

Algorithms in the sky: How to design an optimal airspace?

Valentin Polishchuk
Linköping University

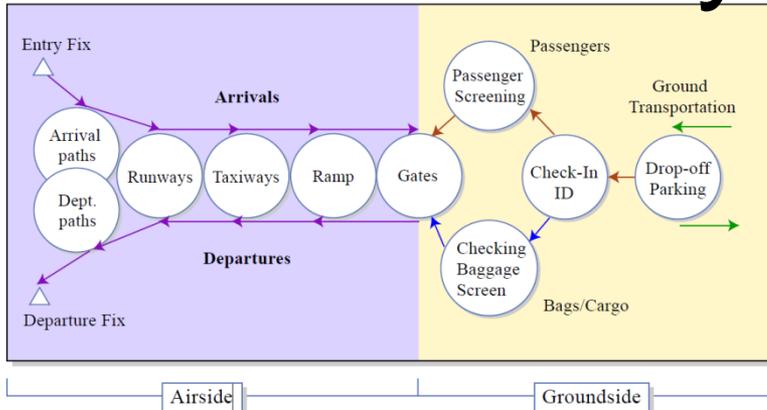
Agenda:

- How air traffic is different from other “traffics”
- Volume, complexity, uncertainty
- Solution approaches: be flexible, think 4D

Industry infrastructure

- Airports
 - Runways
 - Terminals
 - Ground transport interface
 - Servicing
- **Air traffic management (ATM)**
 - **Communications**
 - **Navigation**
 - **Surveillance**
 - **Control**
- Weather
 - Observation
 - Forecasting
 - Dissemination
- Skilled personnel
- Cost recovery mechanism

Industry infrastructure



- **Air traffic management (ATM)**
 - Communications
 - Navigation
 - Surveillance
 - Control

- Weather

- Observat
- Forecas
- Dissemin

• Skilled personnel

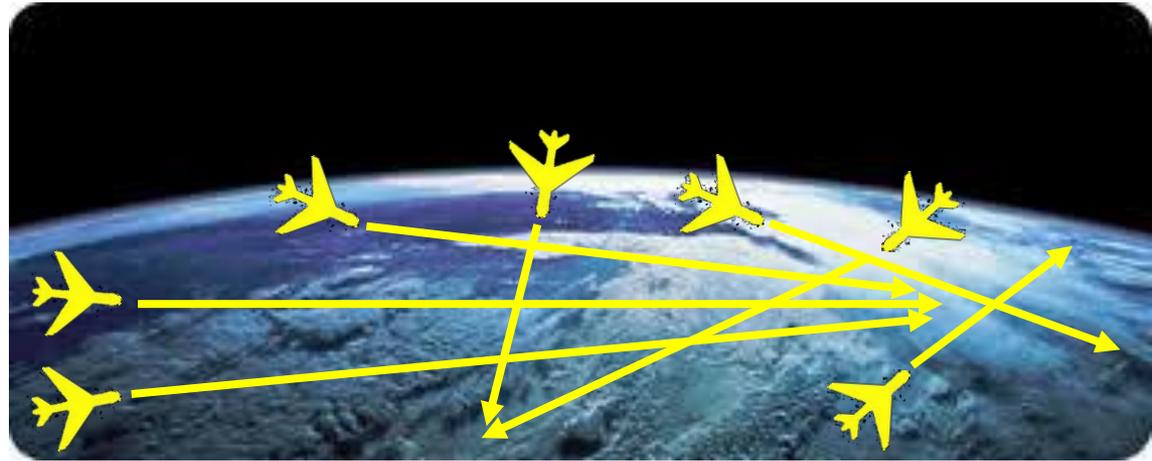
- Cost recovery

- Airports built
- Connections decided and priced
- Tickets bought



Air traffic management (ATM)

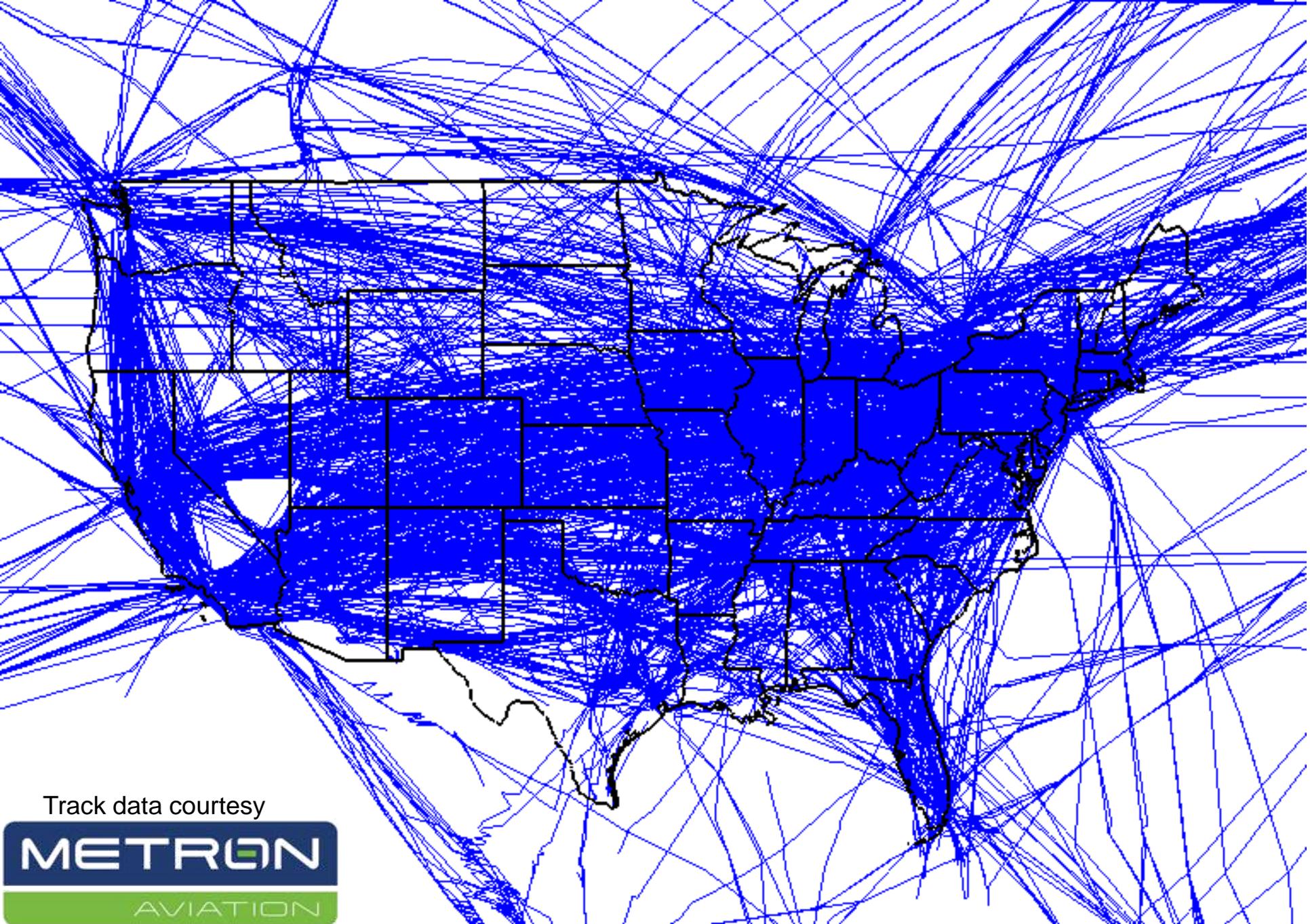
- Given
 - (A,B) pairs
- Find
 - Paths for aircraft
- Subject to
 - safety
 - punctuality
- Minimize *cost*
 - fuel consumption
 - environmental impact (emission, noise)



