Metaheuristic Approach to Probabilistic Aircraft Conflict Detection and Resolution Considering Ensemble Prediction Systems

9 th SESAR Innovation Days

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Introduction

Ensemble Prediction Systems

Problem formulation

Results

Summary

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- Ensemble Prediction Systems
- Problem formulation
- Results
- Summary

Introduction

MOTIVATION AND OBJECTIVES

- The development of **automated decision support tools** is key in the future of **Air Traffic Management (ATM)** system. These tools must integrate and manage **uncertainty** present in the ATM.
- Sources of uncertainty:
  - Uncertainty in data and sensors.
  - Decisions taken by individuals.
  - **Weather uncertainty.**
- It is expected that by considering the weather prediction uncertainty, the **safety** and **efficiency** of the air traffic may be improved.

Objective:

- **Expand the time horizon** of CD tools currently in used in Europe (STCA, MTCD).

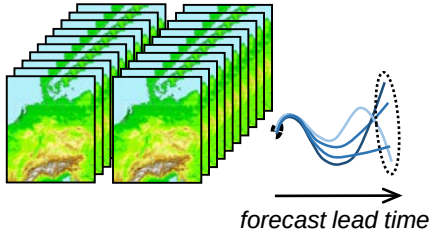
  Strategic Conflict Detection and Resolution (CD&R) methodology that considers **wind and temperature uncertainties** for hundreds of aircraft, and a **time horizon of 60 minutes**.

Introduction

APPROACH

Uncertainty source: **wind** and **temperature**

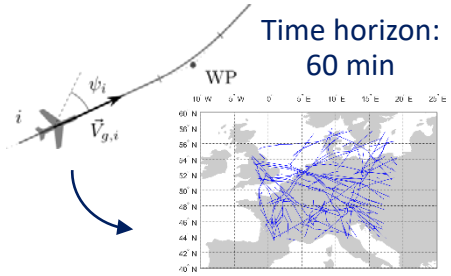
Ensemble Prediction Systems



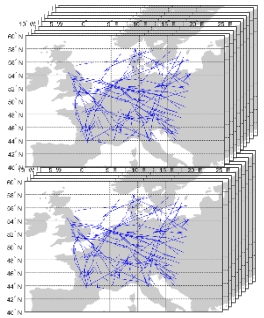
COSMO-D2-EPS

Flight plans

Ensemble trajectory prediction



Time horizon: 60 min

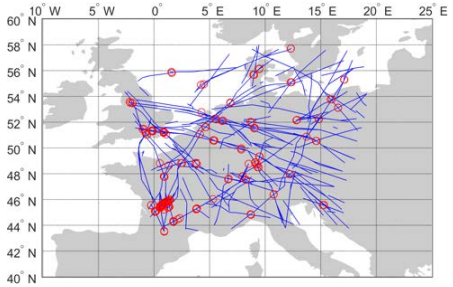


N Aircraft

20 trajectory members

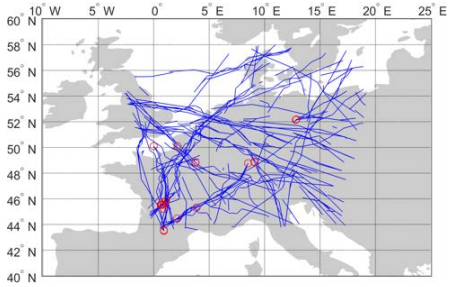
Probabilistic conflict detection (CD)

- Probability of conflict P_{con}
- Grid-based conflict detection



Probabilistic conflict resolution (CR)

- Lower the prob. of conflict
- Vectoring
- Minimise deviation
- Simulated annealing



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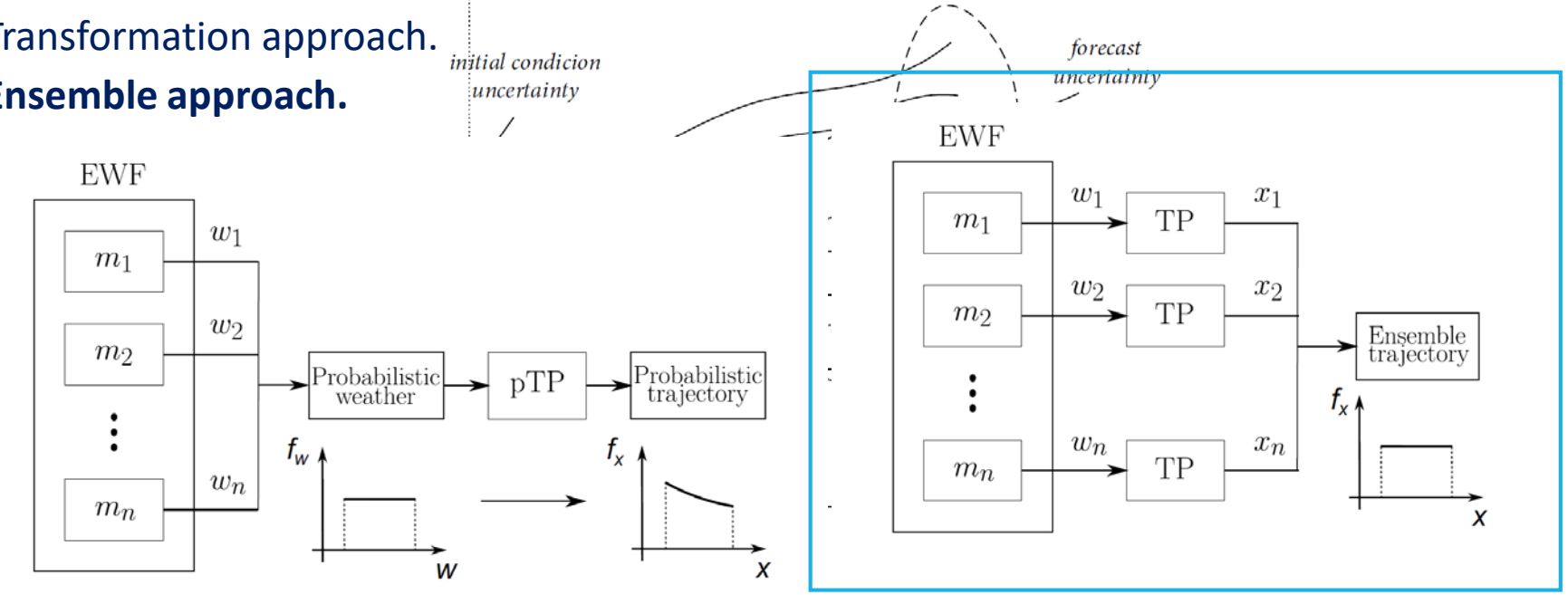
Ensemble Prediction Systems

