

Simulated Annealing for Strategic Traffic Deconfliction by Subliminal Speed Control under Wind Uncertainties

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ECOLE NATIONALE DE L'AVIATION CIVILE



Introduction

Issues of the future Air Traffic Management (ATM)

An increase in global air traffic is foreseen in the coming decades.

- Will airspaces capacities be sufficient ?
- How to increase them without affecting safety ?
- Will Air Traffic Controllers's workload be manageable ?

Introduction

Issues of the future Air Traffic Management (ATM)

An increase in global air traffic is foreseen in the coming decades.

- Will airspaces capacities be sufficient ?
- How to increase them without affecting safety ?
- Will Air Traffic Controllers's workload be manageable ?

ATM system needs to be improved

- Anticipating conflict detection
- Resolving the most of them
- Minimizing impact on flight efficiency
- Through automatic ways thanks to advanced algorithm

Taking into account uncertainties is paramount.

Introduction

A large range of possibilities has been developed

- Consider a micro/mesoscaled or macroscaled airspace ?
- With uncertainties on aircraft positions ?
- Through which separation maneuvers ?
 - Flight level assignment
 - Speed control
 - Heading change
 - Delays on departure ...

Introduction

A large range of possibilities has been developed

- Consider a micro/mesoscaled or macroscaled airspace ?
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 - Flight level assignment
 - Heading change
 - Speed control
 - Delays on departure ...

A strategy seems to be unexplored

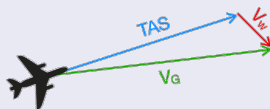
What about a deconfliction using speed control on a macroscaled traffic under uncertainties ?

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 - 2D Case
 - 3D case
- 5 Conclusion

Uncertainties due to wind forecast errors

Wind affects ground speed



$$\vec{V}_G = \vec{TAS} + \vec{V}_W$$

Errors on $\vec{V}_W \Rightarrow$ Errors on $\vec{V}_G$

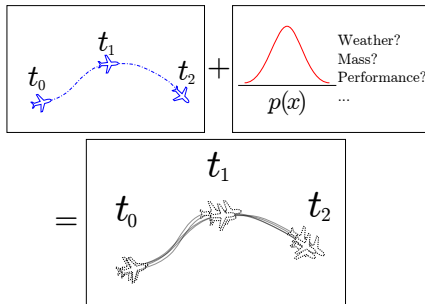
Uncertainties due to wind forecast errors

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$$\vec{V}_G = \vec{TAS} + \vec{V}_W$$

Errors on $\vec{V}_W \Rightarrow$ Errors on $\vec{V}_G$



How to model forecast errors ?

The MétéoFrance PEARP EPS is used to obtain wind uncertainties by generating:

- an initial wind forecast
- 34 other wind scenarios

Data can be accessed at the TIGGE dataset by the European Center for Medium-Range Weather Forecasts (ECMWF).

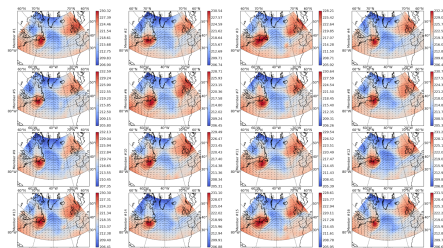
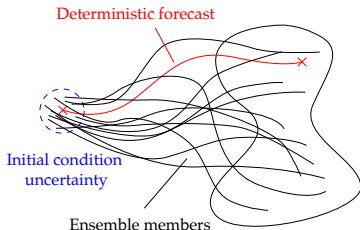
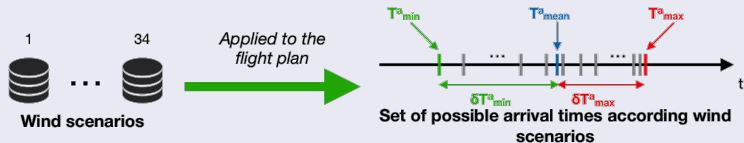


Figure: Uncertainty propagation

Figure: A subset of the PEARP ensemble forecast at 250 hPa

Aircraft position uncertainty modelling

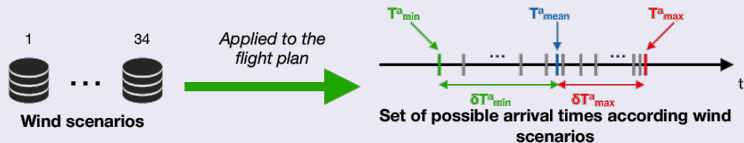
For each aircraft a



Max arrival time uncertainty range: $\Delta T^a = \max(\delta T_{min}^a, \delta T_{max}^a)$

Aircraft position uncertainty modelling

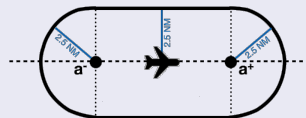
For each aircraft a



Max arrival time uncertainty range: $\Delta T^a = \max(\delta T_{min}^a, \delta T_{max}^a)$

For all t between departure time T_0^a and arrival time T^a :

$$\Delta T^a(t) = \Delta T^a \times \frac{t - T_0^a}{T^a - T_0^a}$$



Uncertainty area at date t .