Q: *What's so hard about it?*

A: *Volume*





Track data courtesy



THE SCIENCE OF HARMONIZING AIR TRAFFIC

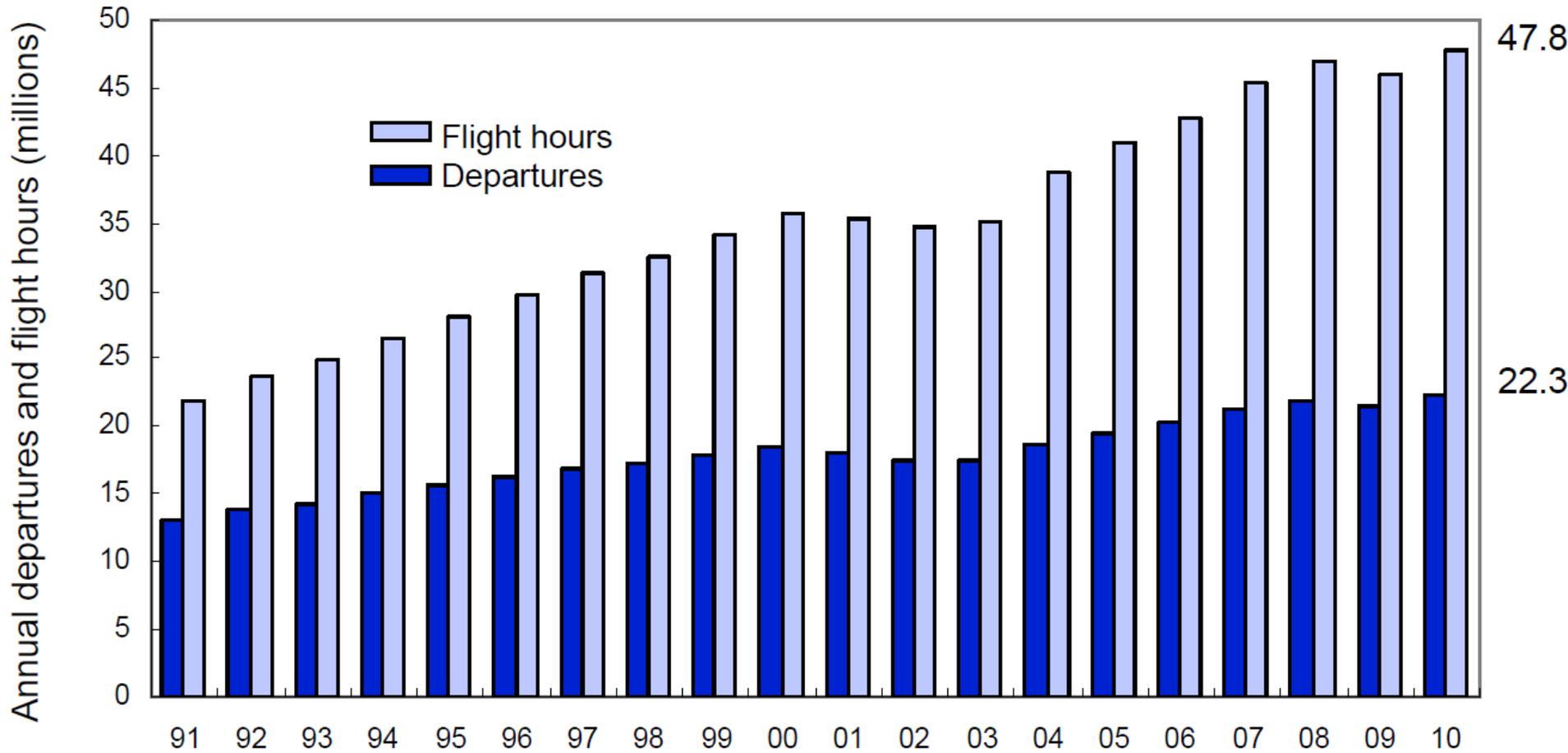


US

Europe

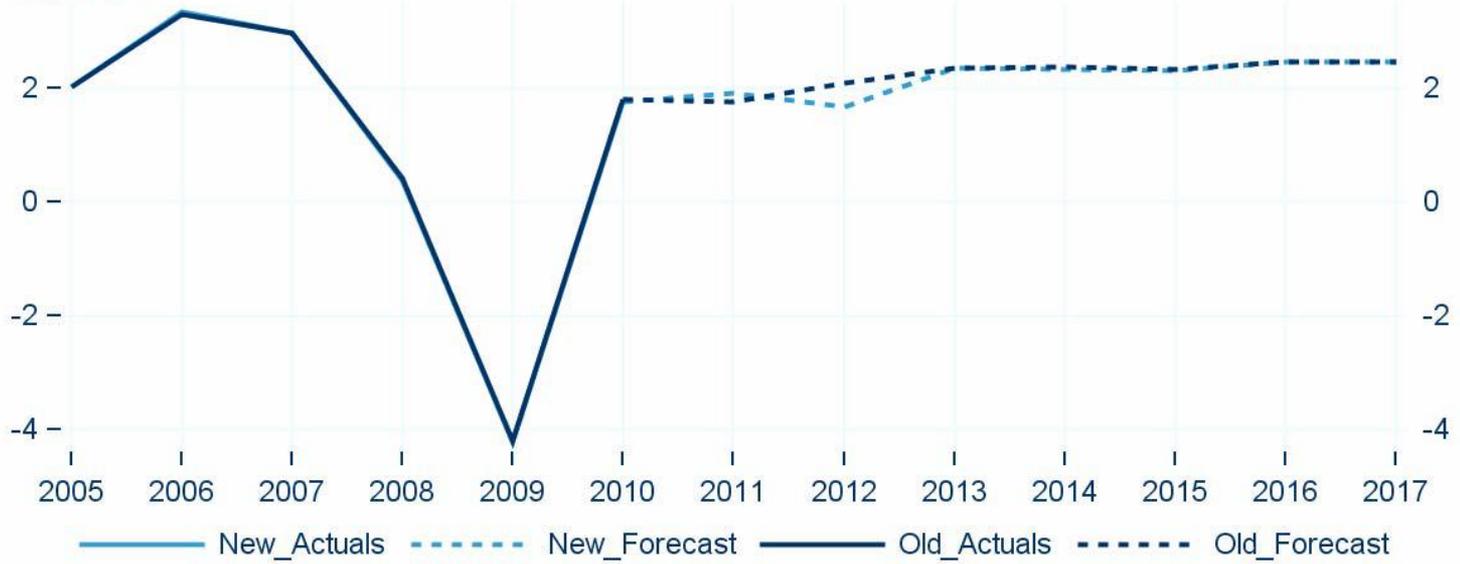
- 60000 flights/day
- 14000 ATCs (18 ATCCs)
