ATC Automation: lessons learned from 25 years of studies

Nicolas Durand – Jean-Marc Alliot

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE
ministère
des Transports
de l'Équipement
du Tourisme
et de la Mer

SESAR consortium

A short history of advanced automation projects

- The centralized way
  - AERA2/AERA3
  - ARC2000
  - CATS...
- The autonomous way
  - Repulsive forces
  - Free-R
  - ASSAP
  - FACES...

The centralized way: AERA1/2/3

- Automated En-Route Air trafic Control
- FAA/MITRE project
- Early 80s
- AERA1 : aid-decision tool
- AERA2 : recommended resolutions
- AERA3 : fully automated conflict resolution

The centralized way: AERA3

- Three hierarchical levels
  - ASF (Automated Separation function)
    - Separation of a pair of aircraft
  - MOM (Manoeuver Option Manager)
    - « Cuts » complex conflicts in pairs to keep ASF happy
  - AMPF (Airspace Manager Planning Function)
    - Controls the density of trafic to ensure that MOM can operate properly
- Only ASF was implemented with the GS (Gentle Strict) algorithm
- MOM and AMPF were not even described in any documents
- AERA was swallowed by the desastrous AAS (Advanced Automation System) project and AERA3 totally disappeared
- URET might be considered as the implementation of AERA1/(2?)

The centralized way: ARC2000

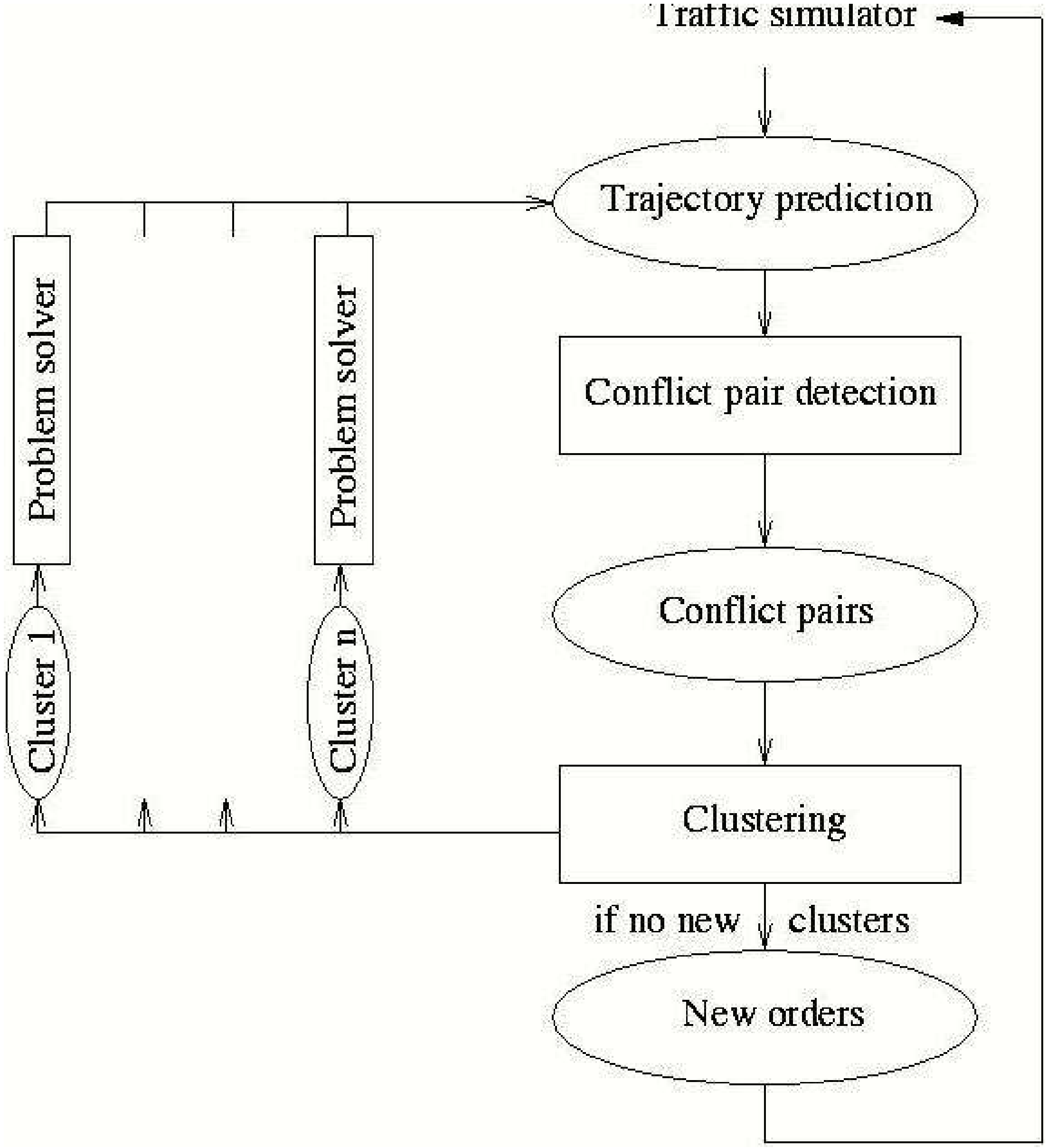
- Eurocontrol/CEE project, late 80s, early 90s
- Requires 4D accurate trajectory planning
- Semi-global algorithm (1-to-n algorithm, called the « rubber-band algorithm », mainly a gradient optimization tool)
- The project evolved from unrealistic hypothesis (4D trajectories from the start) to 20 minutes 4D planning with revisable manoeuvers
- The algorithms evolved from strict 1-to-n resolution to rules-based priority computation of trajectories
- The system never tackled the global optimization problem and was unable to solve complex conflicts. Stopped in 1995.
- The Highly Interactive Problem Solver (HIPS) was an offspring "what-if tool"

