Advanced Airborne Self Separation: Can it accommodate future en route traffic demand?

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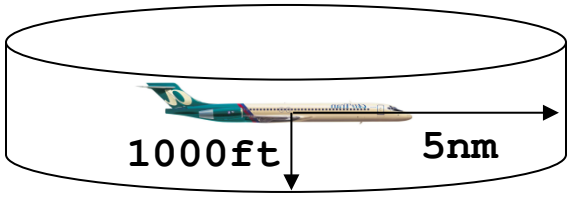
Outline

- iFly CDR hierarchy overview
- Algorithm overview
- Mid term CDR validation
- Short term CDR validation

Safety, conflict detection & resolution

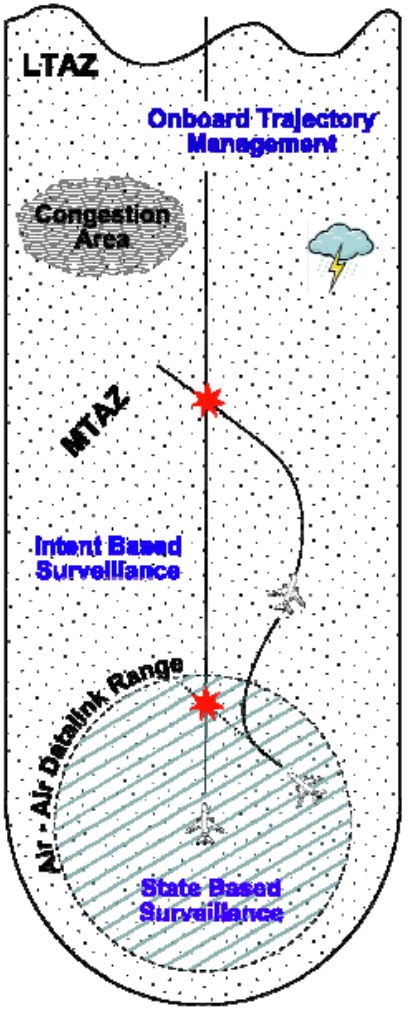
- **Safety primary consideration of air traffic management system**
- **In airborne operations in principle interested**
  - Collision risk
  - Collision avoidance
- **Plus safety margin**
  - Loss of separation
  - “Conflict”



- **Conflict detection and resolution (CDR)**

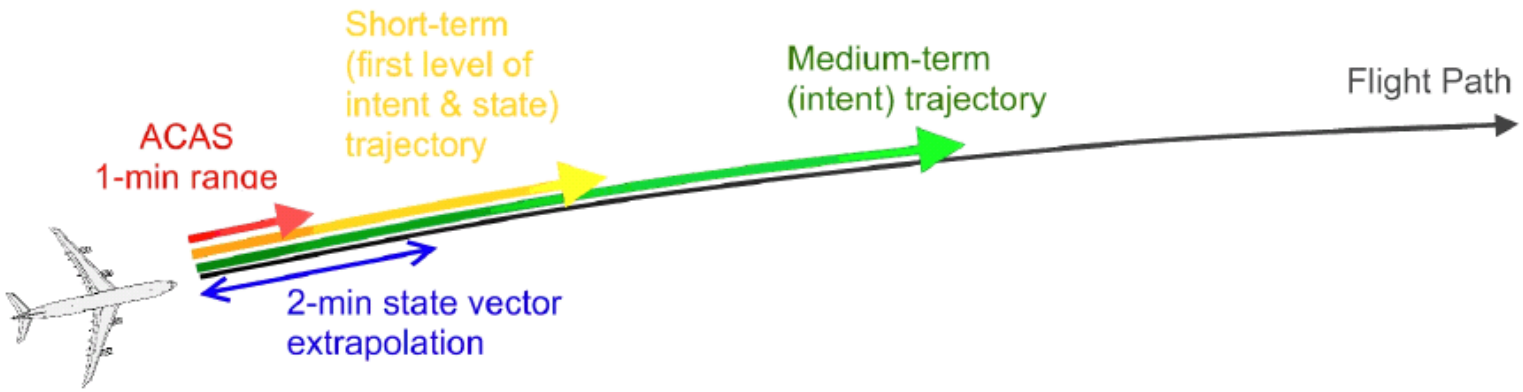
Different levels of CDR

- **Long term CDR**
  - Long term alert zone
  - > 30 minutes into the future
- **Mid term CDR**
  - Mid term alert zone
  - ~ 20 minutes into the future
- **Short term CDR**
  - Short term alert zone
  - < 5 minutes into the future
- **ACAS/TCAS**
  - Last resort safety net
  - ~ 1 minute into the future



(Figure: iFly, D1.3)

Different levels of CDR: Temporal



(Figure: iFly, D1.3)

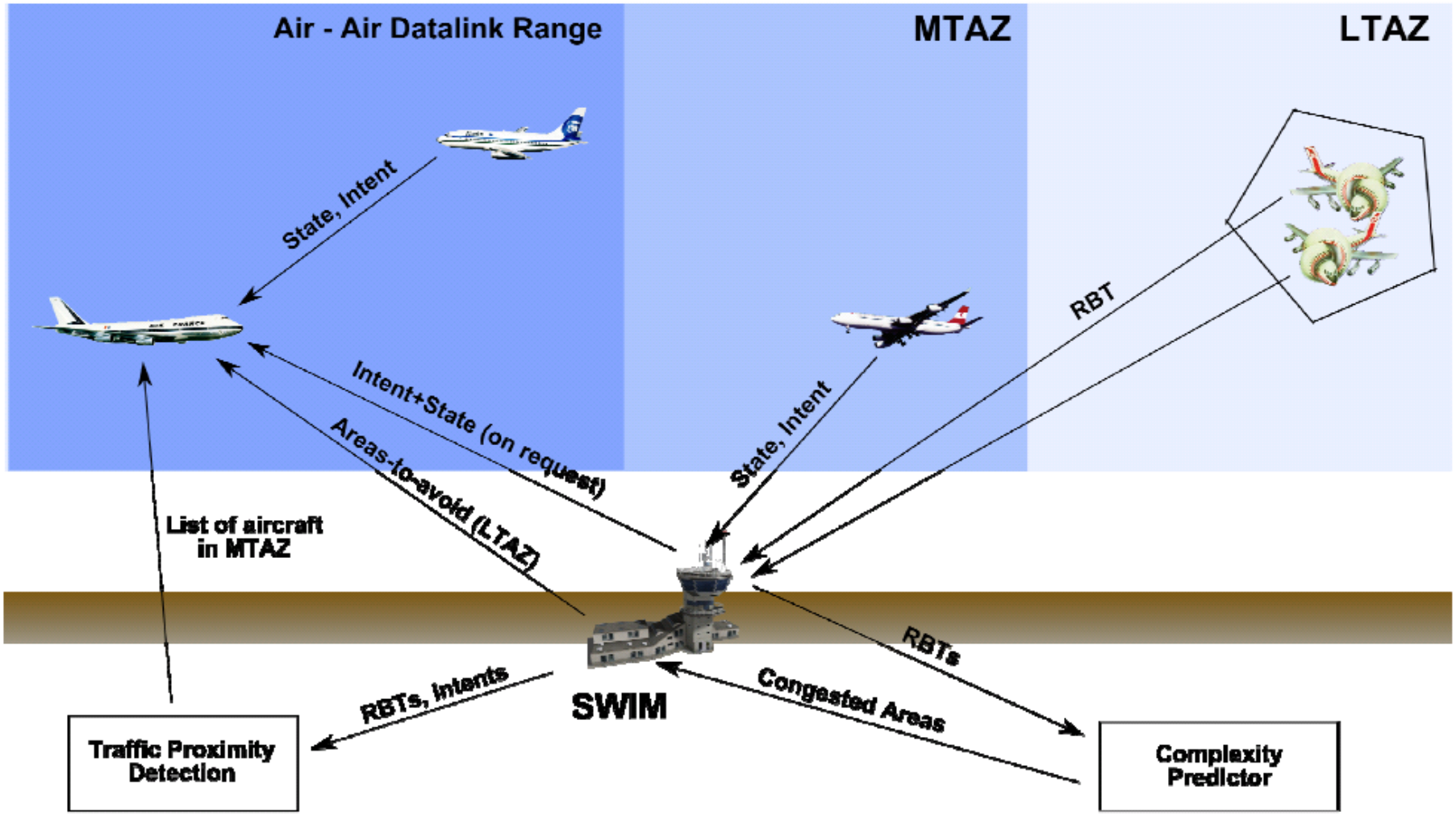
CDR steps

- **Prevention of conflicts series of steps**
- **Trajectory prediction**
  - Predict future positions of aircraft
  - Given all available information
- **Conflict detection**
  - Compare future positions
  - Determine whether loss of separation is likely
- **Conflict resolution**
  - Determine what to do to resolve the problem

Currently

- **Currently CDR**
  - Ground based
  - Performed mostly by air traffic controllers
  - Centralized, coordinated
  - Intent of aircraft generally known (flight plan, or RBT)
- **With the notable exception of ACAS/TCAS**
- **By contrast, in self separation airspace**
  - CDR airborne
  - Responsibility delegated to aircraft/pilot
  - Distributed, decentralized
  - Explicit vs. implicit (or even no) coordination
  - Intent of other aircraft not necessarily known

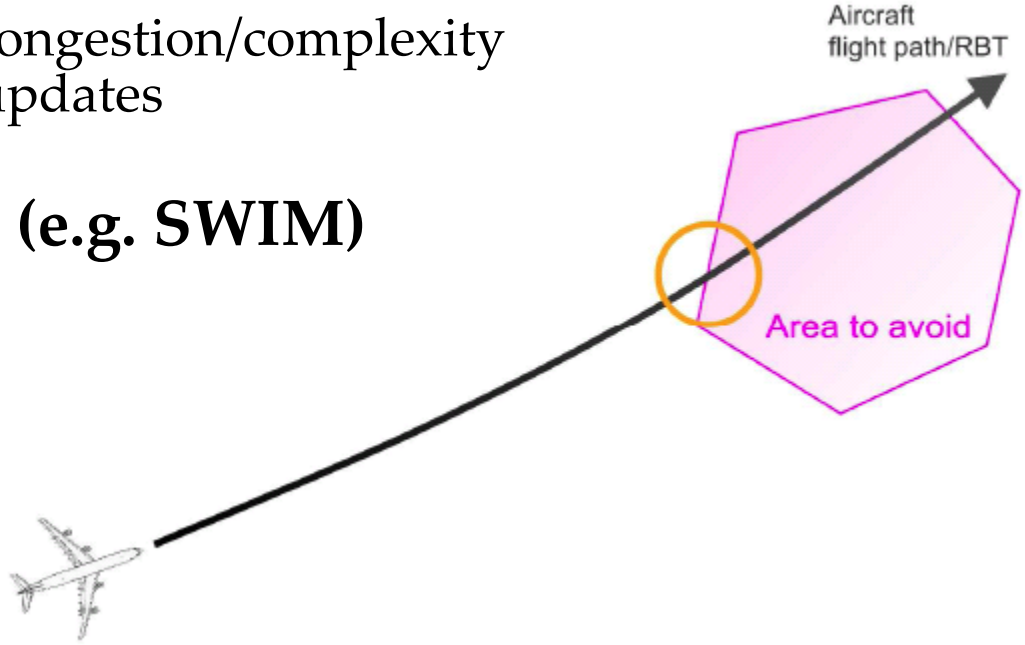
Different levels of CDR: Information



(Figure: iFly, D1.3)

