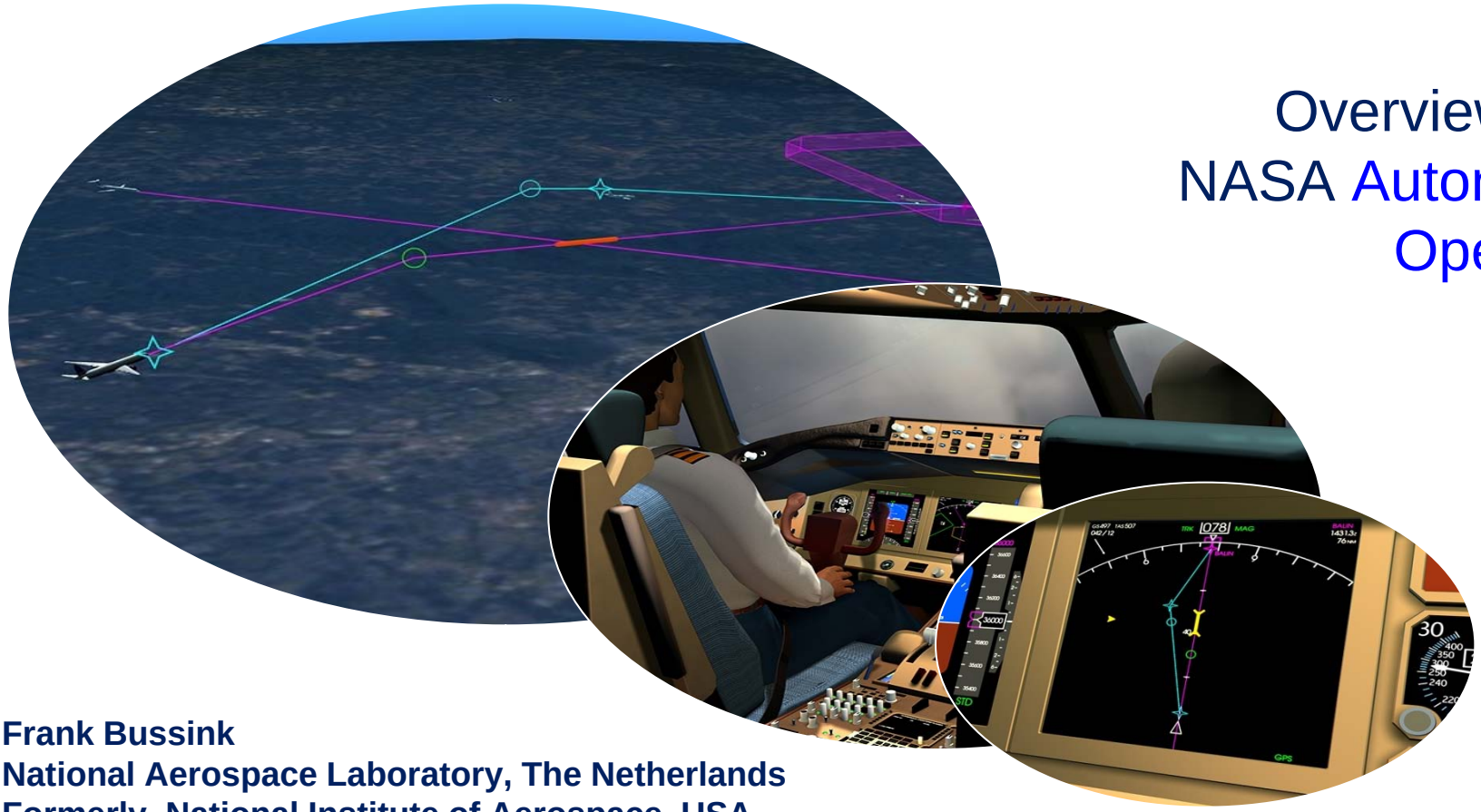
Flight-deck Technology for Trajectory-Based Self-Separation



Overview of the NASA Autonomous Operations Planner (AOP)

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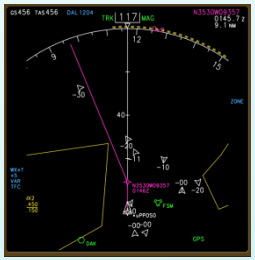
Research Prototype Automation System
NASA Autonomous Operations Planner (AOP)

Flexibility Planning

Trajectory flexibility preservation

Maneuvering Without Conflict

Provisional maneuver CD



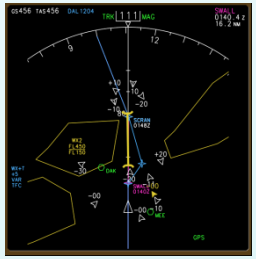
Maneuver restriction bands

TCAS (external to AOP)