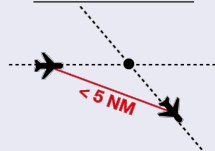
Conflict detection

Two types of conflicts

Link conflict

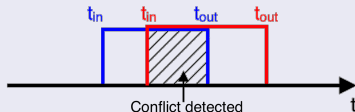


Node conflict



Detection principle

Specific time intervals are considered to detect conflicts as follow:

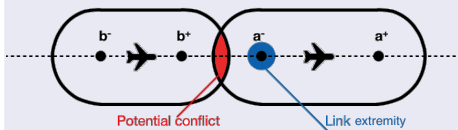


A conflict exists if:

$$t_{in} - t_{out} < 0$$

Conflict evaluation

Time intervals for link conflicts



Time intervals:

$$\text{for } a: [t^{a-}, t^{a-} + \frac{5NM}{V_G^a(l)}]$$

$$\text{for } b: [t^{b+} - \frac{5NM}{V_G^b(l)}, t^{b+}]$$

Potential conflict if:

$$\phi_l(a, b) = (t^{a-} + \frac{5NM}{V_G^a(l)}) - t^{b+} < 0$$

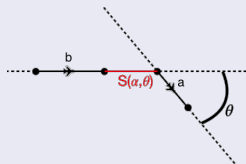
Link conflict evaluation

Let $\mathcal{L}$ the set of links and A_l the set of aircraft couple (a, b) involved into a conflict at the link $l \in \mathcal{L}$:

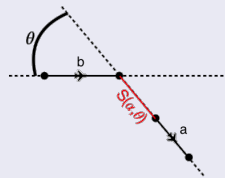
$$\forall l \in \mathcal{L}, \phi_{\mathcal{L}}(l) = - \sum_{(a,b) \in A_l} \phi_l(a, b) \quad (1)$$

Conflict evaluation

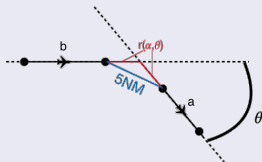
Three configurations of node conflicts



$$\phi_n^1(a, b) = (t_n^{b^+} - \frac{S(\alpha, \theta)}{V_G^b(n)}) - t_n^{a^-}$$



$$\phi_n^2(a, b) = t_n^{b^+} - (t_n^{a^-} + \frac{S(\alpha, \theta)}{V_G^a(n)})$$



$$\phi_n^3(a, b) = (t_n^{b^+} - \frac{r(\alpha, \theta)}{V_G^b(n)}) - (t_n^{a^-} + \frac{r(\alpha, \theta)}{V_G^a(n)})$$

where:

$$\alpha = V_G^b(n)/V_G^a(n)$$

$$S(\alpha, \theta) = 5NM \times \frac{\sqrt{\alpha^2 - 2\alpha \cos(\theta) + 1}}{|\sin(\theta)|}$$

$$r(\alpha, \theta) = 5NM \times \frac{\sqrt{\alpha^2 - 2\alpha \cos(\theta) + 1}}{2 \cos(\frac{\theta}{2})}$$

Conflict evaluation

Node conflict evaluation

Let:

- $\mathcal{N}$ the set of nodes
- $A_n^2 = \{(a, b) / \phi_{n,2}(a, b) < 0\} \setminus A_n^1$
- $A_n^1 = \{(a, b) / \phi_{n,1}(a, b) < 0\}$
- $A_n^3 = \{(a, b) / \phi_{n,3}(a, b) < 0\} \setminus (A_n^1 \cup A_n^2)$

$\forall n \in \mathcal{N},$

$$\phi_{\mathcal{N}}(n) = - \sum_{(a,b) \in A_n^1} \phi_{n,1}(a, b) - \sum_{(a,b) \in A_n^2} \phi_{n,2}(a, b) - \sum_{(a,b) \in A_n^3} \phi_{n,3}(a, b) \quad (2)$$

Total conflict evaluation

$$\Phi(X) = \sum_{n \in \mathcal{N}} \phi_{\mathcal{N}}(n) + \sum_{l \in \mathcal{L}} \phi_{\mathcal{L}}(l)$$

where X is the state vector of the problem.