ENSEMBLE PREDICTION SYSTEMS

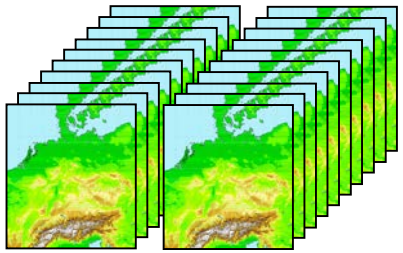
- An ensemble weather forecast is a collection of members that constitute a representative simple of the potental states of the weather outcome.
- Using EPS for trajectory prediction:
  - Transformation approach.
  - **Ensemble approach.**

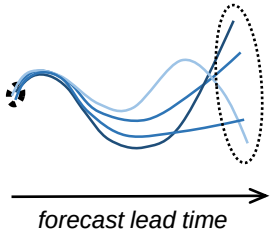


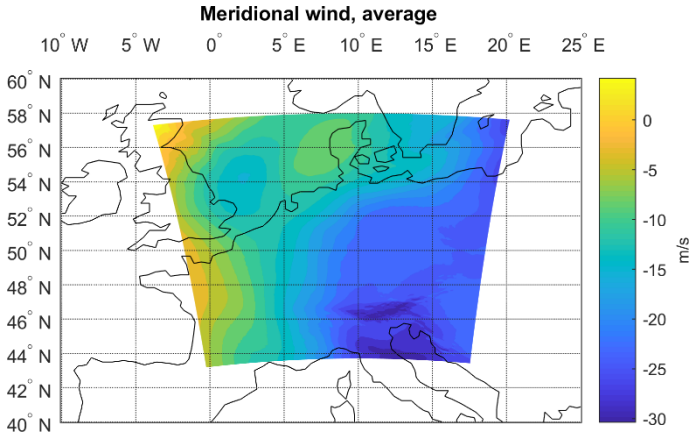
Ensemble Prediction Systems

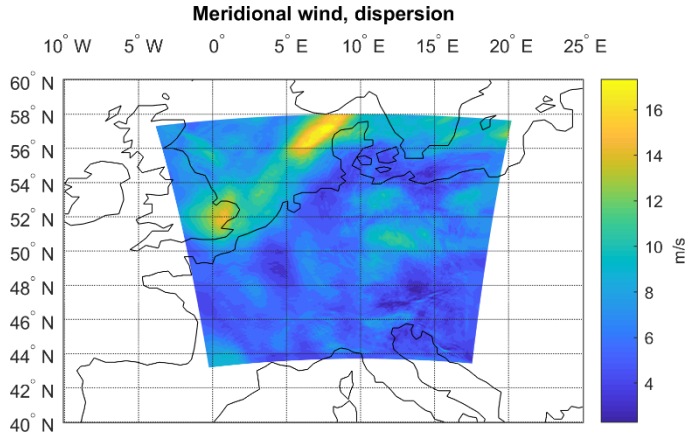
COSMO 2D-EPS

- Developed and operated by the German Weather Service.
- 20 members.
- Horizontal resolution: 2.2km.
- Vertical resolution: 65 atmosphere levels.
- 27 hour forecast every 3 hours.