- 250 Airports

- 30000 flights/day
- 20000 ATCs (80 ATCCs)
- 500 Airports



GDP Growth (%)

Zone=EU



ESRA08 - Grand Total



The more the merrier

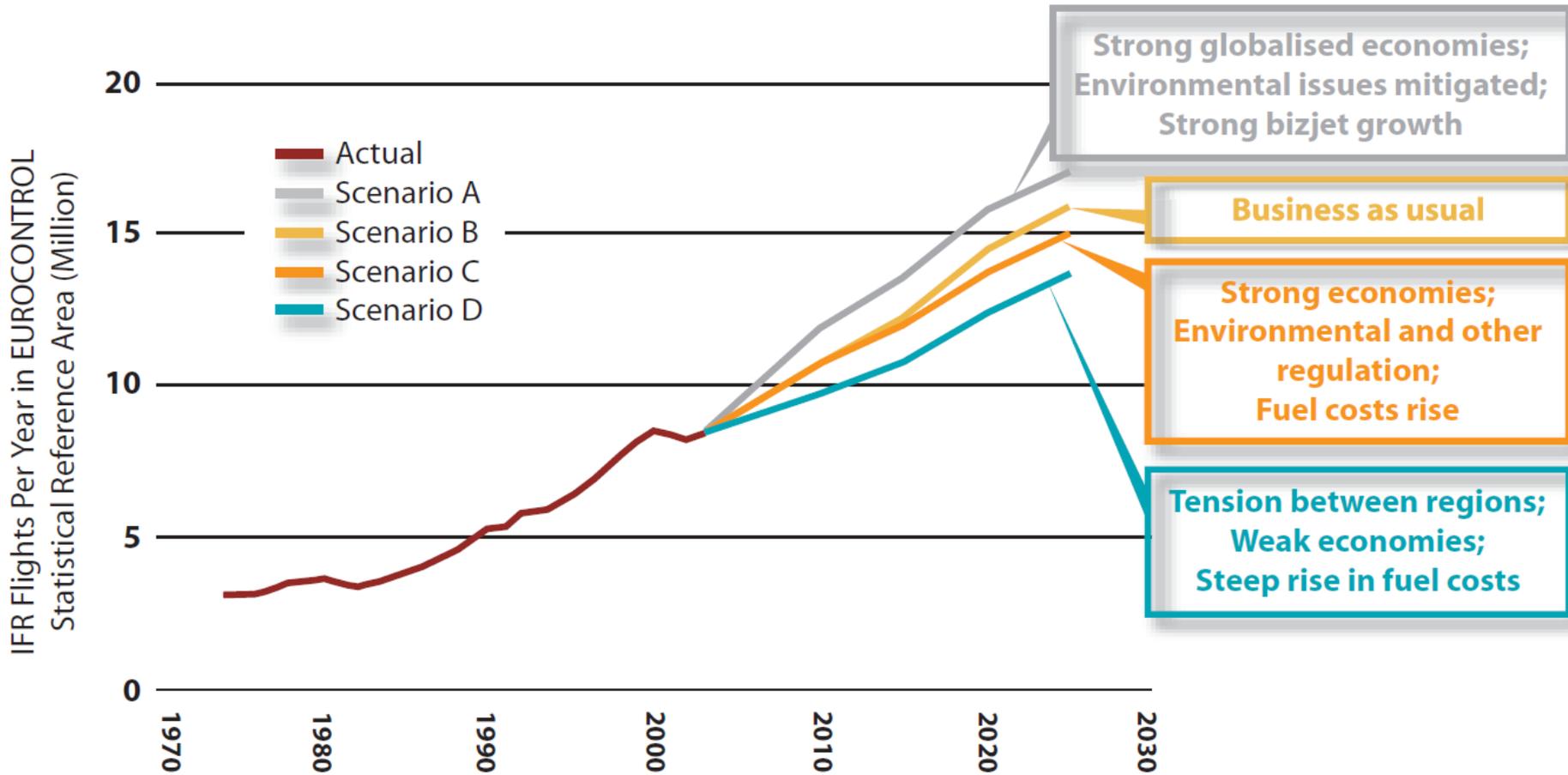
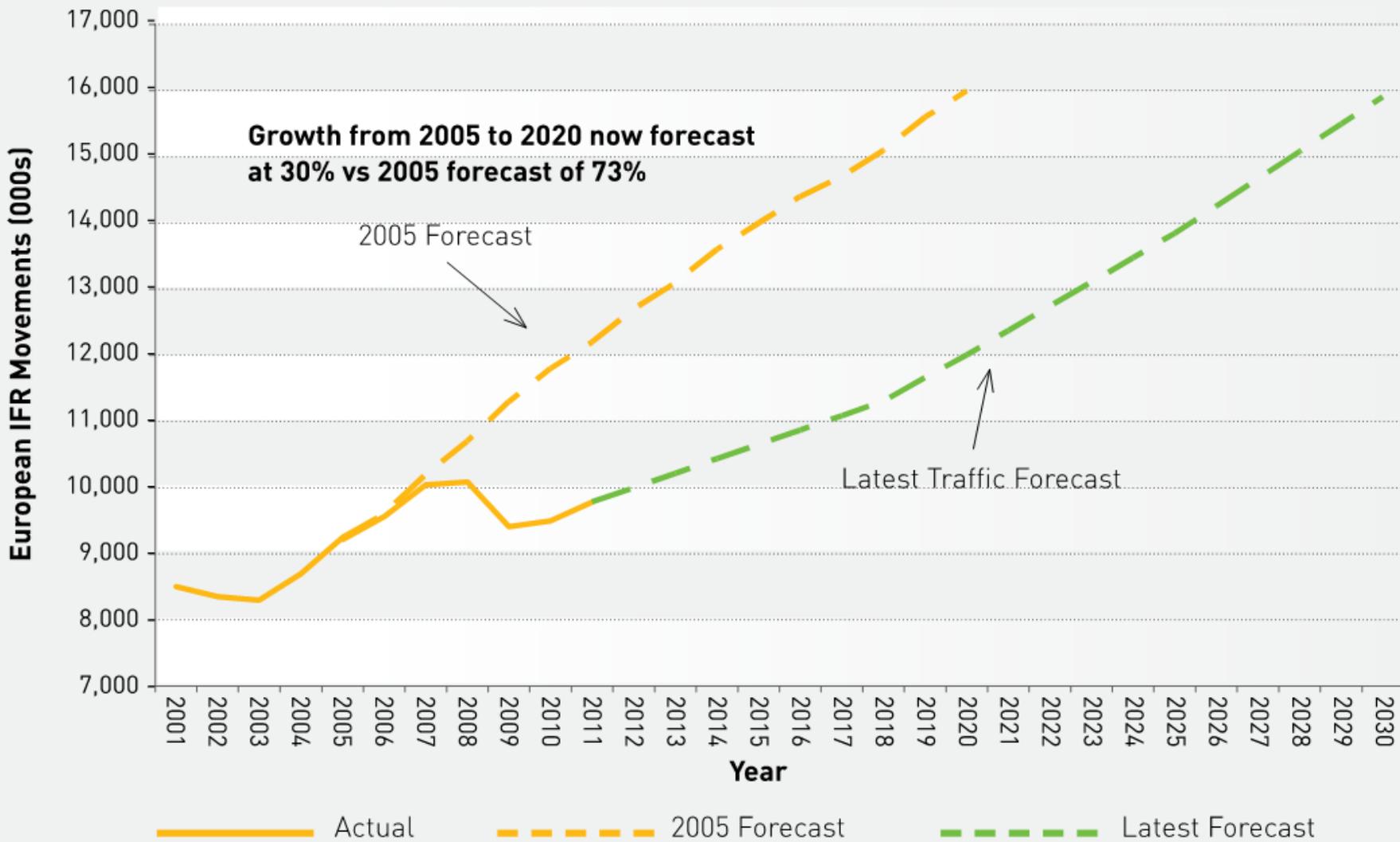