Long term CDR

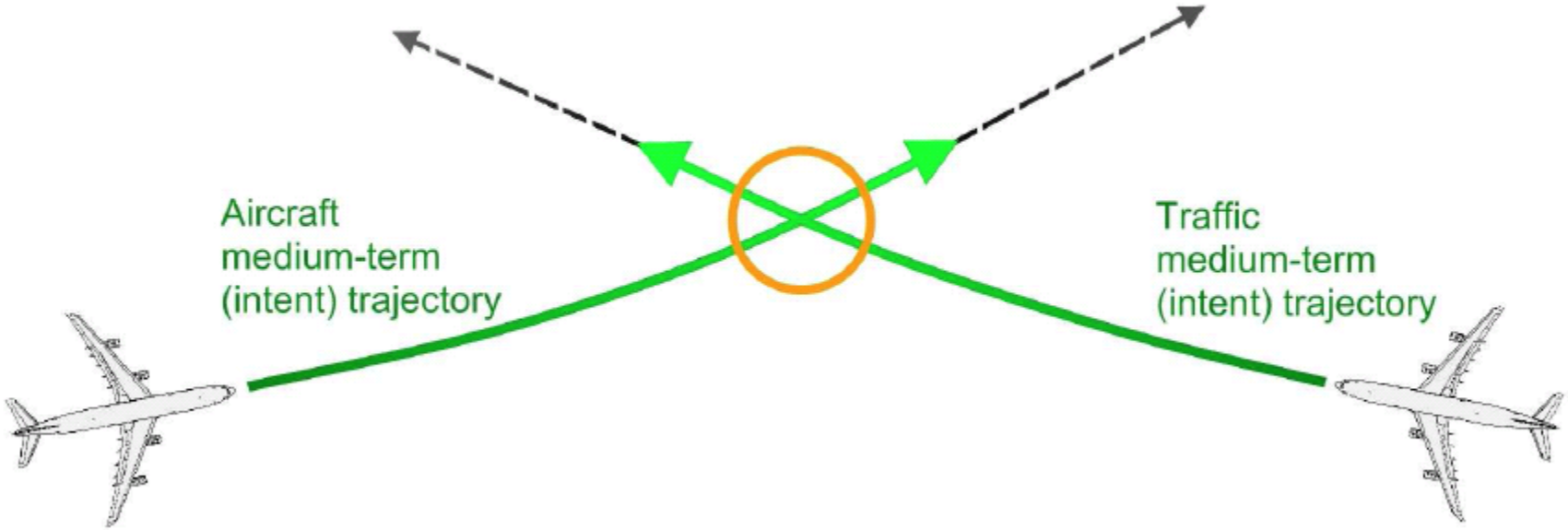
- **Horizons of tens of minutes to hours**
- **Not safety critical at this range**
- **On board trajectory management**
  - Areas to avoid due to weather
  - Areas to avoid due to congestion/complexity
  - Schedule tuning, RBT updates
- **"Global" information (e.g. SWIM)**
- **Candidate algorithms**
  - Optimization based



(Figure: iFly, D1.3)

Mid term CR

- **Horizons of ~20 minutes**
- **Safety critical, conflict most important concern**
- **Access to intent of other aircraft**
  - E.g. through ground based information system



(Figure: iFly, D1.3)

Mid term CR

- **Planning/execution horizons of several minutes**
- **Enough time to compute resolution**
  - E.g. through optimization
- **Enough time to coordinate with other aircraft**
  - E.g. broadcast solution for others to take into account
  - Possibly better suited for explicit coordination

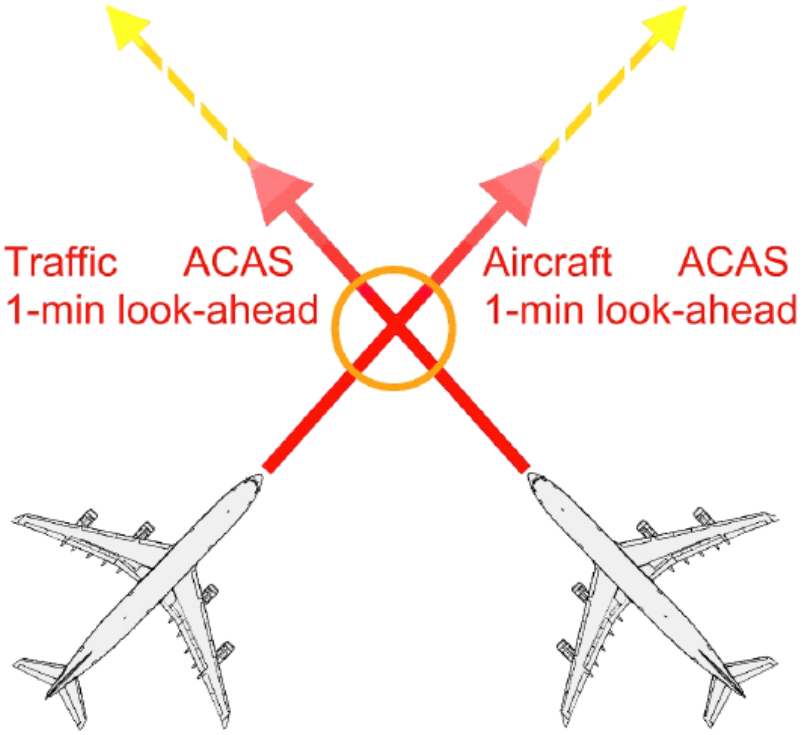
Short term CR

- **Horizons of < 5 minutes**
- **Safety critical, last line of defense before ACAS**
- **Short planning/execution horizons**
  - Fast, possibly implicitly coordinated maneuvers
  - E.g. robotic path planning
- **Access to potentially faster air-air data-link**
- **State based**
  - Measured directly by on-board equipment
  - E.g. positions and velocities of other aircraft
- **First level of intent**
  - Communicated through air-air data-link
  - E.g. next goal of each aircraft

ACAS

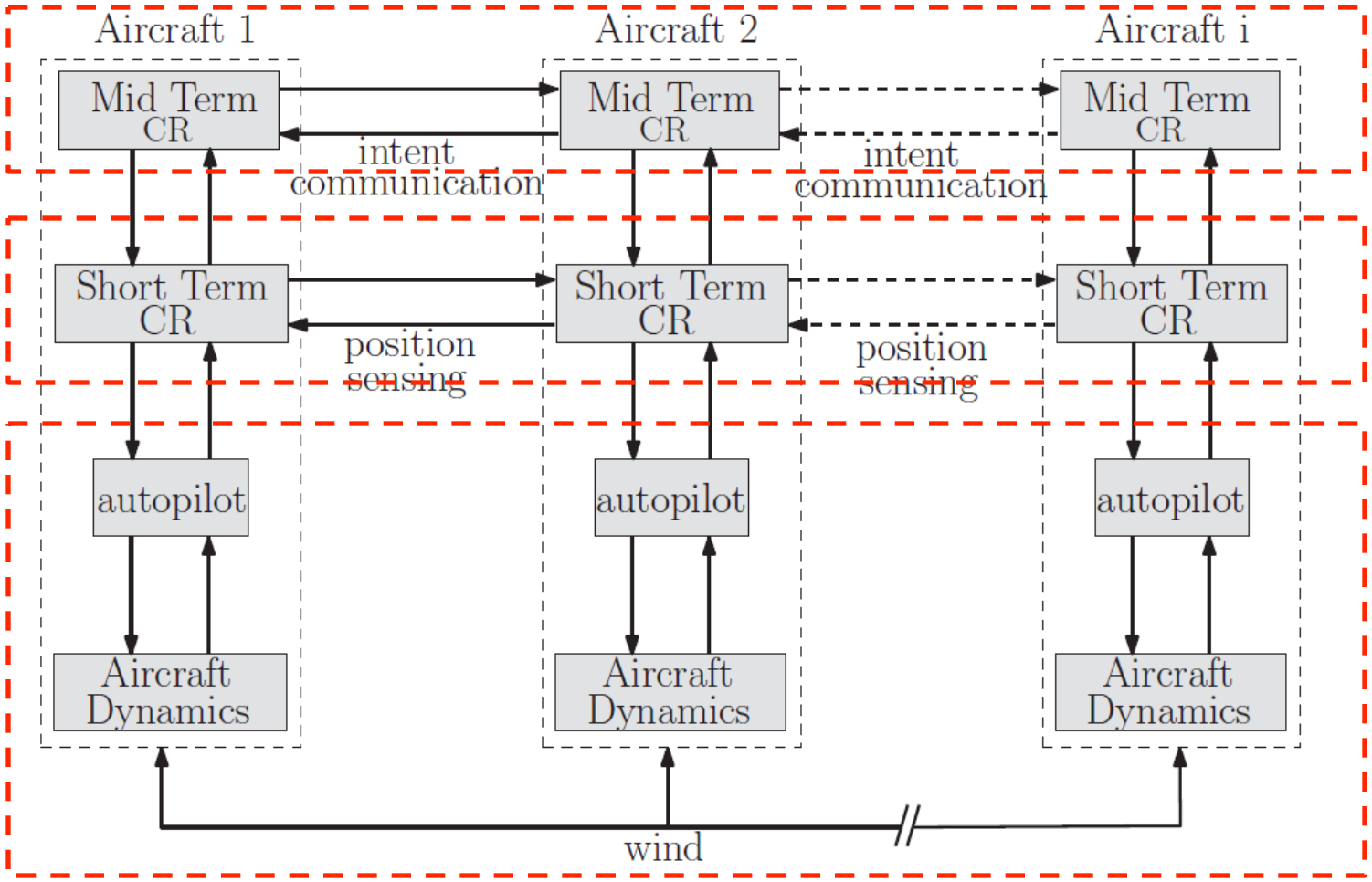
- Horizons of ~1 minute
- Last safety net
- State extrapolation
- ACAS interference concern for other

  CDR levels
- E.g. avoid creating 2 minute state conflict



(Figure: iFly, D1.3)