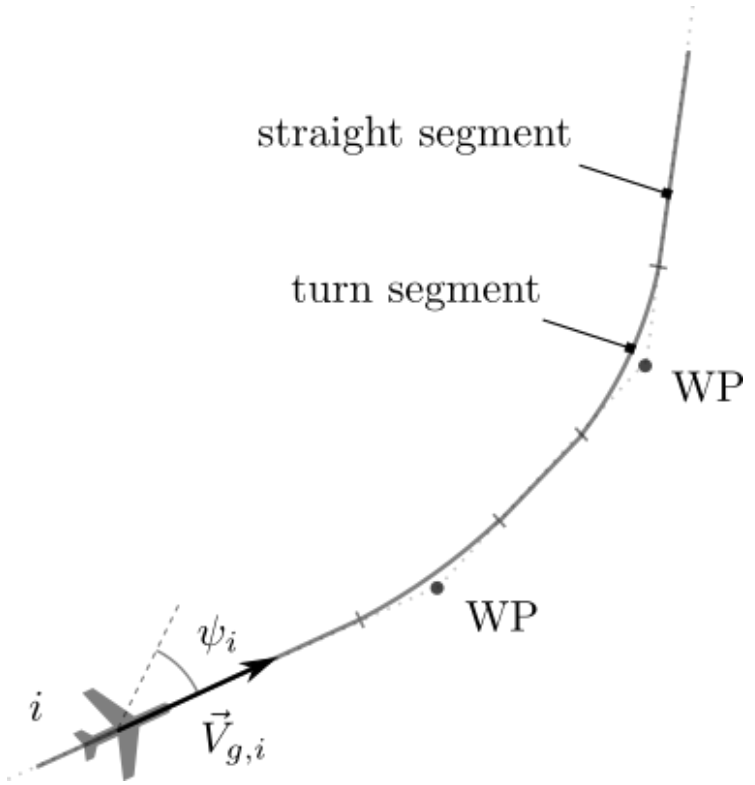




Problem formulation

ENSEMBLE TRAJECTORY PREDICTION: ASSUMPTIONS

- **N aircraft** flying in the same airspace and altitude.
- Multisegmented 2D trajectories defined by **waypoints**.
- **Initial positions are certain and known**.
- **Constant Mach** number, certain and known.
- The aircraft are affected by **horizontal uncertain winds** (w_λ, w_φ), and **air temperature** Θ.
- Spherical, non-rotating Earth model.
- Aircraft motion: point mass with three degrees of freedom.
- Constant radius turns, with no turns at the origin and destination waypoints.
- Quasi-steady state, temporal derivatives of wind and temperature are negligible.



Problem formulation

ENSEMBLE TRAJECTORY PREDICTION: EQUATIONS OF MOTION

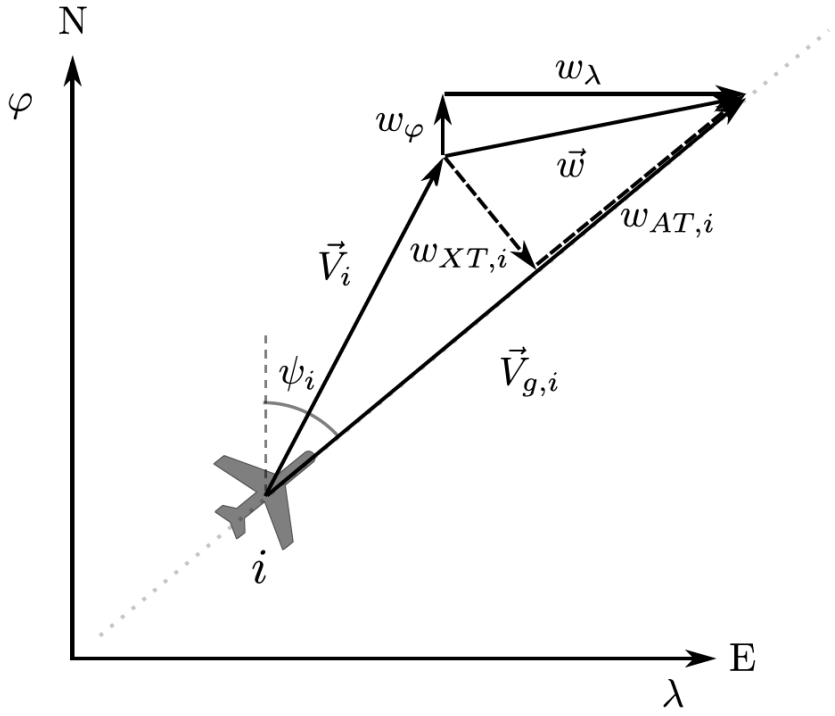
- Equations of motion of aircraft i:

$$\frac{d\varphi_i}{dt} = \frac{1}{R_E + h} V_{g,i} \cos\psi_i$$

$$\cos\varphi_i \frac{d\lambda_i}{dt} = \frac{1}{R_E + h} V_{g,i} \sin\psi_i$$

$$\frac{dr_i}{dt} = \frac{R_E}{R_E + h} V_{g,i}$$

$$\frac{d\psi_i}{dt} = \frac{1}{R_i} \frac{dr_i}{dt}$$



$$V_{g,i} = \sqrt{V_i^2 - w_{XT,i}^2} + w_{AT,i} \qquad V_i = M_i \sqrt{\gamma_g R_g \Theta}$$

Problem formulation

ENSEMBLE TRAJECTORY PREDICTION: EQUATIONS OF MOTION

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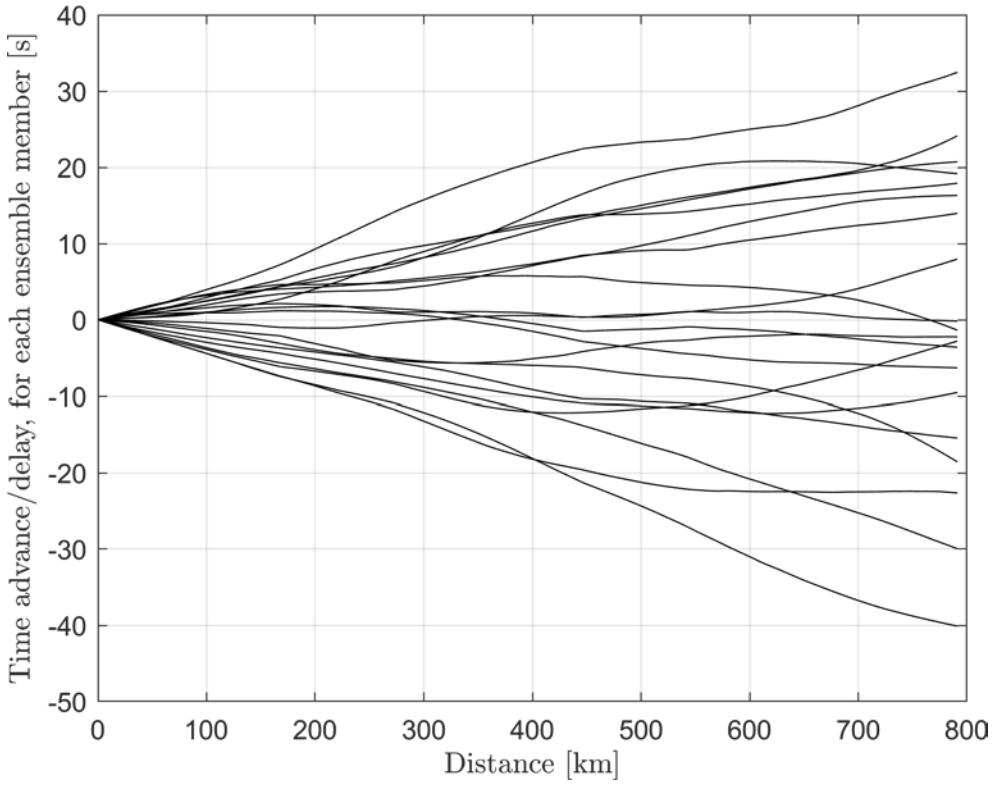


