Emergency Trajectory Design

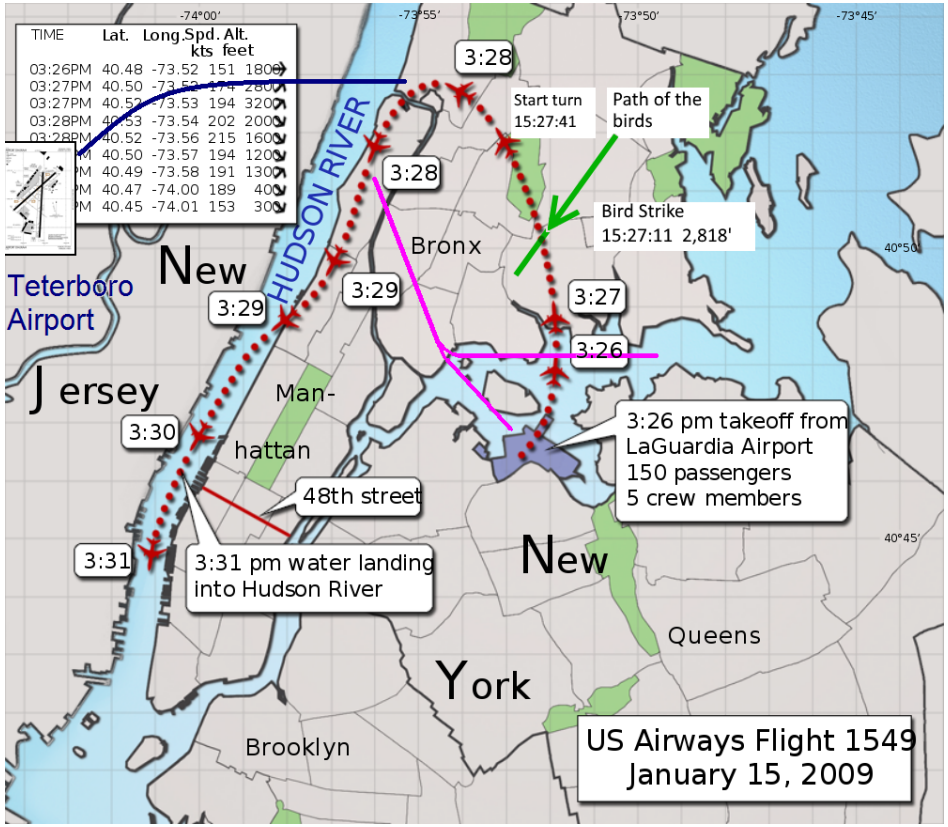
DATS May 7 2024

Pr Daniel Delahaye (with Andréas Guitart and Pr Eric Feron)
ANITI Research Chair (AI for ATM and UTM)
SESAR Scientific Committee
delahaye@recherche.enac.fr

First example of critical situation : US-Airways 1549

Figure: On January 15, 2009, US Airways Flight 1549, an Airbus A320 struck a flock of birds shortly after take-off, losing all engine power.US-Airways 1549 !

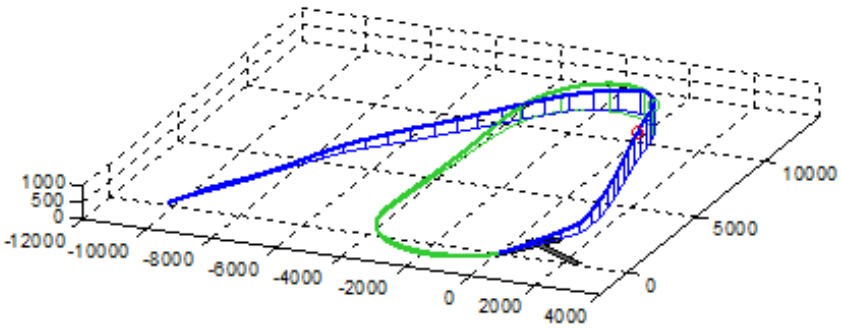
US-Airways 1549

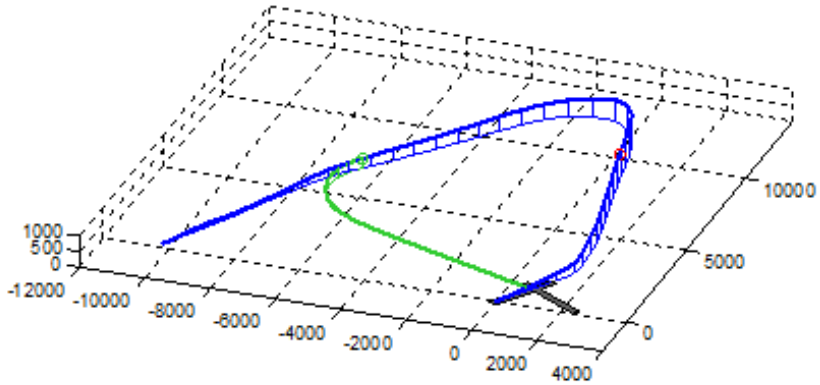


Time : 3 minutes (30 seconds to react)

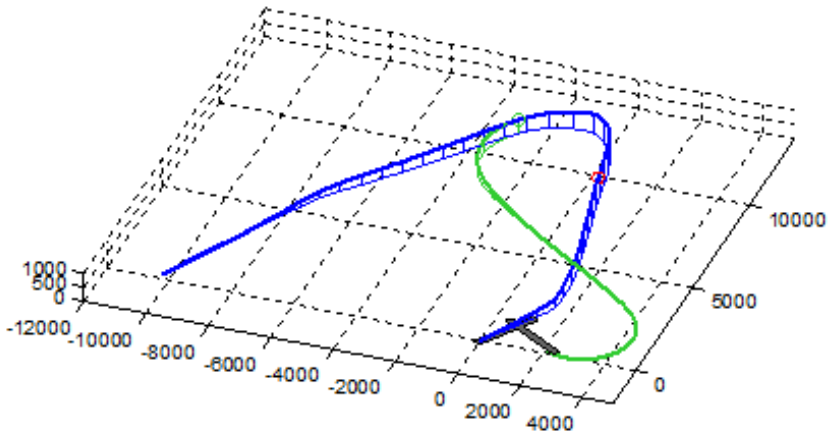
Back-up trajectories (computed a posteriori)

Runway 4

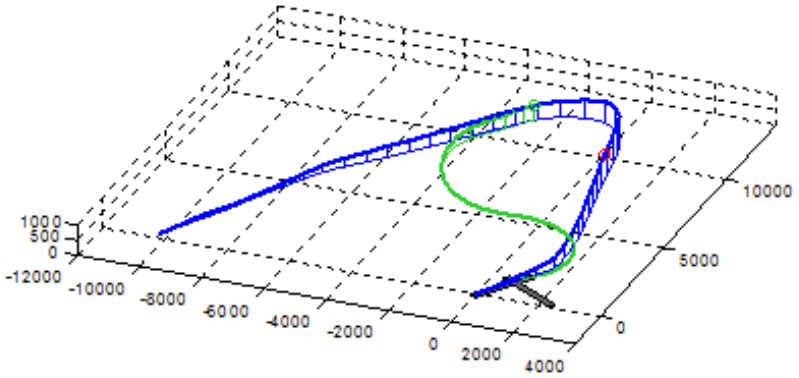




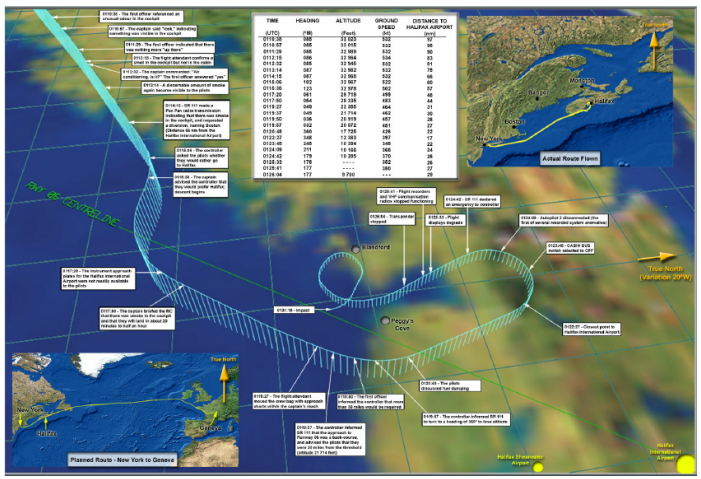
Runway 13

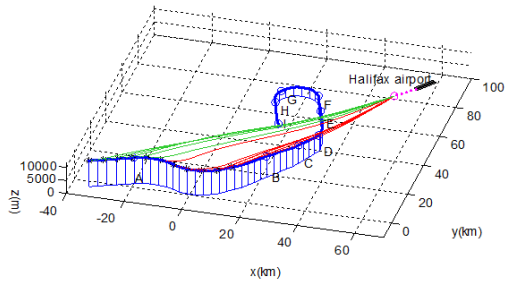


Runway 22



Example of critical situation : Swissair 111 (Fire)





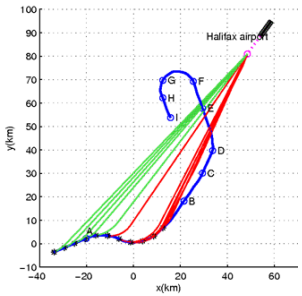


Figure: On September,2 1998, the McDonnell Douglas MD-11 performing New-York-Geneva, crashed into the Atlantic Ocean southwest of Halifax.Time : 14 minutes

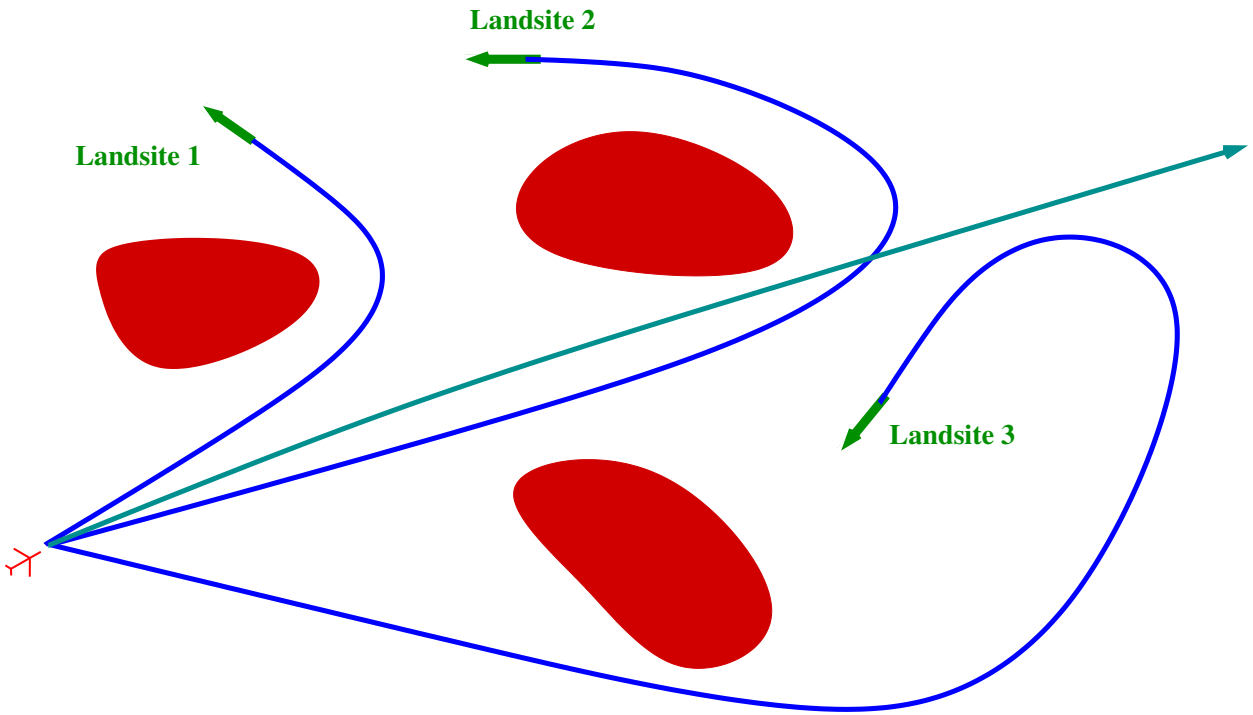
Other example

- Air Transat Flight 236 (Lisbon-Toronto, August 24, 2001)
- 21 minutes of gliding to reach the Azores

