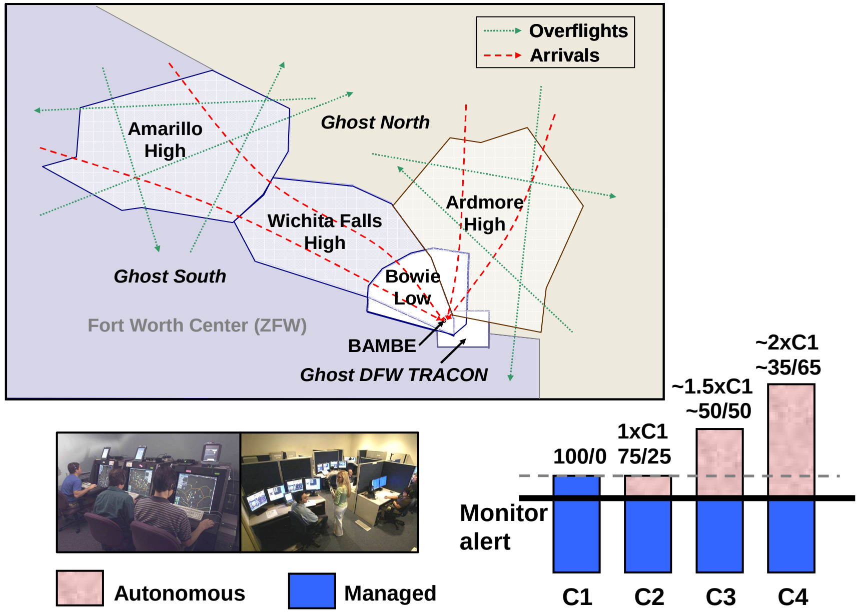
Accomplishments

- Analyzed physical airspace capacity for 10X increase in traffic demand
- Analyzed workload from batch & HITL simulations up to 3X demand
- Modeled controller workload for mixed control traffic
- Acquired performance metrics from air/ground HITL simulation
- Analyzed air/ground integration and operational issues

Demand/Capacity and Human Performance Modeling



NASA Integrated Air-Ground HITL Simulation



Status of Research in Self Separation

Potential for Scalable Capacity

Research Findings

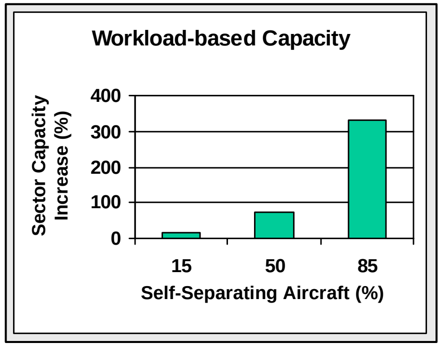
- Physical airspace capacity per sector is sufficient for at least 10X growth
- Sector capacity scales with self-sep. traffic
  - Result of offloading controller workload
  - 85% equipage yields 330% expected post-OEP capacity in nominal weather (see top chart)
- Distributed ATM supports scalability up to at least 3X traffic demand
  - Controller performance in mixed operations is tied to ground-controlled aircraft population (see bottom chart)
  - Controller workload restricts capacity growth of ground-controlled traffic to approximately 1.1X to 1.3X (NLR/EU result)

Unresolved Issues

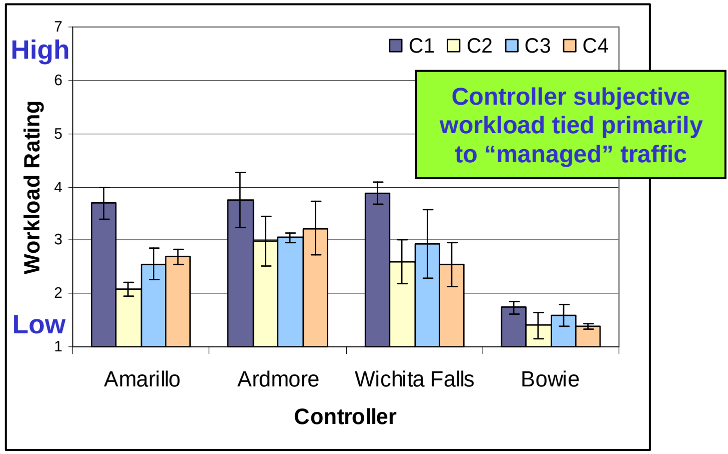
☆Capacity growth limitations due to traffic/airspace complexity

- Controller workload impact as air/ground control ratio exceeds current experimental data (2:1 ratio)
- Performance and issues affecting capacity in situations of high pilot-perceived workload
- Capacity benefit due to distributed control in weather-impacted scenarios (e.g. reduction in weather-related delays)

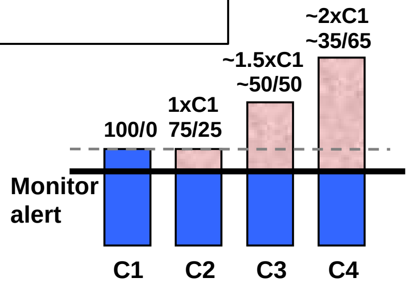
Human Performance Modeling



NASA Integrated Air-Ground HITL Simulation



Controller subjective workload tied primarily to “managed” traffic

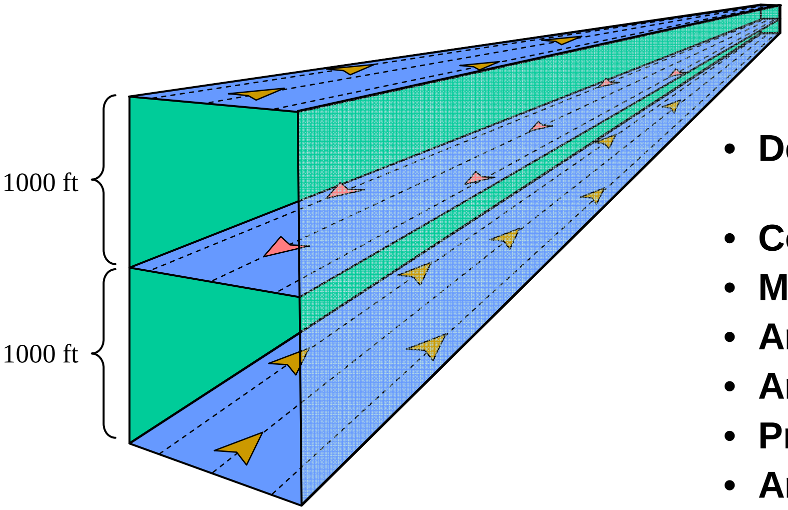


▨ Autonomous 🟦 Managed

OEP - Operational Evolution Plan

Status of Research in Self Separation

Track-Constrained Operations

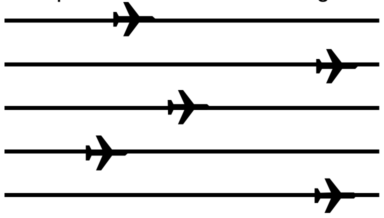


Accomplishments

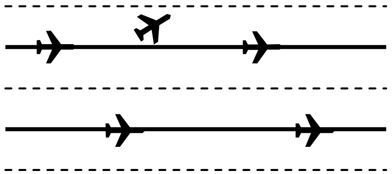
- **Developed an end-state concept description:**
  ***Dynamic Multi-track Airways* (DMA)**
- **Conceptually analyzed 9 critical concept-design issues**
- **Modeled and analyzed multi-track alternatives**
- **Analyzed capacity benefits of a single DMA**
- **Analyzed expected city-pair demand DMAs**
- **Prototyped track spacing and passing capabilities**
- **Analyzed potential as a transitional near-term concept**