Problem formulation

CONFLICT DETECTION

- A conflict exists between two aicraft, i and j, when their distance of closest approach, d_{ij}, is predicted to be less than a given set of **separation minima** ($D = 5\text{NM}$).

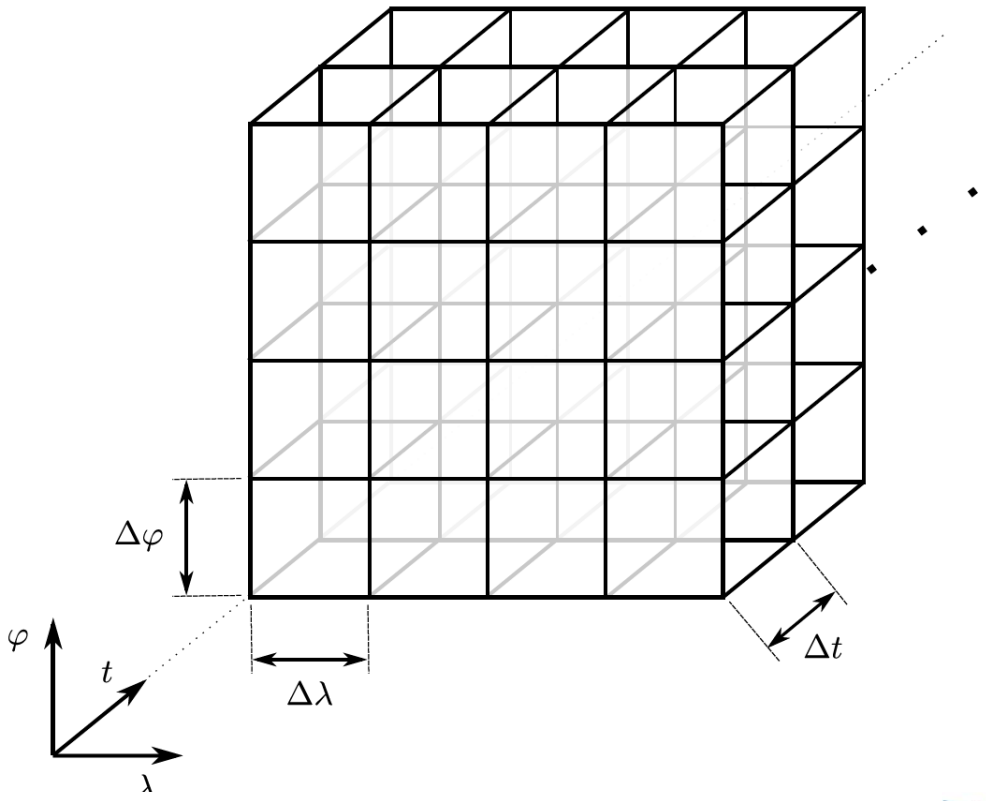
- The **probability of conflict** between i and j, $P_{con,ij}$, is computed as:

$$P_{con,ij} = \frac{1}{20}\sum_{m=1}^{20} c_{ij,m}, \qquad c_{ij,m} = i, ji, \begin{cases} 1 & \text{if} \quad d_{ij,m} \leq D \\ 0 & \text{if} \quad d_{ij,m} > D \end{cases}$$

Problem formulation

CONFLICT DETECTION

- **A grid-based approach** is used: the distance between aircraft is only computed if two aircraft are in the same of adjacent cells.
- **Reduce the computational cost** at the expense of additional required **computer memory.**
- **Hash table:** reduce memory requirement.



Problem formulation

CONFLICT RESOLUTION

- Resolution maneuver: **vectoring**.
- The CR is formulated as an **optimization problem**:
  - **Lower the probabilities of the conflicts**.
  - **Minimise the deviation** from the nominal paths.
  - Control variables: **coordinates** of the trajectory waypoints.

$$\boldsymbol{u} = \{\boldsymbol{u}_1, \boldsymbol{u}_2, \dots, \boldsymbol{u}_i, \dots, \boldsymbol{u}_N\} \qquad \boldsymbol{\Phi} = \sum_{i=1}^{N} \Phi_i = \sum_{i=1}^{N} \left(\sum_{j=1, j \neq i}^{N} (C_{ij} - \delta_{ij}) + a \frac{A_i}{L_{0,i}} \right)$$

- Simulated Annealing.