CDR hierarchy in iFly concept



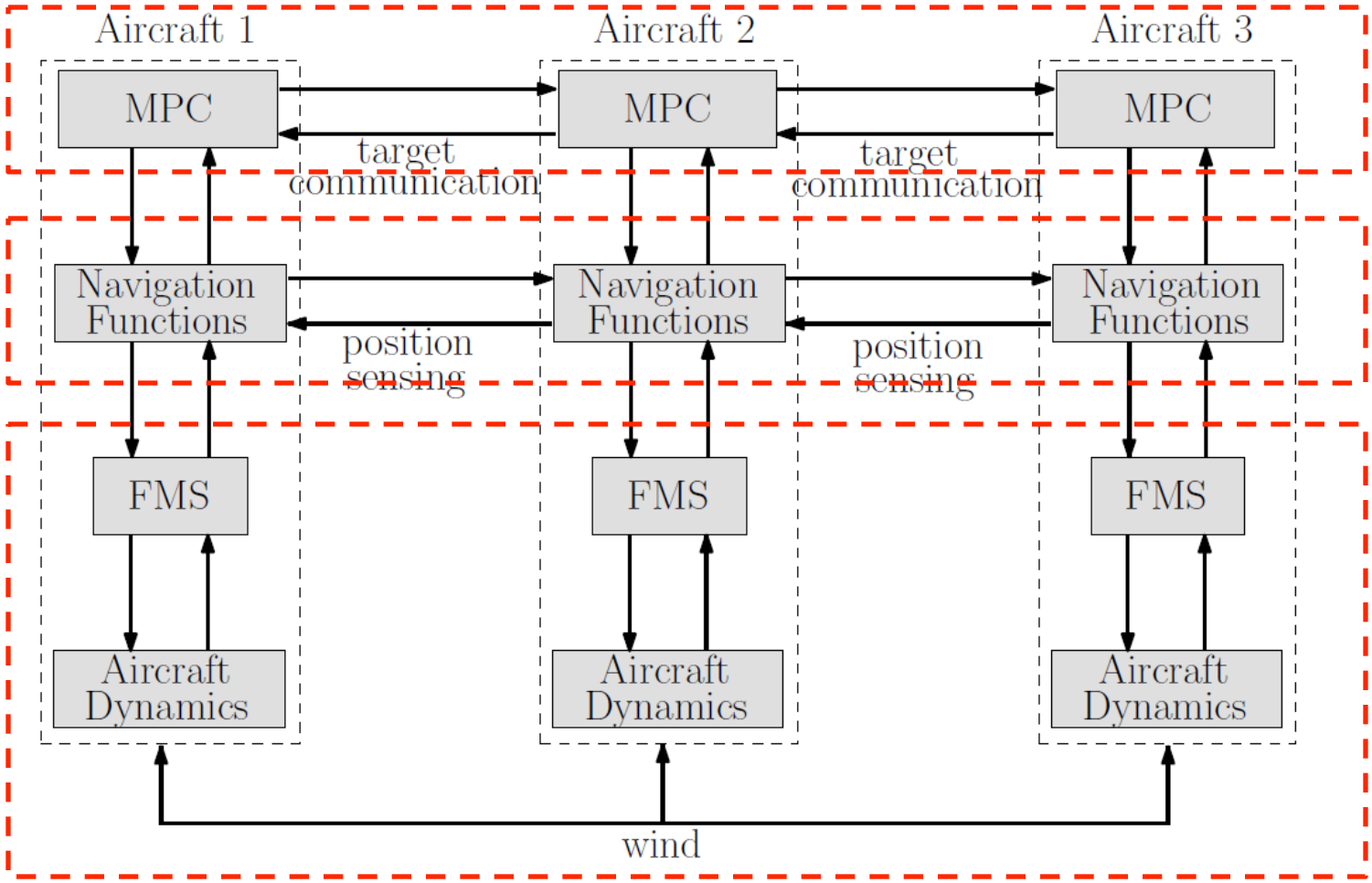
(Figure: iFly, D5.3)

Corresponding algorithm hierarchy

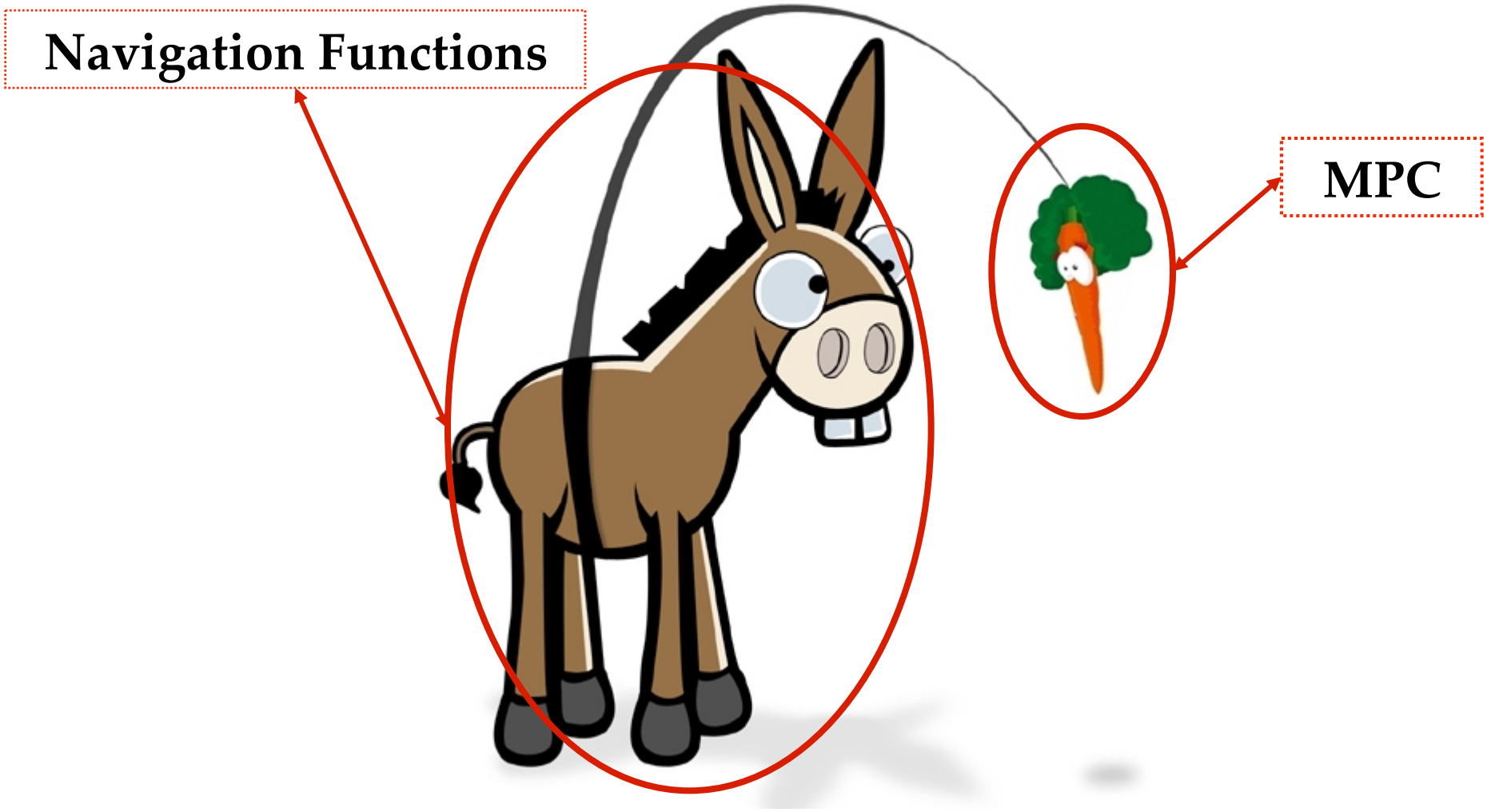
Mid Term

Short Term

Navigation



Joint short- mid-term CDR



Joint short- mid-term CDR

- **Navigation functions + MPC**
  - Combining mid-term and short-term methods
  - Navigation functions often require unrealistic inputs
  - Airspeeds, turning rates, etc.
  - Problem arises due to lack of preview
  - Provide preview through MPC

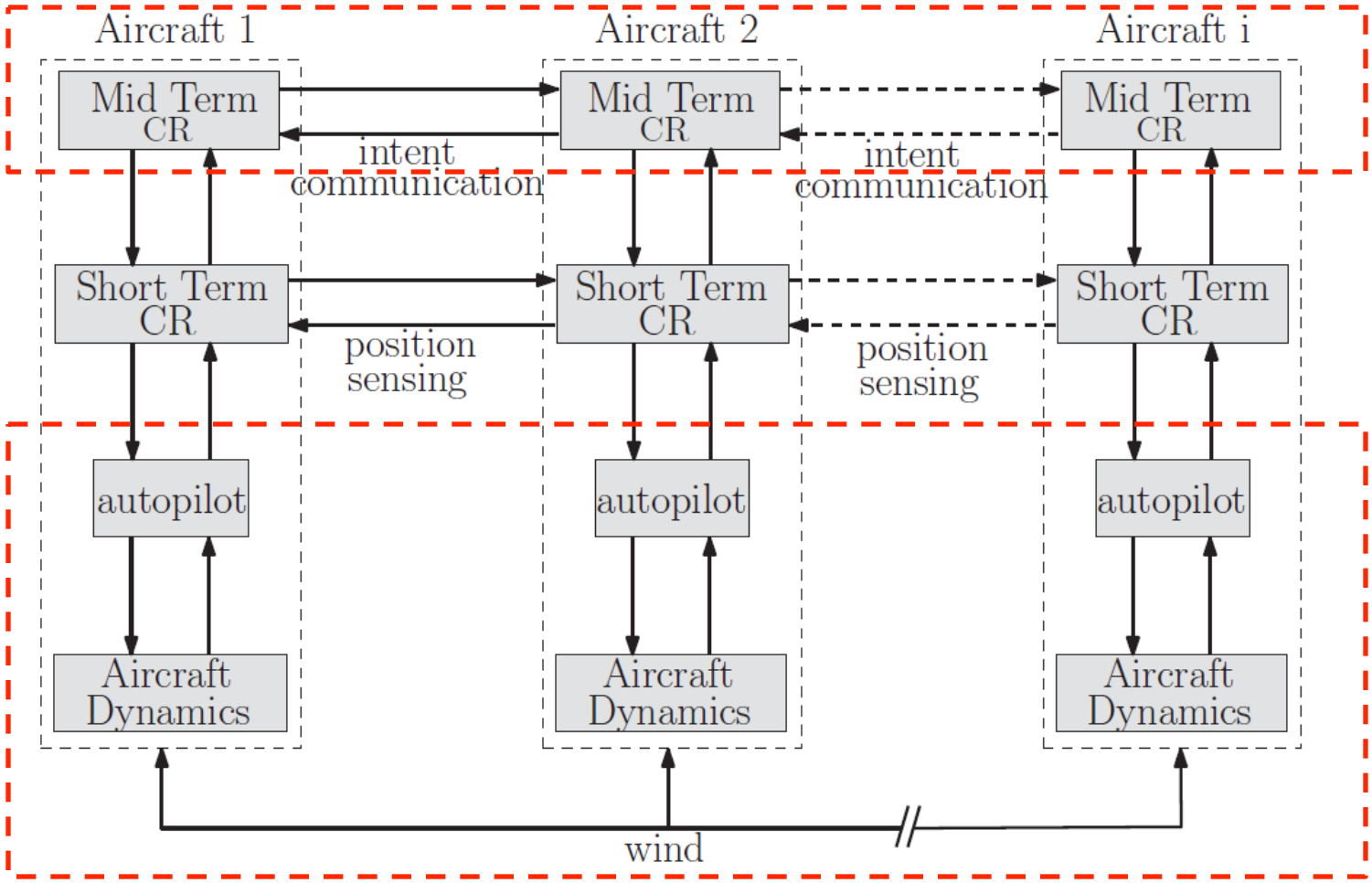
- **Algorithm outline**
  - Use MPC to set goal of NF (say for the next 20 minutes)
  - Fly using NF for a few minutes (say 5)
  - Re-plan the goal and repeat