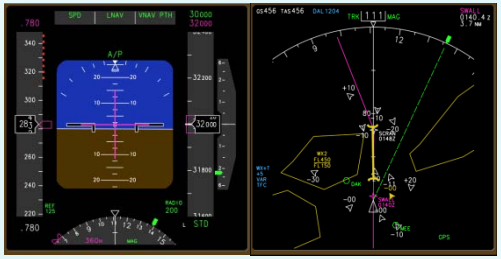
Conflict Management

Intent-based CD w/ prediction uncertainty

Priority-based alerting



Strategic Intent-based CR



Tactical Intent-based CR

Tactical State-based CD&R

CD – Conflict detection
CR – Conflict resolution

AOP Capabilities Overview

- *AOP System Interfaces*
- *Conflict management*
  - Probe multiple maneuvers for situation awareness
  - Conflict detection and resolution details
    - Intent-based and state-based approaches
- *Maneuvering without conflict (conflict prevention)*
  - Provisional (“what-if”) planning
  - Maneuver restriction bands
- *Flexibility planning*
- *Accomplishments*

AOP System Interfaces

Inputs:
- Guidance settings
- Traffic data
- Weather data
- AOP MCDU data

Autonomous Operations Planner (AOP)

Outputs:
- Conflict alerts
- FMS route mods
- MCP setting mods
- AOP MCDU data

Integrates with Existing Avionics & Displays

AVIONICS DATA BUS

Mode Control Panel (MCP)

Flight Management System (FMS)

Flight Control Computer (FCC)

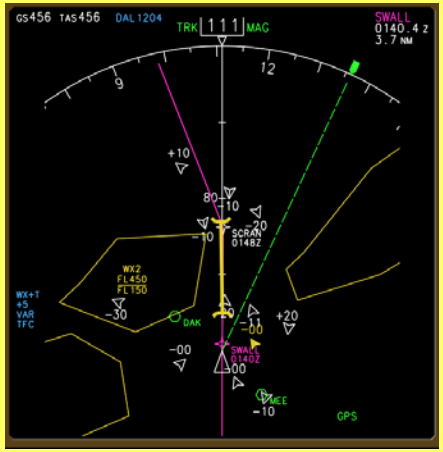
Other Sources:
- GNSS Clock
- ADS-B
- TIS-B
- FIS-B

AOP Inputs

Multi-Function Control & Display Unit (MCDU)

AOP Outputs

Primary Flight Display (PFD)



Navigation Display

Conflict Management

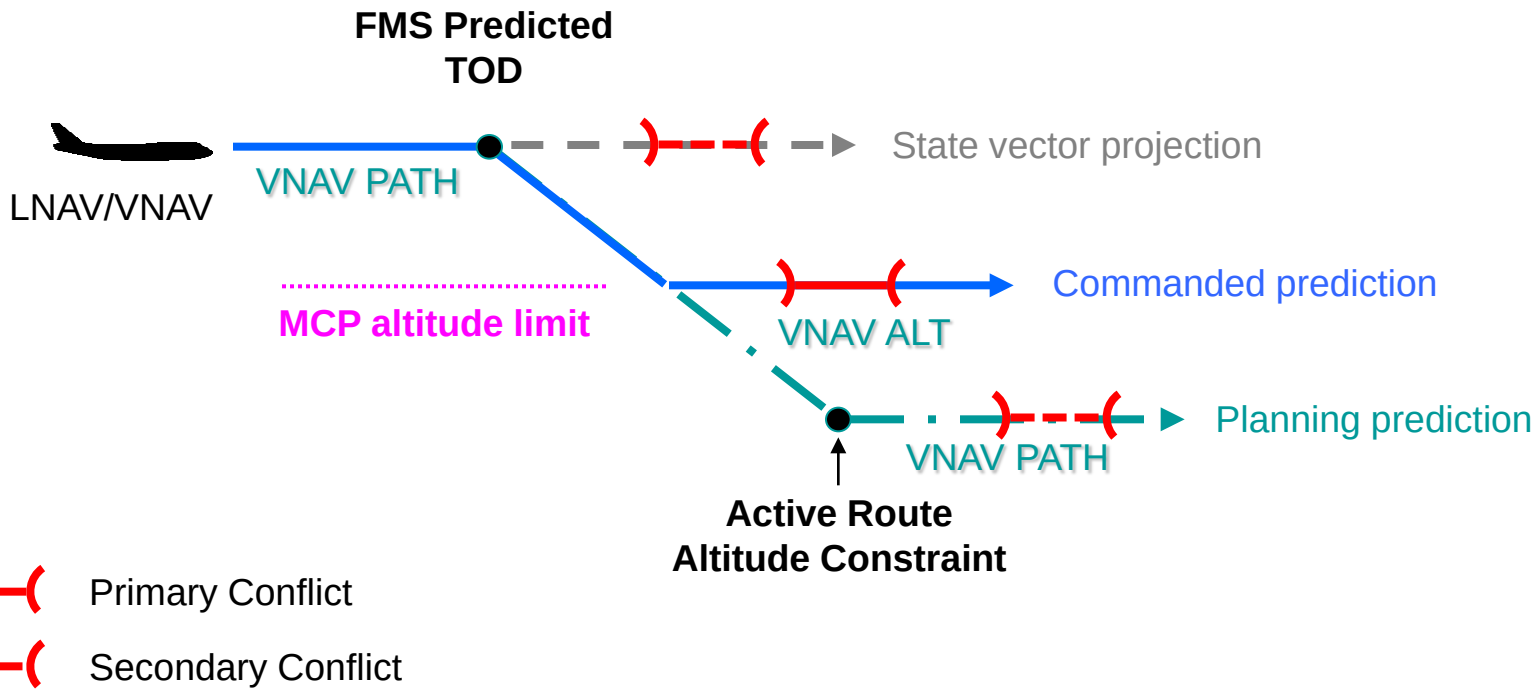
- *Probe all relevant maneuvers (trajectories) requiring evaluation by flight crew*
  - Display all conflicts to provide complete situation awareness
  - Provide resolution capabilities for each maneuver