Design Alternatives

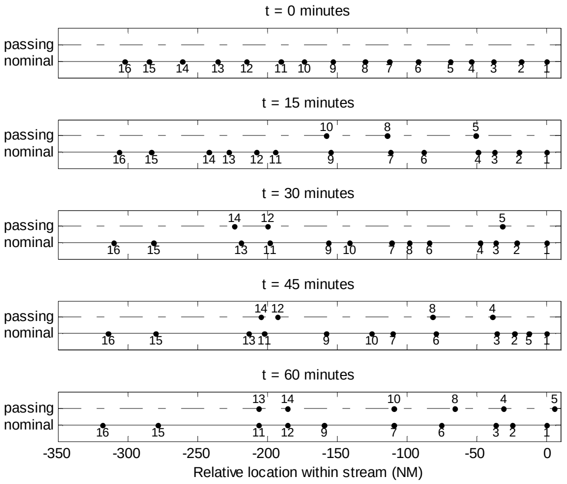
Speed-based Tracks Design



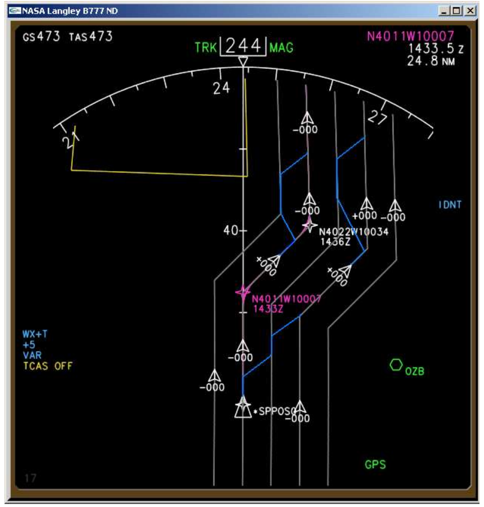
Nominal / Passing Tracks Design



Track Load Modeling



Software Prototype Passing Tool



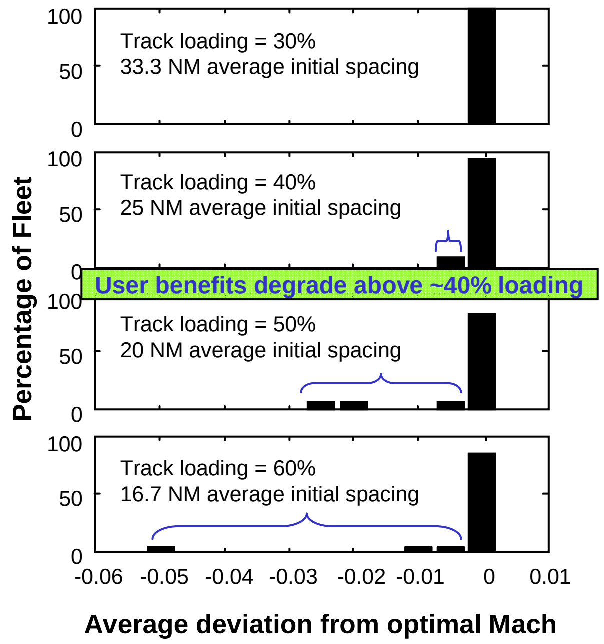
Status of Research in Self Separation

Track-Constrained Operations

Research Findings

- Airborne separation is feasible within an isolated multi-track airway
  - Operational complexity significantly increased by interaction through intersections, merges, and crossing traffic
- Biggest feasibility challenges are
  - Traffic flow management
  - Multi-track airway network design and management
  - Preserving user benefits (see top chart)
  - Dynamic airway adjustment for weather
- Feasibility of human roles
  - Least feasible is the corridor controller
  - Most feasible is the flight crew
- Multi-track airway system absorbs limited demand
  - 25 most likely pooled routes would serve ~10% of total operations (see bottom chart)

Load Analysis of Nominal/Passing Track Configuration

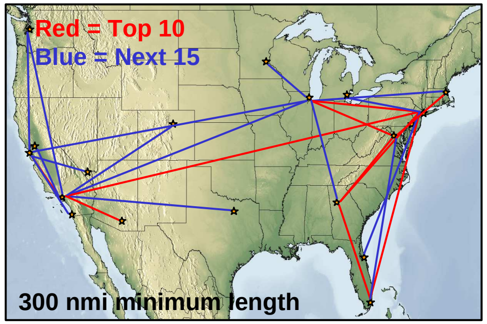


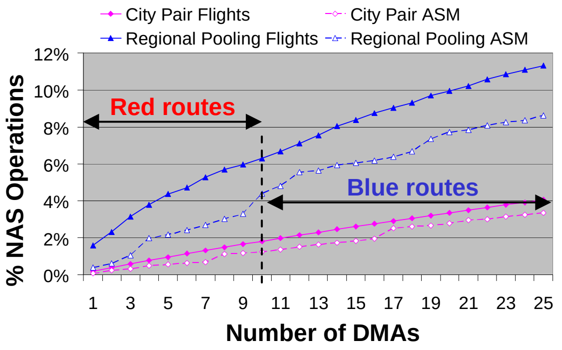
User benefits degrade above ~40% loading

Unresolved Issues

- Utility as a transition step to future operations involving airborne separation
- Feasibility of developing flow-management automation
- User benefits and participation incentives

Demand Analysis of Pooled City Pairs and NAS-wide Fraction





New Research: 2007-2009

Selected Self-Separation Activities

- Quantifying safety in high traffic density
  - Measure safety metrics in a series of high-fidelity batch simulations of increasing realism

- Assessing performance impact of influencing factors
  - Isolate effects of delays, errors, uncertainties, interference, complexity on safety, efficiency, task frequency

- Investigating techniques to mitigate traffic complexity
  - Develop metrics and algorithms for predicting/preserving trajectory flexibility and minimizing constraints

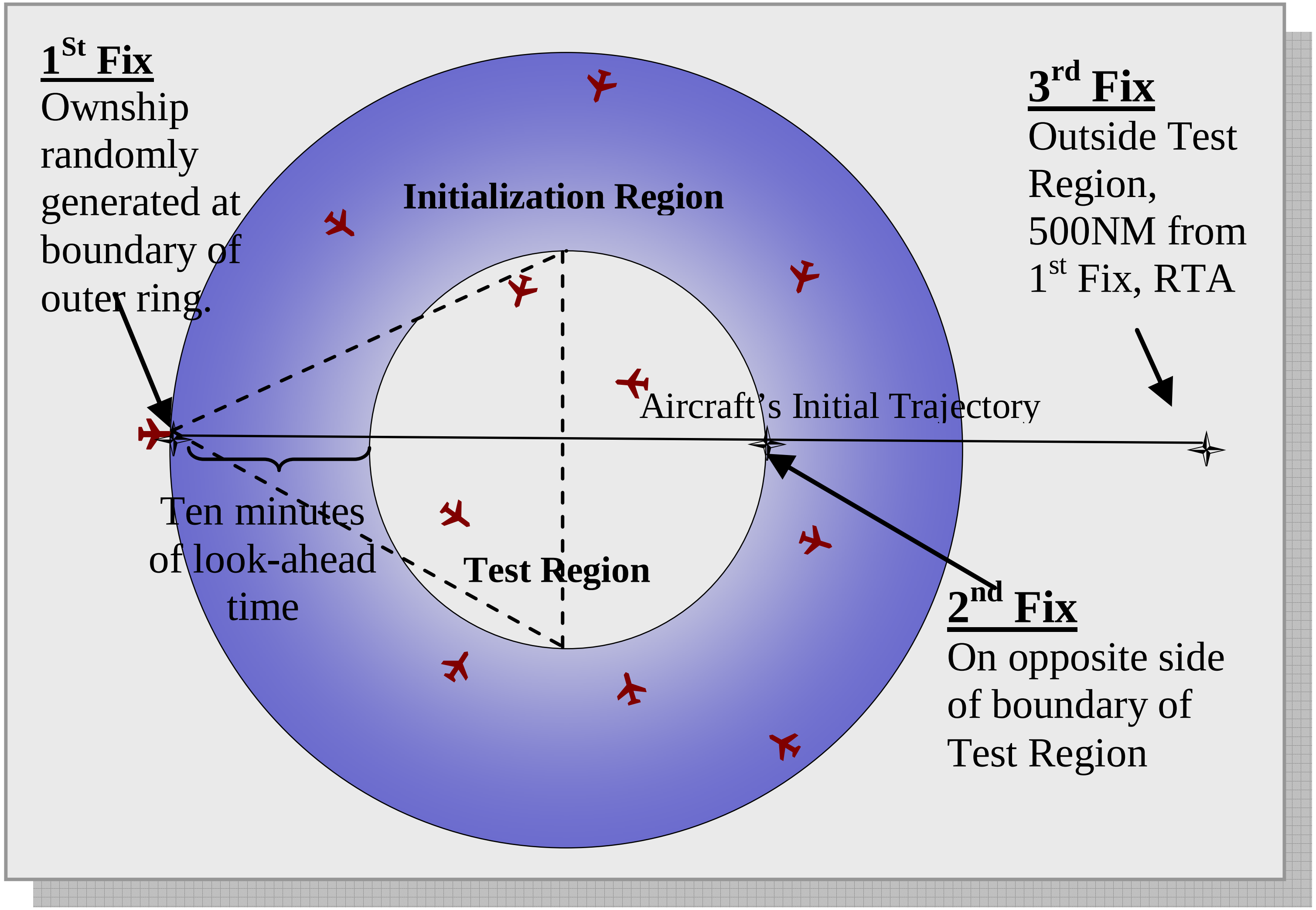
- Assessing uncertainty handling techniques
  - Size and tune of prediction-uncertainty buffers