- **Disadvantages**
  - Difficult to incorporate priorities
  - Based on randomized methods
  - Not clear whether algorithm reaches global optimum
  - Validation for many aircraft impractical

Validation: Mid term CDR

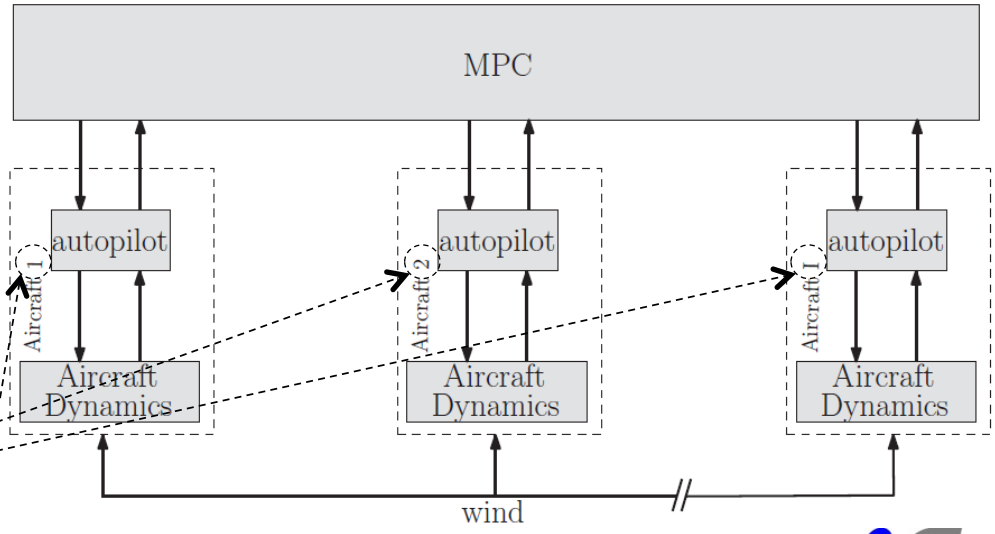
Mid Term

Navigation



MPC with Priorities

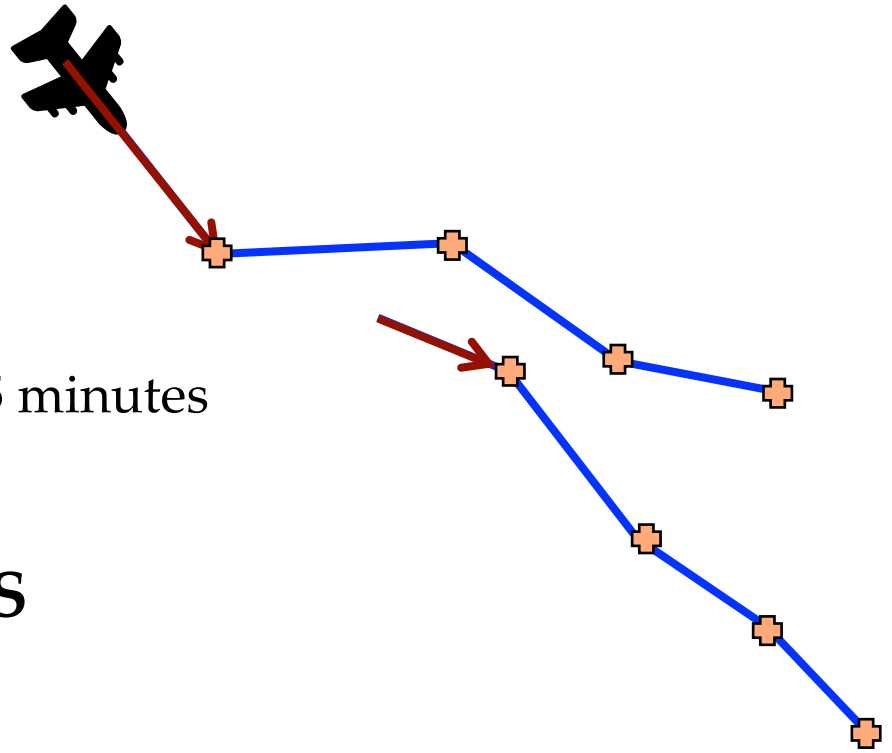
- **Problem requirements:**
  - Identify and resolve conflicts on time
  - Be efficient in terms of fuel consumption
  - **Respect priorities**
    - **Aircraft with higher priority should not maneuver unless there is no other option to avoid a conflict**
  - Respect operational constraints for speed
  - Respect passenger comfort
    - Bounded accelerations
  - Be able to resolve big traffic instances



Priority Numbers:
Higher numbers indicate higher priority

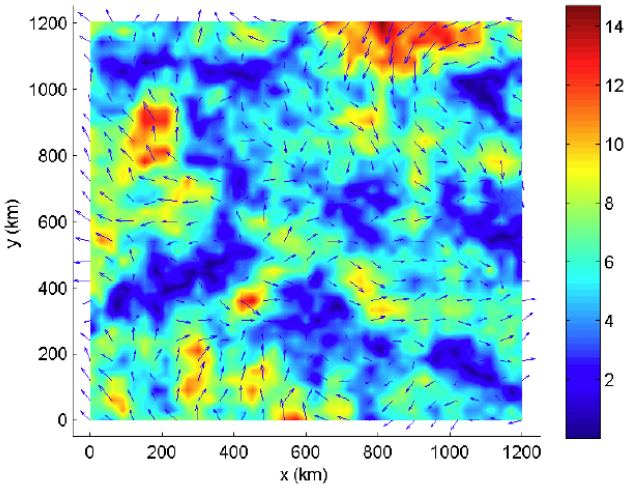
MPC with Priorities

- **Optimization based algorithm**
- **Cost = deviation from nominal flight plan & airspeed**
- **Constraints**
  - Bound on airspeed
  - Separation constraints
- **Compute optimal solution**
  - Every 3 minutes
  - Optimal flight path for next 15 minutes
  - 5 waypoints every 3 minutes
- **Enter first way point in FMS**
- **Repeat after 3 minutes**



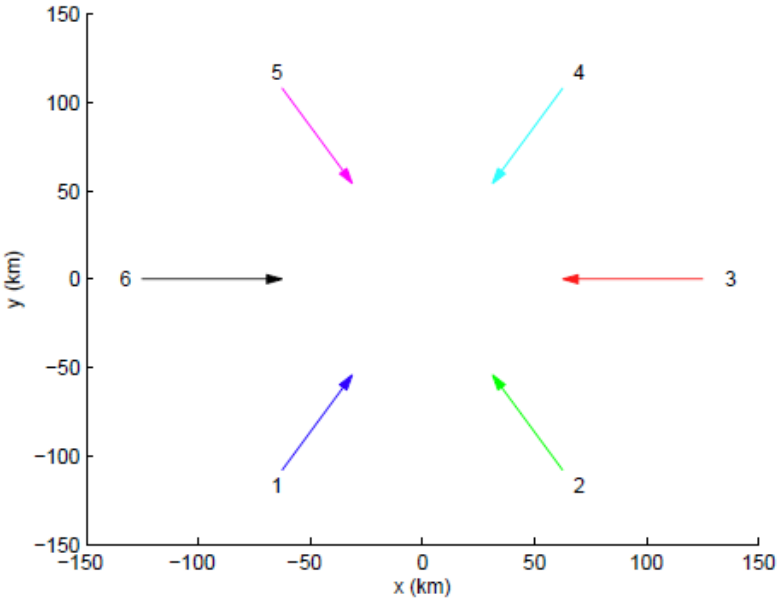
MPC with Priorities

- **Approximations for computational efficiency:**
  - Dynamics approximated by linear
  - Separation constraints approximated as linear + binaries
  - Acceleration and speed constraints approximated as linear
- **Priorities implemented by binary variables**
- **Extra priority: Loss of separation**
- **Wind uncertainty**
  - Might take large values
  - Aircraft flying close experience similar wind
  - Also more likely to be in conflict!



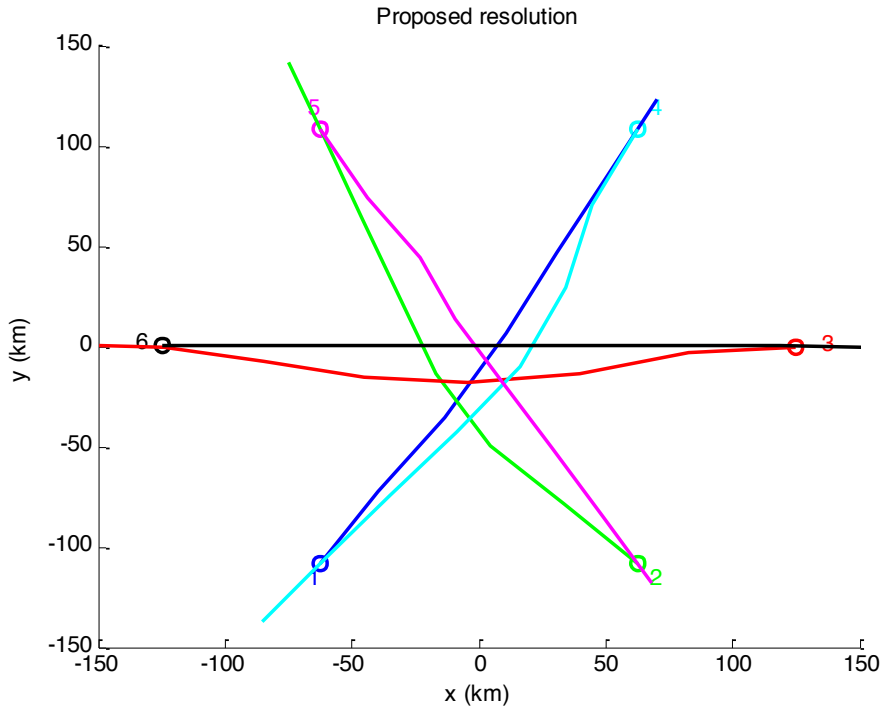
Converging aircraft scenario

- 4 to 8 aircraft heading to mid-air collision
- Update every 3 minutes, prediction horizon 15 minutes
- Robust against most wind scenarios, i.e. for 99.7% of the cases
- Because of extreme winds & model mismatches robust feasibility might be lost
  - Attempt to maximize separation in such cases