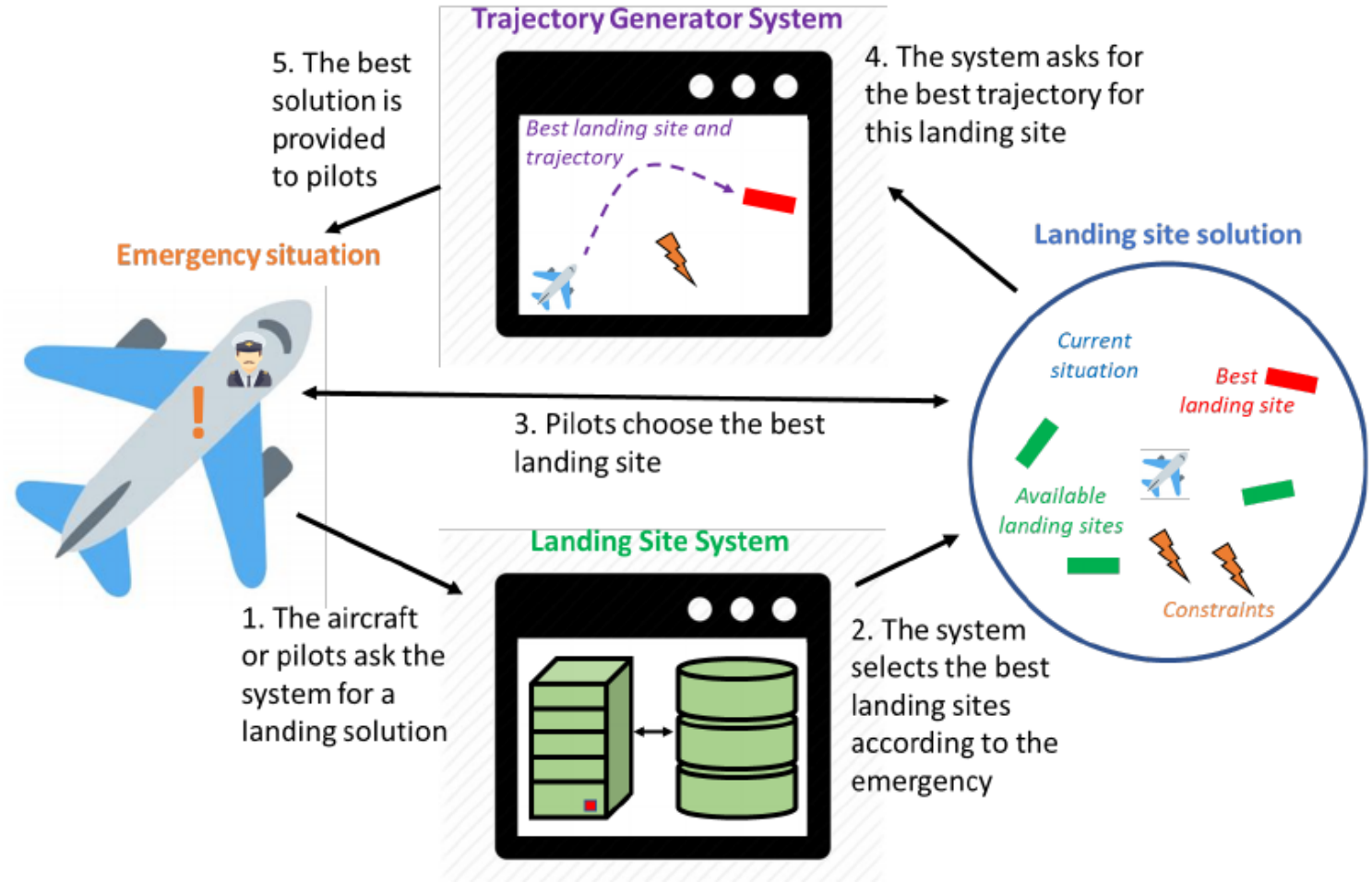
What are the issues?

Support pilots in stressful situations

Principle



SafeNcy project



Study cases definition

Types of emergency

- ANSA: At Nearest Suitable Airport
- ASAP: As Soon As Possible
- TEFO: Total Engine Flame Out
- FIRE: ASAP emergency in which there is fire on board
- DEPRESSURIZATION: ANSA emergency in which there is a loss of pressure in the cabin
- MEDICAL EMERGENCY : ANSA emergency (airport with the right medical equipment)

Study cases definition

Types of emergency

- ANSA: At Nearest Suitable Airport
- ASAP: As Soon As Possible
- TEFO: Total Engine Flame Out
- FIRE: ASAP emergency in which there is fire on board
- DEPRESSURIZATION: ANSA emergency in which there is a loss of pressure in the cabin
- MEDICAL EMERGENCY : ANSA emergency (airport with the right medical equipment)

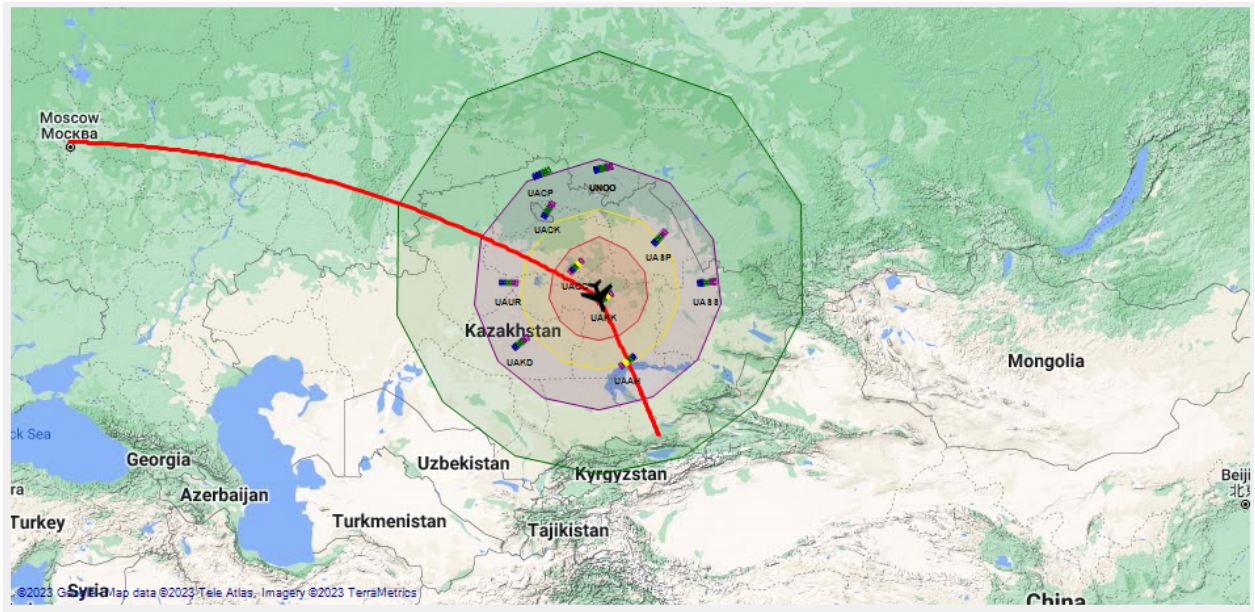
Features

- Approach procedure: does the landing site have a suitable IFR approach?
- Maneuverability: aircraft is fully or not fully maneuverable;
- ....

Landing Site Selector

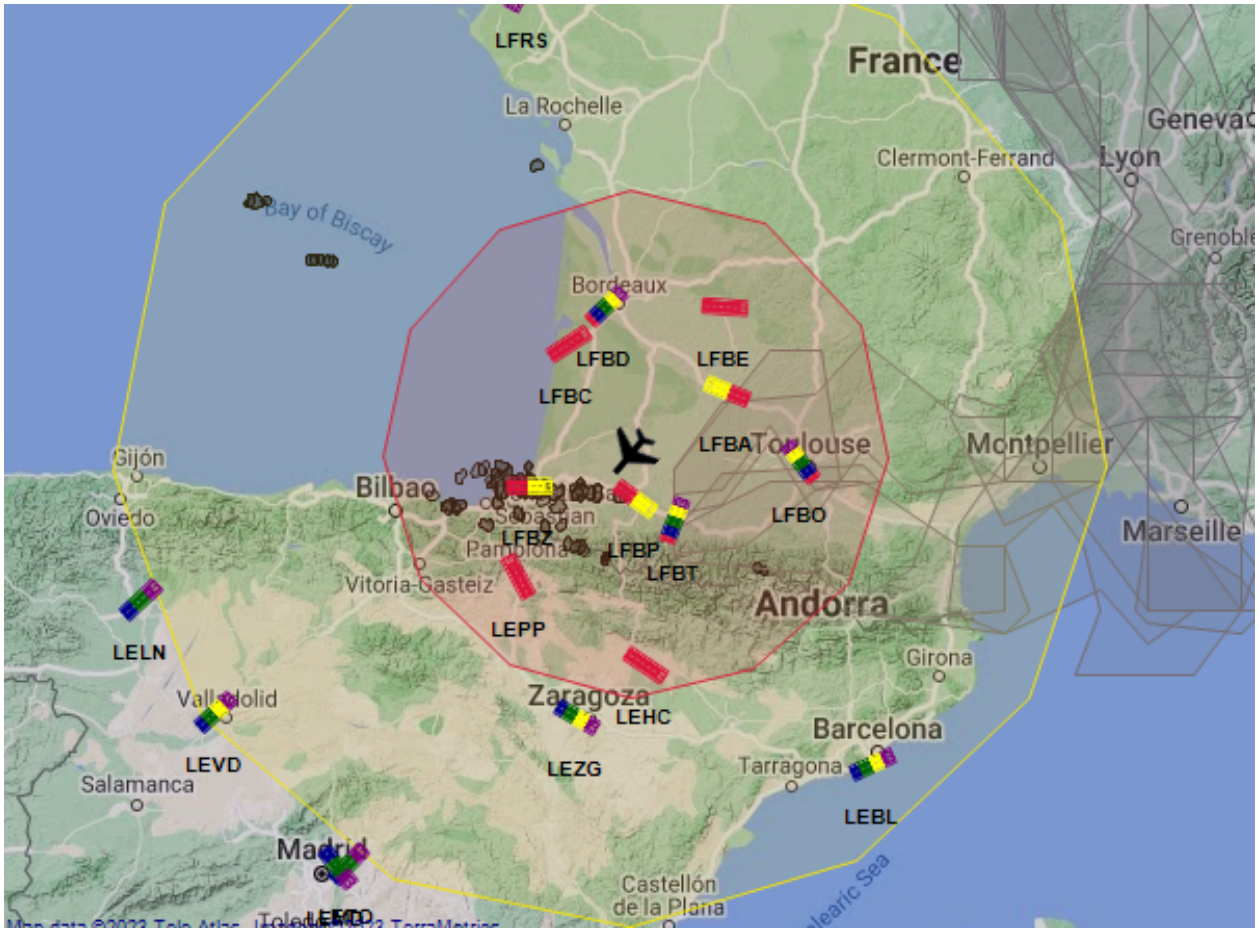
Ranges

- ANSA: Amount of fuel remaining
- FIRE: 20 minutes of flight
- TEFO: Flying at the maximum lift-to-drag ratio
- DEPRESSURIZATION: The same as for ANSA but reduced by flying at a lower altitude
- ASAP: Same as for ANSA but also select lower class airport



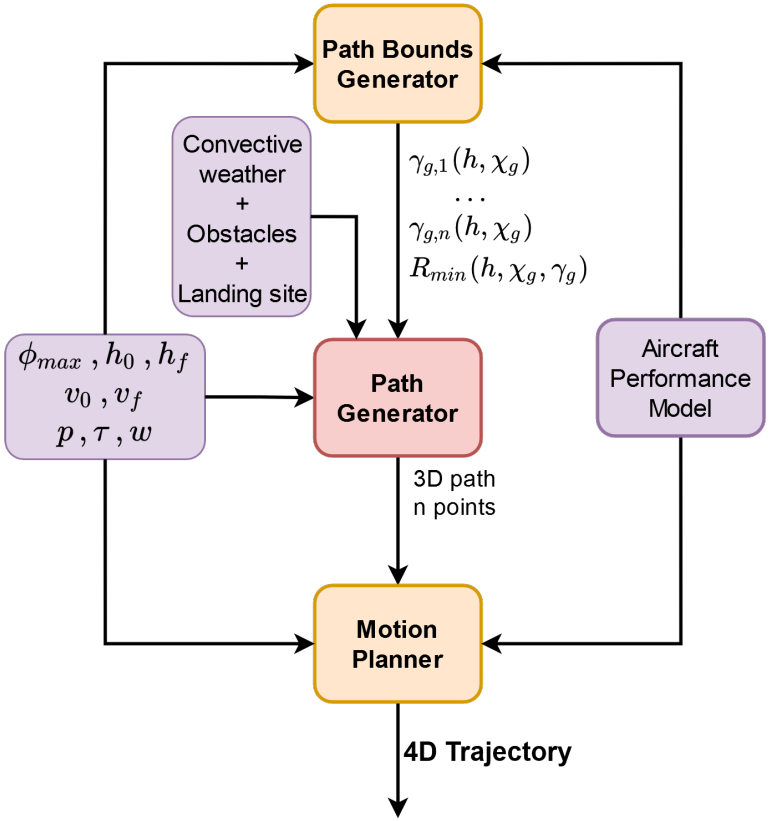
Landing Site Selector

- Weather data (wind, thunderstorms, icing, . . .)