Safety of Self Separation

Experiment Scenario Design

Experiment Scenario

Test Region Diameter = 160 NM
1 Flight Level Only



Safety of Self Separation

Traffic Demand Levels

- **Demand level calibration using the NASA ACES tool**
  - **Determined the traffic count for every high altitude sector in the United States, at each flight level, for the a hour period**

- **Analysis based on ETMS flight data from 19 February 2004**
  - **JPDO's good weather, high-traffic day representing "1X" density**

- **High-altitude sectors selected based on traffic density**
  - **Median: ZOA31**
  - **Dense: ZOB46**

	Median Sector ZOA31 (Oakland Center) 16,624 NM^2		*Dense Sector ZOB46 (Cleveland Center) 5,959 NM^2*	
	Mean Density	*Peak Density*	*Mean Density*	*Peak Density*
Traffic Count at FL310 (busiest altitude in these sectors)	*3*	*5*	*5*	*10*
Normalized 1X Density per 10,000 NM^2	*1.8*	*3*	*8.45*	*16.85*

Safety of Self Separation

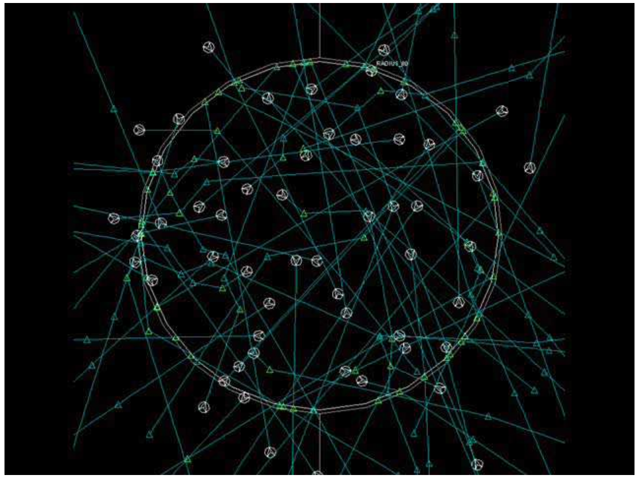
Summary of Simulation Runs

Test Region 20,106 NM^2	Sustained Traffic Density		Normalized Traffic Density Ratio			
	Normalized to 10,000 NM^2		ZOA31 (Median Density)		ZOB46 (High Density)	
Run Set	**Mean**	**St. Dev.**	**To Mean**	**To Peak**	**To Mean**	**To Peak**
1	3.45	0.59	1.9X	1.2X	0.4X	0.20X
2	6.11	0.83	3.4X	2X	0.7X	0.36X
3	8.61	0.97	4.8X	2.9X	1X	0.51X
4	11.64	1.23	6.5X	3.9X	1.4X	0.69X
5	15.24	1.49	8.4X	5.1X	1.8X	0.90X
6	17.18	1.54	9.5X	5.7X	2X	1.06X

Range Tested

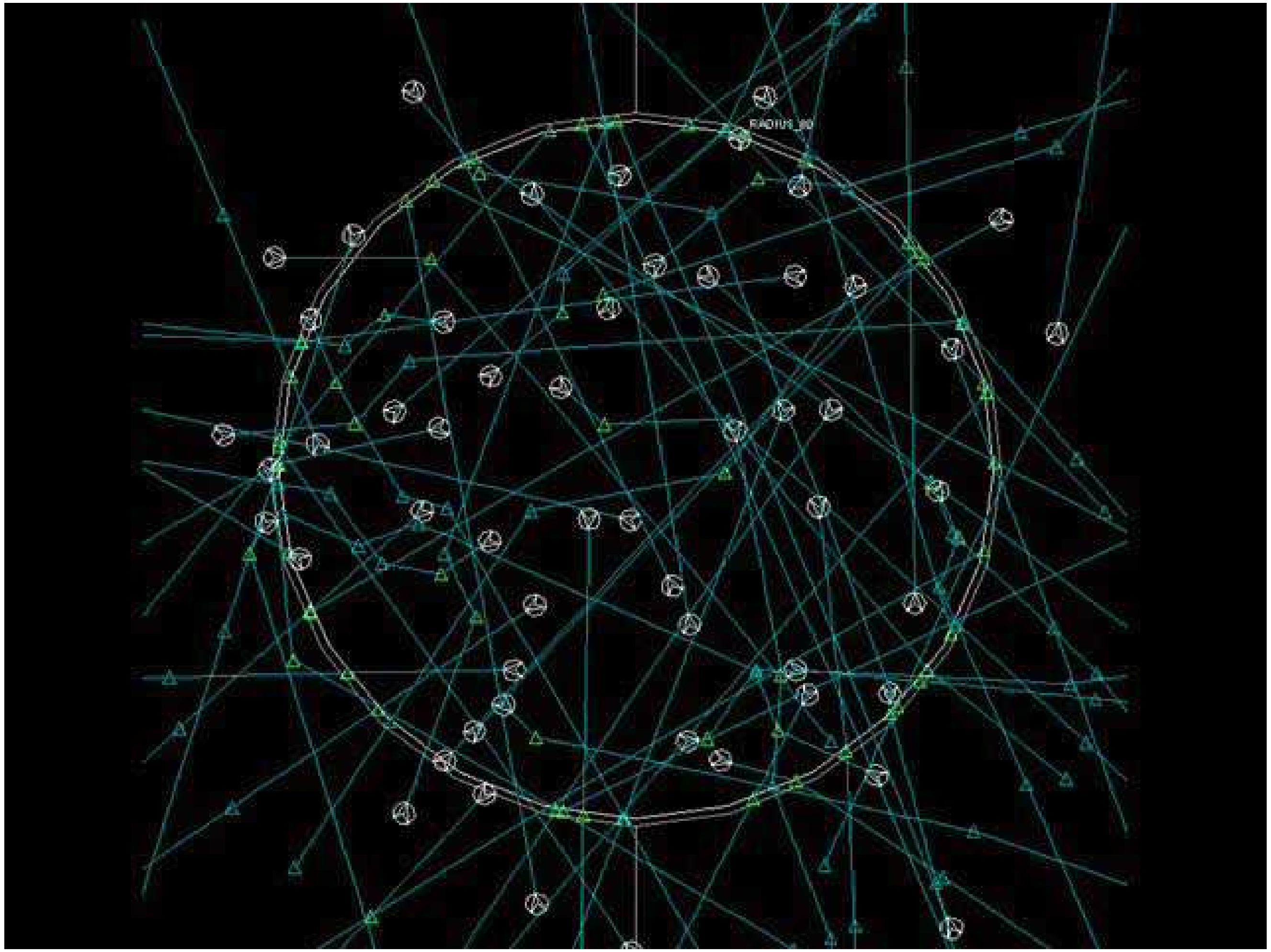
Run Set	Sim Hours	Flights	Flight Hours	Conflicts
1	36	881	237	195
2	36	1527	418	550
3	36	2195	545	1018
4	36	3000	797	1788
5	12	1302	347	963
6	12	1560	399	1256
Totals	168	10,465	2744	5770