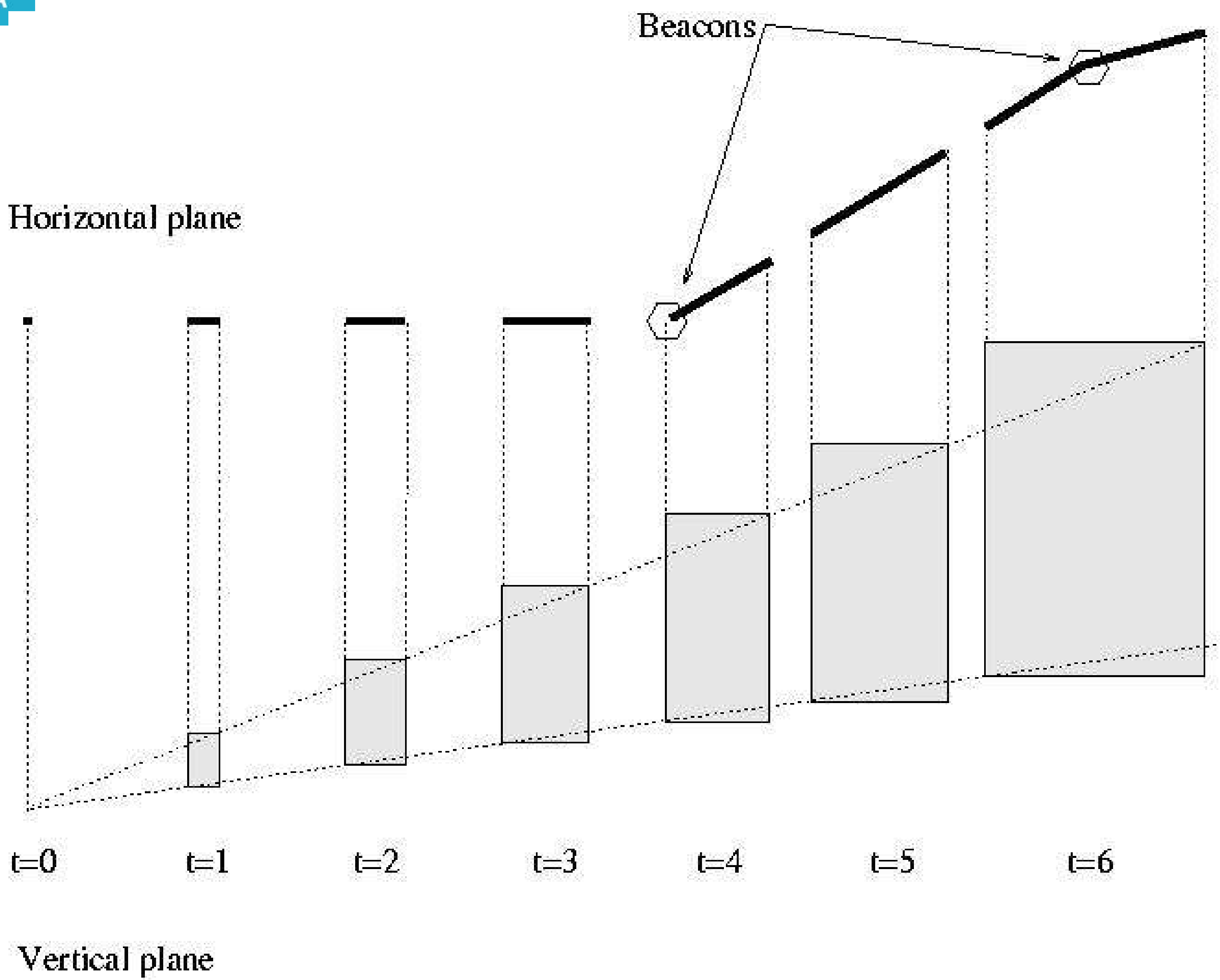
The centralized way: SAINTEX

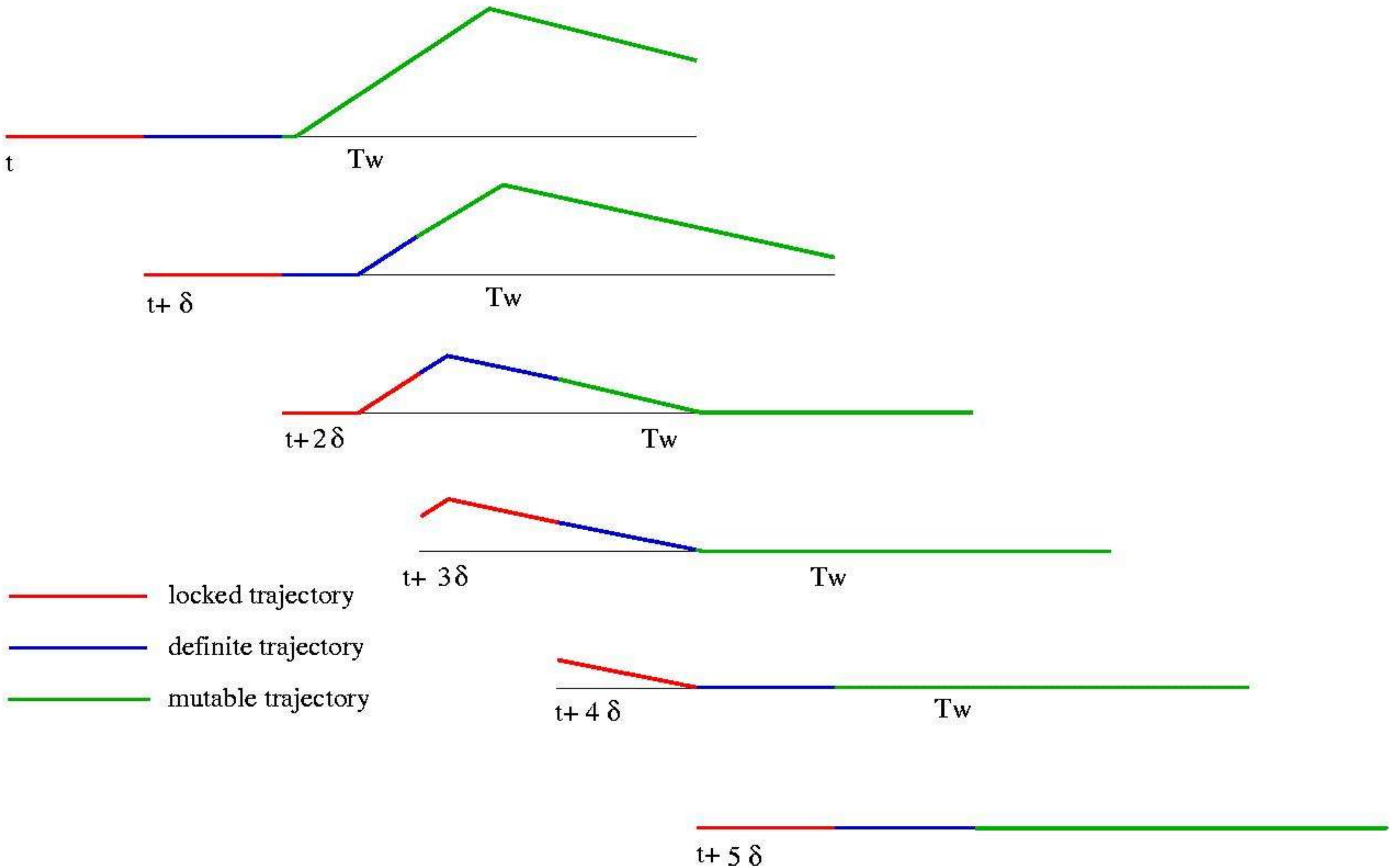
- CENA project, late 80s
- Rules based (« expert system » approach)
- Tried to mimic the controller's behaviour, by classifying conflicts and using « expert manoeuvers » to solve them
- Could only solve two-aircraft conflicts, and never adressed the problem of complex conflicts
- An hybrid scenario, using some ideas also found in ARC2000, tried to mix the expert system approach with a 4D approach
- The project, as many expert systems, was plagued by inconsistency problems and never passed the mock-up stage