- *AOP can simultaneously predict/evaluate multiple ownship maneuvers*
  - Maintaining current guidance (Commanded Prediction)
    - Evaluate impact of current guidance settings
    - "What happens if I don't change the guidance settings?"
  - Reconnecting to strategic route (Planning Prediction)
    - Advise & evaluate maneuver to re-establish FMS active route
    - "How do I get back to my long-range plan?"
  - Stop maneuvering (State-vector projection)
    - Evaluate impact of maintaining current state
    - "What happens if I stop or don't start/continue maneuvering?" (e.g., blunder)

- *Not all maneuvers always relevant*

Conflict Management

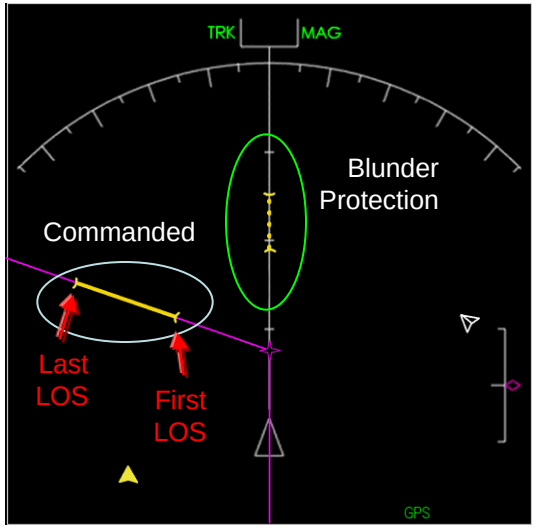
Example: Aircraft Approaching Top-of-Descent (TOD)



Conflict Management
Maneuver Probing

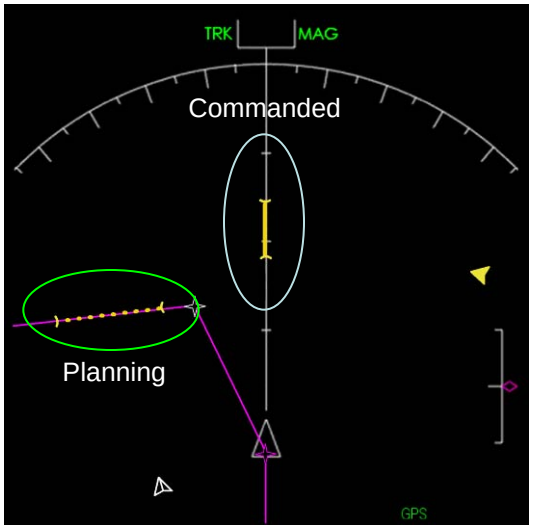
- Primary conflicts on the commanded prediction
- Secondary conflicts on planning and blunder (state-vector) predictions