Run set 6 10x playback speed



Safety of Self Separation

Recording at 10X playback speed – airspace view



Mean Density 17.18 aircraft per 10000 NM^2

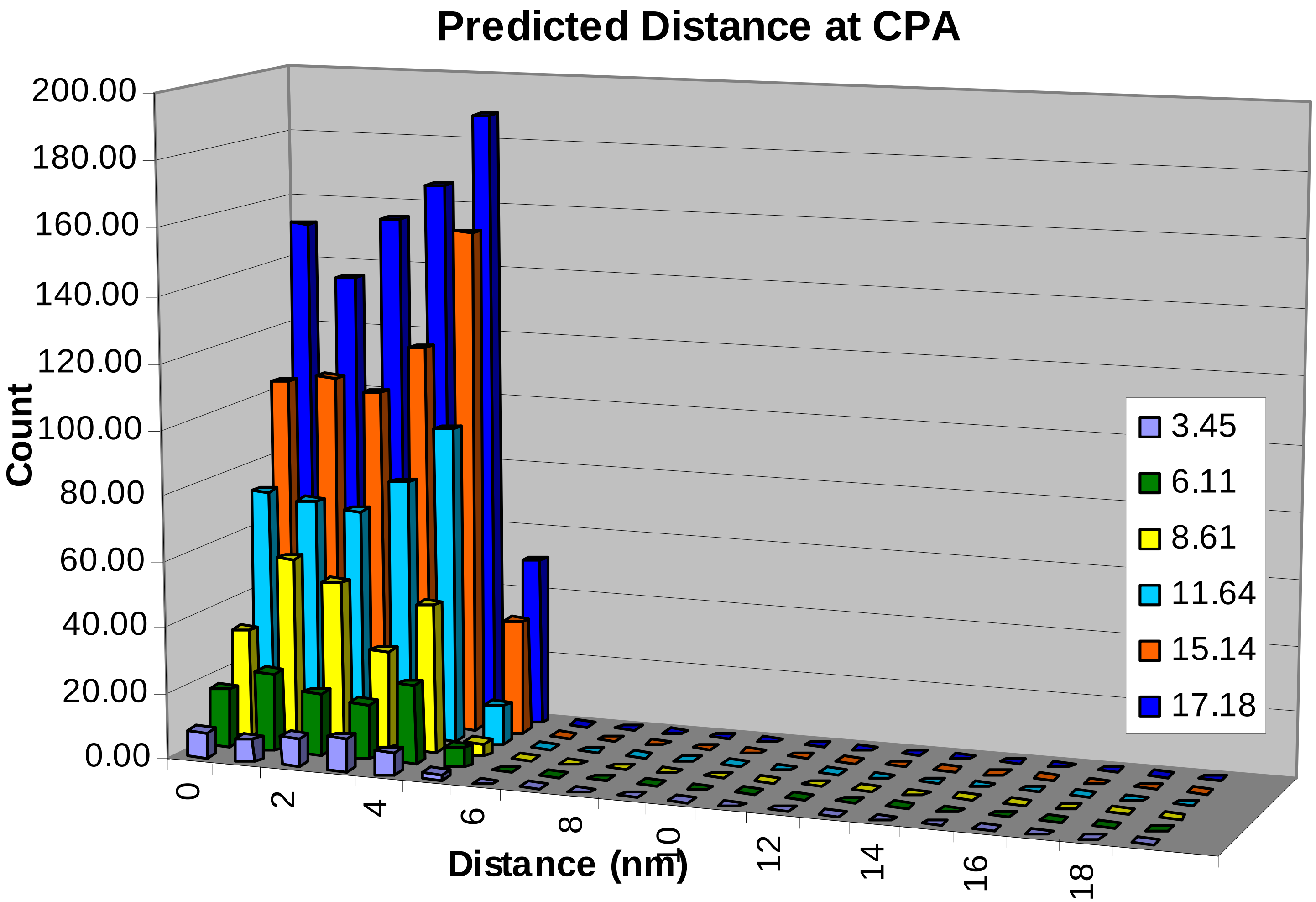
Safety of Self Separation

Recording at 10X playback speed – aircraft view

Mean Density 17.18 aircraft per 10000 NM2

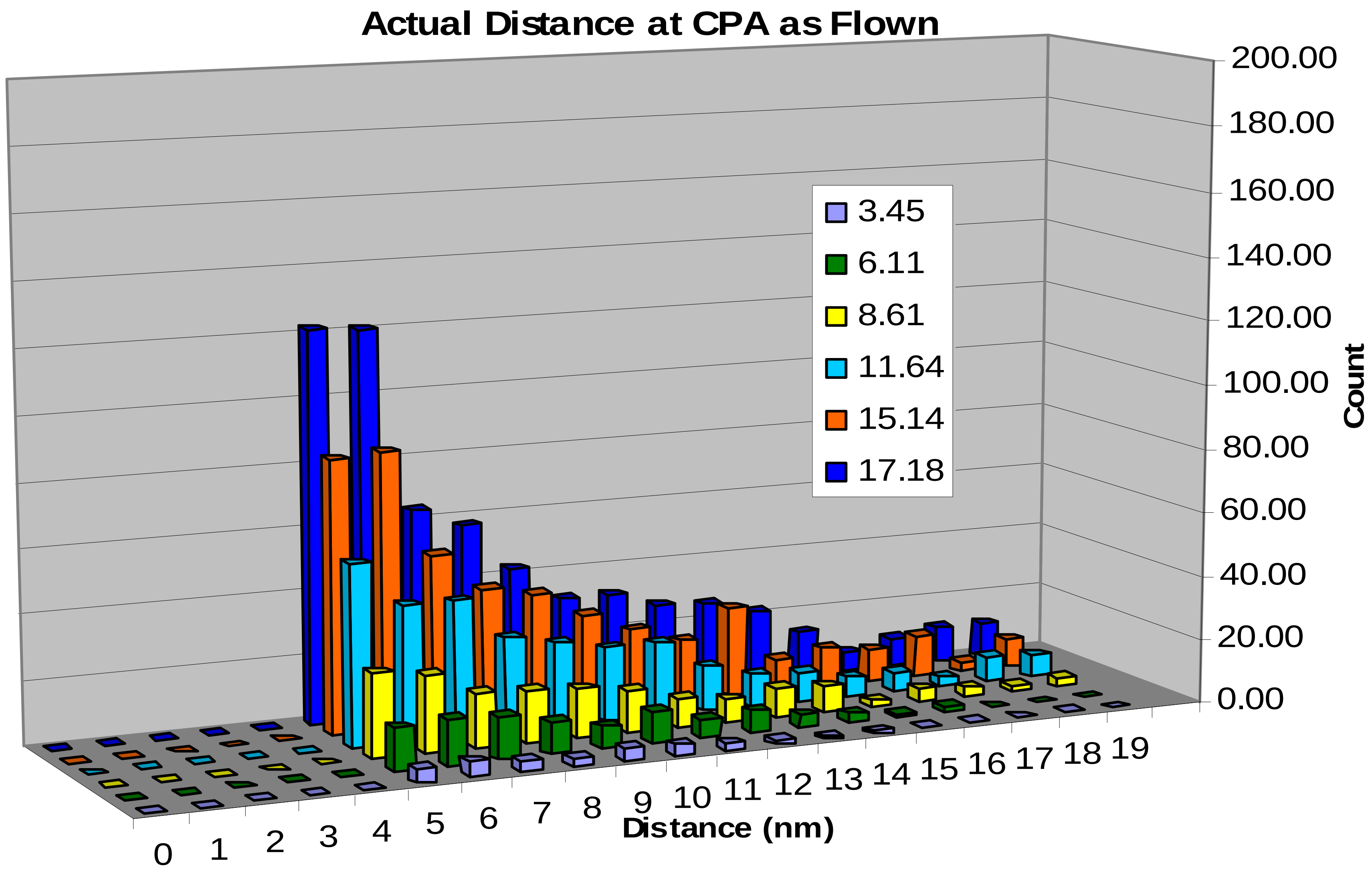
Safety of Self Separation

Predicted Distance at Closest Point of Approach (CPA)



Safety of Self Separation

Actual CPA as Flown



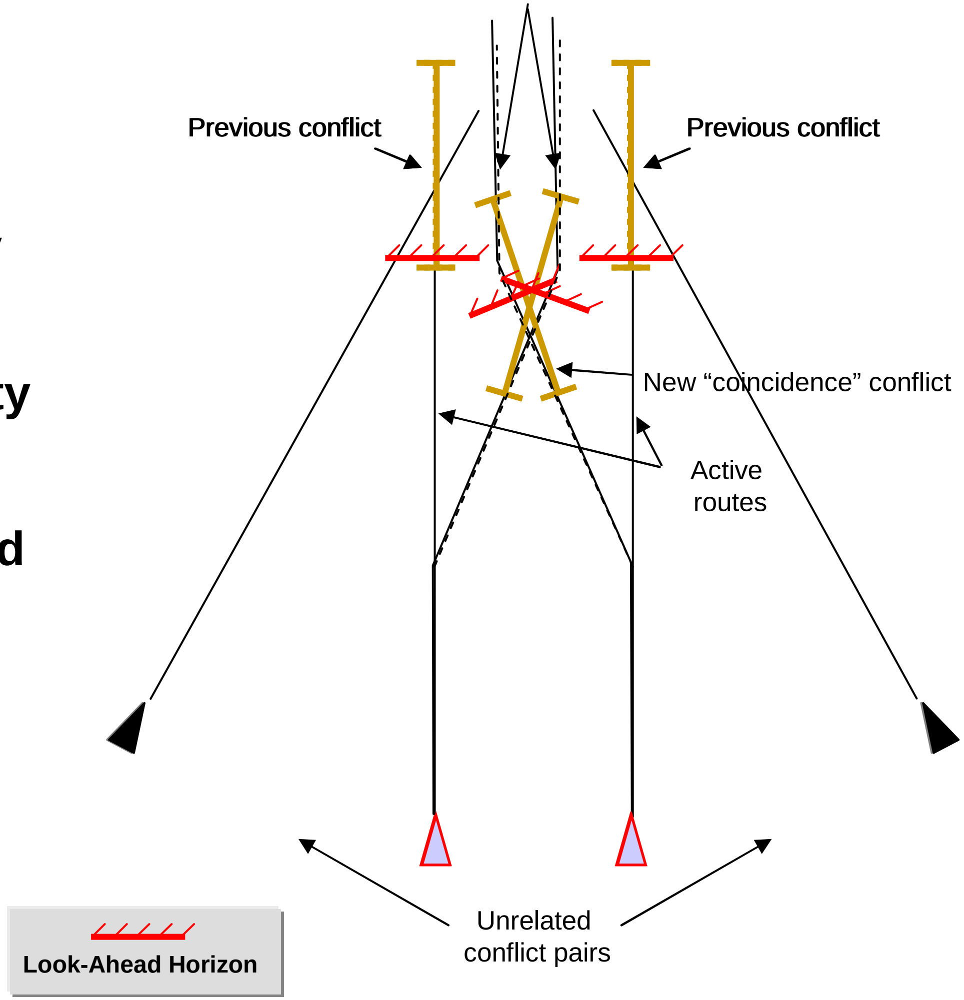
Three penetrations of 0.014, 0.011, and 0.001 NM.