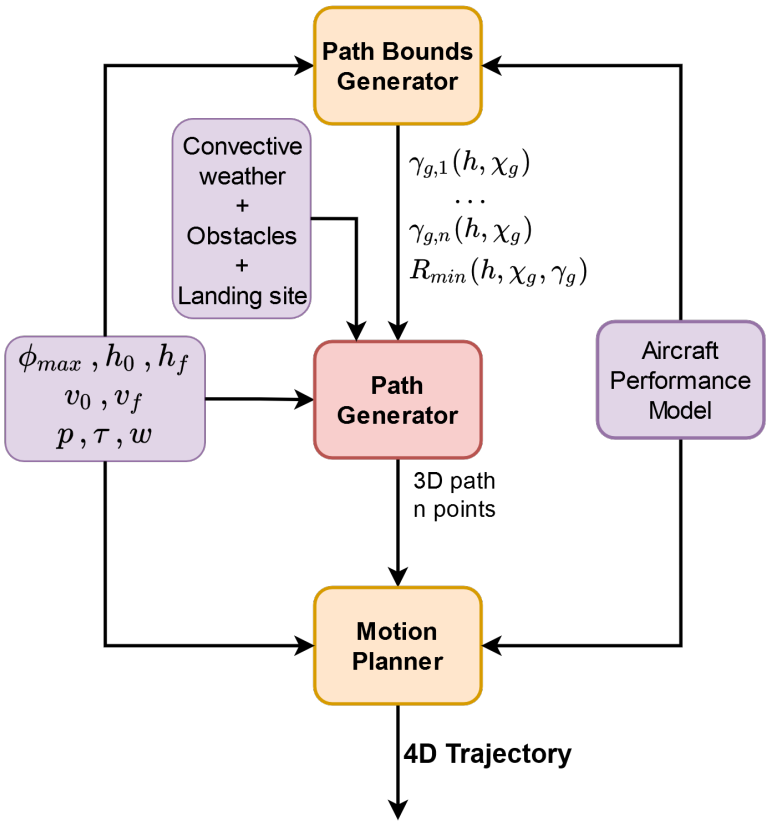


Algorithm

Trajectory Generator



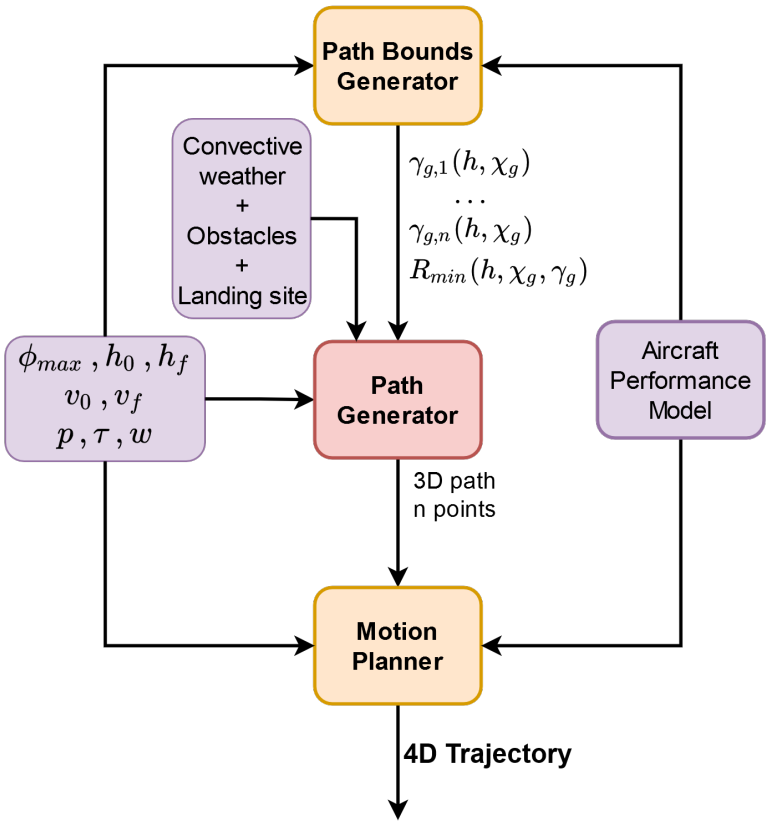
Trajectory Generator



Path bounds Generator

- Fixed flight path angles as a fonction of the altitude and the track
- Minimum turn radius depending on the altitude and the track

Trajectory Generator



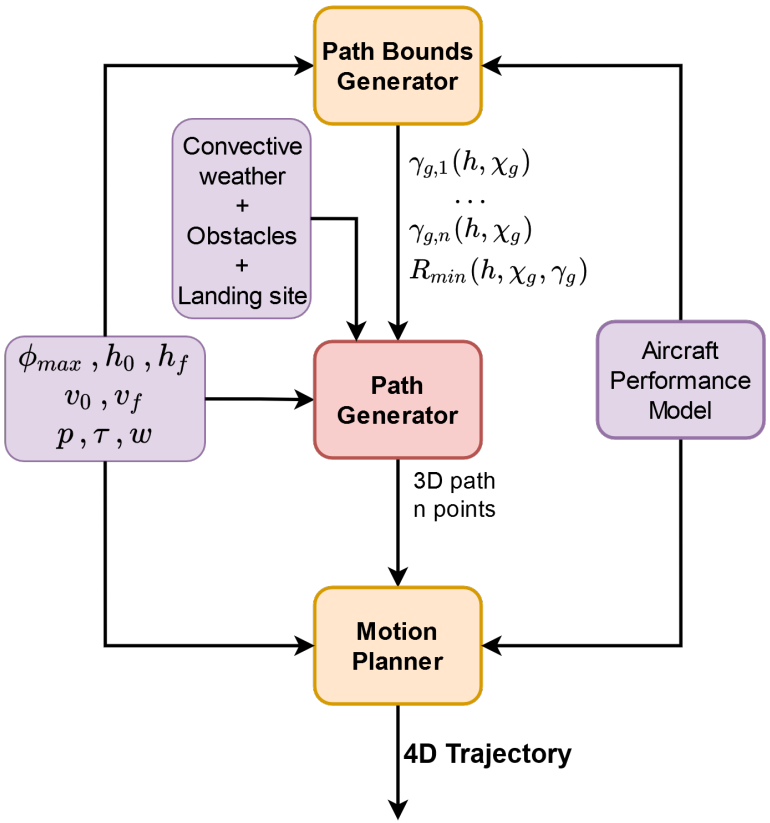
Path bounds Generator

- Fixed flight path angles as a fonction of the altitude and the track
- Minimum turn radius depending on the altitude and the track

Path Generator

- Generates the paths from aircraft position to landing sites
- Considers weather, terrain elavation, landing site data and outputs of path bound Generator

Trajectory Generator



Path bounds Generator

- Fixed flight path angles as a fonction of the altitude and the track
- Minimum turn radius depending on the altitude and the track

Path Generator

- Generates the paths from aircraft position to landing sites
- Considers weather, terrain elavation, landing site data and outputs of path bound Generator

Motion Planner

- Generates the 4D trajectories
- Trajectory Prediction

Fast Marching : General principle

Methods introduced by J.A. Sethian (1996)

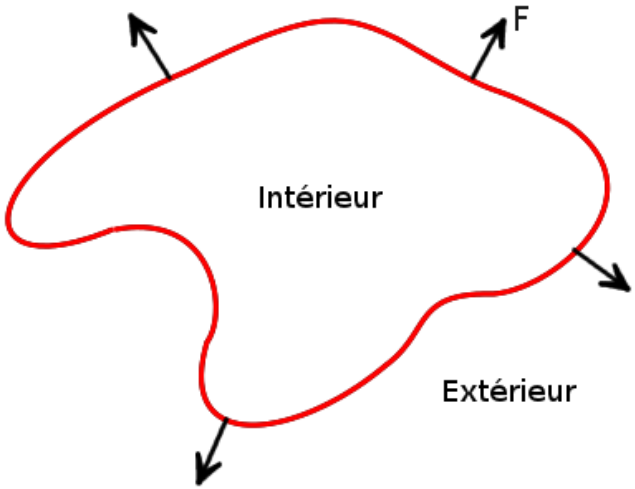


Figure: Curve propagating with speed F in normal direction.

Goal :

Track the motion of a front as it evolves.

How ?

We caracterize the position of the front by the computation of the arrival time $u(x, y)$ at each point (x, y).

$\Rightarrow$ Map of isocost.

Propagating front methods

Fast Marching :

→ **Isotropic problem**

The speed of propagation F is the same in any directions, it only depends on the position.

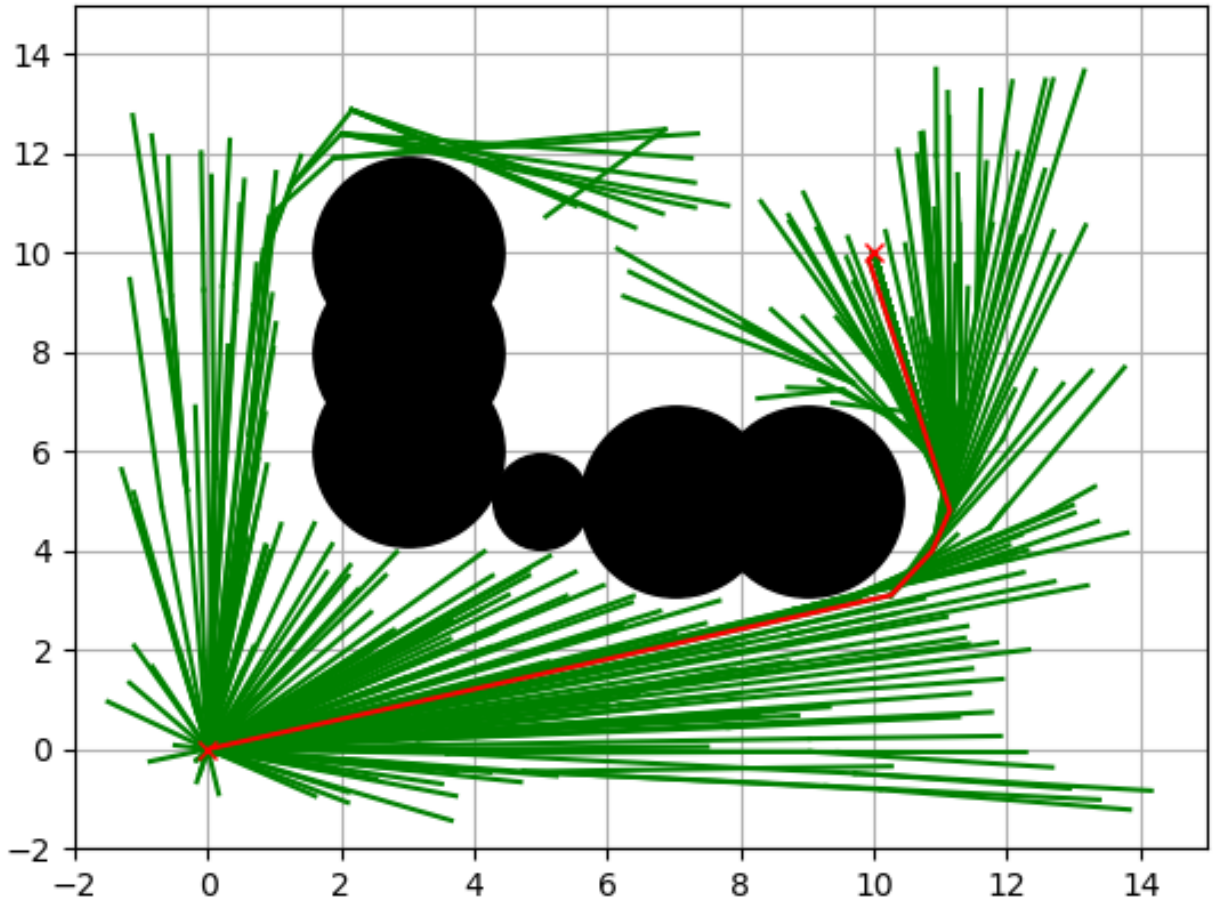
Ordered Upwind :

→ **Anisotropic problem**

The speed of propagation depends on position and direction of the propagation.