LNAV



On path

TRACK HOLD



Off path
Within capture

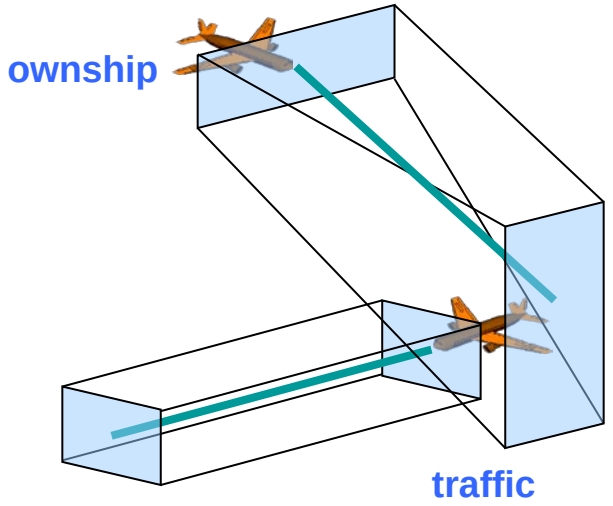
LOS – loss of separation

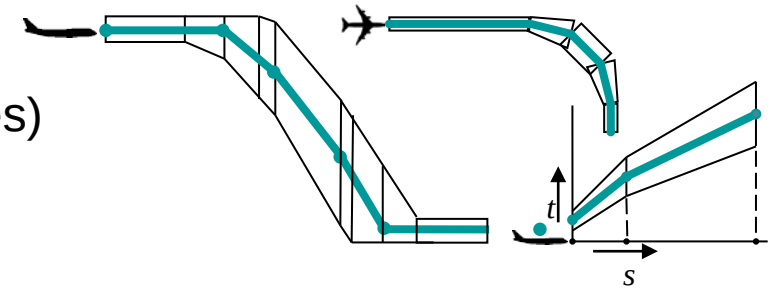
Conflict Management:
Conflict Detection & Resolution

- *Intent-based conflict detection*
  - Conflict detection
    - Trajectory prediction uncertainty buffers
  - Trajectory prediction
    - Ownship
    - Traffic
- *Intent-based conflict resolution*
  - Strategic & tactical
- *State-based CD&R*

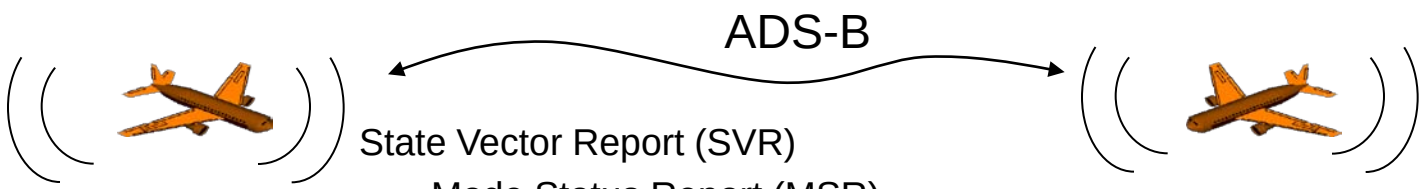
Conflict Management
Intent-Based Conflict Detection

- *1xN probing of ownship versus all hazards (traffic and area)*
  - Probes ownship 4D trajectory against all traffic aircraft 4D trajectories and area hazard geometries
- *Configurable research parameters*
  - Required separation zone
    - Independent values for AFR & IFR traffic
  - Look-ahead
    - Typically 10 minutes
- *Uses prediction uncertainty bounds*
  - Independent definitions for
    - ownship and traffic
    - different maneuvers (flight modes)
  - Conflict = predicted loss between uncertainty regions





Conflict Management
Intent-Based Trajectory Prediction



- *Ownship*
  - Generated from avionics and guidance settings
    - MCP, FMS, FCC, MCDU settings
    - initial condition from sensors
  - Numerical integration
    - FMS quality trajectory prediction for all guidance modes
  - One trajectory generated for each intent-based CD
    - Commanded
    - Planning

- *Traffic*
  - Generated from ADS-B data
    - SVR: initial condition
    - TCR: represents predicted trajectory
      - TCP+N approach
  - No numerical integration
  - TSR used when no TCR data
    - Uses numerical integration
  - One trajectory per traffic aircraft
    - used for all intent-based CD applications