Safety of Self Separation
Second Generation Conflicts

- Created as a result of solving a previous conflict
  - Sidewalk (same aircraft, both simultaneously resolving)
  - Coincidence (different aircraft, both simultaneously resolving)
  - Postponed or traded (time-to-loss-of-separation purposefully delayed)
- Associated with system stability and efficiency
- Only 11 conflicts were identified as possibly second generation
  - Out of 2744 simulated flight hours and 5770 conflicts
  - Type: coincidence conflicts
  - With initial detection occurring near 10 minutes from predicted loss of separation, all of these cases were safely resolved

Coincidence Conflict

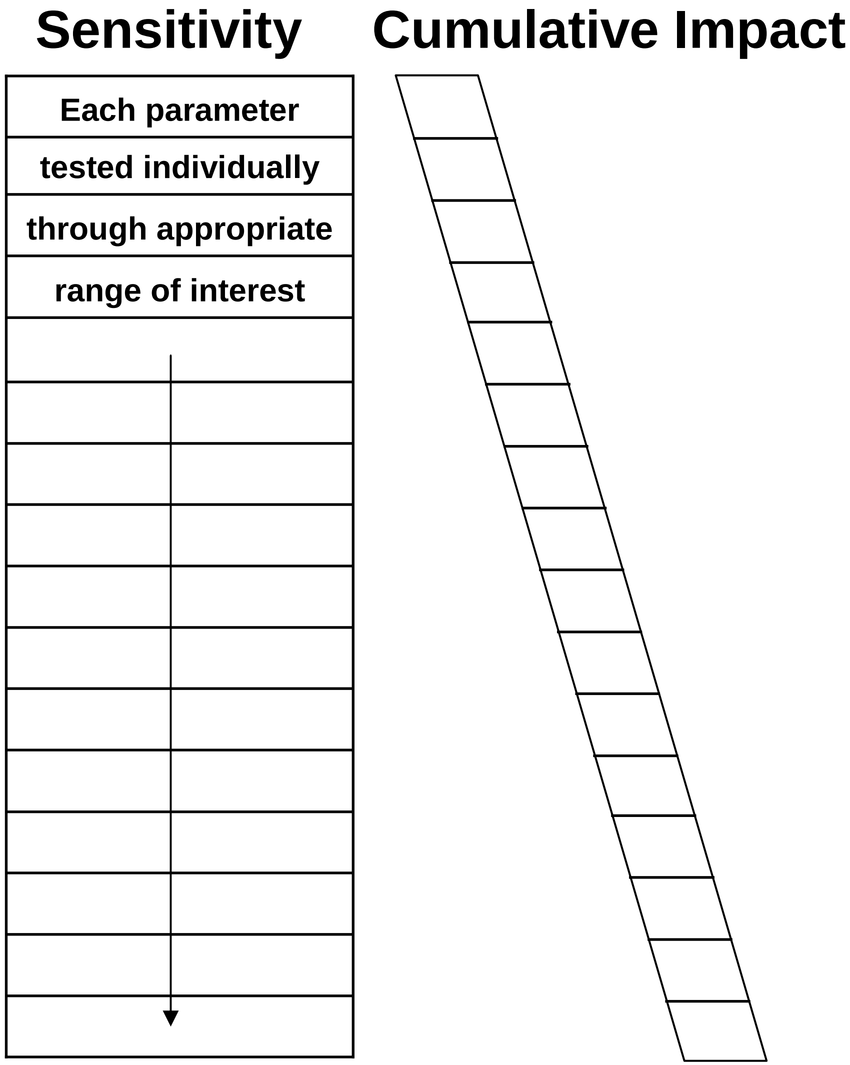
Non-coordinated coincidental resolutions



Performance Characterization of SSEP

Planned Parametric High-Fidelity Batch Studies

Categories	Parameters
ADS-B Surveillance Performance	**Interference Level**
	Amount of Intent Broadcast
	Transmission Rate
Trajectory Prediction Uncertainty Sources	**Truth Wind Strength**
	Forecast Wind Error Vector
	Aircraft ANP
Maneuvering Constraints	**Weather Coverage**
	Vertical Resolution D.O.F.
	Climb Performance
	Separation Standard
Coordination and Responsiveness	**Priority Rules**
	Pilot Response
	IFR/AFR Operations Mix
	Detection Horizon
Traffic Geometry Variability	**2D Route Structure**
	3D Flight Phase Mix



Sensitivity

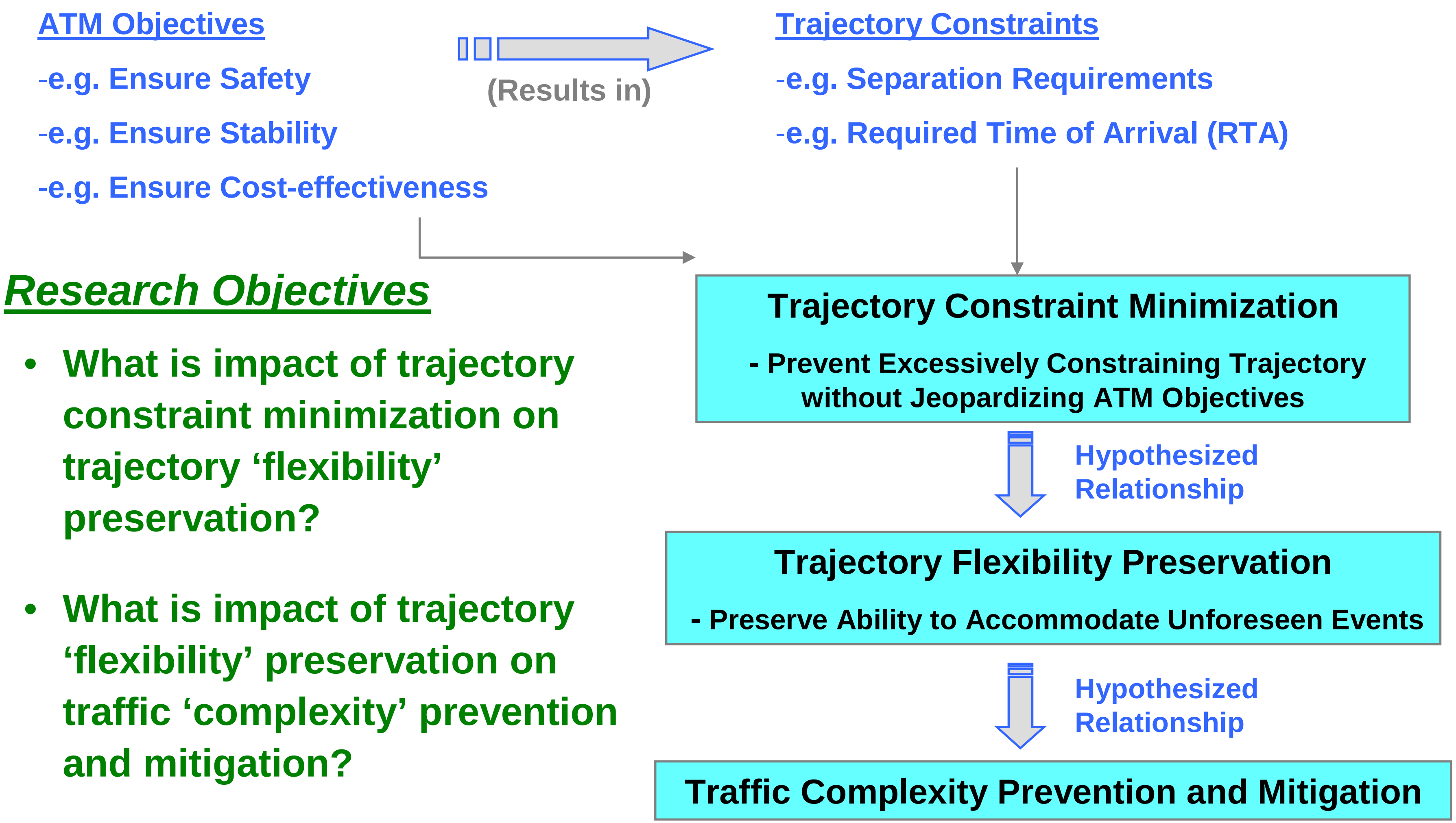
Each parameter tested individually through appropriate range of interest