The centralized way: CATS

- CENA project, 1992 to 2006
- 14 years of development and enhancement
- Clustering and global optimization algorithms
- Based on a « contracting » hypothesis: aircraft must remain inside « uncertainty boxes » that become larger as time advances
- Use very simple manoeuvers, easy to implement
- Can solve extremely complex conflits (more than 30 aircraft in the same cluster)
- Tested in fast time simulation on real trafic
- Can solve every problems for a heavily loaded day in the european airspace


Traffic simulator
Trajectory prediction
Conflict pair detection
Conflict pairs
Clustering
if no new clusters
New orders
Problem solver
Problem solver
Cluster 1
Cluster n

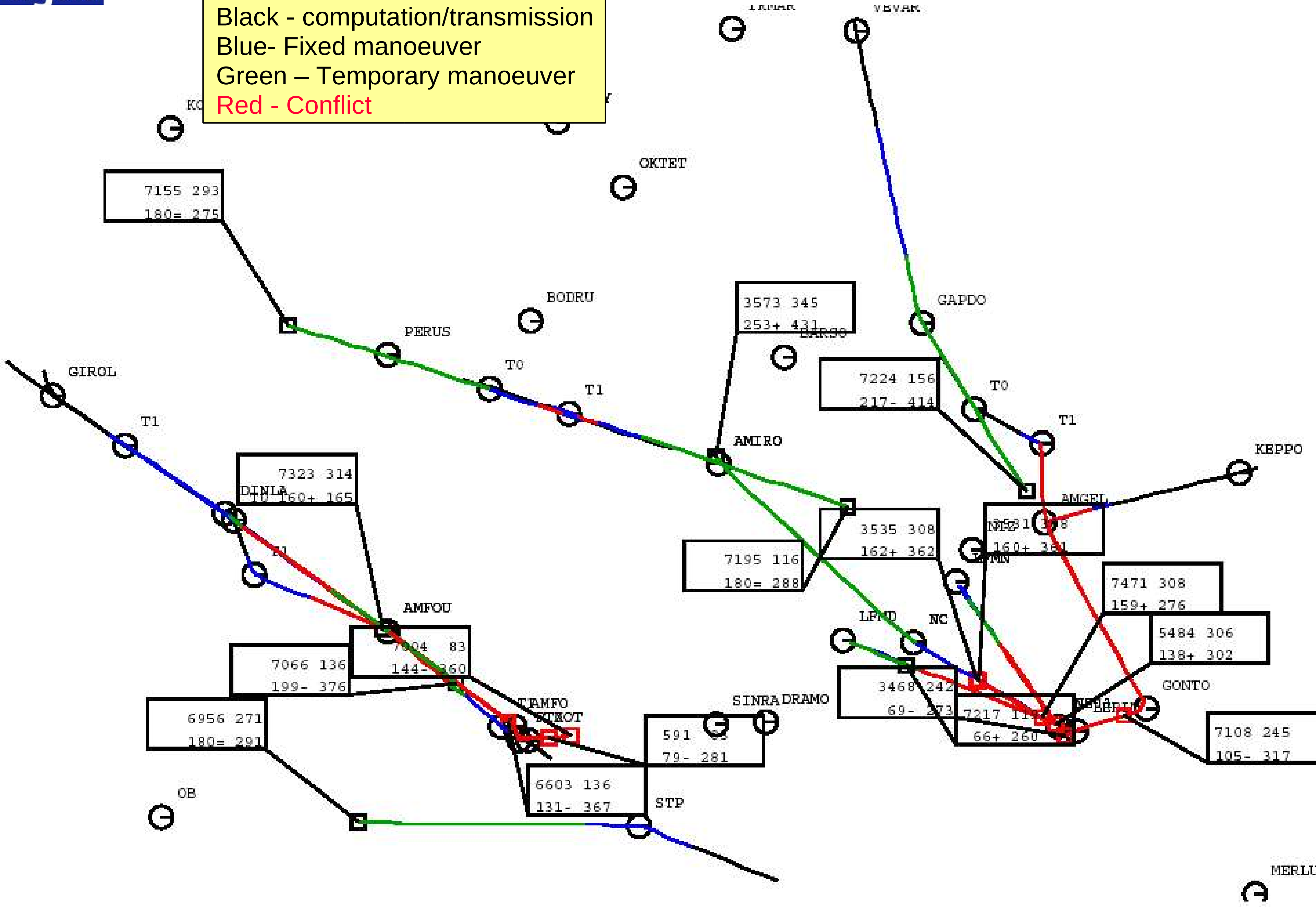

Beacons
Horizontal plane
t=0
t=1
t=2
t=3
t=4
t=5
t=6
Vertical plane



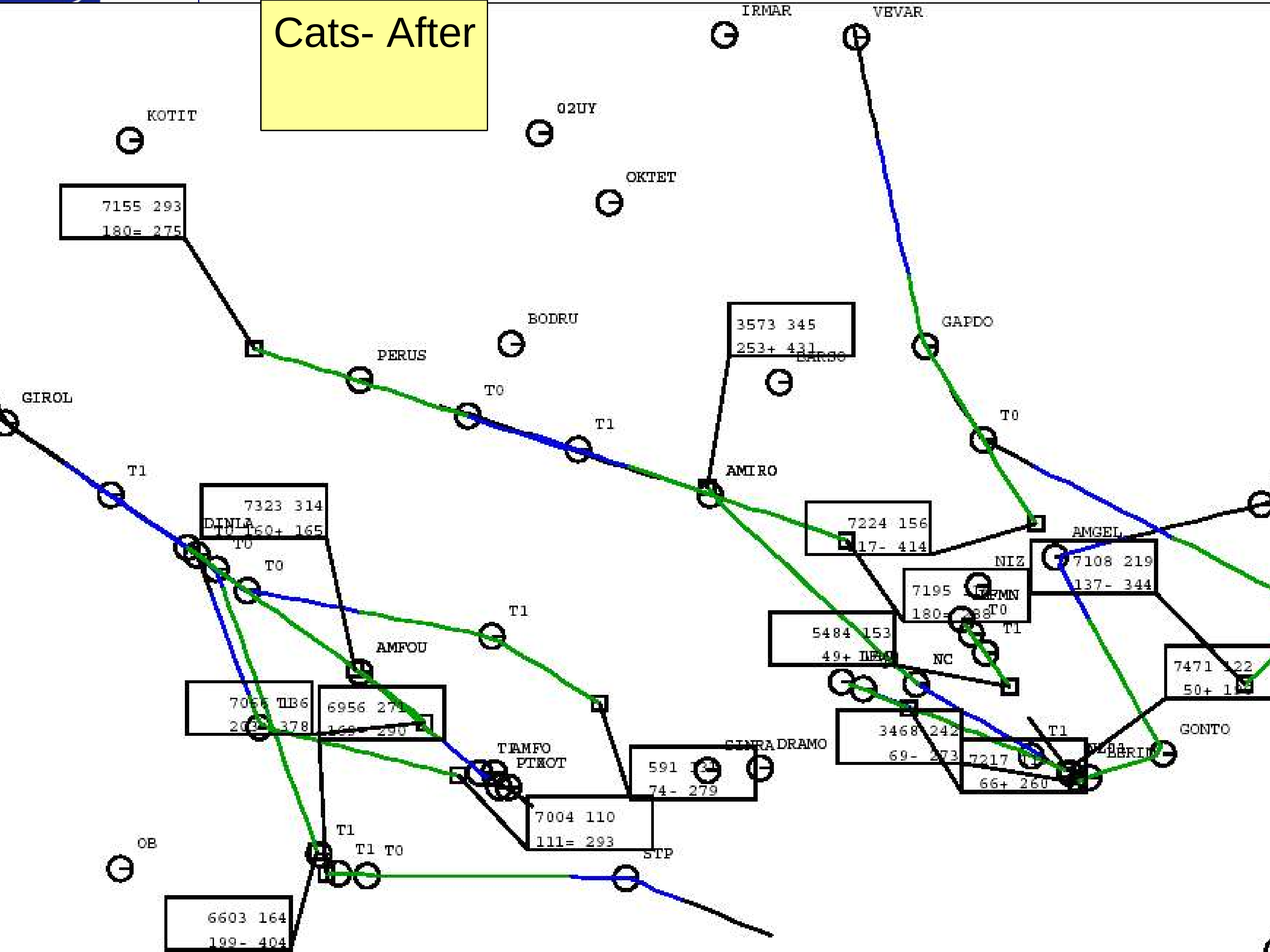
t
Tw
t+ δ
Tw
t+2δ
Tw
t+ 3δ
Tw
t+ 4 δ
Tw
t+ 5 δ
locked trajectory
definite trajectory
mutable trajectory