Figure 8 Growth from 2005 to 2020 now forecast at 30% vs 2005 forecast of 73%



Challenges

- **Volume**

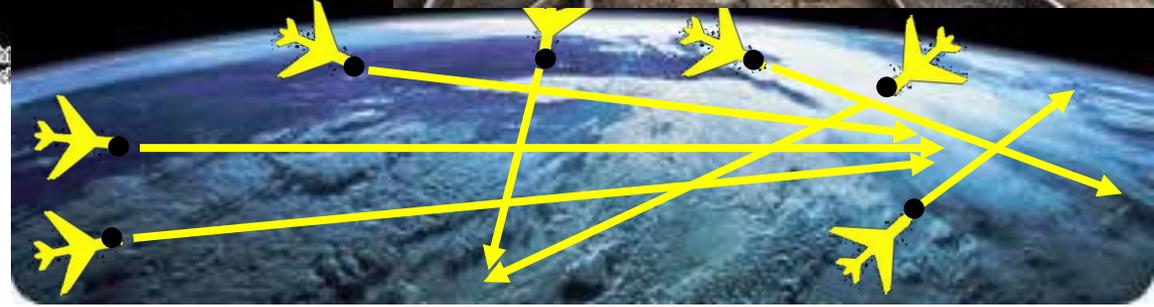


Related

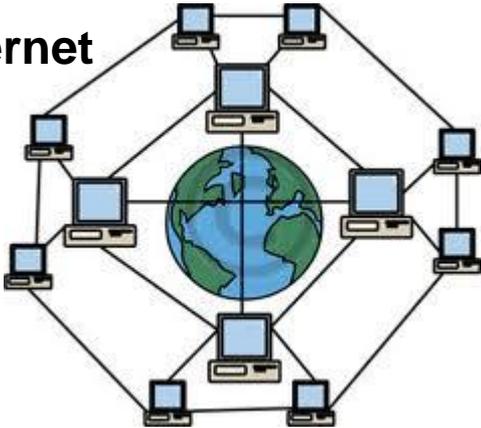
- Cars, trains
- Military
- Ships routing
- Data transfer



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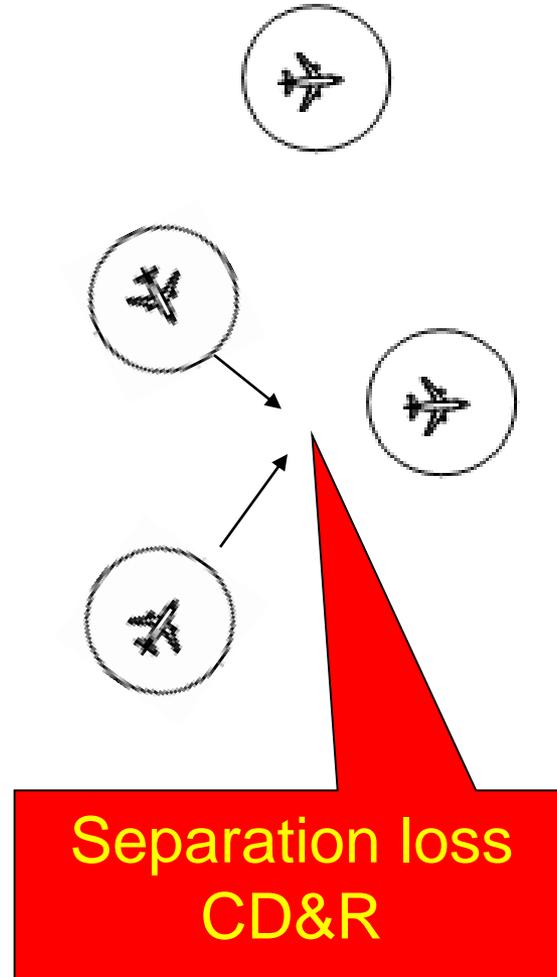
Internet