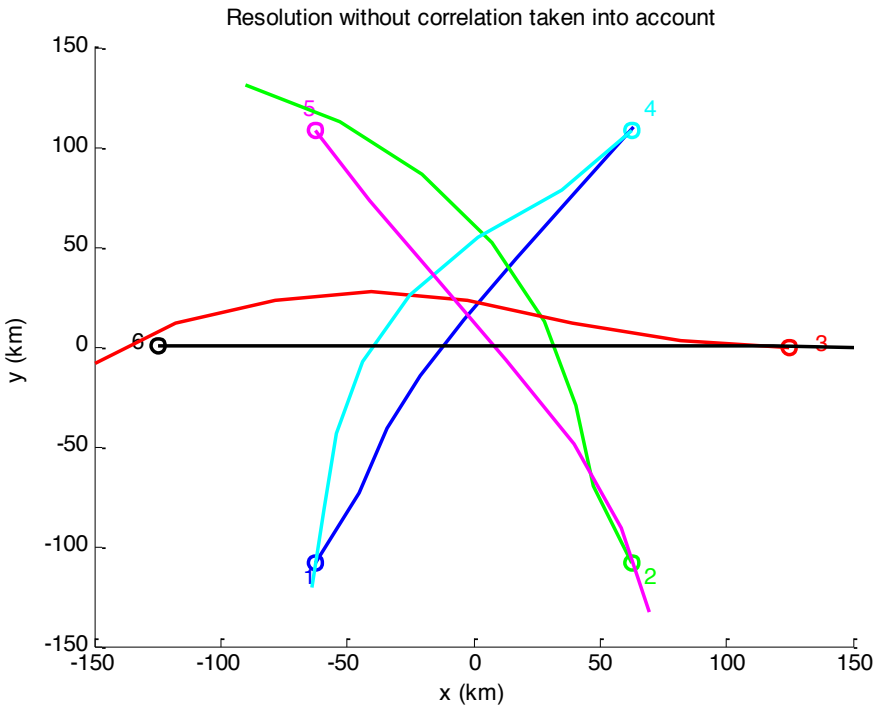


Conflict Resolution Results

Algorithm with priorities and correlation



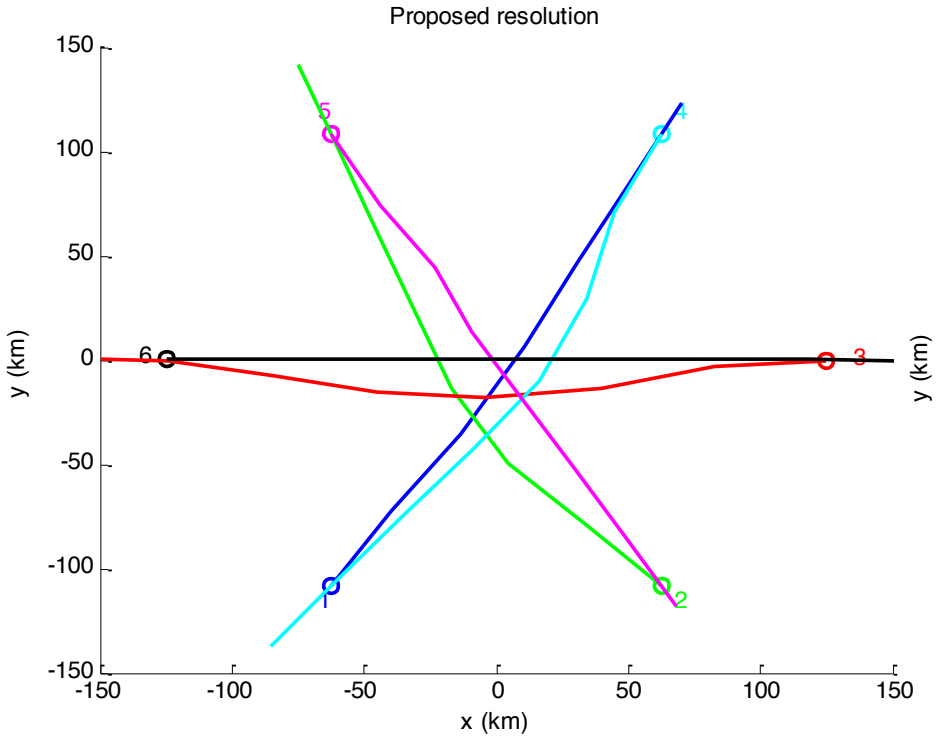
Algorithm without correlation



More than twice extra distance flown!

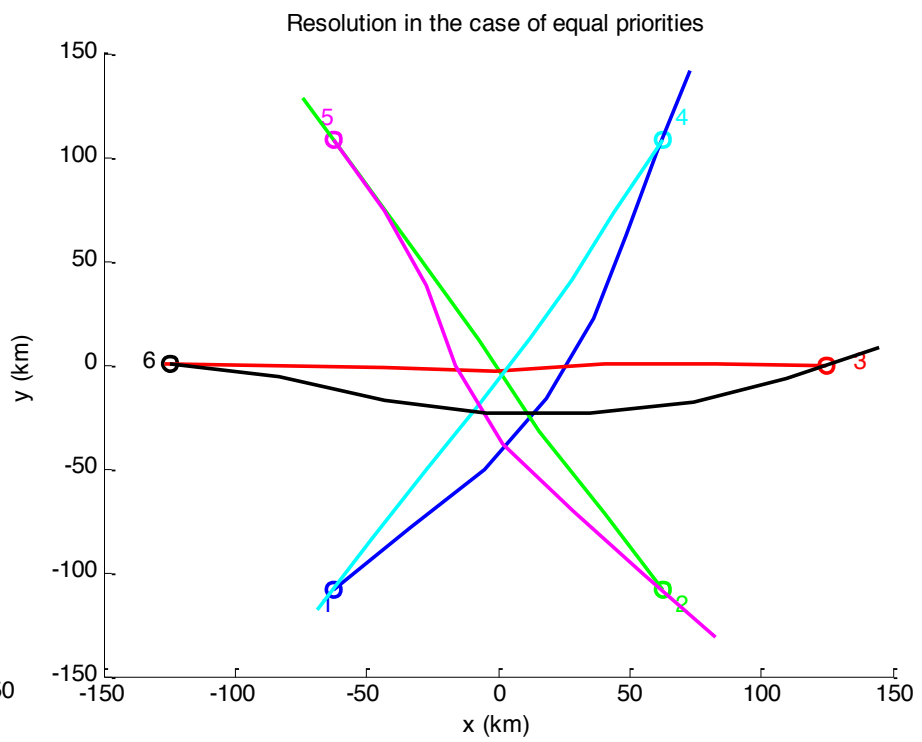
Conflict Resolution Results

Algorithm with priorities and correlation



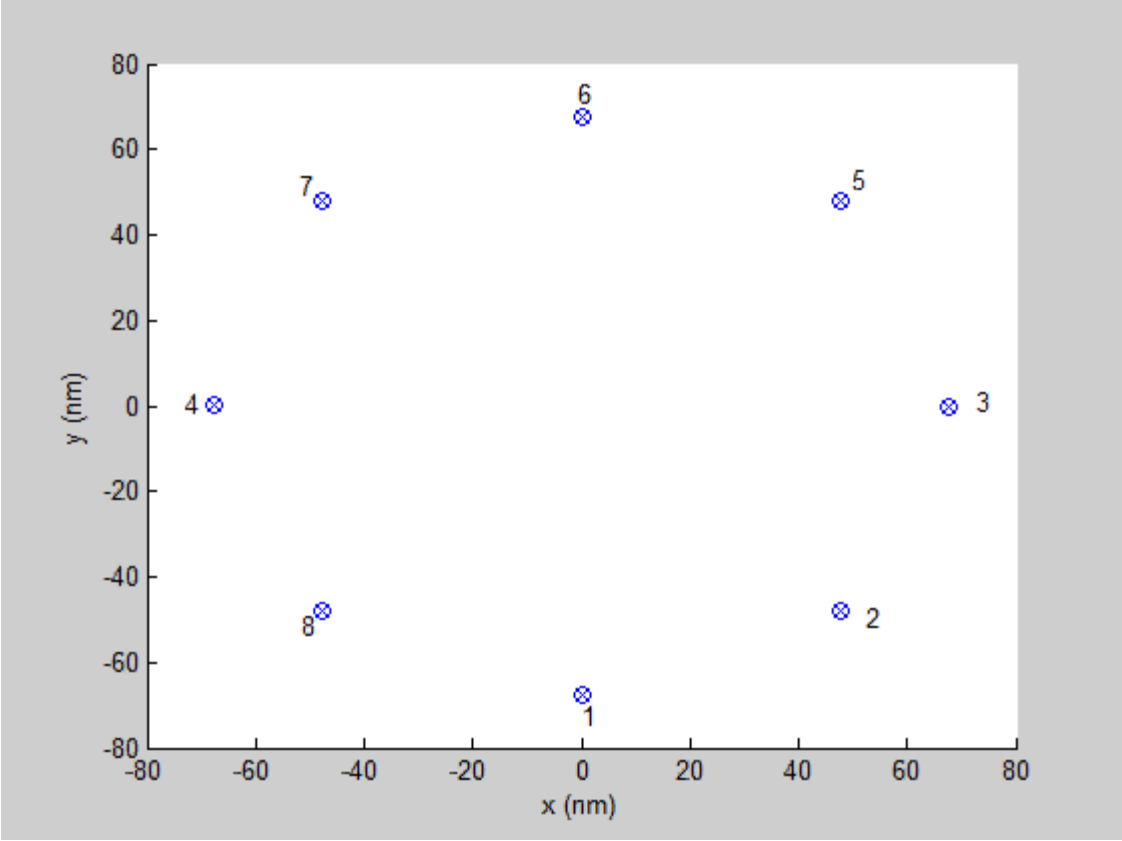
Uneven distribution of extra distance flown