Cats- before

Black - computation/transmission
Blue- Fixed manoeuver
Green – Temporary manoeuver
Red - Conflict



Cats- After



IRMAR
VEVAR
KOTIT
02UY
OKTET
7155 293
180= 275
BODRU
3573 345
253+ 431
PERUS
GAPDO
GIROL
T0
T1
AMIRO
7323 314
160+ 165
7224 156
17- 414
AMGEL
7108 219
137- 344
NIZ
7195
5484 153
NC
AMFOU
6956
7066
DRAMO
591
74- 279
3468 242
69- 273
7217
66+ 260
7471
GONTO
7004 110
111= 293
STP
OB
T1 T0
6603 164
199- 404

The autonomous way: the repulsive forces method

- Developped by Karim Zeghal during his PhD thesis at ONERA in 1992
- Combination of repulsive forces (between aircraft), attractive forces (toward the aircraft destination) and sliding forces (to break the symmetries and bypass obstacles)
- The method is robust and efficient in low density areas
- In high density areas, the lack of global information creates new conflicts when trying to solve actual conflicts
- Manoeuvers are continuous and thus impossible to implement in the current ATC system. The method would also require a major change in FMS certification.

The autonomous way: FREER-1

- Designed at Bretigny in 1995
- Entirely autonomous aircraft in low density areas (above FL390 or the mediterranean sea)
- Extended Flying Rules (EFR) which are an extension of VFR rules are applied to solve automatically conflicts
- The algorithm was not sound, and was not able to solve conflicts including more than 4 (and sometimes 3) aircraft
- Experiments showed that clusters up to 14 aircraft had to be solved, even in upper space, as acknowledged by the designers themselves.
- EFR were never enhanced to solve the above problems and the project gave way to FREER-2

The autonomous way: FREER-2

- Continuation of FREER-1
- FREER-2 changed considerably. It became a tool to be proposed for partial delegation of conflict resolution
- The aircraft had to be equipped with ASAS
- Tests are currently carried out to evaluate the feasibility of partially delegating separation tasks to fligh crews (spacing queued separation)
- It is no longer an automation project

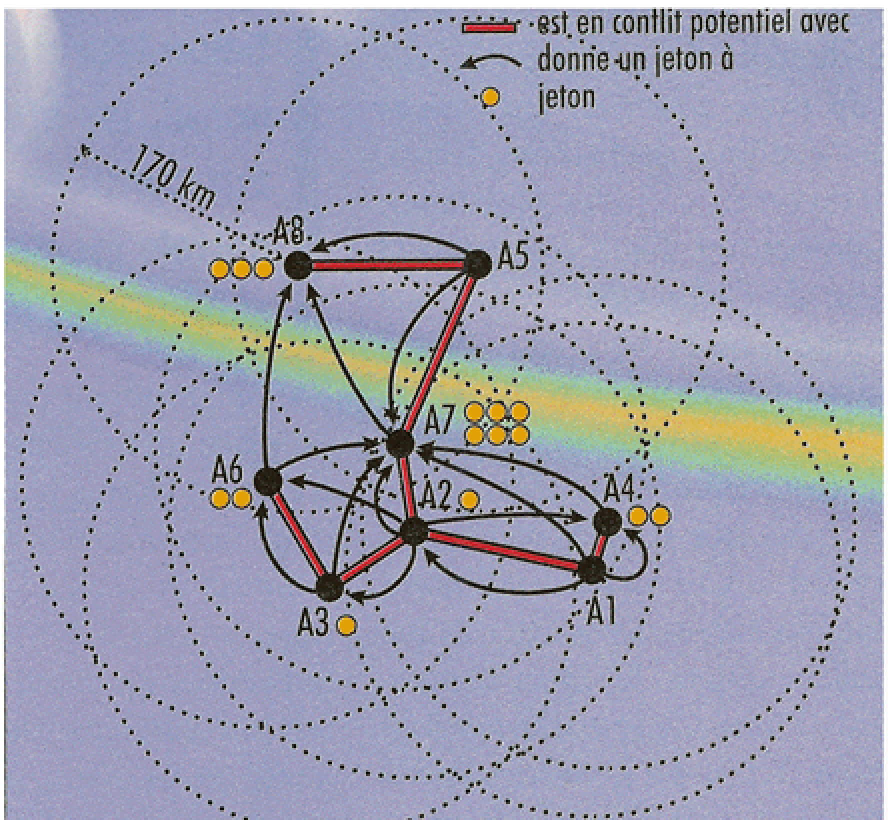
The autonomous way: the NLR Free Flight with ASAS