Problem formulation

CONFLICT RESOLUTION: OBJECTIVE FUNCTION AND CONSTRAINTS

- Objective function:

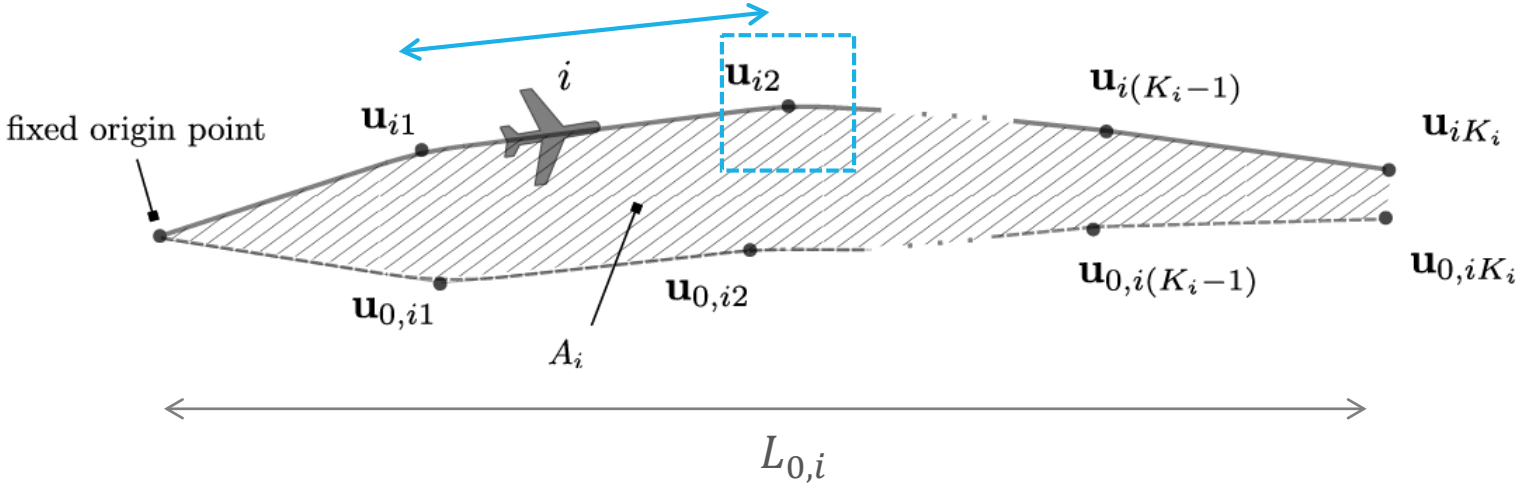
$$\Phi = \sum_{i=1}^{N} \Phi_i = \sum_{i=1}^{N} \left(\sum_{j=1, j\neq i}^{N} \boxed{(C_{ij}} \boxed{- \delta_{ij})} + \boxed{a \frac{A_i}{L_{0,i}}} \right)$$

- Conflict probability

$$C_{ij} = \begin{cases} P_{con,ij} & \text{if } P_{con,ij} \geq P_\tau \quad \text{(high prob.)} \\ 0 & \text{if } P_{con,ij} < P_\tau \quad \text{(low prob.)} \end{cases}$$

- Loss of separation at the starting point →**tactically solved.**
- Deviation from the nominal trajectories.

- Constraints:
  - Minimum segment length.
  - Maximum waypoint lateral deviation.



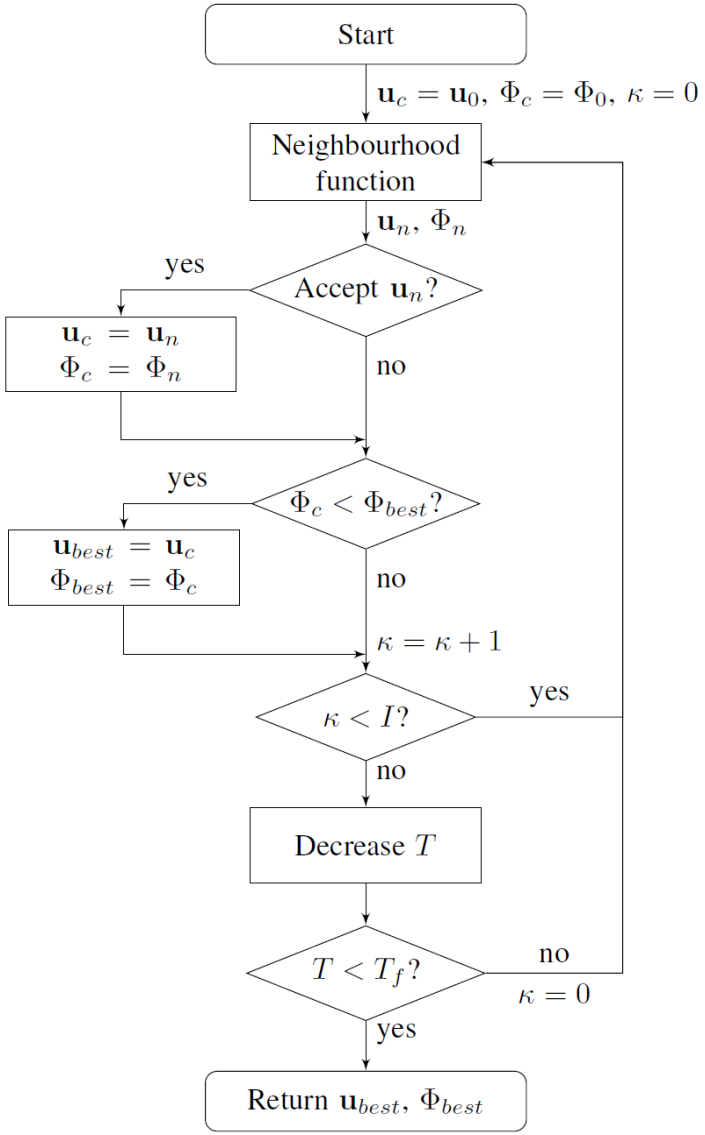
Problem formulation

CONFLICT RESOLUTION: SIMULATED ANNEALING

- **Neighbourhood function:** Starting from a current state $\mathbf{u}_c$ and cost $\mathbf{\Phi}_c$, it generates a neightbour state $\mathbf{u}_n$ and cost $\mathbf{\Phi}_n$.
  1. Randomly chose aircraft $i \in \{1, \dots, N\}$.
  2. Randomly choose waypoint $k \in \{1, \dots, K_i\}$.
  3. Coordinates of $u_{i,k}$ are randomly modified.