Rapidly-exploring Random Tree (RRT)

Methods introduced by S.M Lavalle (1998), RRT* S.Karaman and E.Frazzoli (2011)



Path Generator : three methods tested

1. Fast Marching Tree algorithm
   - Fast algorithm (less than 10s)
   - Asymptotically optimal
   - Can take into account the turn constraints
   - Impossible to take into account the constant descent angle

Path Generator : three methods tested

1. Fast Marching Tree algorithm
   - Fast algorithm (less than 10s)
   - Asymptotically optimal
   - Can take into account the turn constraints
   - Impossible to take into account the constant descent angle
2. Fast Marching on simplexes (triangular or tetrahedral meshes)
   - Very fast algorithm (less than 3s)
   - Finds the optimal path for a given mesh
   - Difficult to take into account the constraints

Path Generator : three methods tested

1. Fast Marching Tree algorithm
   - Fast algorithm (less than 10s)
   - Asymptotically optimal
   - Can take into account the turn constraints
   - Impossible to take into account the constant descent angle
2. Fast Marching on simplexes (triangular or tetrahedral meshes)
   - Very fast algorithm (less than 3s)
   - Finds the optimal path for a given mesh
   - Difficult to take into account the constraints
3. Rapidly-exploring Random Tree
   - Fast algorithm
   - Asymptotically optimal
   - Can take into account all constraints of the SafeNcy project

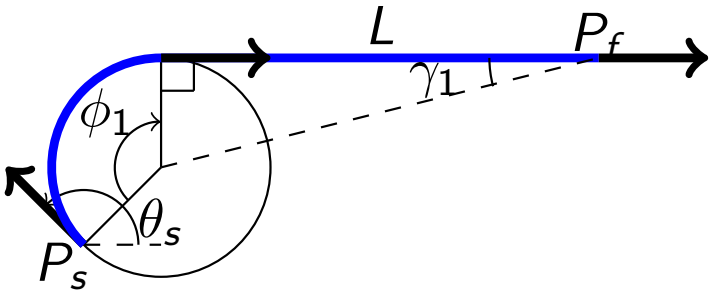
Path Generator : three methods tested

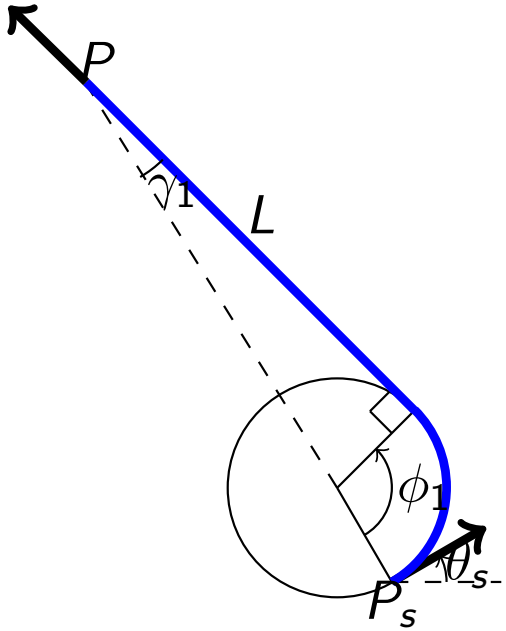
1. Fast Marching Tree algorithm
   - Fast algorithm (less than 10s)
   - Asymptotically optimal
   - Can take into account the turn constraints
   - Impossible to take into account the constant descent angle
2. Fast Marching on simplexes (triangular or tetrahedral meshes)
   - Very fast algorithm (less than 3s)
   - Finds the optimal path for a given mesh
   - Difficult to take into account the constraints
3. Rapidly-exploring Random Tree
   - Fast algorithm
   - Asymptotically optimal
   - Can take into account all constraints of the SafeNcy project