Conflict Management:
Intent-Based Conflict Resolution

1. *Conflict resolution in strategic flight modes*

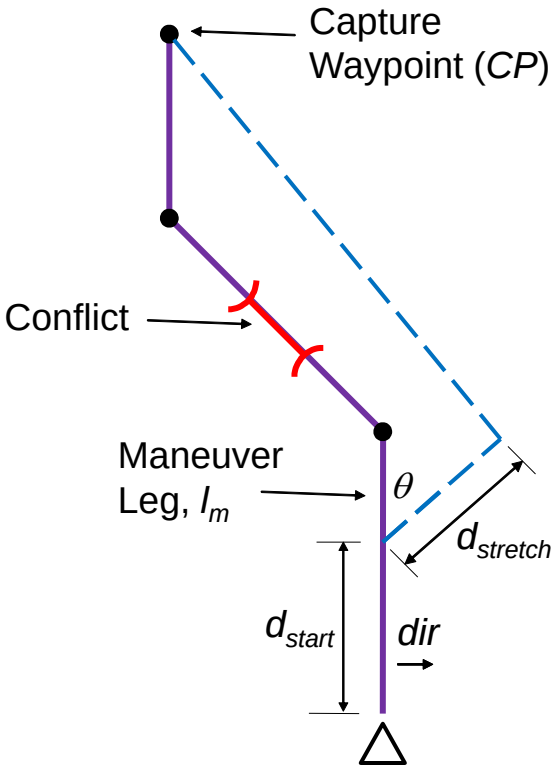
- Primary and preferred method for 4D trajectory-based operations
- Remain fully coupled to FMS
- Lowest pilot workload
- Broadcast best intent

2. *Conflict resolution in tactical flight modes*

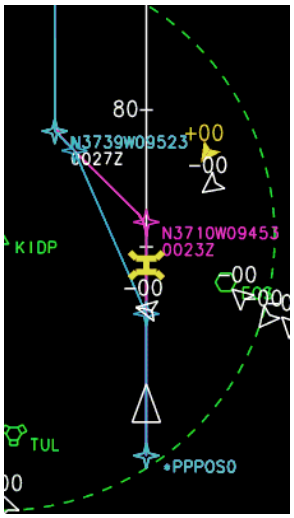
- Automatic override of strategic tool for unresolved and pop-up conflicts
- Dynamic head-up situations (e.g. tactical weather avoidance)

Conflict Management:
Intent-Based Conflict Resolution

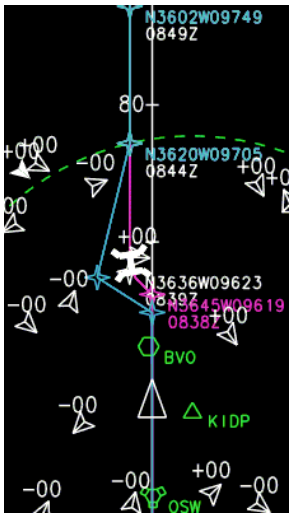
- *Strategic Intent-based Conflict Resolution (SICR)*
  - Develops FMS-compatible routes
    - Independent lateral and vertical maneuver options
    - Uploaded directly into FMS
  - Crew requested
  - Approach:
    - Resolves for all conflicts and constraints
    - Non-cooperative (full resolution)
    - Pattern-Based Genetic Algorithm