- NLR project based on the ASAS concept (ASSAP=Airborne Surveillance and Separation Assurance Processing)
- Many algorithms considered:
  - For "state based conflict" : a "brother" of Karim Zeghal (uncredited) repulsive force algorithm (Modified Voltage Potential – Hoekstra 2001)
  - For "intent based conflict" : the foggy "modification of flight plan" algorithm
- It doesn't explain clearly how to take into account (a) uncertainties on speed and (b) the multiple aircraft resolution problem.
- Algorithms were never statistically validated in fast time simulation with real traffic density and large clusters.
- The NLR itself recommends "to reconsider the conflict resolution algorithms with respect to conflicts in which multiple aircraft are involved". (Obbink / Scholte 2006)
- "The promising perspectives" of the project sound extremely optimistic

The autonomous way: FACES

- Project started at CENA in 1995
- Solves the FREER priority problem with a token allocation strategy
- Solves conflict by applying a 1 against n strategy, with an A* algorithm to find the shortest path inside a set of trajectory
- Requires synchronous (GPS) clocks, an airborne accurate TP prediction for the next 5 minutes
- The algorithm can be proved to be safe regarding priority
- Works very well in low density areas (above FL 310 for example)
- In high density areas, the algorithm, as all local algorithms, fails to operate properly as soon as uncertainties on speeds are set to realistic values.

The autonomous way: FACES



	Etape 1	2	3	4	5	6
A7	6	4	3	1	0	
A8	4	3	3	2	1	0
A4	2	1	0			
A6	2	2	1	0		
A2	1	0				
A3	1	1	0			
A1	0					
A5	0					

Lessons learned: complexity

- Solving the conflict resolution problem is a very complex operation from a mathematical point of view
- For a clusters with n aircraft, the number of operations to solve the problem needed grows as $2^{n(n-1)/2}$
- The problem belongs to the NP-complete category, which is the most difficult category of problem to solve
- Algorithms needed to solve the problem belongs to the global optimization category, and mainly to the stochastic optimisation category
- All geometrical or local methods fail in high density airspace