$\Rightarrow$ **Rapidly-exploring Random Tree**

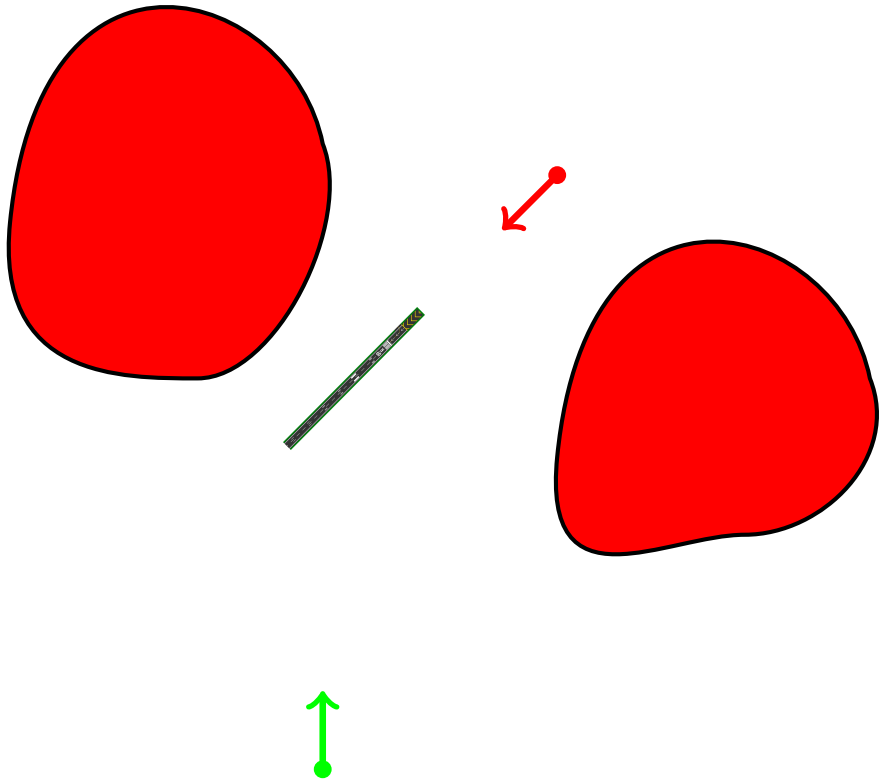
Path Generator

Replace connections with single turn curves

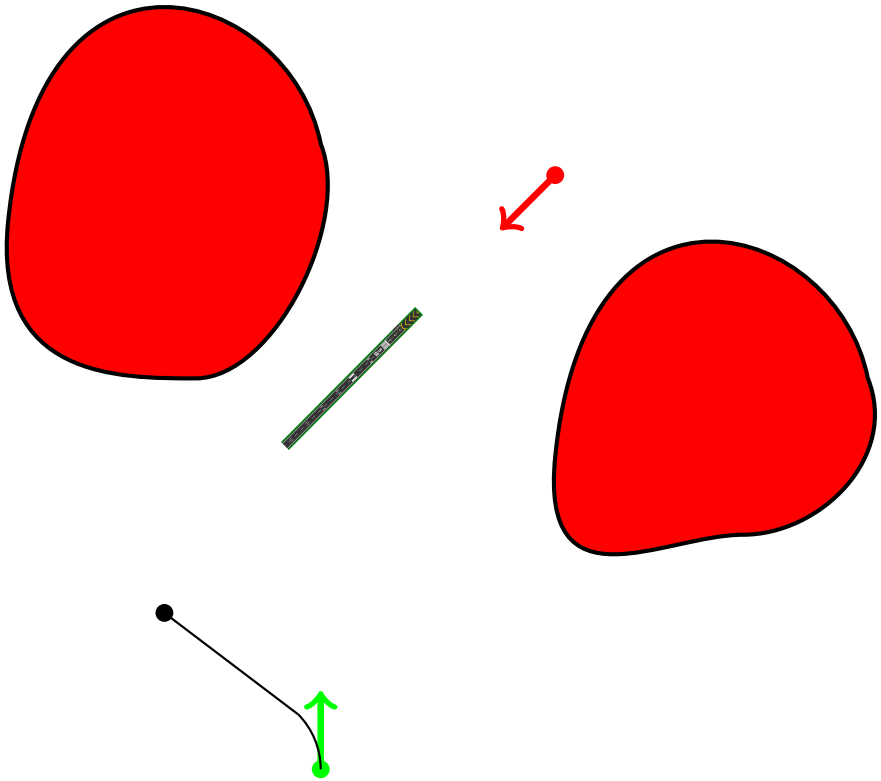




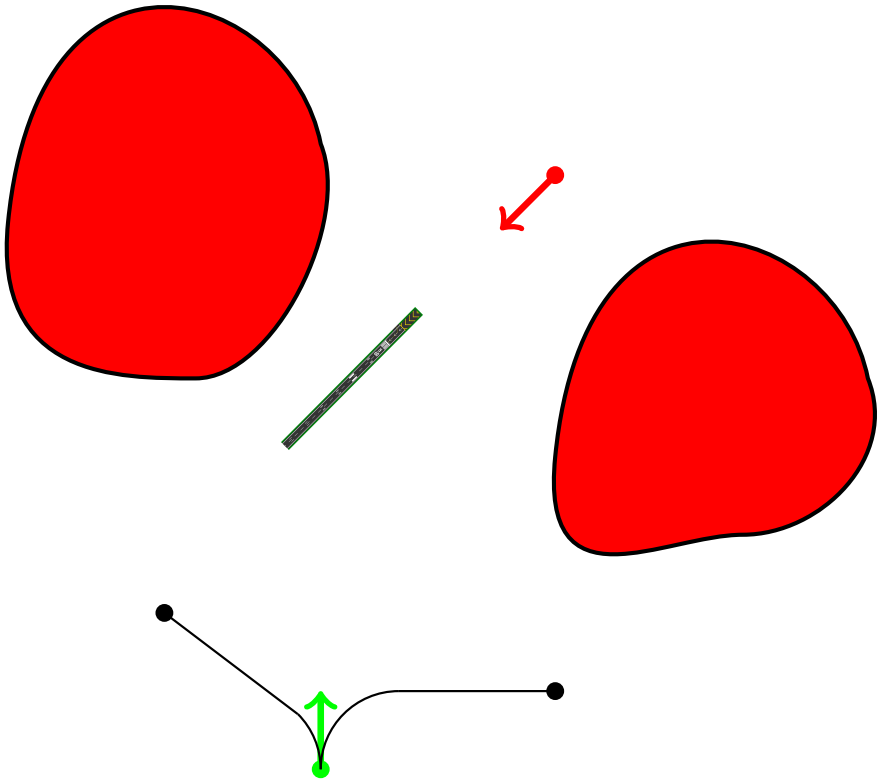
Path Generator



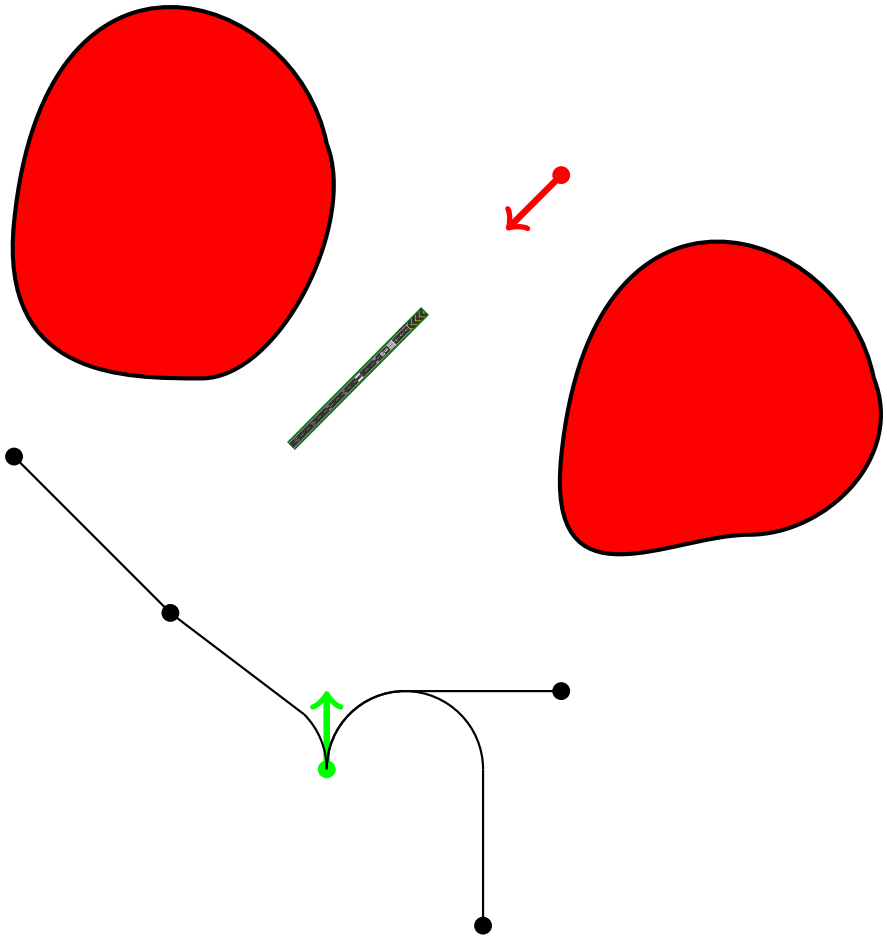
Path Generator



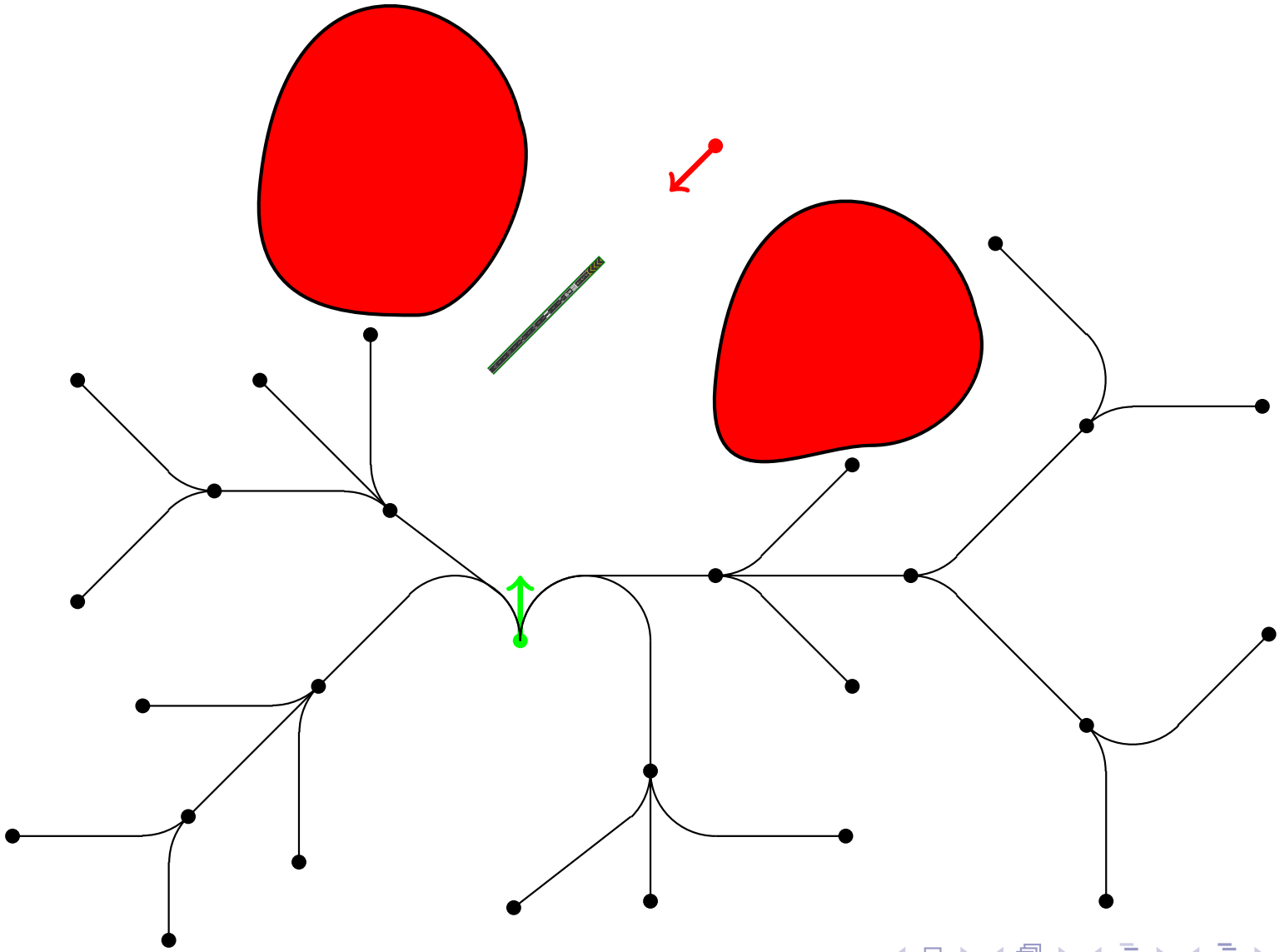
Path Generator



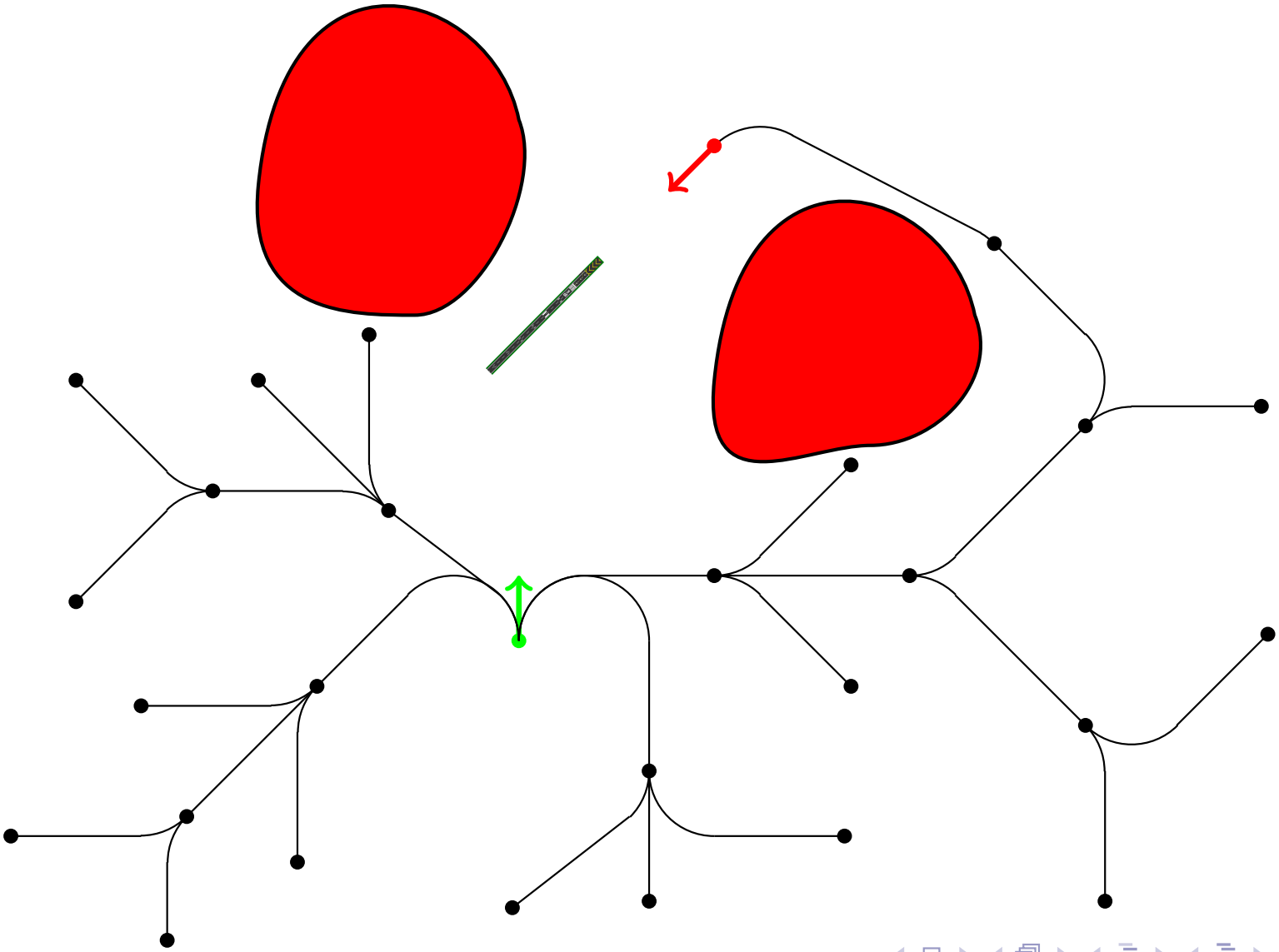
Path Generator



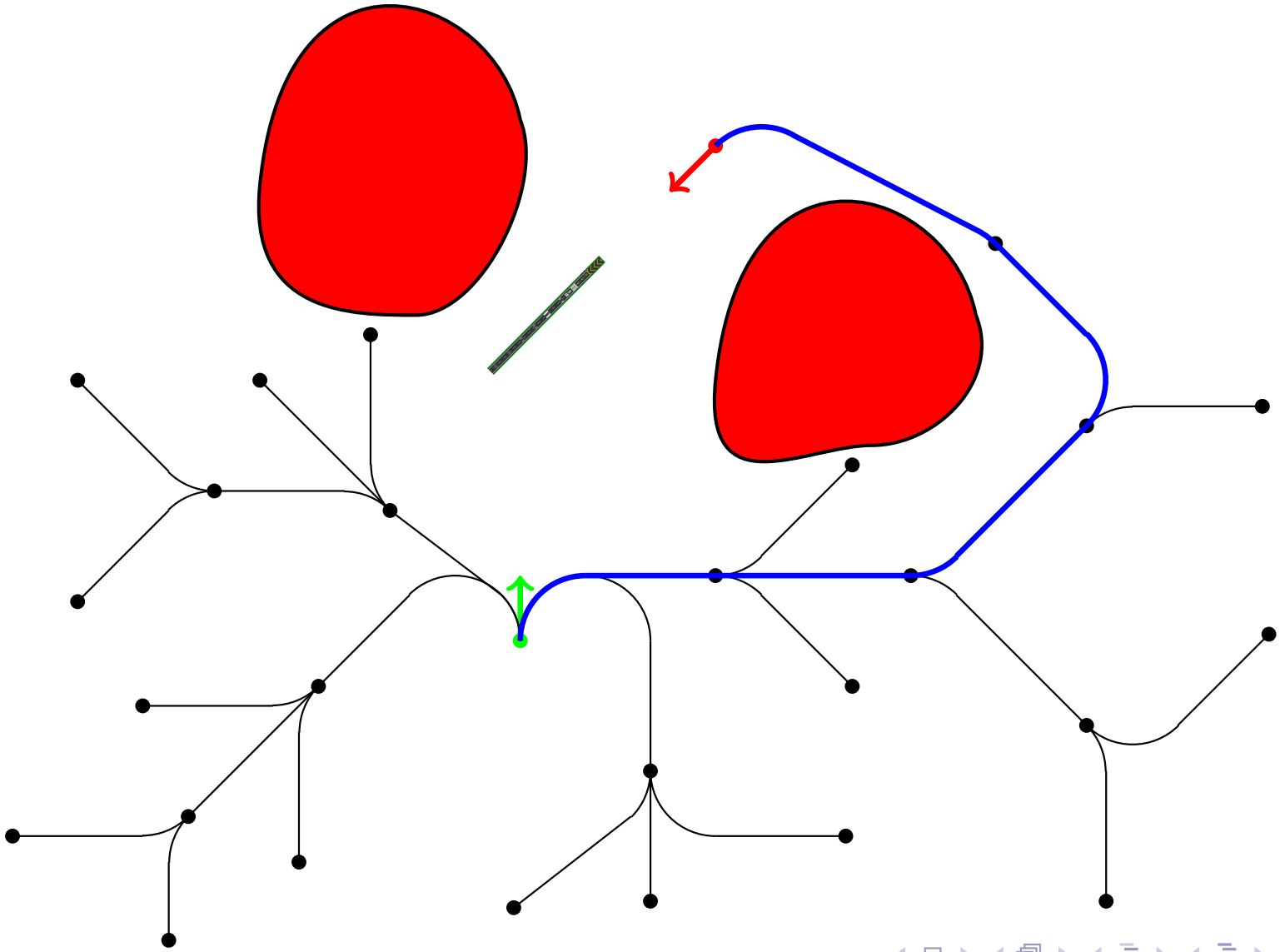
Path Generator



Path Generator



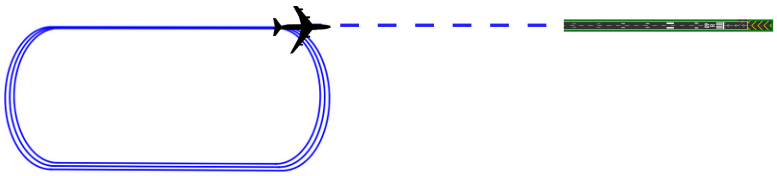
Path Generator

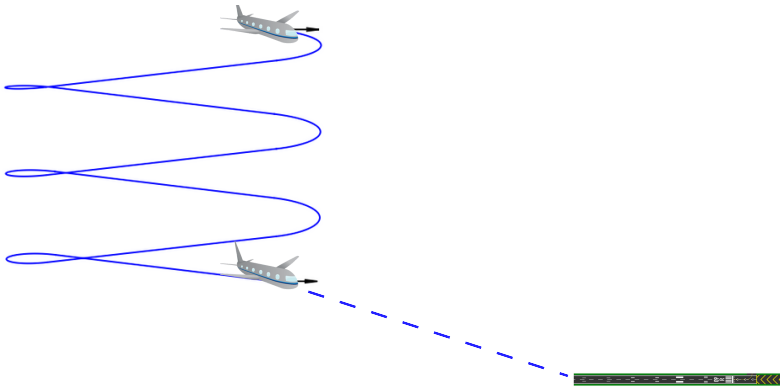


Pilot requests

Racetrack patterns

- Emergency over an airport
- ANSA emergency

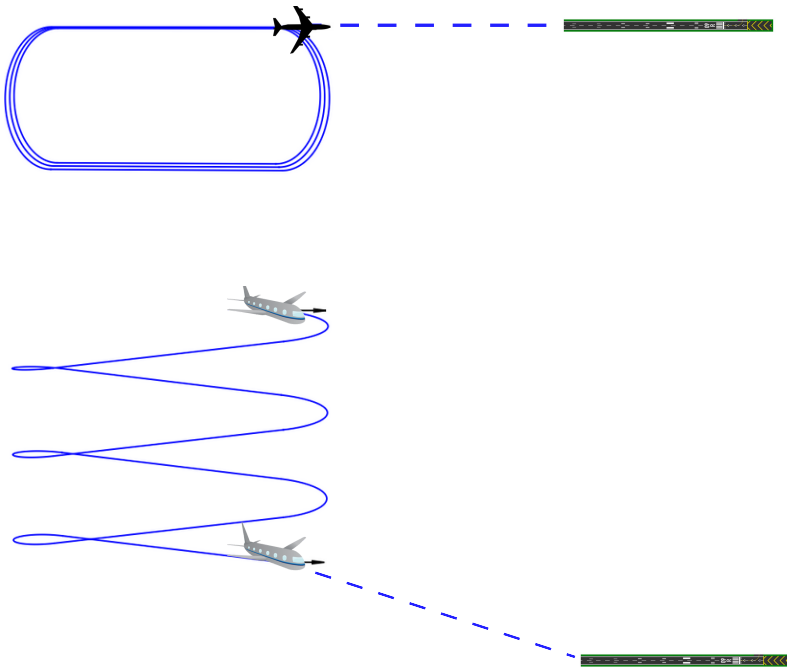