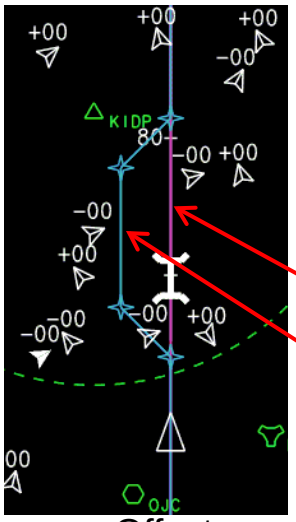
Path Stretch Pattern



Direct Intercept



Path Stretch



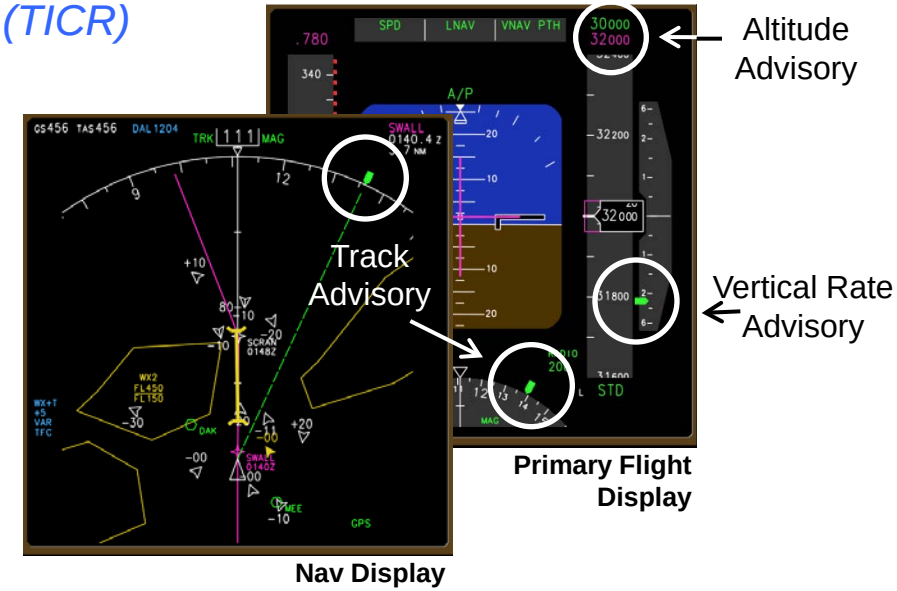
Offset

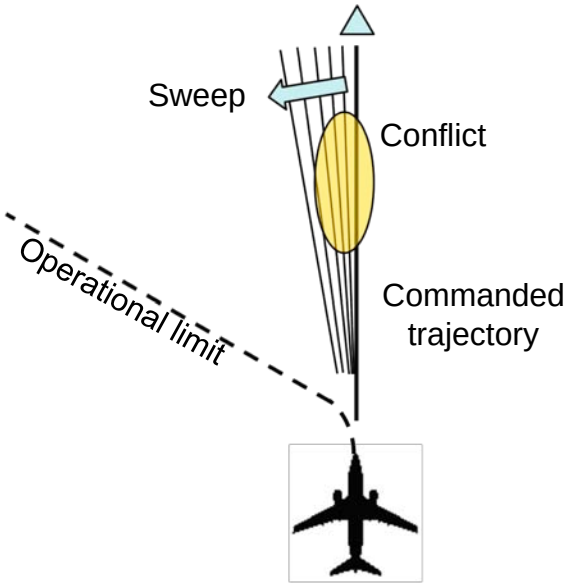
Active Route: Magenta

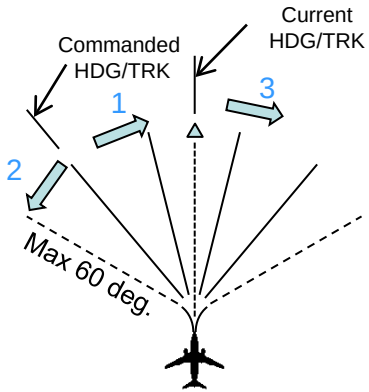
Resolution Route: Blue

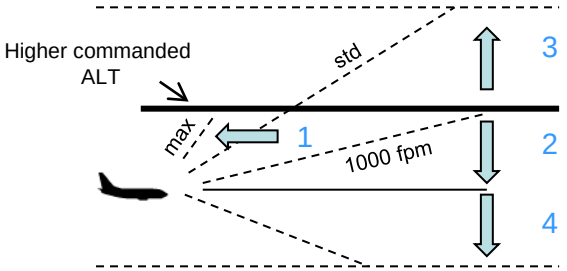
Conflict Management:
Intent-Based Conflict Resolution

- *Tactical Intent-based Conflict Resolution (TICR)*
  - Develops MCP setting advisories
    - Altitude, vertical rate, heading/track
  - Automatic (not crew requested)
  - Approach:
    - Resolves for all conflicts
    - Non-cooperative (full resolution)
    - Sweep until first conflict-free setting found









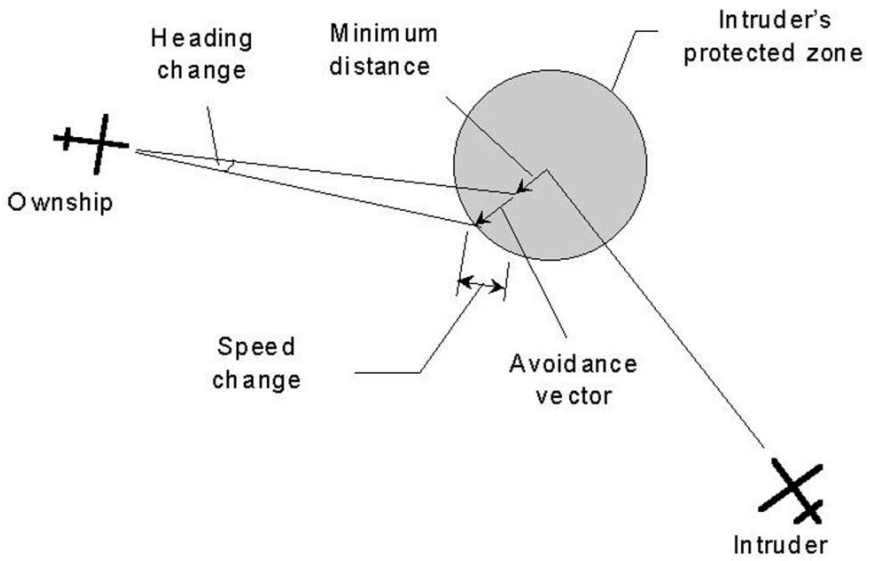
Conflict Management
State-Based Conflict Detection & Resolution