Lessons learned: constraints

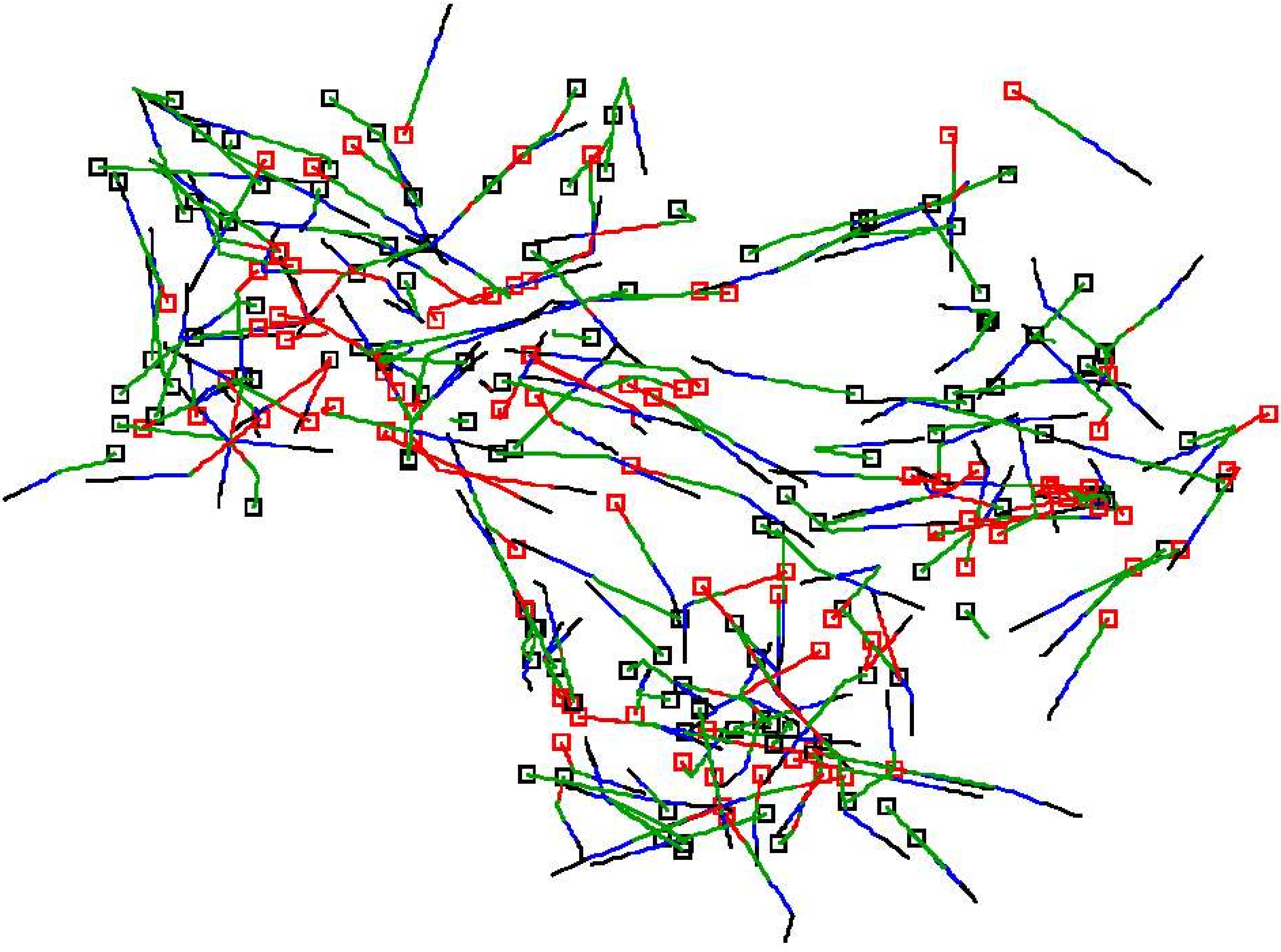
- An aircraft cannot modify its speed (or only very slightly) except during the descent phase
- An aircraft cannot be considered to be flying at a constant speed except possibly while crusing with no wind
- While climbing and descending, an aircraft path is not rectilinear. It cannot be described analytically.
- The evaluation of an aircraft future positions requires a TP module either on board or on the ground, and thus rules out all analytical methods

Lessons learned: TP sensitivity

- All algorithms are highly sensitive to TP quality.
- Mathematical results show that with a ground speed error of 5%, a vertical speed error of 30% and a 20 minutes time window, the numbers of conflicts detected is three times the number of actual conflicts. Algorithms fail to solve conflicts if errors are too large.
- This result applies equally to computer TP and to human TP, thus showing that controllers certainly monitor much more conflicts that they would if they had usable TP-based tools.
- Building good TP is a very difficult task. Discussions currently in progress within the ERASMUS project with FMS designers show that without highly accurate meteo models, a good 20 minutes TP is almost unreachable in an open loop system, even with an FMS.

Lessons learned: fallback

- Efficient algorithms solve conflicts in a "non-human" way, even when they use standard deviation methods.
- Using a fully automated CDR process would significantly change the kind of work the controller is doing: falling back to manual procedures in case of system failure would be impossible.



Lessons learned: development

- All automation projects needed years to be completed, and only up to the mock up stage.
- The system cannot be stopped to be upgraded, and all operational system evolutions take years to be implemented.
- Developing a completely automated operational CDR system requires lot of things which are not yet available:
  - Good meteo models with centralized databases of meteo information returned by aircraft FMS (currently, these informations do not leave the airlines operation centers)
  - 4D, CDR-enabled FMS for many, if not all, aircraft
  - "Closed loop" system, with FMS monitoring and ***enforcing*** trajectories planned by the ground system
  - Harmonization of all european ATC systems.

Lessons learned: transition

- Even if automation becomes possible, there must be a transition path
- This transition path must take into account a lot of different factors, both technicals factors and human factors
- This transition must be able to cope with intermediate situations where equipped and "older" aircraft will have to live in the same airspace
- The path must be defined along with the automation solution, as all automation solutions do not require the same (re)qualification of operators
- The path should go from aid decision tools to CDR automation in a smooth way, without any (even transitory) loss of security or capacity.
- The ERASMUS project is currently trying to design such a transition path.