- **Acceptance function:** If the new cost is improved ($\mathbf{\Phi}_n < \mathbf{\Phi}_c$), the neighbor state is automatically accepted. Otherwise, it is accepted with a probability

$$\mathrm{P}_{\mathrm{accept}} = e^{-(\mathbf{\Phi}_n - \mathbf{\Phi}_c)/T}$$



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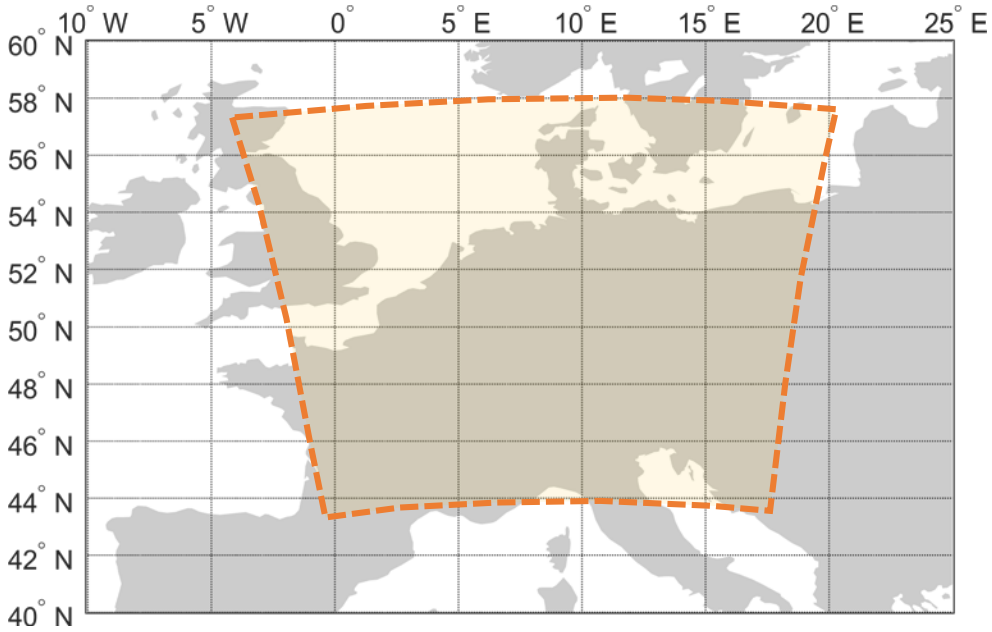
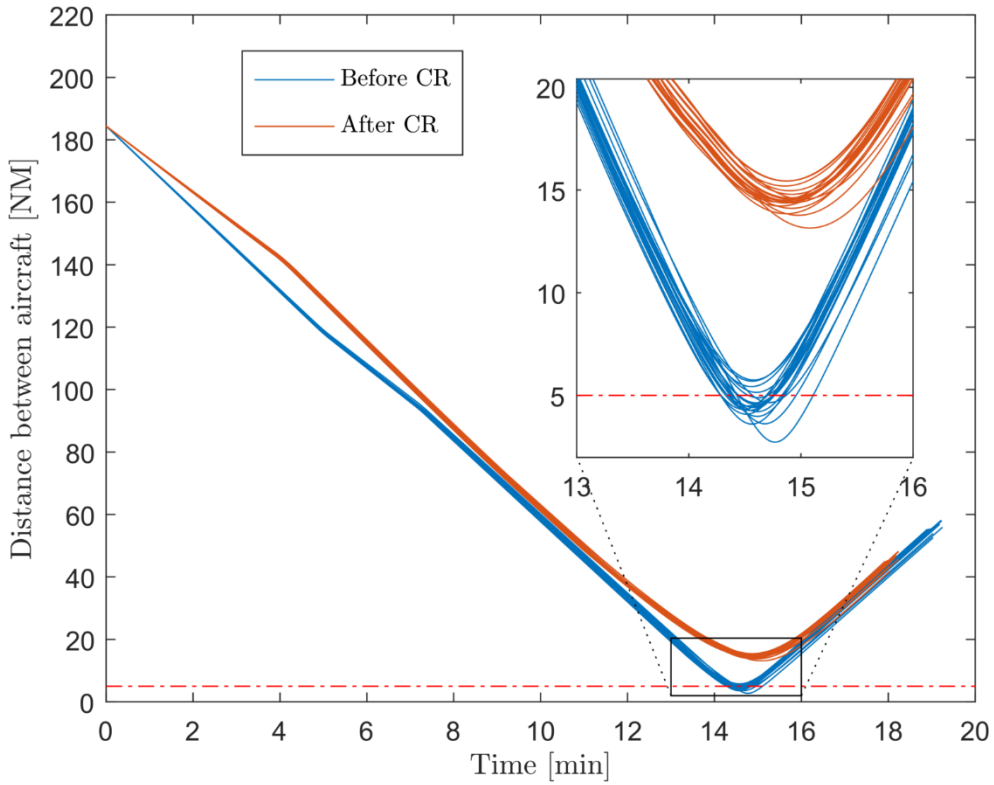
APPLICATION



- Traffic in Europe inside the COSMO-D2-EPS coverage area.
- 12:00 UTC, 14th of February 2019.
- Flight plans data from Eurocontrol's Demand Data Repository.
- Aircraft Mach number and bank angle values from BADA 3.13.
- 2 scenarios:
  - **Low-density scenario**: N = 92 (FL380)
  - **High-density scenario**: N = 214 (artificially mergin FL370-FL380-FL390)