- *<u>Independent</u> system from intent-based CD&R*
  - Blunder protection and override for short term conflicts
  - Two options
    - Langley (ACCoRD)
    - NLR (Modified Voltage Potential)

- *Detection*
  - Look-ahead at 5 minutes (configurable)
  - No area hazard detection
  - Does not consider uncertainty

- *Resolution*
  - Develops MCP settings advisories
    - track/heading, vertical rate, altitude
  - Automatically displayed when needed
  - Approach
    - Resolves most immediate conflict
      - Cooperative/Non-cooperative (configurable)
    - Maneuver to increase to minimum separation standard
    - Implicitly coordinated with other traffic maneuver

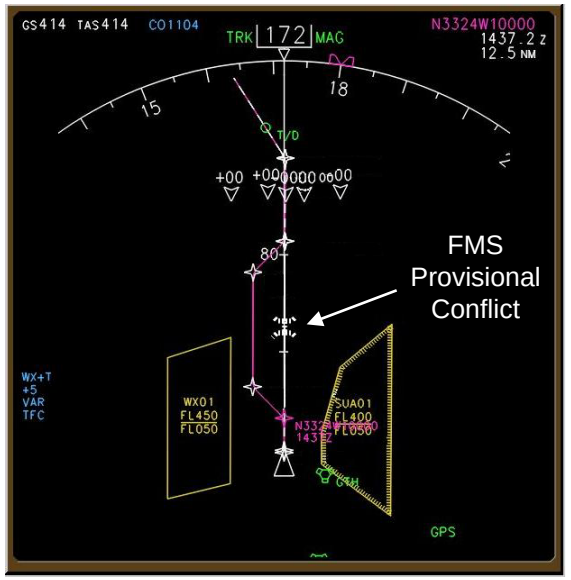
Modified Voltage Potential



Maneuvering Without Conflict
Conflict Prevention

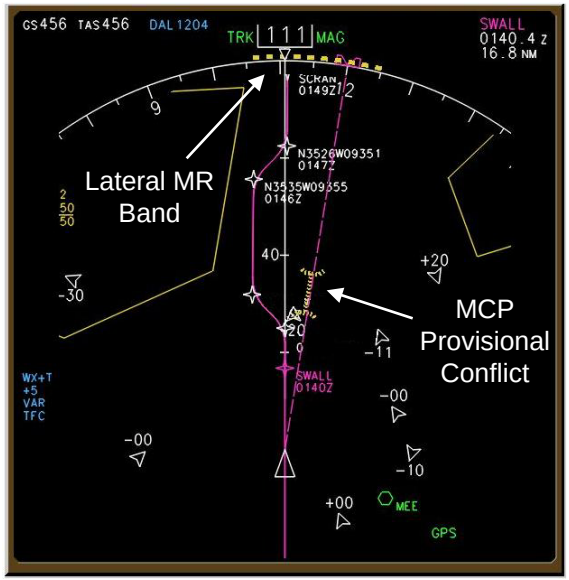
- *Provisional (what-if) planning*
  - Non-conflict generated maneuver
    - Probe for conflicts before execution
  - FMS provisional
    - Automatic probe of FMS MOD route
  - MCP provisional
    - Automatic probe of non-active MCP inputs

Manual MOD Route in FMS



- *Maneuver restriction (MR) bands*
  - Protect against unallowable maneuvers
    - Conflicts requiring resolution
  - Bands show unallowable MCP settings
    - Lateral (track/heading)
    - Vertical (vertical rate)
  - Always “On”

Non-active Change in MCP Track Setting (e.g., in LNAV)

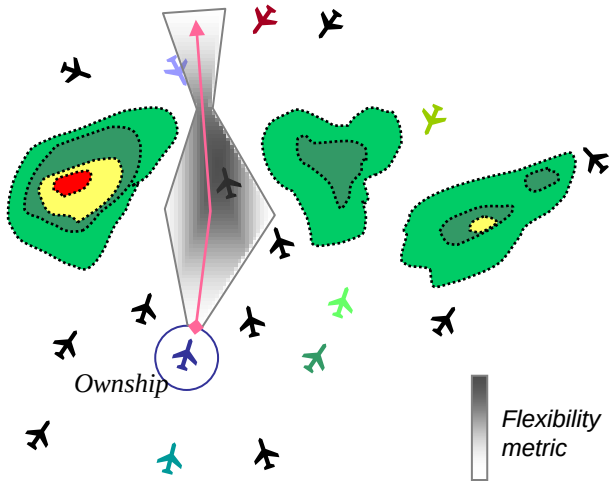


Flexibility Planning
Complexity Management

- *Trajectory Flexibility Preservation*
  - Proposed capability under research and development
  - Computes measures of a trajectory's flexibility
    - Adaptability and Robustness
    - Current or any proposed route (e.g. conflict resolution)
  - Long time horizon
    - Reduce or prevent exposure to complex airspace
  - Short time horizon
    - Bias resolutions to "clear air"
    - Reduce proximity to other traffic, weather