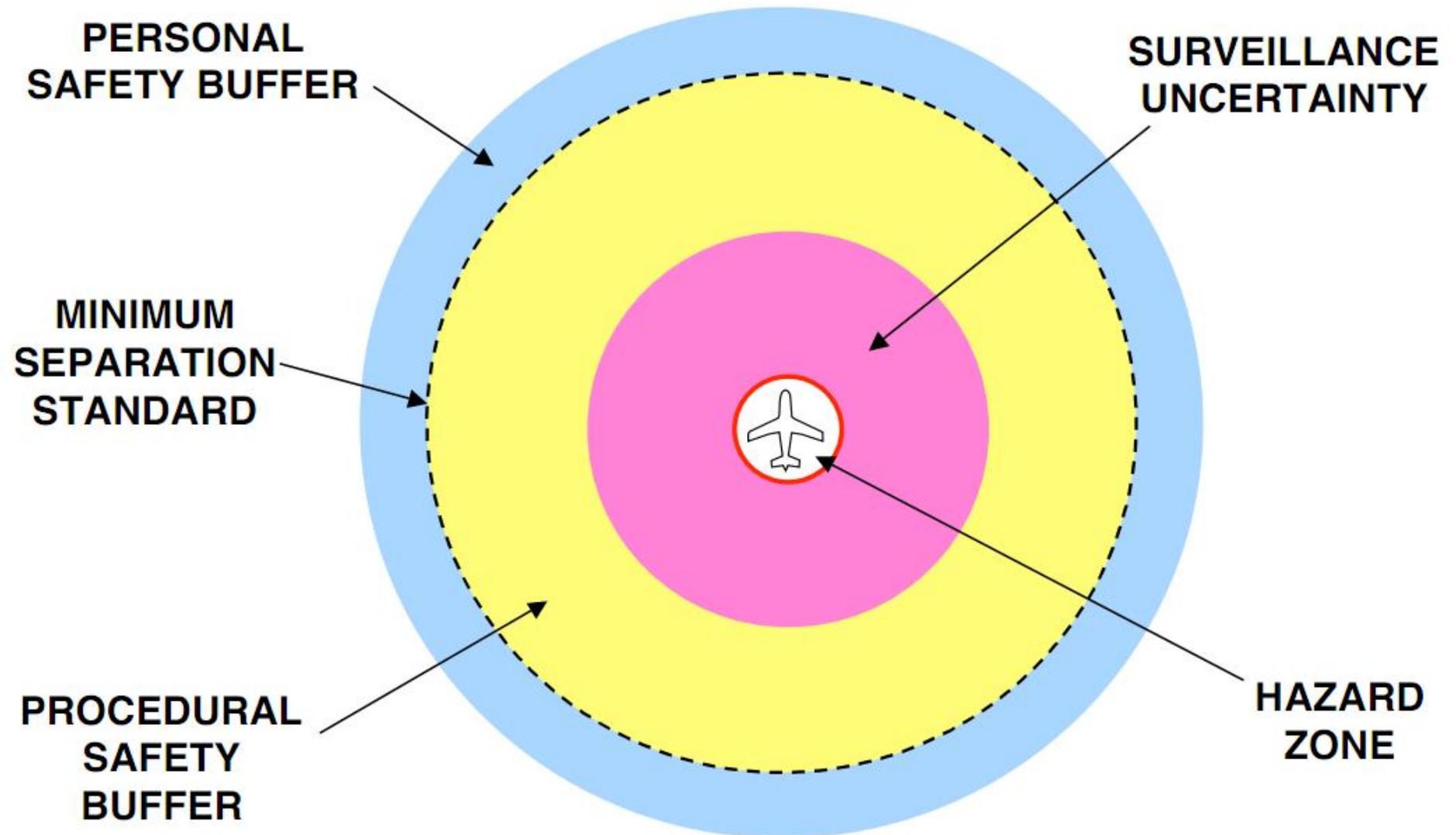
High volume...
Packets collision and loss