Cumulative Impact

All parameters to be tested at ~1x, 3x, 5x traffic density

Traffic Complexity Prevention / Mitigation

Research Objectives



ATM Objectives

-e.g. Ensure Safety

-e.g. Ensure Stability

-e.g. Ensure Cost-effectiveness

(Results in)

Trajectory Constraints

-e.g. Separation Requirements

-e.g. Required Time of Arrival (RTA)

Trajectory Constraint Minimization

- Prevent Excessively Constraining Trajectory without Jeopardizing ATM Objectives

Hypothesized Relationship

Trajectory Flexibility Preservation

- Preserve Ability to Accommodate Unforeseen Events

Hypothesized Relationship

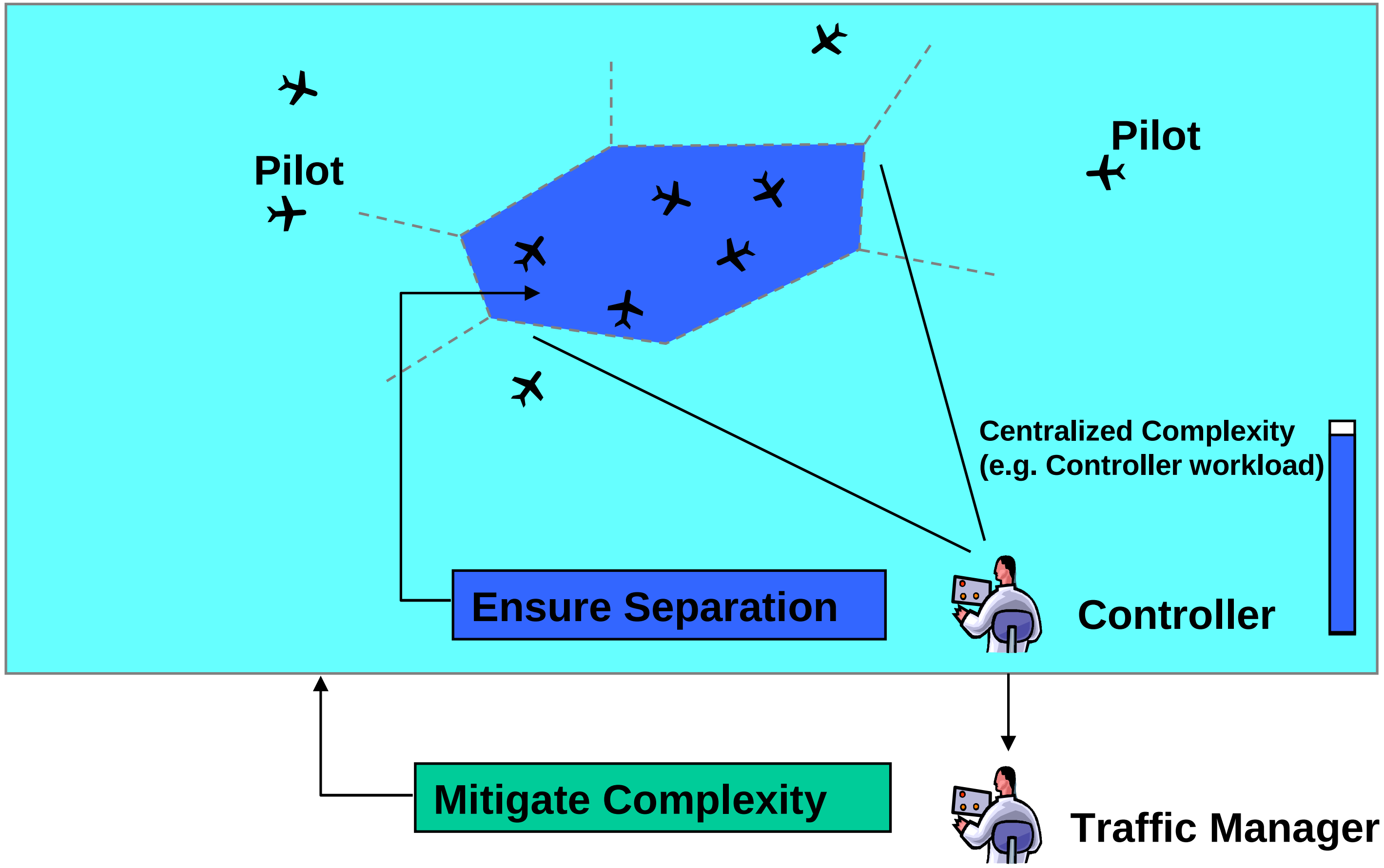
Traffic Complexity Prevention and Mitigation

Research Objectives

- **What is impact of trajectory constraint minimization on trajectory ‘flexibility’ preservation?**
- **What is impact of trajectory ‘flexibility’ preservation on traffic ‘complexity’ prevention and mitigation?**

Traffic Complexity Prevention / Mitigation

Current Centralized Operations



Pilot

Pilot

Centralized Complexity
(e.g. Controller workload)

Ensure Separation

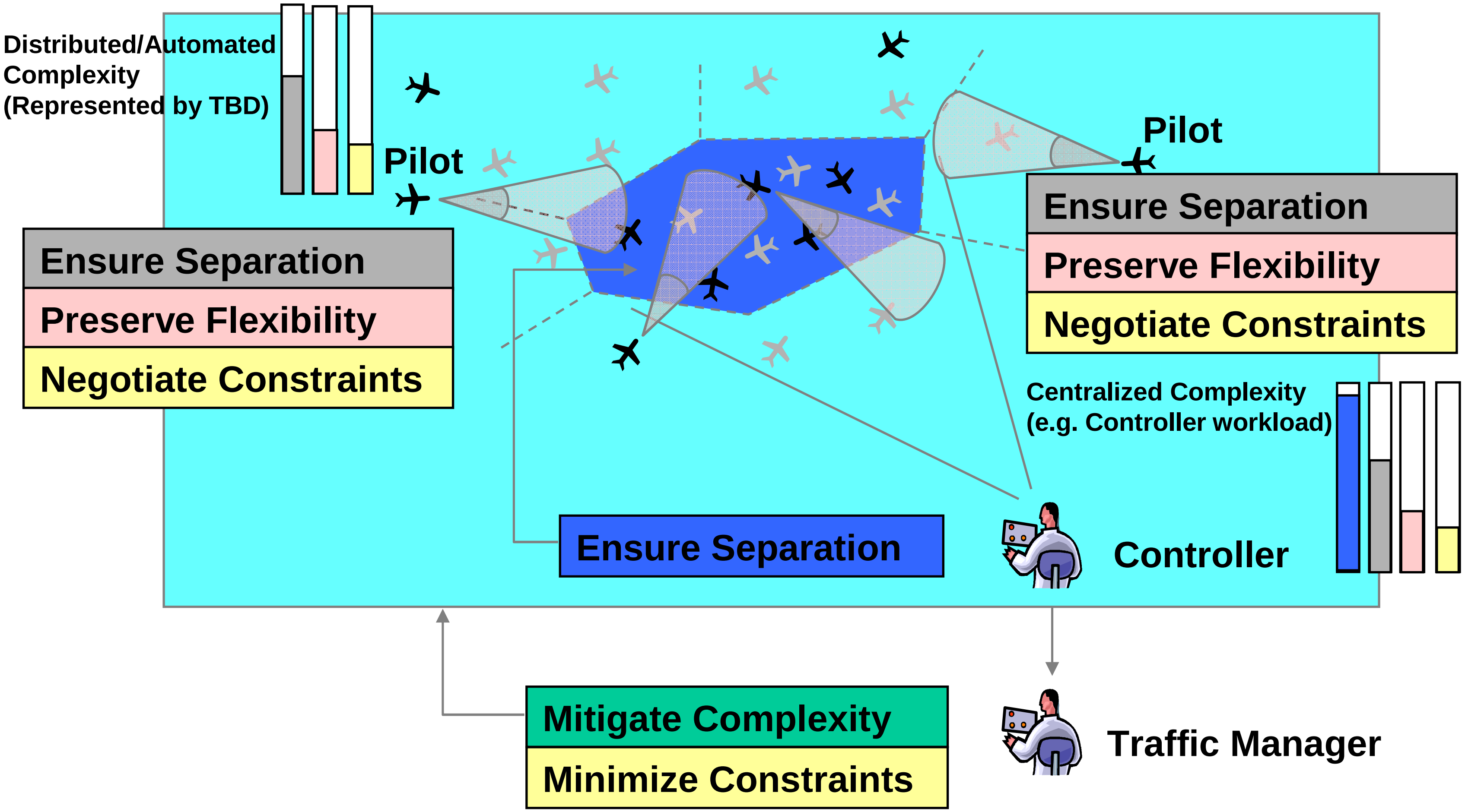
Controller

Mitigate Complexity

Traffic Manager

Traffic Complexity Prevention / Mitigation

Future Distributed Operations



Distributed/Automated Complexity (Represented by TBD)