Results

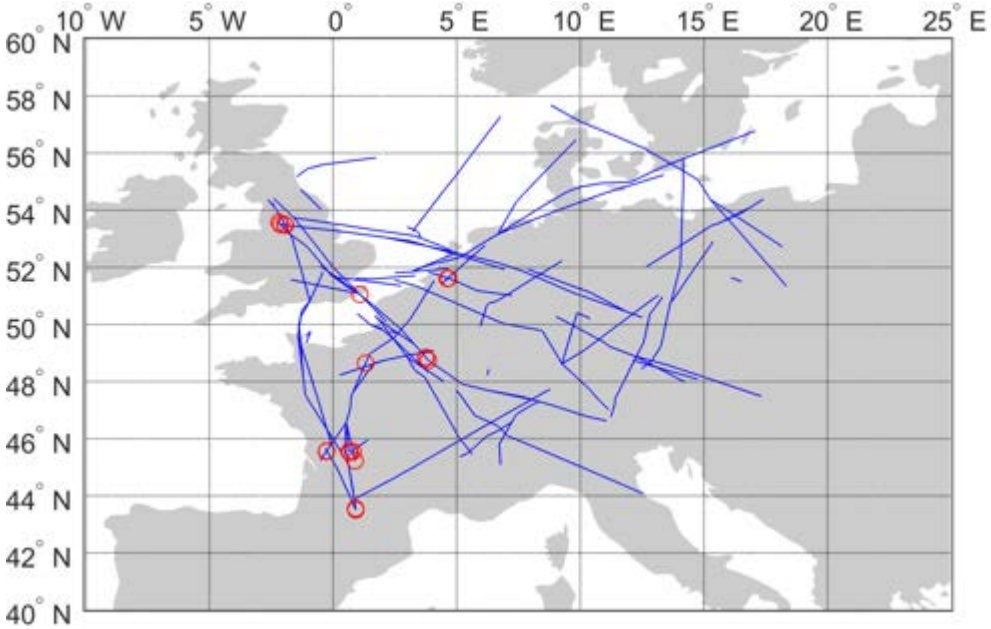
EFFECTS OF THE CONFLICT RESOLUTION METHODOLOGY



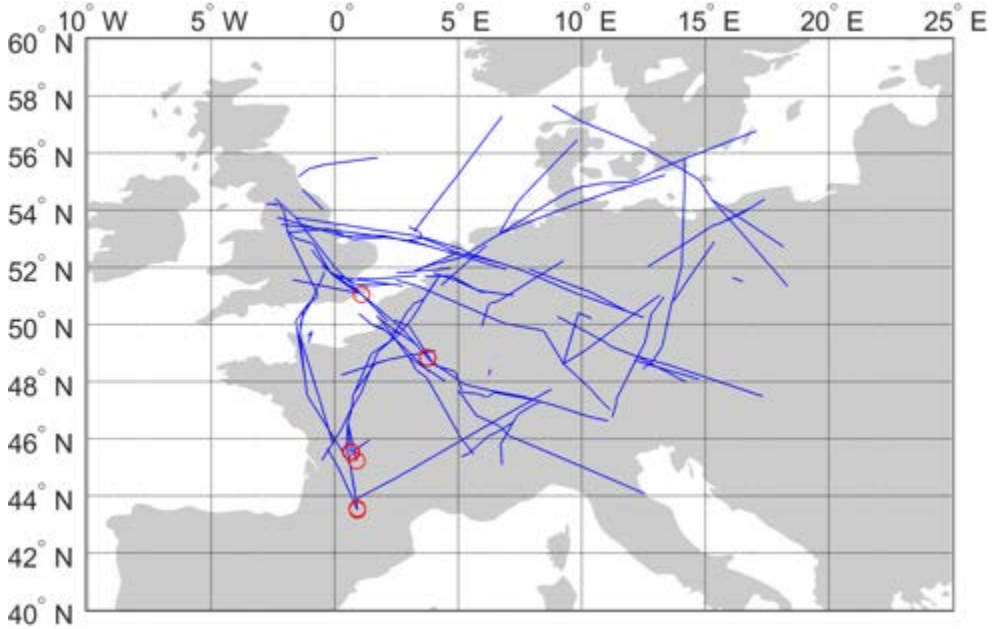
- Distance between two aircraft over time.
- 5NM: minimum separation requirement.
- Before CR: $P_{con} = 80\%$.
- After CR: $P_{con} = 0\%$.

Results

LOW-DENSITY SCENARIO



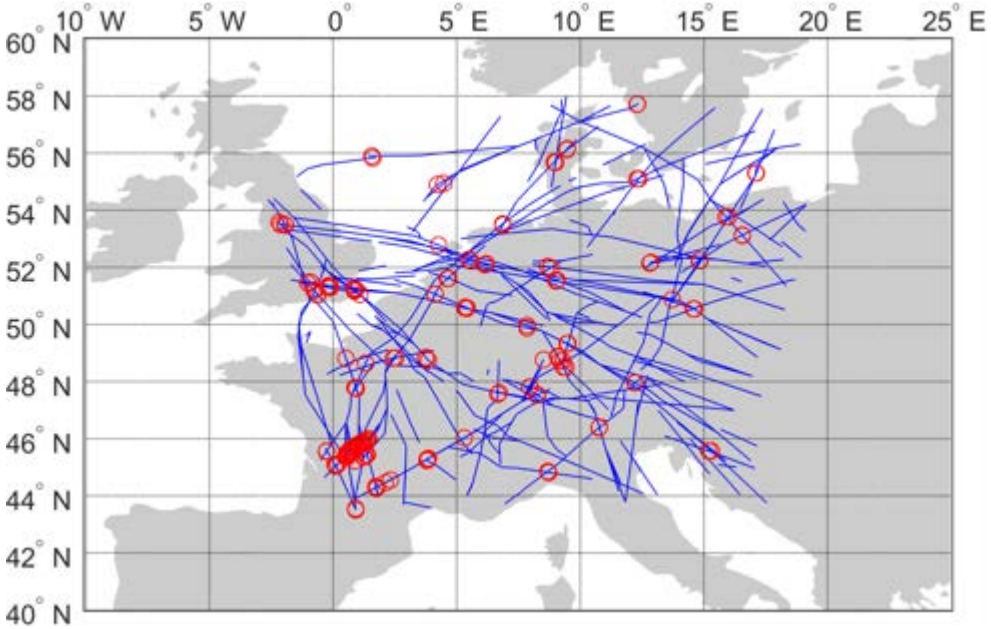
- Number of low prob. conflicts: 2
- Number of high prob. conflicts: 11
- $\Phi = 9.9$