- *Constraint Minimization*
  - Proposed capability under research and development
  - Propose constraint relaxation to maximize flexibility
  - Support air/ground negotiation on trajectory constraints (e.g. RTA)

Applicability of Trajectory Flexibility Prediction



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?

Accomplishments

- *Have achieved full integration of TBO functionality in AOP*
  - **Traffic separation** in FMS (4D/strategic) and MCP (3D/tactical) flight modes
    - Intent-based conflict detection with trajectory-based 4D uncertainty bounding
    - Strategic (closed-loop) resolutions: *primary operational mode for 4D TBO*
    - Tactical (open-loop) override resolutions for short time horizons
    - State-based CD&R for final separation assurance; proven correct and coordinated
    - Strategic reconnect capability (with integrated conflict detection and resolution)
  - **Trajectory constraints** conformance
    - Flow constraint (RTA conformance; "Resolve RTA conflict" for delay absorption)
    - Weather polygon and airspace restriction (SUA) avoidance
    - Other trajectory constraints (e.g. crossing altitude)
  - **Provisional probing** for conflict-free trajectory changes
    - "What if" probing in both strategic and tactical modes
  - **Coordination** with traffic
    - Right-of-way rules integrated into alerting logic
    - Near-term tactical maneuver coordination
  - **Optimization** of resolutions
    - User preferences in both strategic and tactical modes

- *Exploratory integration of complexity management functionality*
  - **Trajectory flexibility** quantification and preservation

Accomplishments

- *Algorithm performance testing*
  - Strategic intent-based CD&R
    - Stress-tested to extreme density (10x +)
    - Randomly generated conflicts, random blocking traffic, altitude constrained, RTA constrained
    - Baseline study: 5700+ conflicts, all resolved
    - Pilot delay study: 5 to 240 seconds, 99%+ conflicts resolved except longest delay at highest density (12x)
    - Wind prediction error study : up to 40 kt error
      - 1X – all resolved w/ no buffer required
      - 8x – all resolved w/ 60% buffer
  - Tactical intent-based CD&R
    - Initial observations of stress testing indicate strong performance
  - State-based CD&R
    - Formally verified properties of correctness and coordination

10X playback speed

Strategic intent-based CD&R stress test
NASA Air Traffic Operations Lab
Airborne tool: NASA Autonomous Operations Planner
All aircraft co-altitude, circle diameter 160 NM
Sustained Mean Density[1] 17.18 aircraft per 10k NM[2]
~9.5X sector ZOA31, FL310, 19 Feb 2004

Accomplishments

- *Previous HITL testing:*
  - Unconstrained cruise (→3X traffic)
  - Restrictive airspace / hazard scenarios
  - Flow-constrained cruise/descents in mixed-equipage operations (→2x traffic)

- *2010 HITL Experiment*
  - First of multiple paired HITL simulations
    - Langley ATOL and Ames AOL platforms
    - Same scenarios, metrics
    - Air/ground function allocation: all airborne or all ground-based (baseline)
  - Study of operational "agility"
    - Coincident timing of multi-aircraft trajectory changes
    - Up to 2x max traffic density, Kansas City Center en-route/transition airspace
    - Metrics: safety, efficiency, usability, acceptability (data analysis in progress)

Summary

- *Autonomous Operations Planner developed by NASA for research of feasibility and functional requirements of self-separation operations*

- *Primary requirements addressed*
  - Conflict Management
    - Conflict detection accounting for ownship auto-flight mode, traffic intent and state, and prediction uncertainty
    - Conflict resolution alternatives in lateral and vertical directions, and strategic and tactical flight modes
  - Maneuvering without Conflict
    - Provisional capability to verify planned trajectory changes are conflict-free before execution
    - Maneuver restriction bands for quick assessment of tactical options
  - Flexibility Planning
    - Proposed capability under research and development
    - Quantification and preservation of maximum trajectory flexibility

- *Use*
  - Designed for mixed-equipage airspace, trajectory-based operations, 4D constraints
  - Supports ongoing research in self-separation
    - Dynamic weather, traffic complexity, mixed-equipage (air/ground) operations, failure modes

Thank You