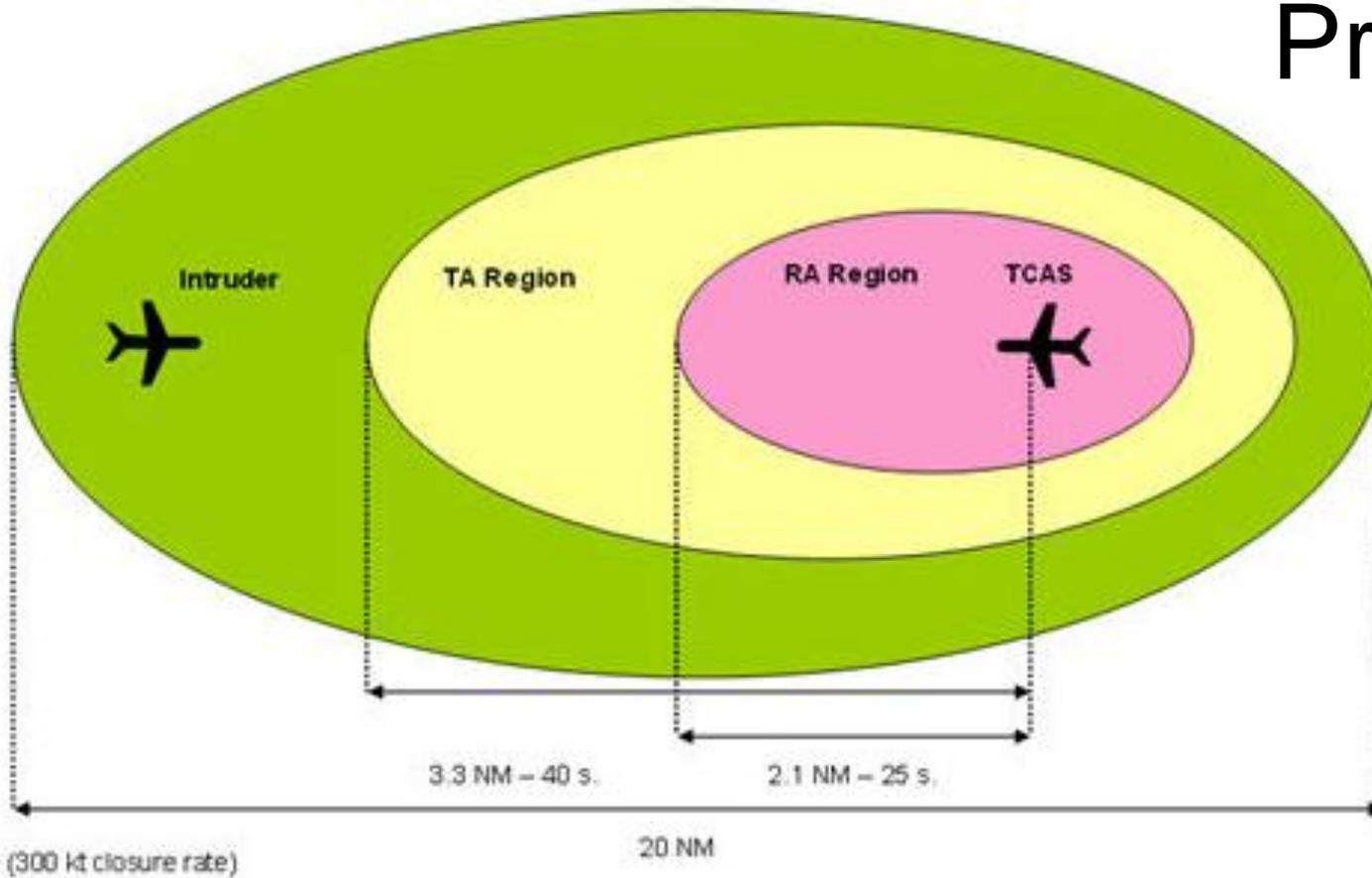
Separation standards



Protected airspace zone (PAZ)



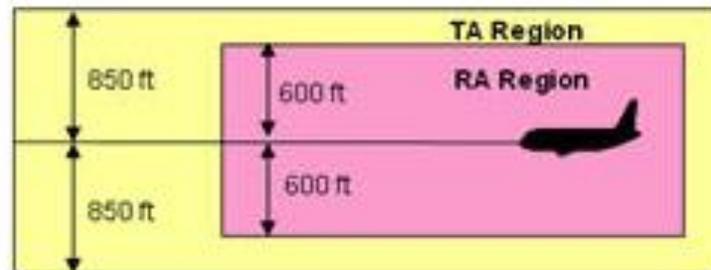
Protection Volume



Time criterion (300 kt closure rate)



Altitude criterion



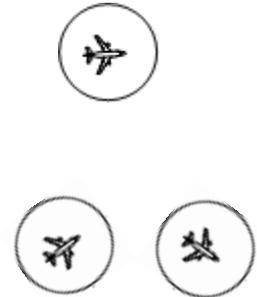
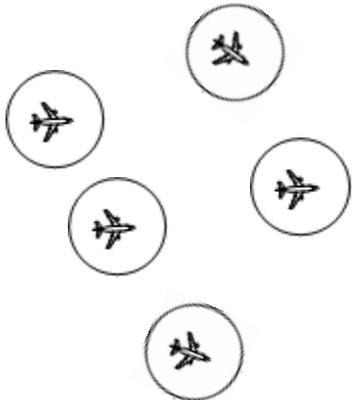
Example of ACAS Protection Volume between 5000 and 10000 feet

Challenges

- Volume
- Safety



Separation assurance



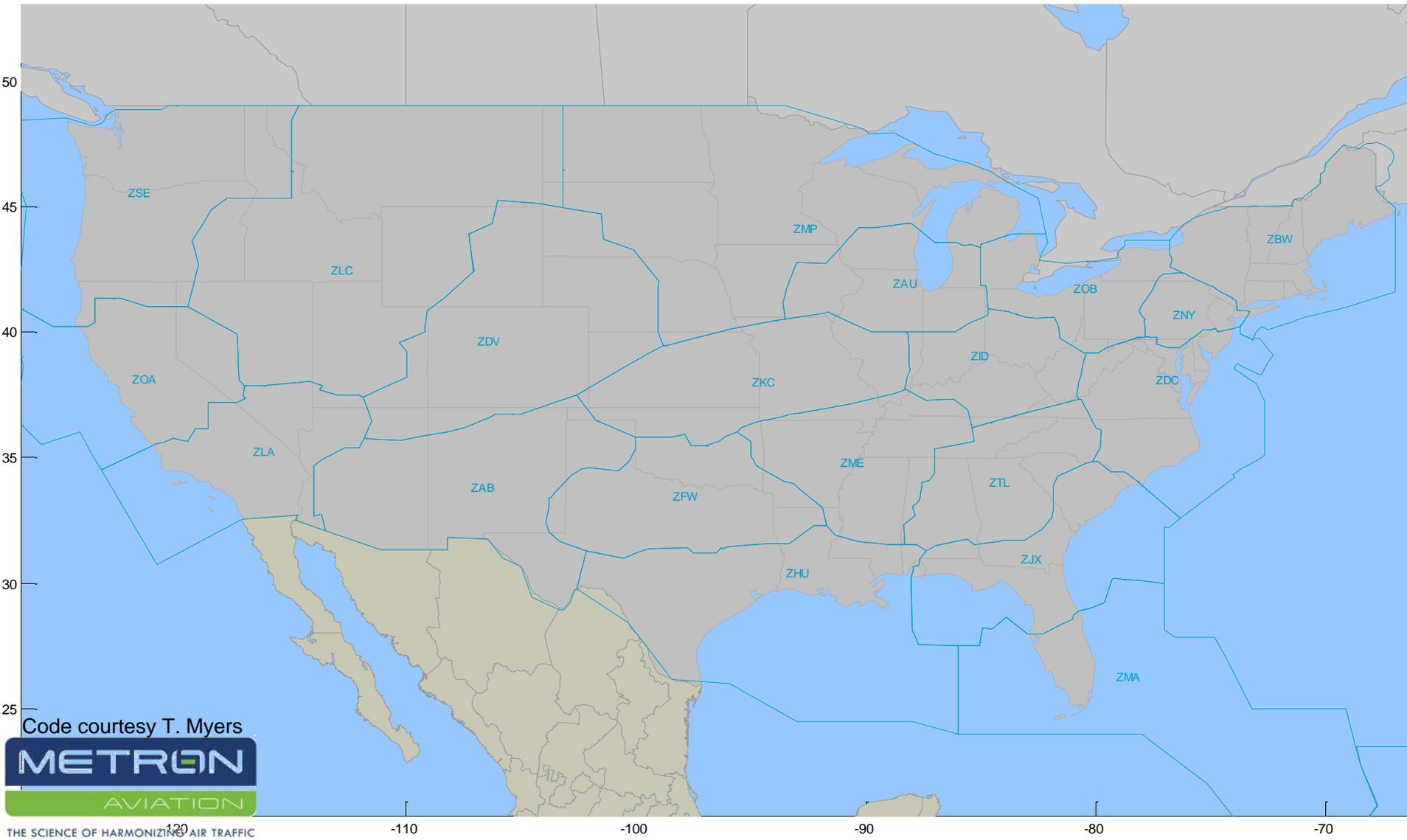
Cars on roads: High volume, separation requirement