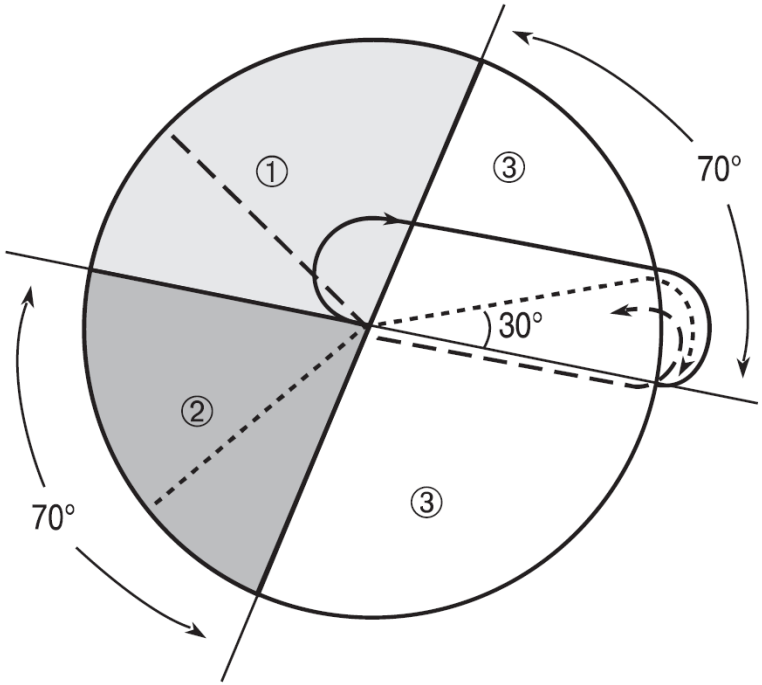
Pilot requests

Racetrack patterns

- Emergency over an airport
- ANSA emergency



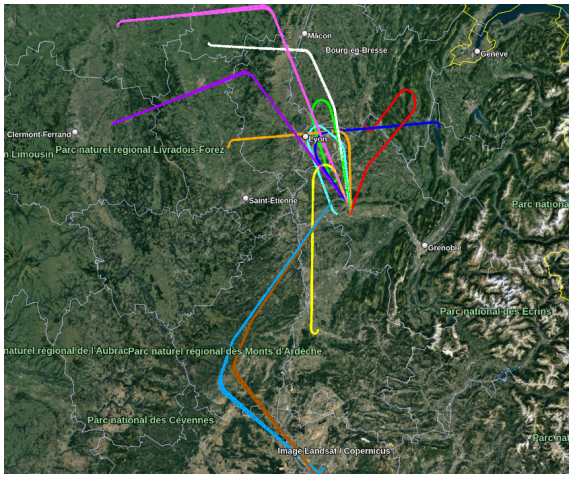
Approach procedures

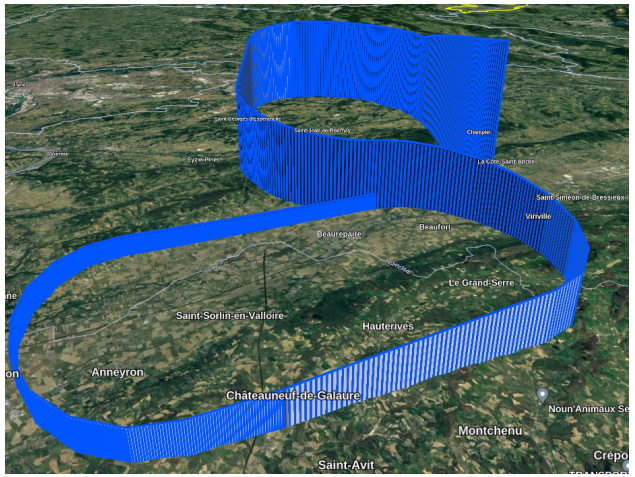


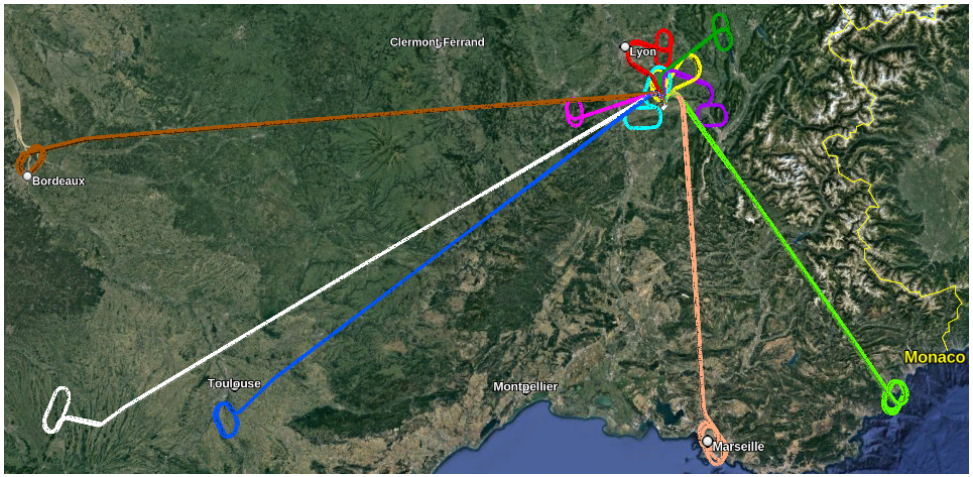
Results

First Results (Path generation)

Optimized RRT* algorithm (50 ms for generating one trajectory)



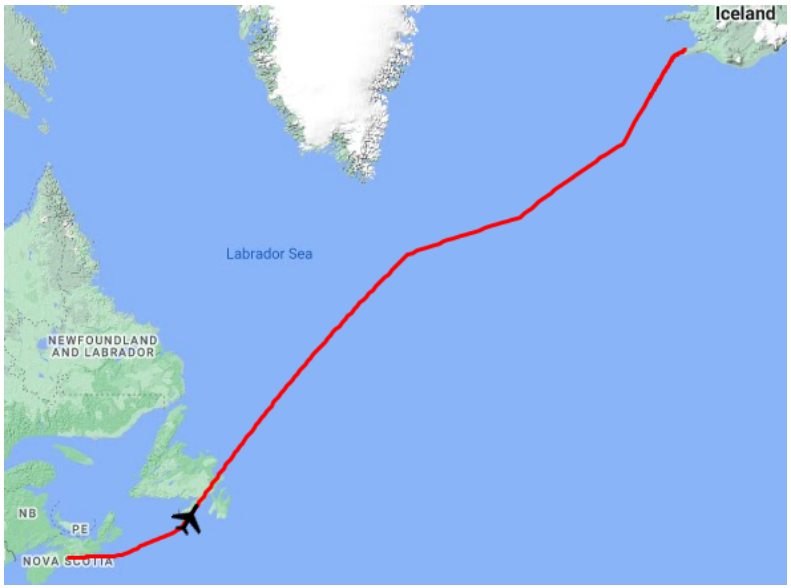


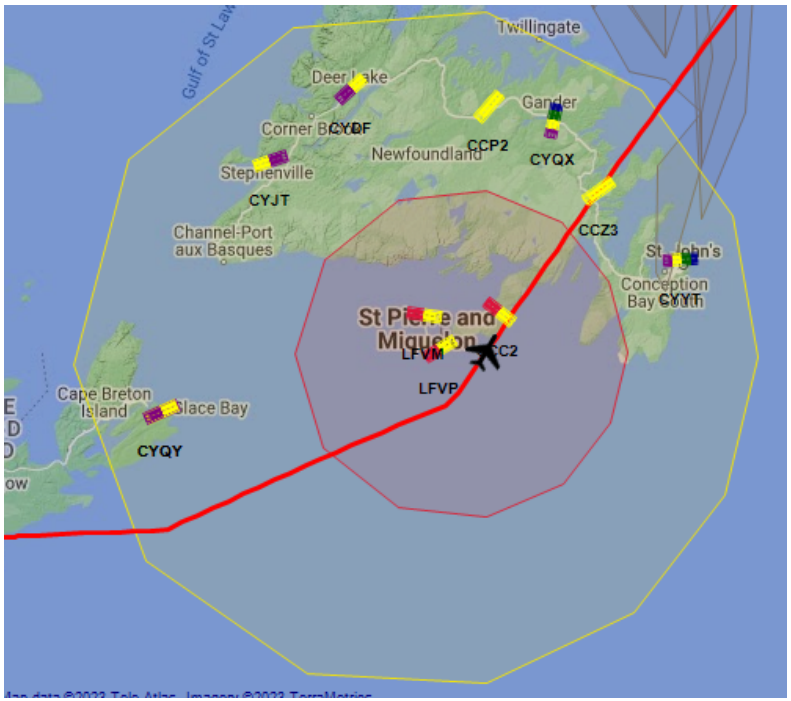


Implementation into the Thales FMS Prototype

TEFO in cruise

- Halifax airport (CYHZ) to Keflavik airport (BIKF)
- Emergency declared over Saint Pierre and Miquelon.
- 3 Airports for TEFO emergency
- Saint Pierre airport is preferred (Class 3)