Algorithm without priorities



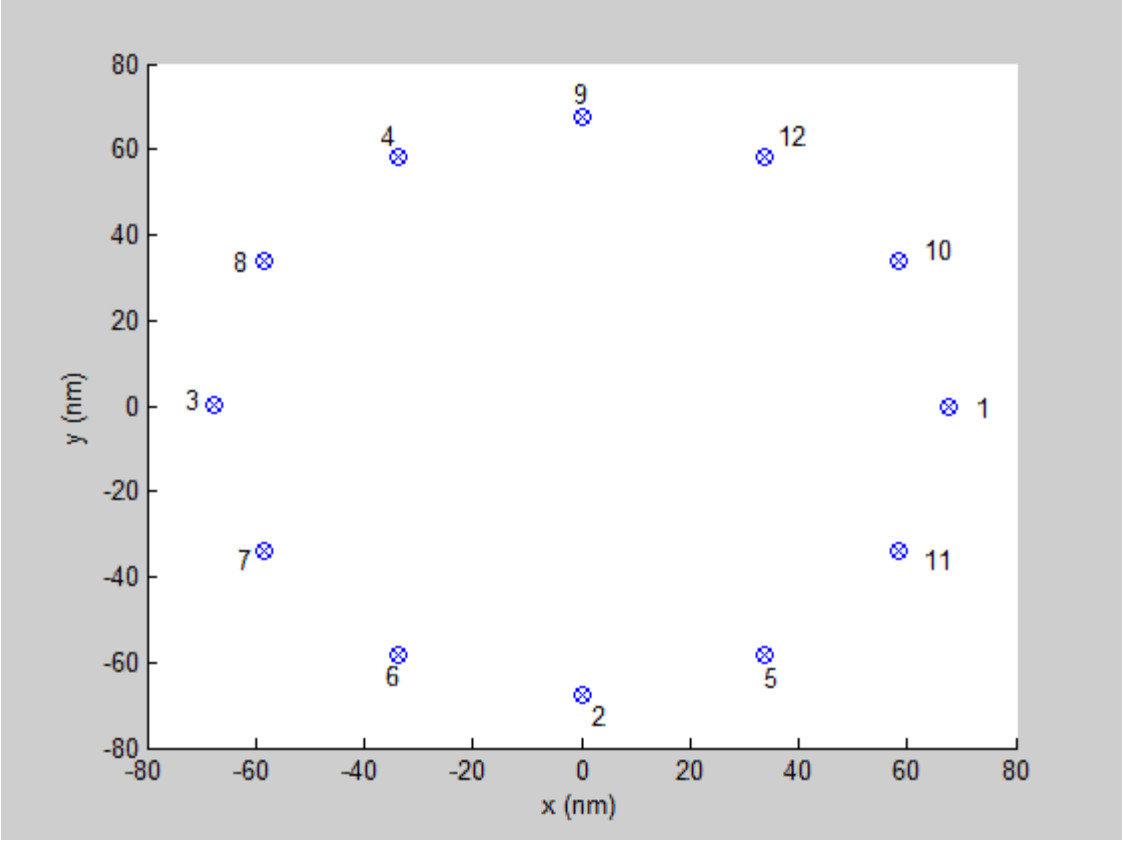
Total extra distance flown somewhat greater

8 Converging aircraft



- Priority according to number
- Red → aircraft currently not flying straight to destination

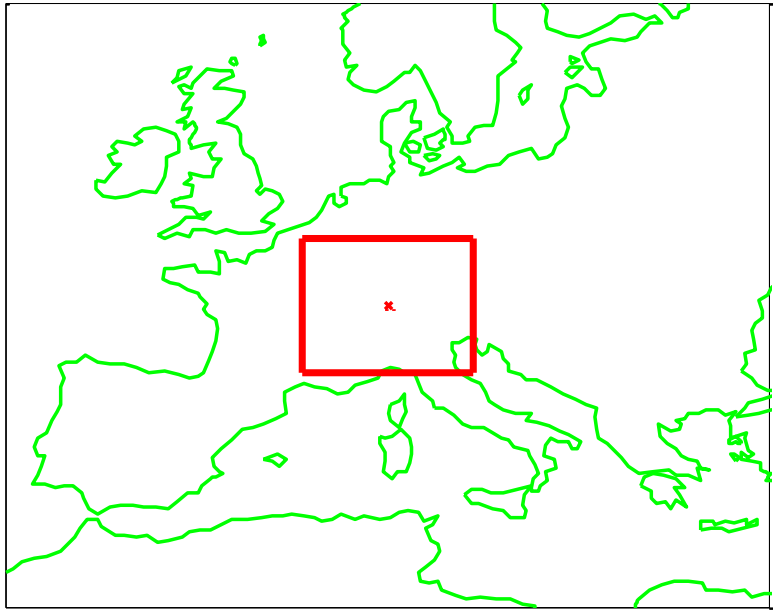
12 Converging aircraft



- Priority according to number
- Red → aircraft currently not flying straight to destination

2035 Traffic Sample

- **Traffic sample provided by Eurocontrol**
  - Based on projection for 2035
  - Triple as much traffic as in 2006
  - Flight plans for 1 day
  - Flights that start, end or pass through area of 400x400nm centered at Zurich



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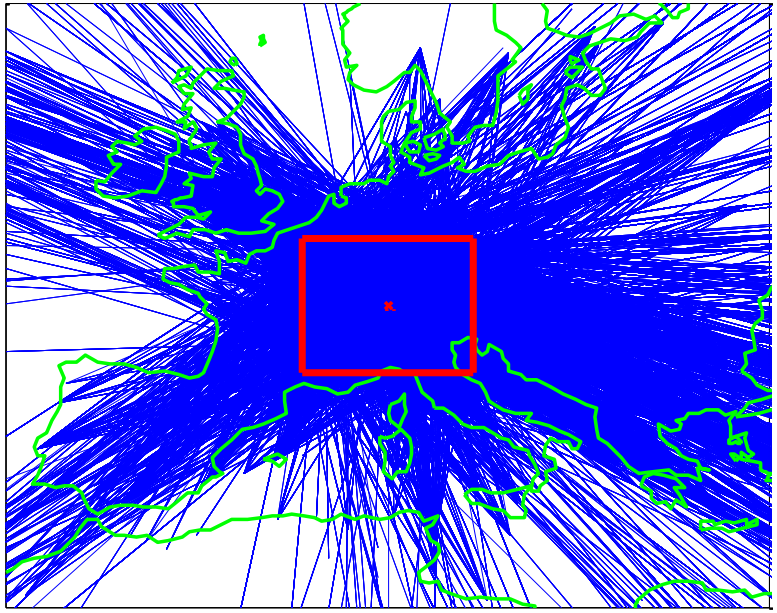
- **Traffic sample provided by Eurocontrol**
  - Based on projection for 2035
  - Triple as much traffic as in 2006
  - Flight plans for 1 day
  - Flights that start, end or pass through area of 400x400nm centered at Zurich

- **35588 flights in total**

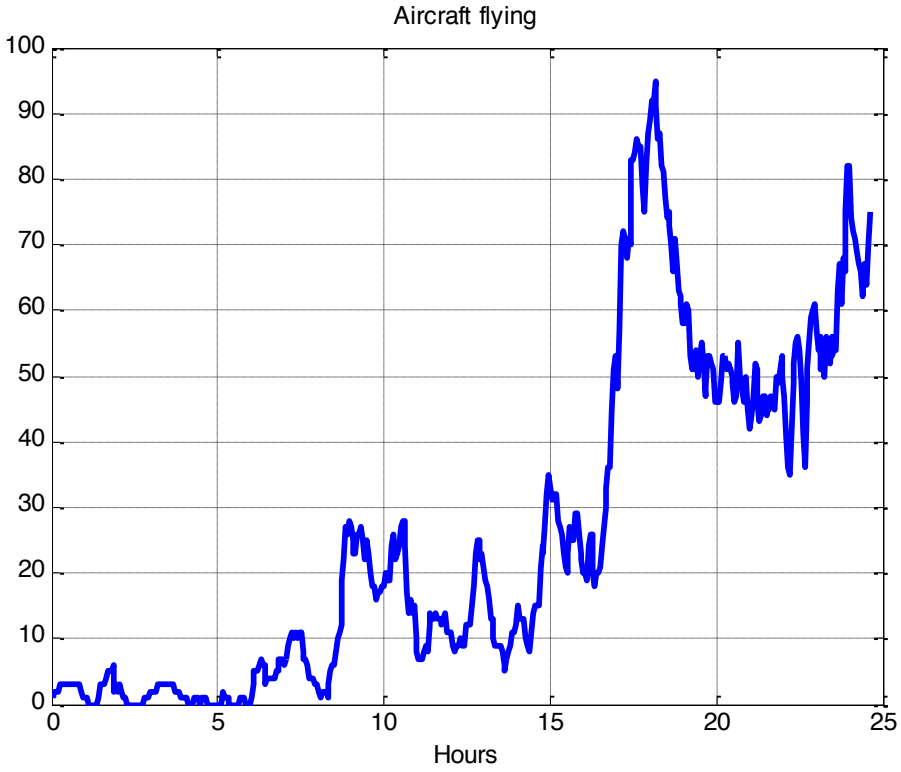


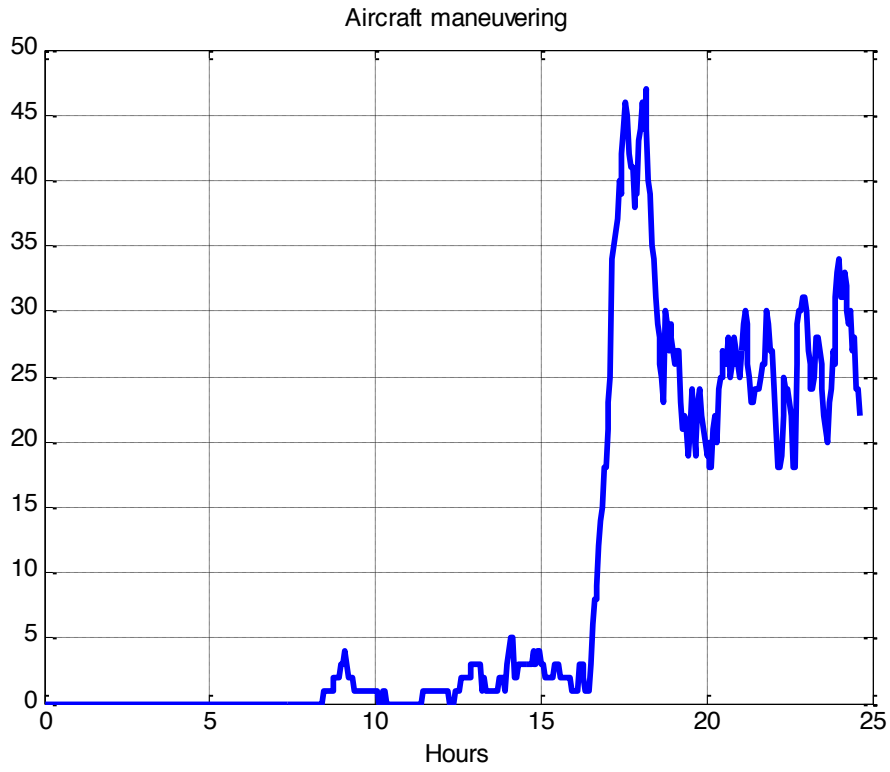
2035 Traffic Sample: Modifications

- **Assign flight levels,**
  - According to BADA flight levels for aircraft type
- **Some flights start at exactly the same time & point**
  - Separate them by one artificial minute
- **Hundreds of aircraft flying simultaneously**
  - Partition problem into smaller ones
  - Examine which aircraft are in potential conflict with which
  - Construct graph
    - Aircraft as nodes
    - Potential conflicts as edges
  - Determine connected components and solve them separately
- **Initial simulations for one flight level and without wind feasible (in terms of computation time)**
  - Up to ~200 aircraft simultaneously per flight level