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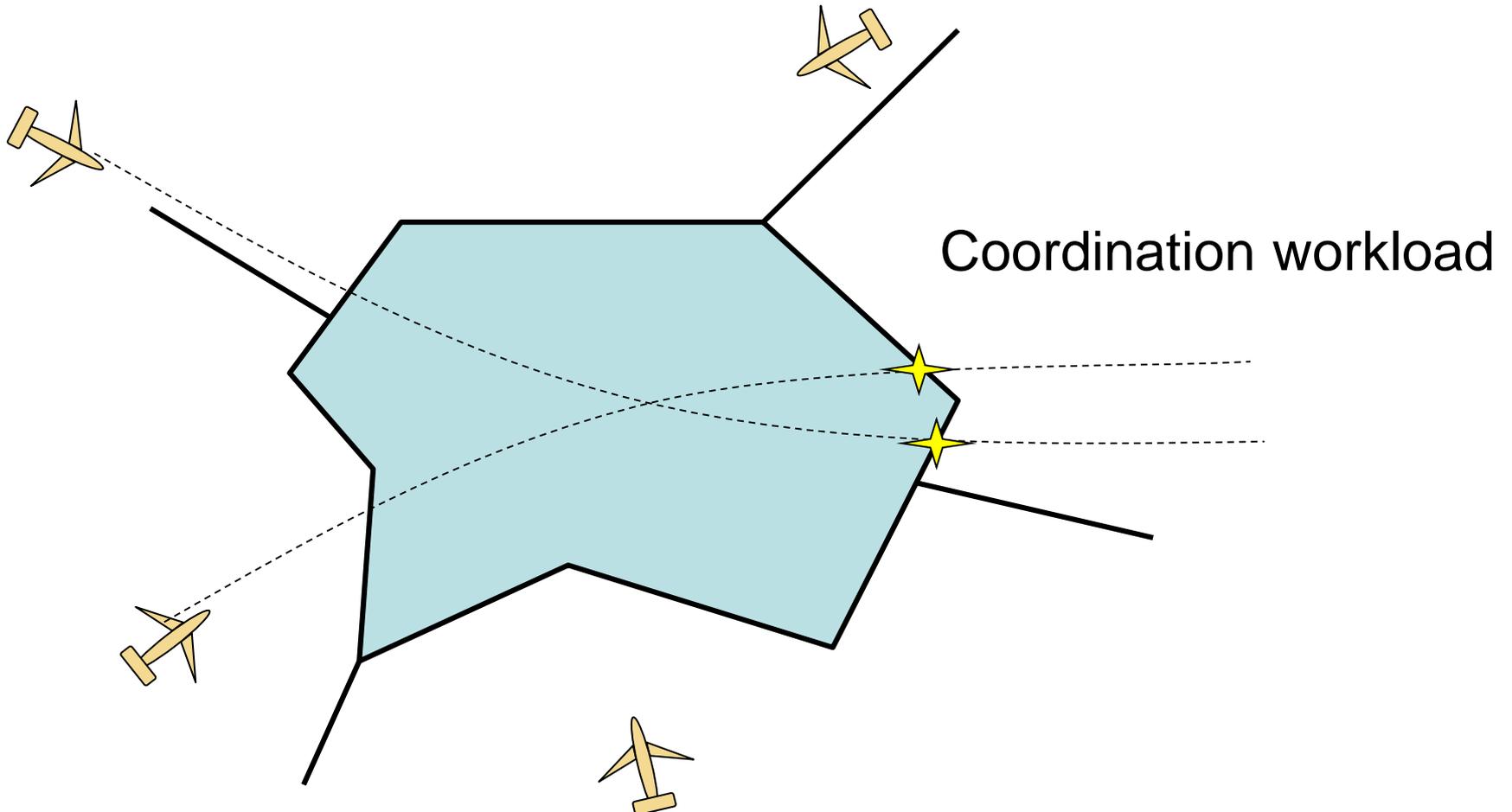
Сергей Венявский | www.donreporter.ru | 2011