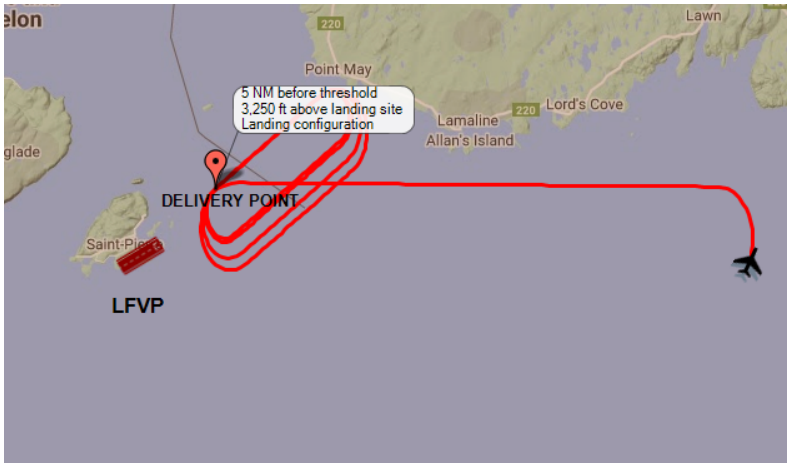


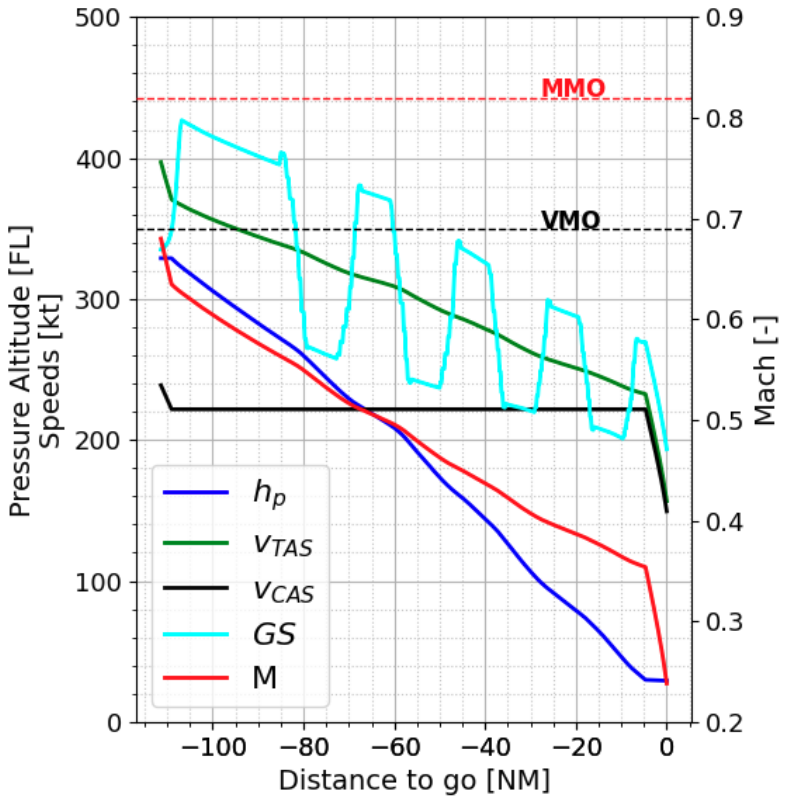


TEFO in cruise

Trajectory to LFVP airport

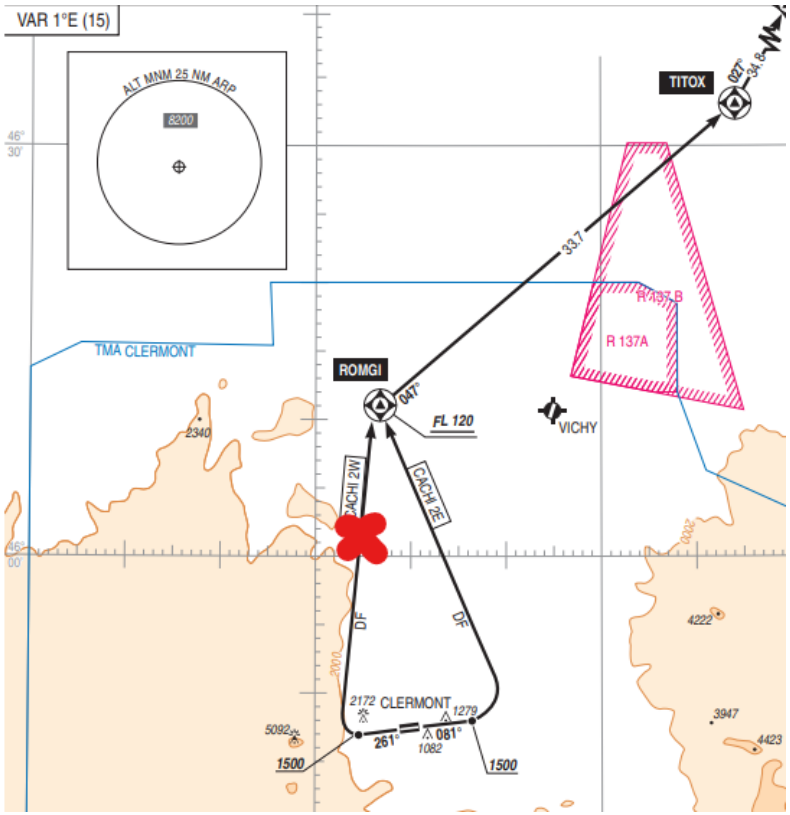
- Flight distance: 99NM
- Flight time: 21 minutes

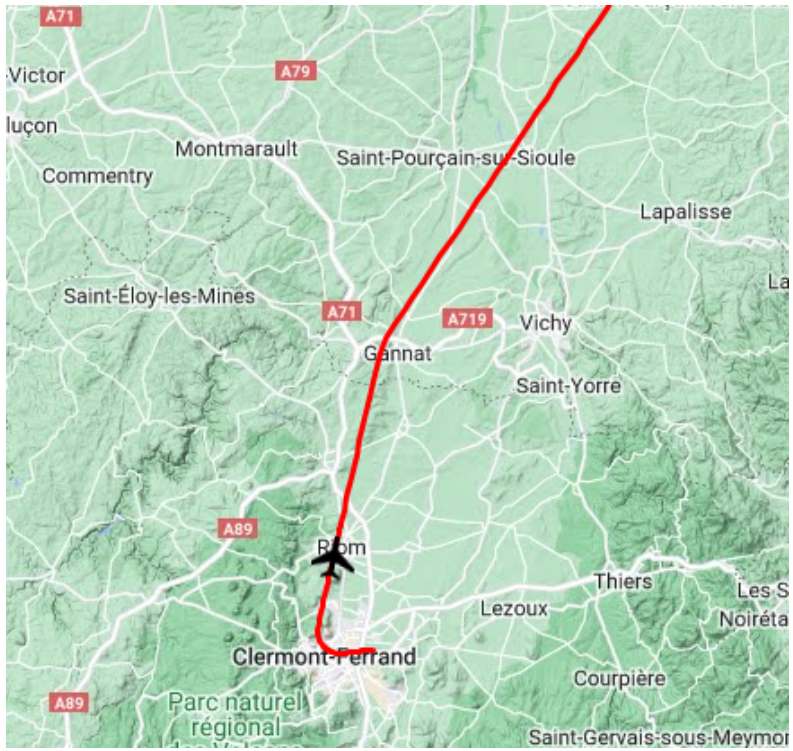




TEFO at low altitude

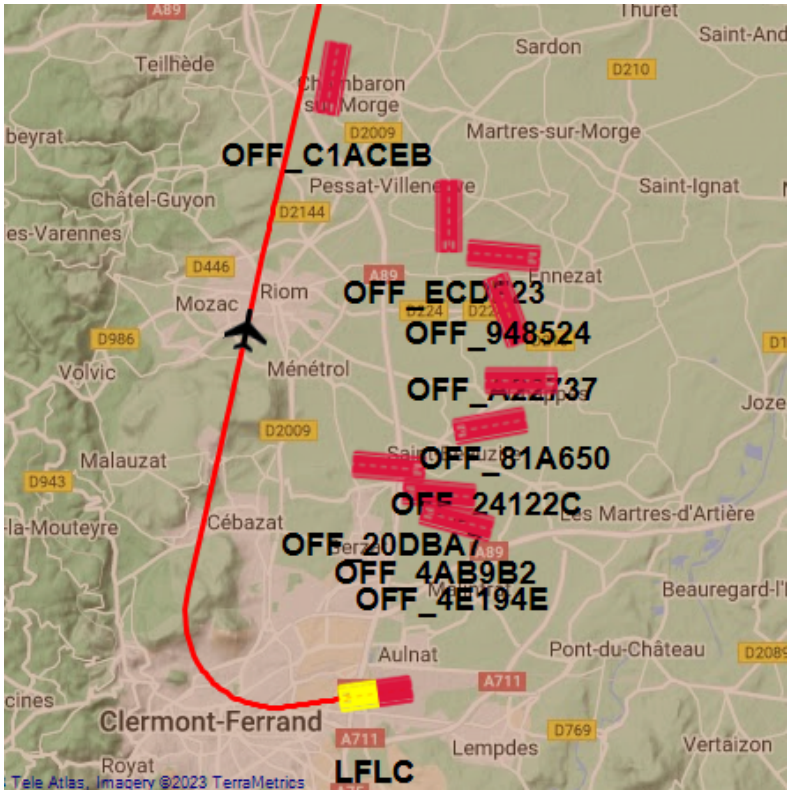
- Emergency declared at 8000ft after take-off from Clermont-Ferrand airport
- Off-airports generated by the landing site selector