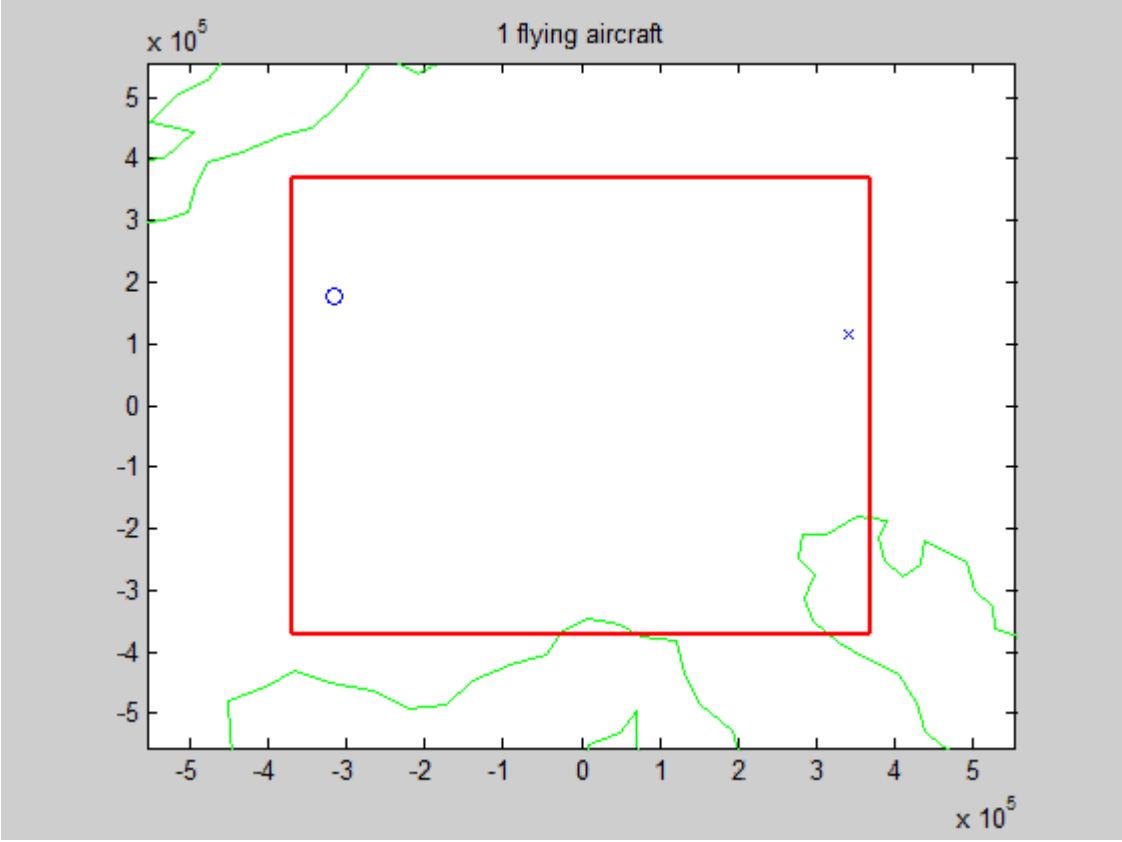
2035 Traffic Sample: Initial Results

Execution time: 10 hours (2.5x real time)





Big traffic sample



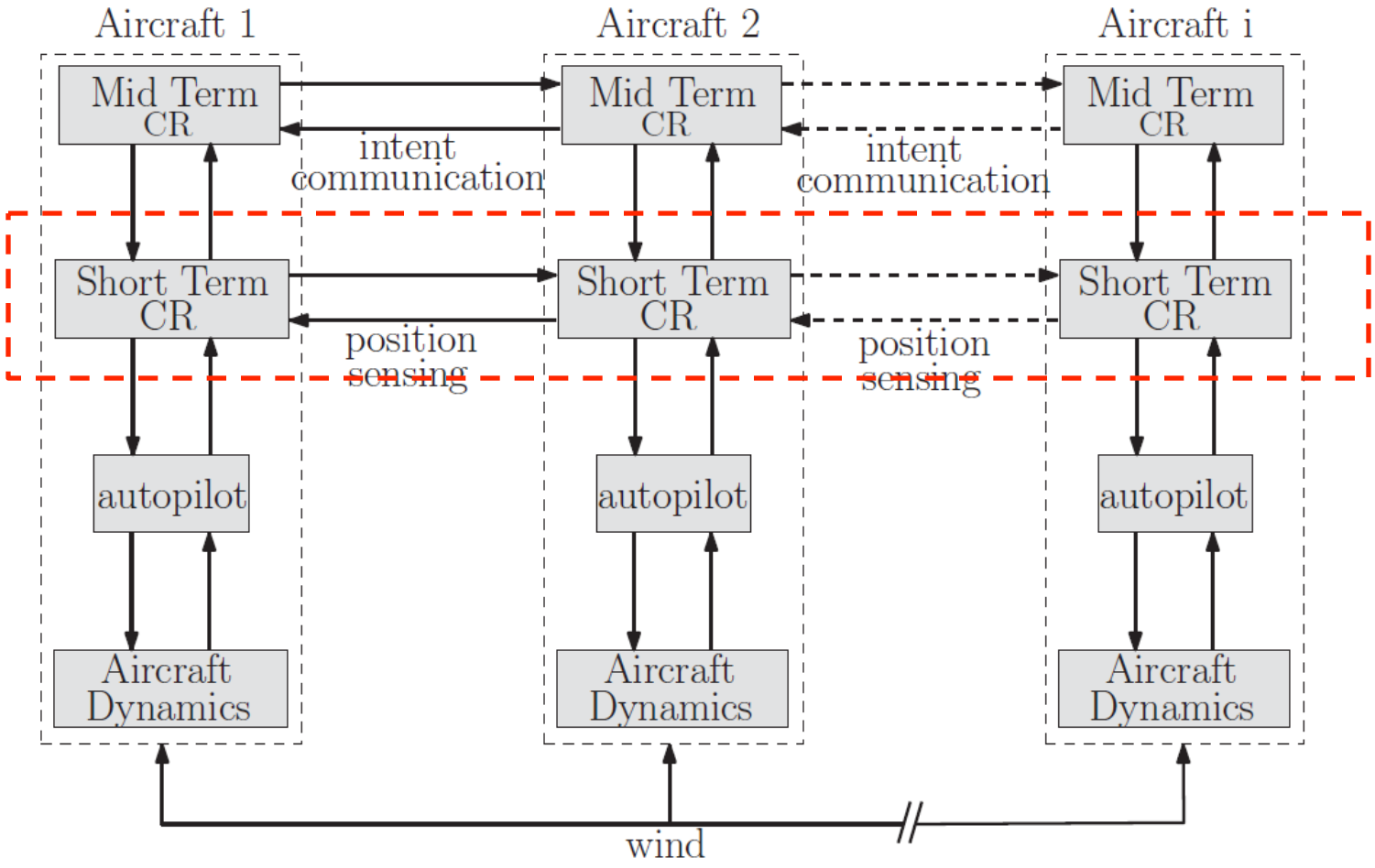
Traffic at 35000ft

2035 Traffic Sample: Initial Results

- **On going, so far:**
  - 1895 aircraft
  - 1038 admitted at 35kft
  - 857 send to lower flight levels
  - 995 have completed their flight path at their initial flight level
- **No conflicts occurred**
  - Assuming perfect wind and model!
  - Monte-Carlo investigation on-going
- **Resolution not as demanding as one would expect**
  - “Easier” than the converging aircraft case
  - Aircraft reasonably separated/sequenced by “flight plan”

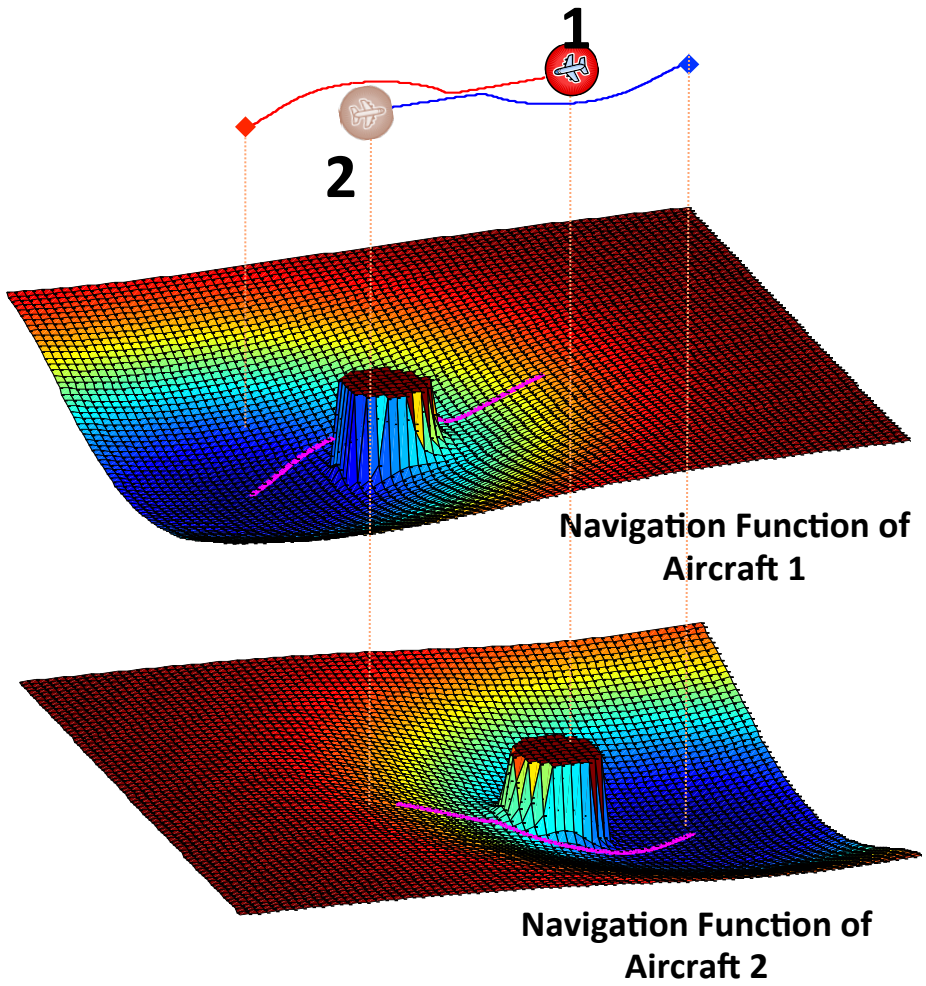
Hierarchy in iFly concept

Short Term



Navigation Functions for Aircraft CD&R

- **Artificial Potential Field**
  - Attractive goal
  - Repulsive obstacles
- **Real-time feedback**
  - Computationally fast
  - Handle errors, wind
- **Formally guaranteed conflict avoidance and convergence to the goal**