Mathematical modelling setting up

State vector

$$X = (x_i)_{i=1..N} \in \mathbb{Z}^N$$

where: N = number of flights

x_i = TAS variation applied to the aircraft i

Subliminal control constraint

$$\forall i \in \llbracket 1, N \rrbracket, -0,06 \times v_i \leq x_i \leq 0,03 \times v_i$$

where v_i is the initial TAS of the aircraft i .

Objective function

$$\min f = M \times N \times \Phi(X) + \sum_{i=1}^N |x_i|$$

Problem statement

Objective function:

$$\min f = M \times N \times \Phi(X) + \sum_{i=1}^N |x_i|$$

Subject to:

$$\forall i \in \llbracket 1, N \rrbracket, -0,06 \times v_i \leq x_i \leq 0,03 \times v_i$$

$$\forall k \in \llbracket 1, N \rrbracket, x_k \in \mathbb{Z}$$

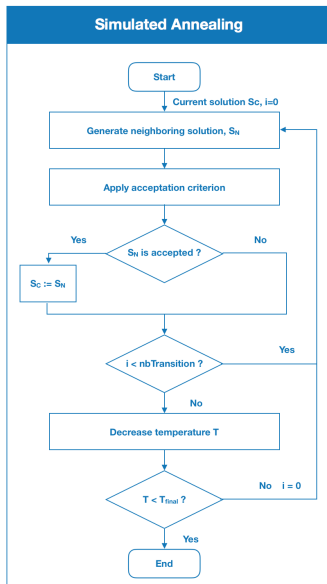
Where:

$$\Phi(X) = \sum_{n \in \mathcal{N}} \phi_{\mathcal{N}}(n) + \sum_{l \in \mathcal{L}} \phi_{\mathcal{L}}(l)$$

$$\forall l \in \mathcal{L}, \phi_{\mathcal{L}}(l) \leftarrow (1)$$

$$\forall n \in \mathcal{N}, \phi_{\mathcal{N}}(n) \leftarrow (2)$$

General description of simulated annealing



Main parameters

- Initial solution X_0
- Initial temperature T_0
- Neighbourhood function
- Number of transitions
- Cooling up law
- Stop criterion

Acceptance probability

Let $f_c = f(S_c)$ and $f_n = f(S_n)$:

$$P(S_n \text{ accepted}) = \begin{cases} e^{-\frac{f_n - f_c}{T}} & \text{if } f_n > f_c \\ 1 & \text{otherwise} \end{cases}$$

Neighbourhood function

Pseudo code

Input: Current solution X_c

Procedure:

- **new** $X_n \leftarrow X_c$
- Chose a flight index $i \in \llbracket 1, N \rrbracket$
- Generate a random TAS variation δx
- **ensure** $(X_c[i] + \delta x) \in [-0.06 \times v_i; 0.03 \times v_i]$
- $X_n[i] \leftarrow X_c[i] + \delta x$

Output: Next solution X_n

Flight index choice function

The likelihood of choosing a flight increases with the number of conflicts encountered during this flight.

Adaptation of SA for our problem

Initial solution

No modification of TAS planed into the flight schedule:

$$X_0 = (0)_{i \in \llbracket 1, N \rrbracket}$$

Initial temperature

T_0 is chosen so as to obtain 80% of acceptance rate.

Tuneable parameters

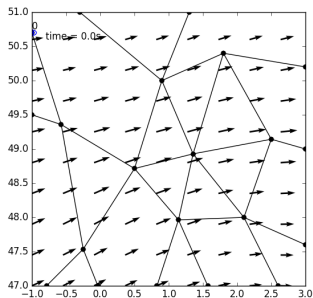
- Number of transitions: 200
- Geometric cooling up law: $T_{i+1} = \alpha \times T_i$ with $\alpha = 0.96$
- Stop criterion: $T_{final} = \varepsilon \times T_i$ with $\varepsilon = 10^{-4}$

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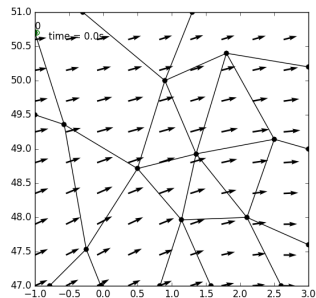
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Proof of concept

Before resolution



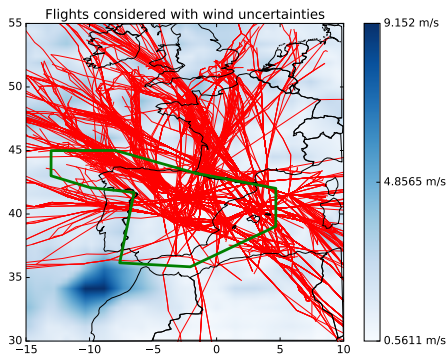
After resolution



Simulation context

Case study

The data set corresponds to air-traffic over Spanish airspace on 26th July 2016 between 12. am and 4. pm associated with corresponding wind forecast. 1060 flights are considered.