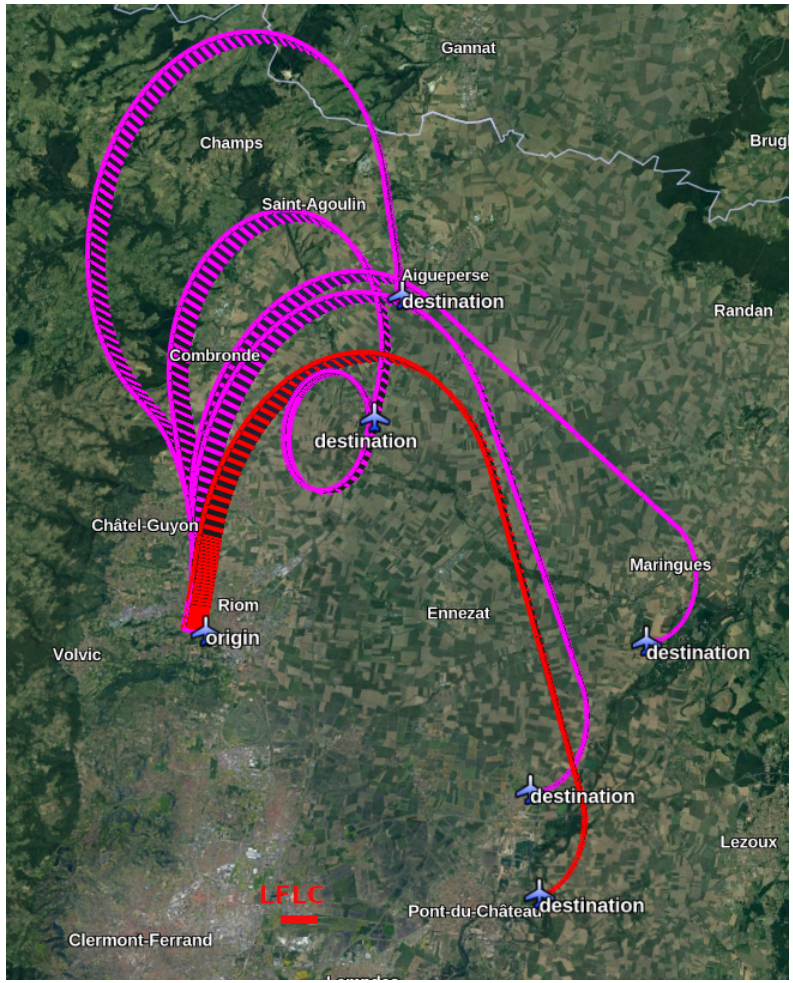




TEFO at low altitude

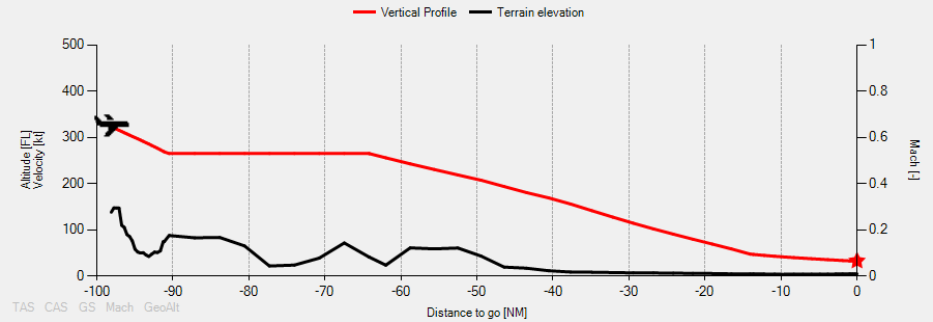
- 5 trajectories among 10 landing sites
- A solution to return to Clermont-Ferrand Airport





ASAP

(a) Lateral view



(b) Vertical profile with terrain

Figure: ASAP emergency for an A320 cruising at FL330 over Mont Blanc (flight from Paris Charles de Gaulle LFPG to Roma Fiumicino LIRF); trajectory to Milan Malpensa Airport (LIMC).

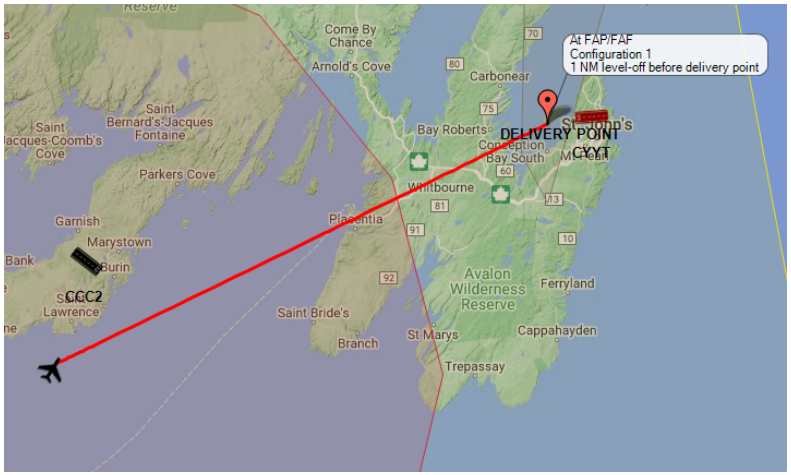
ANSA

(a) Horizontal view of the trajectory to Valladolid Airport (LEVD).

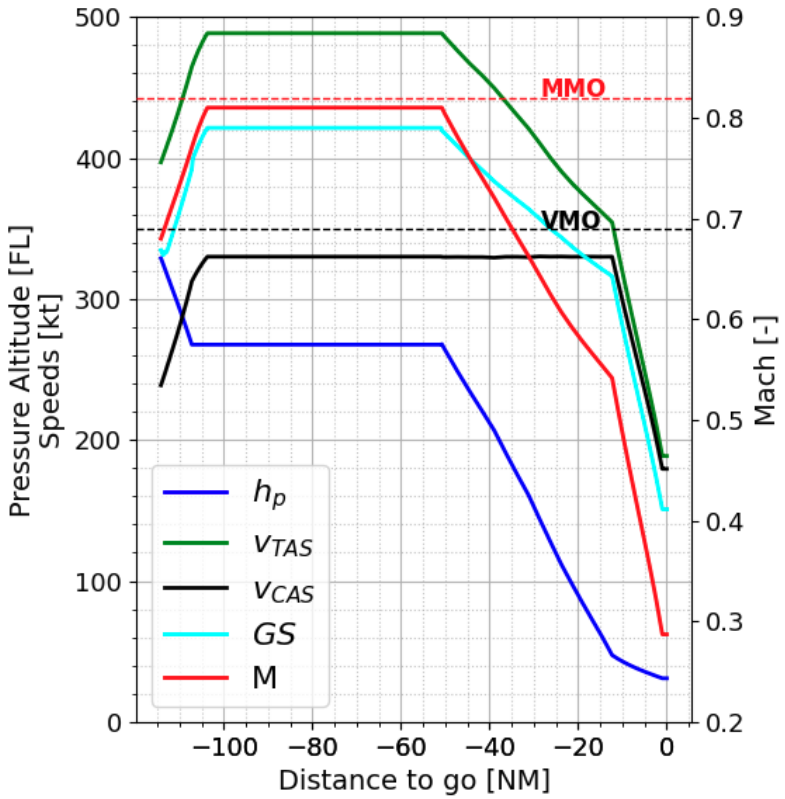
(b) Horizontal view of the trajectory to Zaragoza Airport (LEZG).

Figure: At Nearest Suitable Airport (ANSA) emergency for an A320 at FL330 near the Pyrenees with the presence of stormy areas (in grey).

Fire



(a) Horizontal view



(b) Vertical profile

Figure: Fire emergency for an A320 cruising at FL 330 south of Newfoundland (flight from Halifax CYHZ to Reykjavik BIRK); trajectories to St. John's International Airport (CYYT).

Hudson

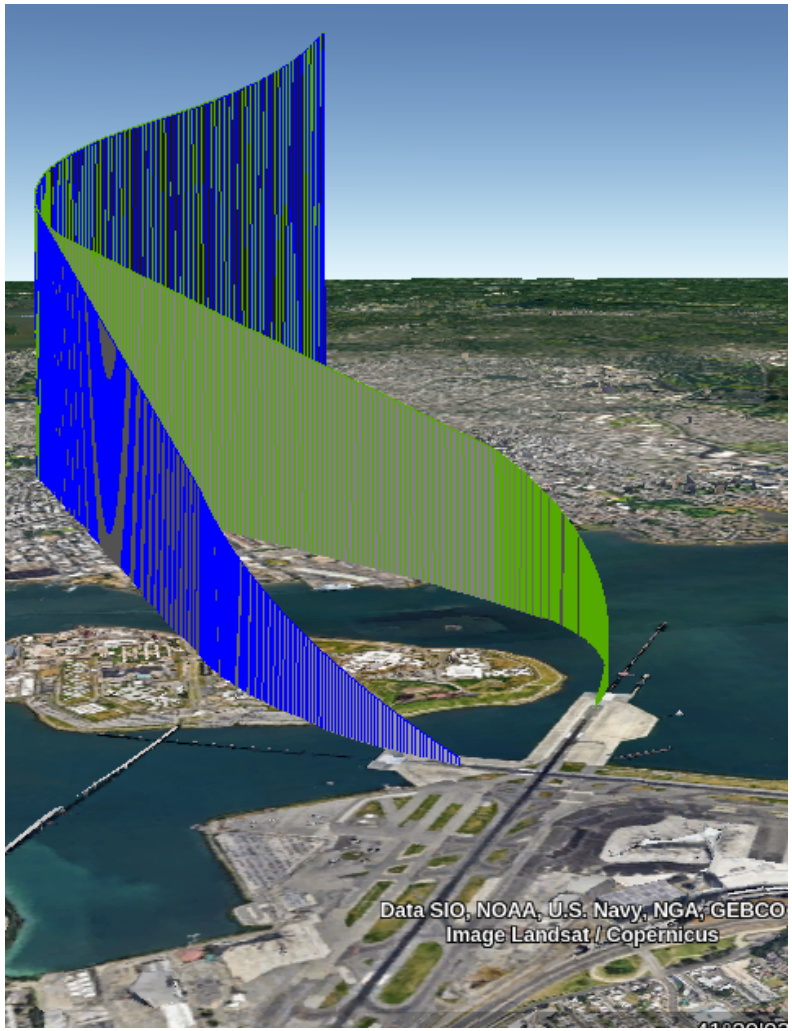


Figure: Trajectories to return to Laguardia Airport.

Conclusion

- Three methods tested (FMT, FM and RRT)
- Development of the path generator of the SafeNcy Project
- Adaptable method to several emergency scenarios
- Computation times are good for Path Generator (ASAP: <2s, ANSA: <3s and TEFO: < 5s) ...
- ...but could be improved for the whole process (ASAP: <10s, ANSA: <15s and TEFO: 1 min)

Conclusion

- Three methods tested (FMT, FM and RRT)
- Development of the path generator of the SafeNcy Project
- Adaptable method to several emergency scenarios
- Computation times are good for Path Generator (ASAP: <2s, ANSA: <3s and TEFO: < 5s) ...
- ...but could be improved for the whole process (ASAP: <10s, ANSA: <15s and TEFO: 1 min)

Perspectives

- Reduce the computing time of some scenarios
- Ensure that the system finds a trajectory for all suitable landing sites
- Limit the number of computed trajectories (3 for instance) to reduce the computation time
- Extend the failure catalog

Publications

Journal papers

- Guitart, Delahaye, and Feron. “An accelerated dual fast marching tree applied to emergency geometric trajectory generation." Aerospace 9.4 (2022): 180.
- Guitart *et al.* “Collaborative Generation of Local Conflict Free Trajectories With Weather Hazards Avoidance." IEEE Transactions on Intelligent Transportation Systems (2023).
- Guitart *et al.* “Multi criteria methodology for aircraft trajectory planning algorithm selection: A survey.” IEEE Transactions on Intelligent Transportation Systems.
- Guitart *et al.* “SID/STAR Design Optimization considering noise impact by Simulated Annealing: the Paris case study” Submitted to IEEE Transactions on Aerospace and Electronic Systems.
- Ligny *et al.* “A 3D Fast Marching method on tetrahedral meshes built from octrees and its application to aircraft emergency trajectory design considering wind.” Submitted to ACM Transactions on Mathematical Software.
- Saez *et al.* “An Automated Airborne Support Tool for Aircraft Emergencies: Selection of Landing Sites and 4D Diversion Trajectories.” Submitted to IEEE Transactions on Intelligent Transportation Systems.

Publications

Conference papers

- Sáez *et al.* “A fast and flexible emergency trajectory generator enhancing emergency geometric planning with aircraft dynamics." Fourteenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2021). 2021.
- Ligny *et al.* “Aircraft Emergency Trajectory Design: A Fast Marching Method on a Triangular Mesh." Fourteenth USA/Europe Air Traffic Management Research and Development Seminar. 2021.
- Bonin *et al.* “Optimal path planning for soaring flight." Conference on Guidance Navigation and control (CEAS EuroGNC 2022). 2022.
- Sáez *et al.* “An Automated Emergency Airport and Off-Airport Landing Site Selector." 2022 41st Digital Avionics Systems Conference.
- Demouge, Guitart and Delahaye. “Fast Marching Tree applied to geodesic trajectories in presence of uncertain wind: a day of flights in Europe study." IEEE/AIAA 42nd Digital Avionics Systems Conference (DASC). IEEE, 2023.
- Demouge *et al.* “An adapted Fast Marching Tree for contrails mitigation: A short-and long-range flight study." 26th IEEE International Conference on Intelligent Transportation Systems ITSC 2023. IEEE, 2023.
- Lebegue *et al.* “Aircraft cruise alternative trajectories generation: a mixed RRG-clustering approach." EAI INTSYS 2023 - 7th EAI International Conference on Intelligent Transport Systems. EAI, 2023.

Questions ?