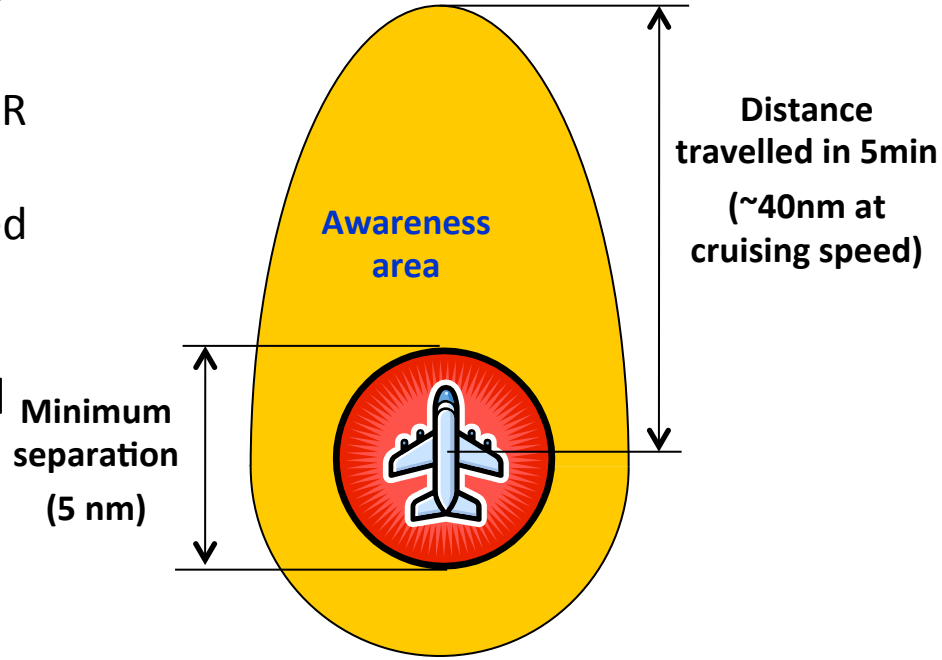


Modification: Local awareness

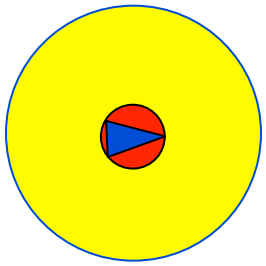
- **Local awareness area for each aircraft**
  - Complete decentralization
  - No clustering/grouping required
  - No “encounter” definition

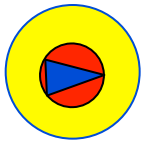
- **Awareness area shape chosen to enable timely resolution and reduce deviation**
  - Forward range to match Short-term CD&R time horizon
  - Reduced side and rear range for improved efficiency

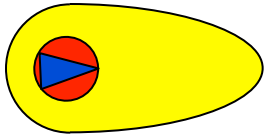
- **Aircraft outside awareness area ignored in navigation function calculation**
  - Efficiency improvement

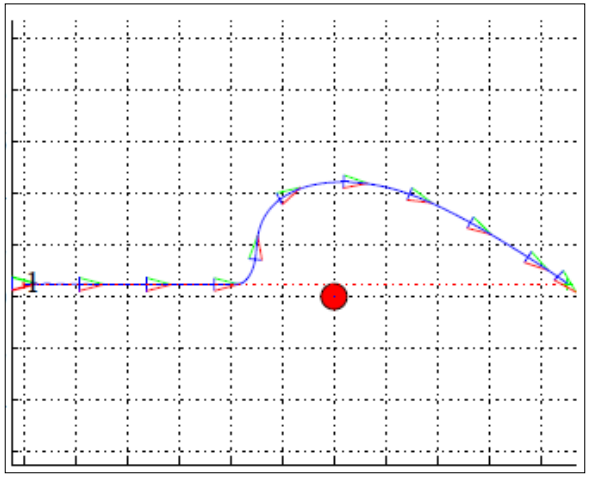


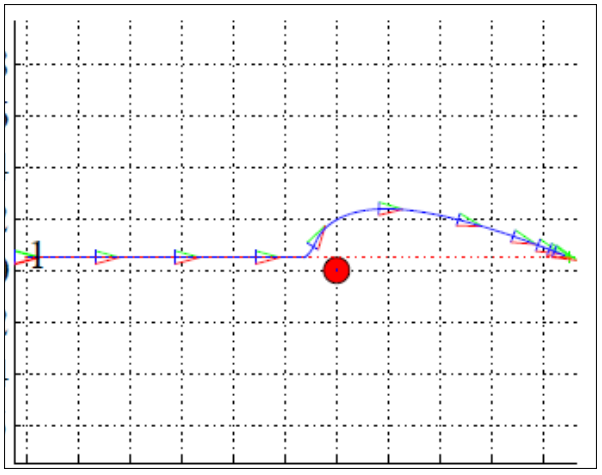
Sensing scheme effect

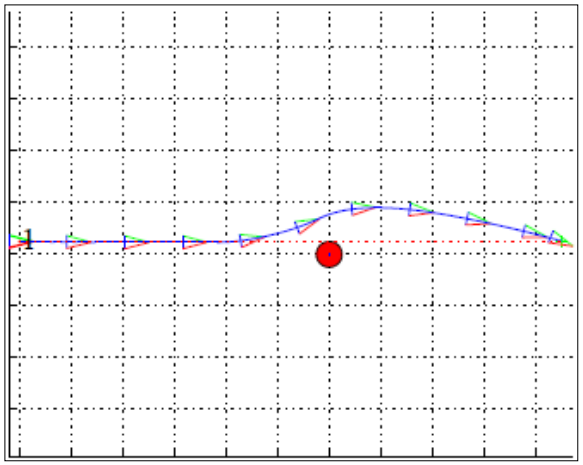












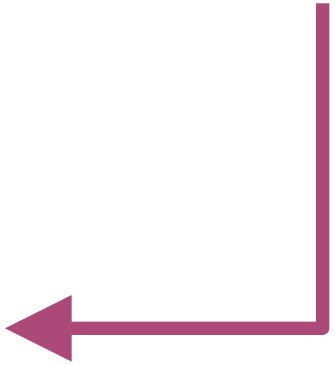
Computation Time	25s	26s	20s
Path length	7.56	6.59	5.13
Total steering angle	6.11	5.00	3.66

Aircraft Control Scheme

- **Main Idea: Each aircraft follows direction that minimizes its NF potential value**

- **Requirements**
  - Ensure **decreasing potential** for conflict avoidance and convergence to the destination
  - **Reduced maneuvering**

- **Simple Control Logic Used**
  - Continuous switches based on
    - **Evolution** of potential value
    - **Distance** from the target
  - Practical tuning parameters
  - Simple, predictable maneuvers

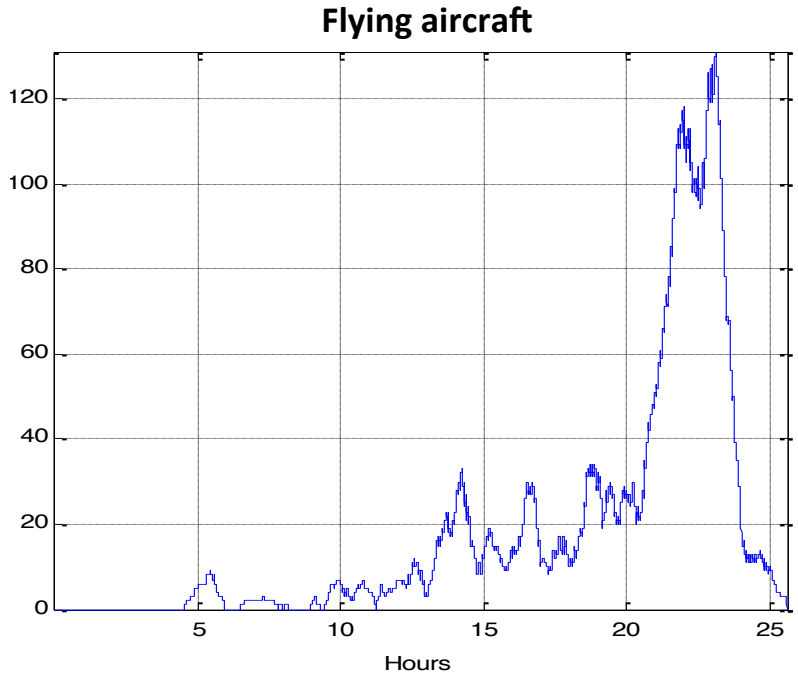


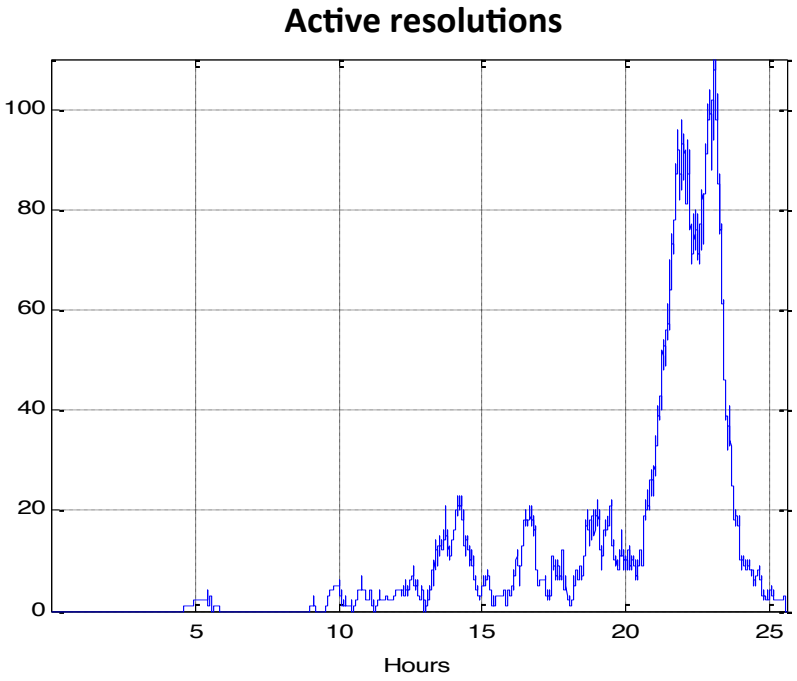
Navigation Functions with Air Traffic samples

- **Simplified SESAR Traffic sample provided by EEC**
- **Application of Navigation Functions with realistic flight samples**
  - Interest area around Zurich (~ 400x400nm)
  - Entry and exit points as start, goal
  - Realistic aircraft characteristics (cruising speed ~450knots)
  - Algorithm parameters to match Short-term CD&R (local awareness scheme)

2035 Traffic Sample: Initial Results

- Traffic Sample of 1000 flights
- 300 total flight hours simulated (1 sec control update)
- ~110 min execution time (for ALL aircraft) (~165x real time for single computer implementation)





2035 Traffic Sample: General impressions

- **No conflicts occur**
- **No major difficulties in running the scenarios**
- **Very small extra distance flown (typically << 1%)**
- **Algorithm significantly faster than real time**
  - Distributed implementation will be a lot faster