All aircraft are flying at the same FL

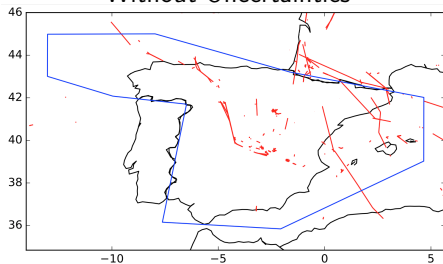
It can illustrate the expected increase of air traffic.

→ but we need to separate flights flying to East and those flying to West.

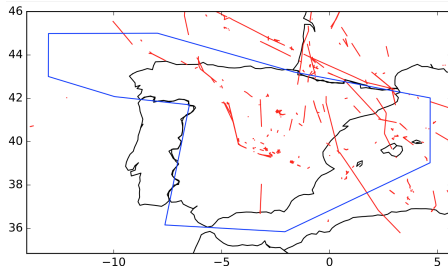
Visualisation

Before Resolution

Without Uncertainties



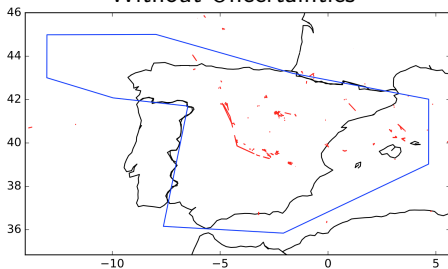
With Uncertainties



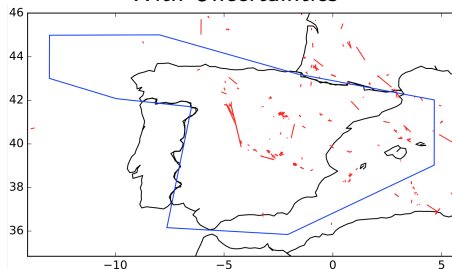
Visualisation

After Resolution

Without Uncertainties



With Uncertainties



2D results

	Without Unc.		With Unc.	
	West	East	West	East
$\tilde{c}$	1407	1239	2496	2405
$\tilde{c}^*$	300	211	604	469
$\tilde{p}$	78.7%	83.0%	75.8%	80.5%
c	312	289	427	457
c^*	116	81	224	198
p	62.8%	72.0%	47.5%	56.7%
Computing time	1458 s	1816 s	1493 s	1960 s

Notations

- $\tilde{c}$ = Virtual conflict count
- $\tilde{c}^*$ = $\tilde{c}$ after resolution
- $\tilde{p}$ = pourcentage of virtual conflict resolved
- c = Real conflict count
- c^* = c after resolution
- p = pourcentage of real conflict resolved

Effect of annealing parameters

Annealing parameters changed

- Number of transitions: 400 (vs 200)
- $\alpha = 0.98$ (vs 0.96)

Consequences: Much more solutions explored but higher computing time

Results with uncertainties:

Direction	West	East
$\tilde{c}$	2496	2405
$\tilde{c}^*$	507	432
$\tilde{p}$	79.7%	82.0%
c	427	457
c^*	199	182
p	53.4%	60.2%
Computing time	6615 s	7233 s

3D simulations

Changes in the model

- Consideration of FL evolution without any uncertainty
- Conflict detected if: Loss of horizontal separation (under uncertainty) **and** loss of vertical separation
- No need to separate flight flying to East with those flying to West

	Without horizontal Unc.	With horizontal Unc.
$\tilde{c}$	489	1338
$\tilde{c}^*$	57	159
$\tilde{p}$	88.3%	88.1%
c	143	289
c^*	25	79
p	82.5%	72.7%
Computing time	1518 s	1578 s

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Conclusion

Resume

- We proposed a formulation for deconfliction of macroscaled traffic based on subliminal speed control under uncertainties.
- We tackled uncertainties thanks to a robust optimisation problem (solving the worst case).
- We have obtained promising results even if not all conflicts were resolved.

Perspectives of improvement

- Find the optimal annealing parameters.
- Implement additional maneuver(s) (Heading change, delays on departure ...).
- Evaluate the realism of our uncertainty modelling by comparing with real data.

Questions ?