Pilot

Ensure Separation

Preserve Flexibility

Negotiate Constraints

Pilot

Ensure Separation

Preserve Flexibility

Negotiate Constraints

Centralized Complexity (e.g. Controller workload)

Ensure Separation

Controller

Mitigate Complexity

Minimize Constraints

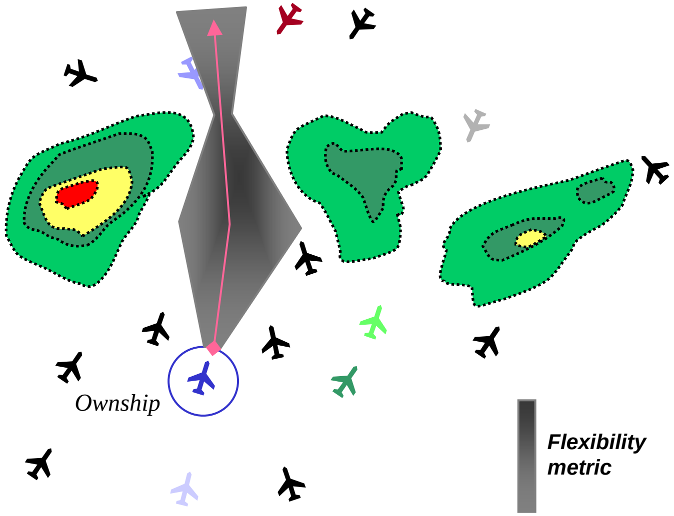
Traffic Manager

Traffic Complexity Prevention / Mitigation

Flexibility Preservation

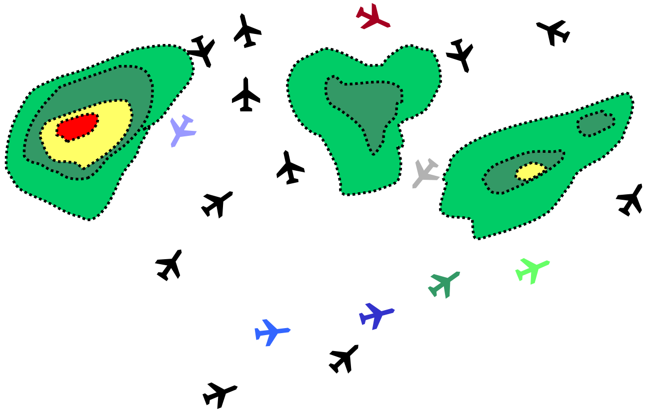
- **Traffic Congestion Situation**

Flow Management Without Flexibility Preservation



Airborne flexibility function will question:
Do I have enough flexibility to safely proceed?
Can I modify my trajectory to increase my flexibility?
Do I need to avoid this airspace entirely and replan?

Flow Management With Flexibility Preservation

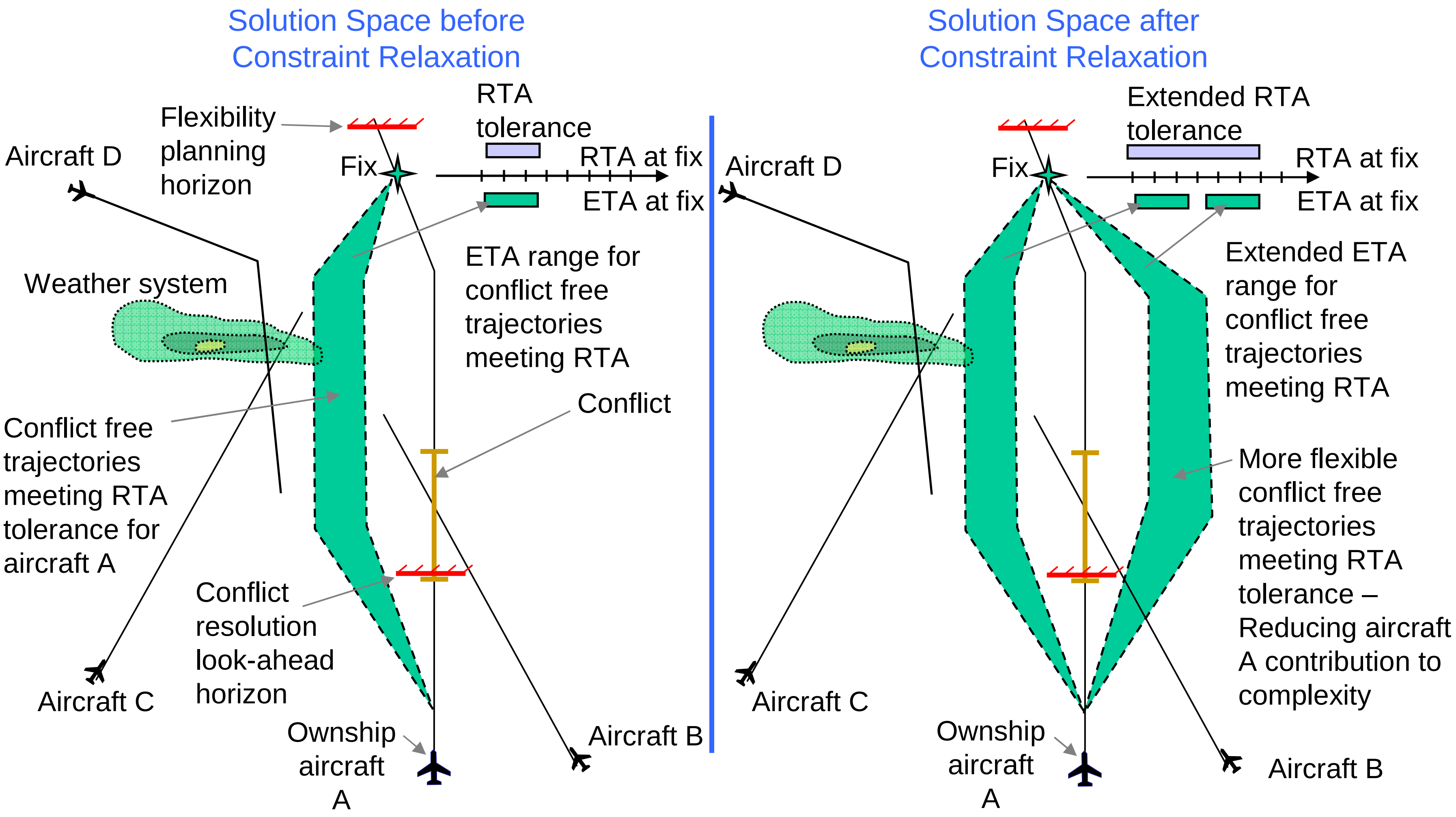


Hypothesis:
If all aircraft apply flexibility preservation function, complexity automatically will be reduced

"Two roads diverged in a wood, and I- I took the one less traveled by, And that has made all the difference" ...Robert Frost