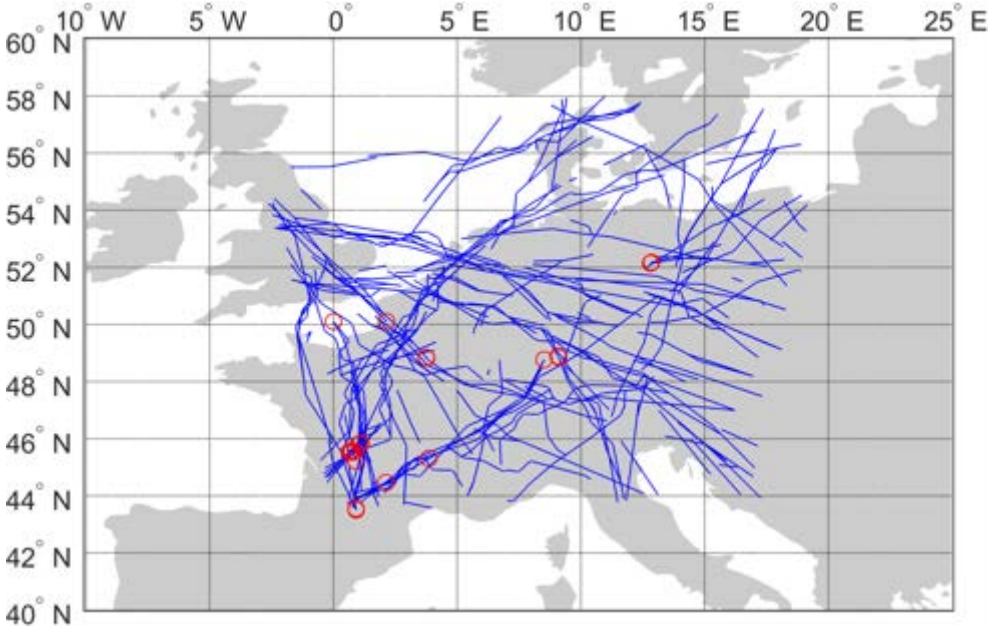
- Number of low prob. conflicts: 0
- Number of high prob. conflicts: 5
- $\Phi = 4.5 \cdot 10^{-4}$

Results

HIGH-DENSITY SCENARIO



- Number of low prob. conflicts: 12
- Number of high prob. conflicts: 88
- $\Phi = 146.5$



- Number of low prob. conflicts: 20
- Number of high prob. conflicts: 14
- $\Phi = 4.2$

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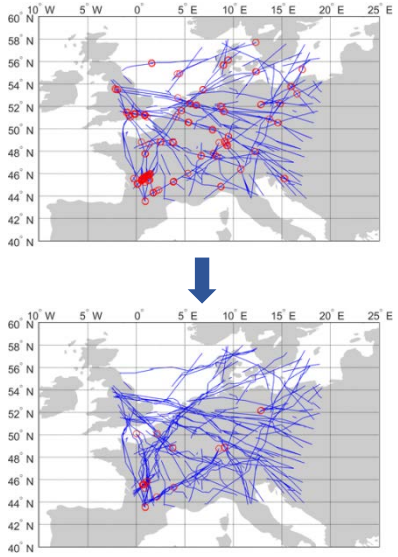
CONCLUSIONS

- A **probabilistic CD&R methodology** for en-route aircraft has been introduced:
  - **60 minutes time horizon**.
  - **Wind** and **temperature uncertainties**, retrieved from **EPS**.
  - **Probabilistic conflict detection:**
    - **Probability of conflict.**
    - Ensemble trajectory prediction.
  - **Probabilistic conflict resolution:**
    - **Lower the probabilities of conflict**, while **minimising deviation** from nominal trajectories**.**
    - **Tactical conflicts are omitted**.
    - **Resolution trajectories** are generated using **vectoring.**
- The methodology has been successfully applied to two different en-route conflict scenarios. **The number of high-probability conflicts was significantly reduced**.

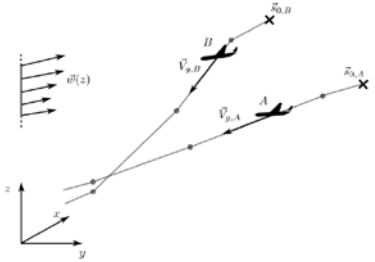
Summary

FUTURE WORK

2D CD&R



3D trajectories

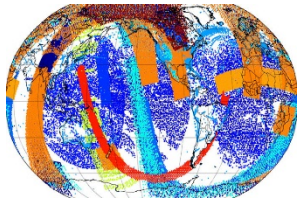


Uncertainty sources

- Departure time
- Aircraft initial positions

EPS coverage

- Global EPS integration
- ECMFW



Control variables

- Aircraft airspeeds
- Flight level
- Departure time

THANKS FOR YOU ATTENTION