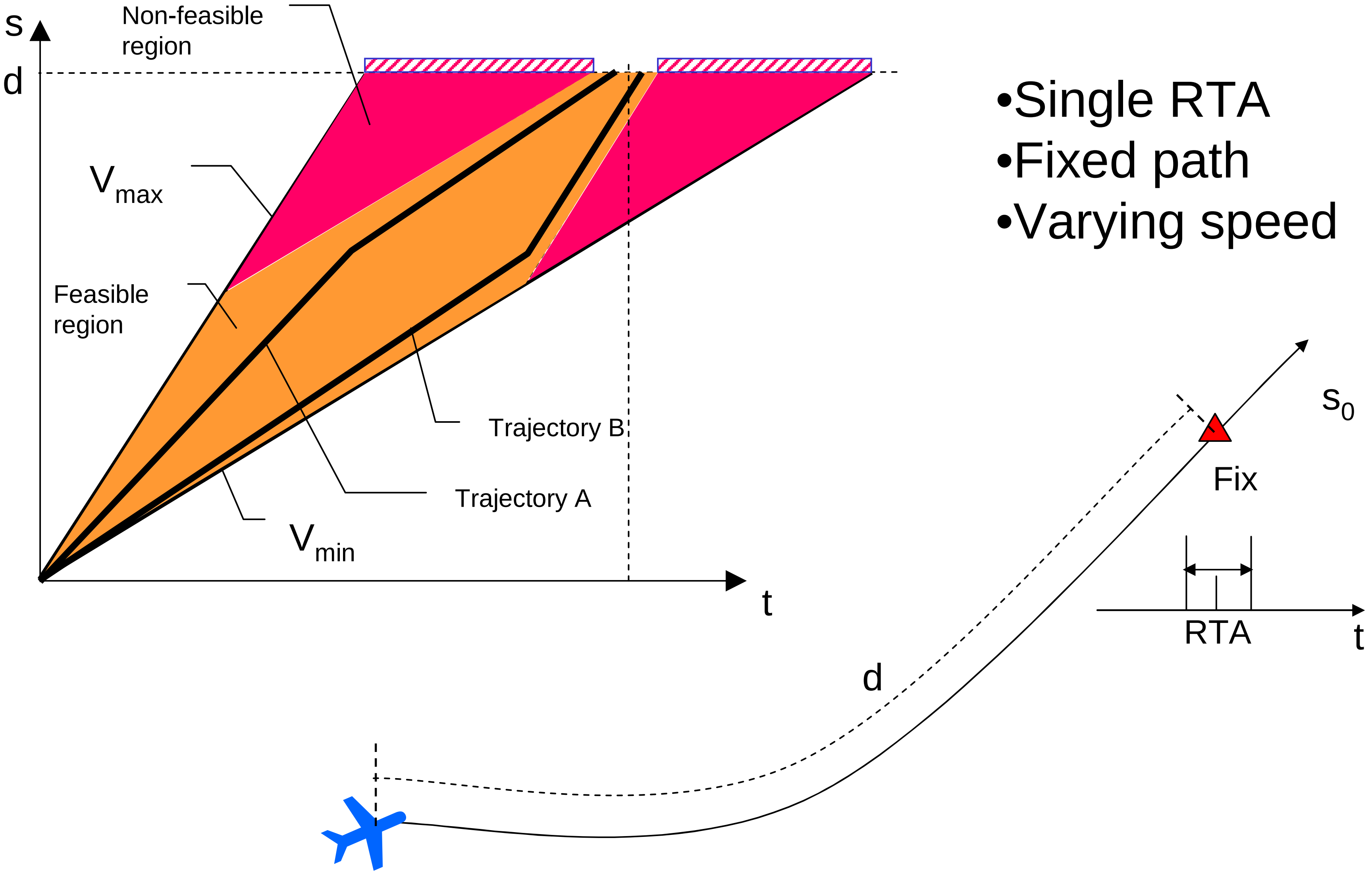
Traffic Complexity Prevention / Mitigation

Constraint Minimization



Traffic Complexity Prevention / Mitigation

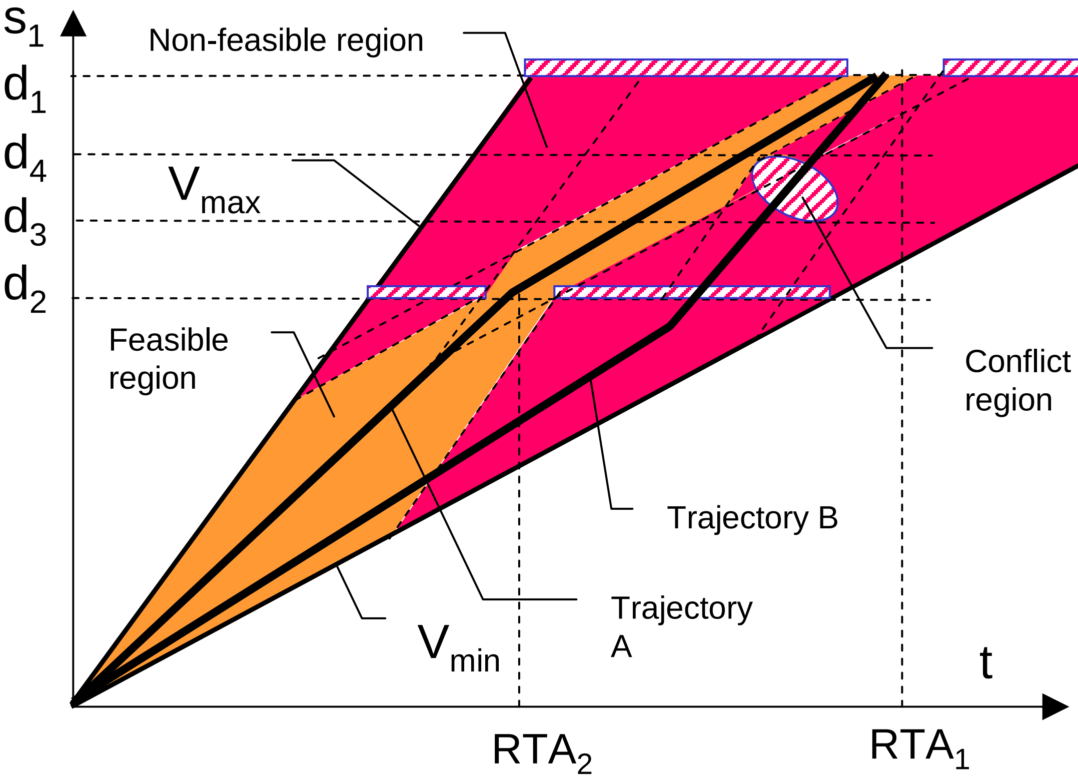
Example: Single RTA



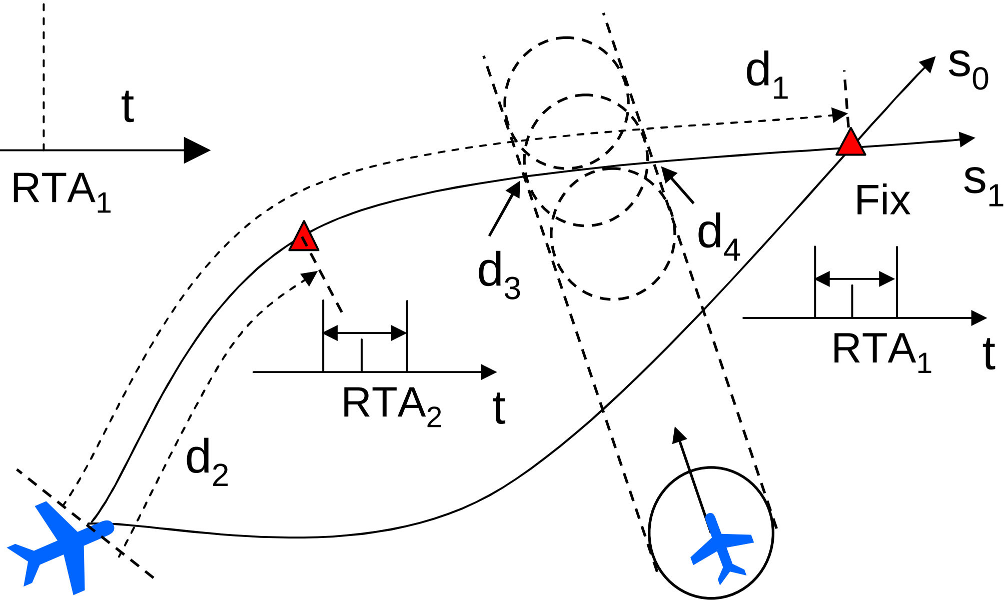
- Single RTA
- Fixed path
- Varying speed

Traffic Complexity Prevention / Mitigation

Example: Multiple RTA and Traffic Conflict



- Multiple RTA
- Conflict constraints



Conclusions

- Continuous study of self separation since 1998
- Results all point to positive feasibility, safety potential, and benefits
- Research is shifting to higher fidelity investigations
  - Safety quantification
  - Performance characterization "under the influence"
  - Complexity management
  - Trajectory prediction uncertainty handling
- Potential opportunities for NASA and iFLY to leverage each other's activities
  - Operational concepts; algorithm experience; safety/complexity analyses; performance with failure/degraded modes

(Wait! One more important slide…)

ATC Quarterly Special Issue on ASAS

- “Special Issue” focusing on specifically on ASAS
  - Guest editor: David Wing
  - First ASAS Special Issue since 2005 (Vol 13, #2, Casaux)
- Soliciting a paper from iFLY on self-separation research
  - Can include one or more iFLY activities
  - Focus on technical activities, data, results
- Timing
  - Target for final draft paper: March 2008
  - Near term need: 1 page abstract and commitment

http://www.atca.org/information/quarterly_desc.asp