Jets in the sky: Highly supervised



Workload: System constraint

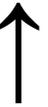
Conflict Resolution workload



Coordination workload

Challenges

- **Volume**
- **Safety**
- **Complexity**



Separation assurance

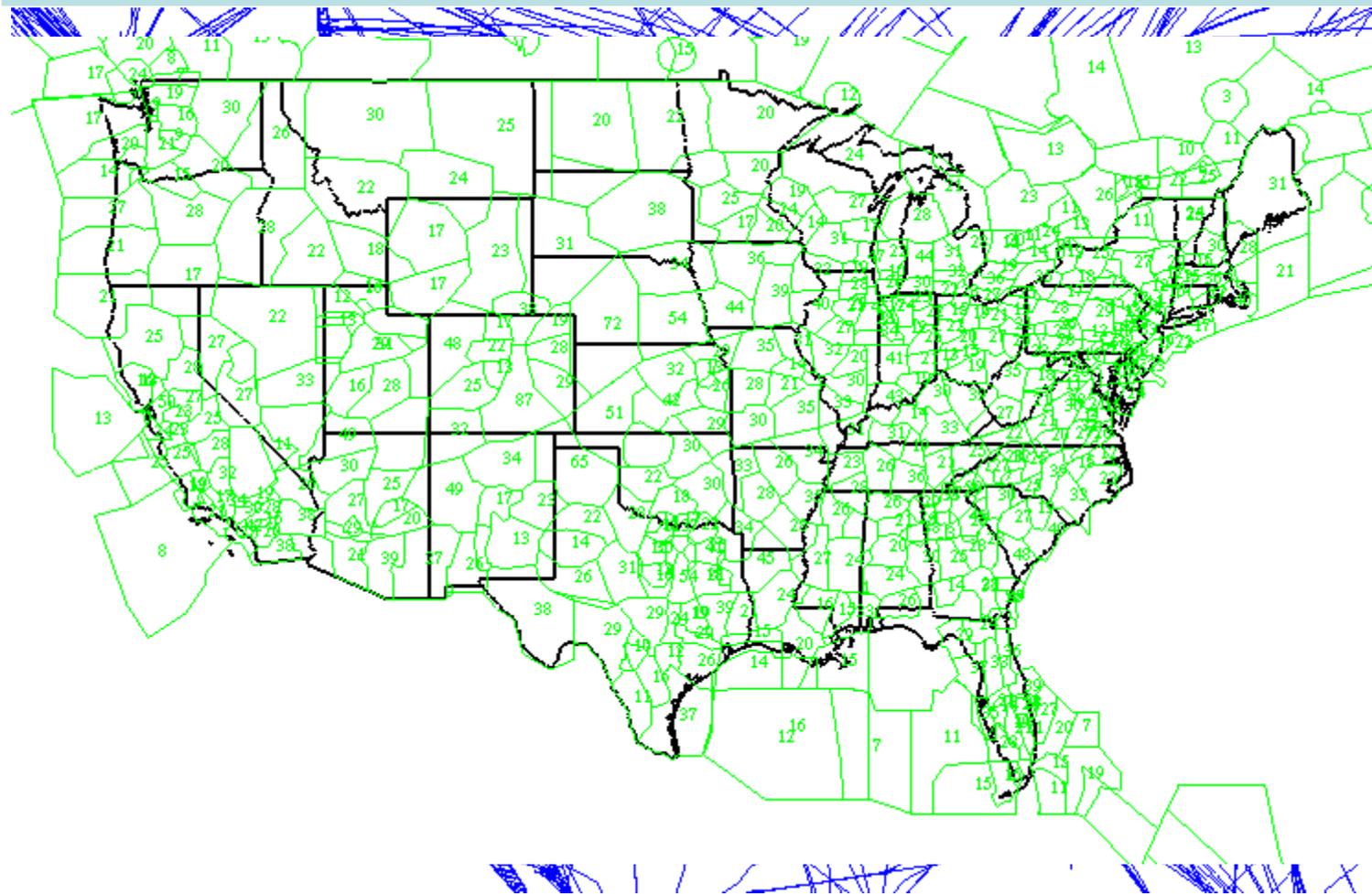
Human-in-the-loop

[RVSM](#) (2000feet →1000feet):

<http://www.youtube.com/watch?v=i58OteU3gZ4>

<http://www.youtube.com/watch?v=wIQIUBsxRY>

Airspace Sectorization Problem



Motivation

- The existing sectors boundaries
 - determined by historical effects
 - have evolved over time
 - not the result of analysis of route structures and demand profiles
- Hence the sectors are not WL balanced
- Also of the 15,000 Air Traffic Controllers, 7,000 are retiring in next few years
- Novel Partitioning : Non-static (Steiner) points

Objectives

- Design and implement efficient algorithms to compute optimal (or nearly-optimal) airspace configurations
- Devise novel methods that may assist in maximizing safe utilization of airspace
- Explore future concepts of operations

"Provide flexibility where possible and structure where necessary."

Parimal Kopardekar (NASA Ames)

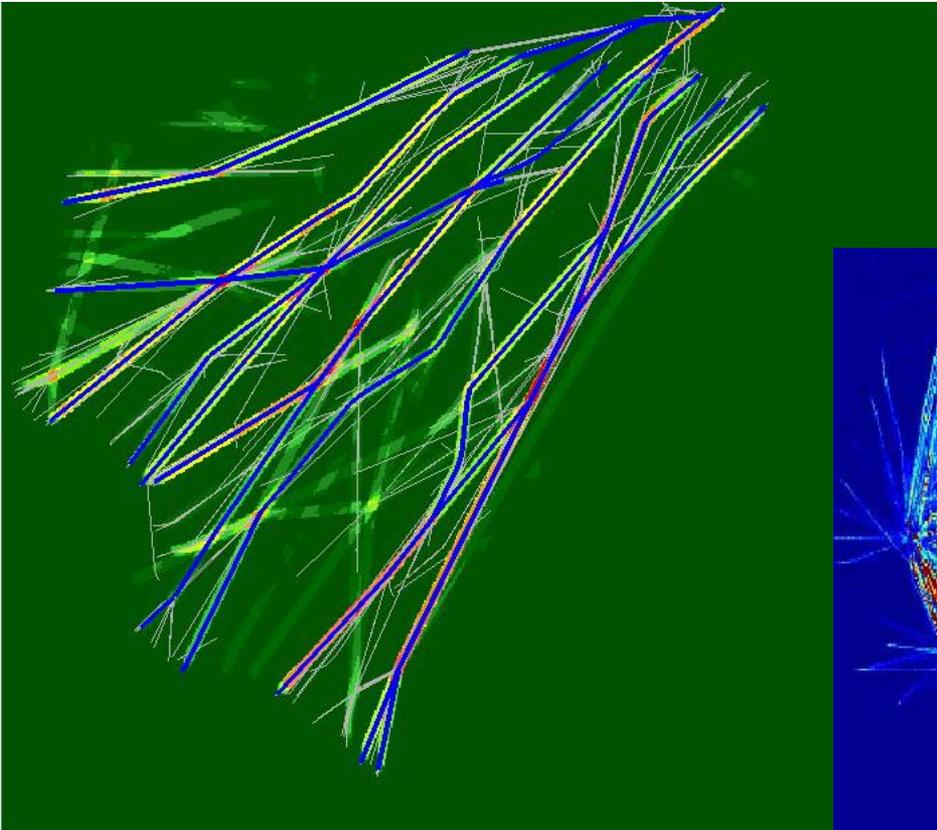
Design for Control

- Determine a mapping of controllers (or oversight processes) to flights.
- Approaches:
 - Partition airspace into sectors, other structural elements
 - Partition aircraft (e.g., into “gaggles”)
 - (Possible) future: ATC/flight
 - full en-route portion

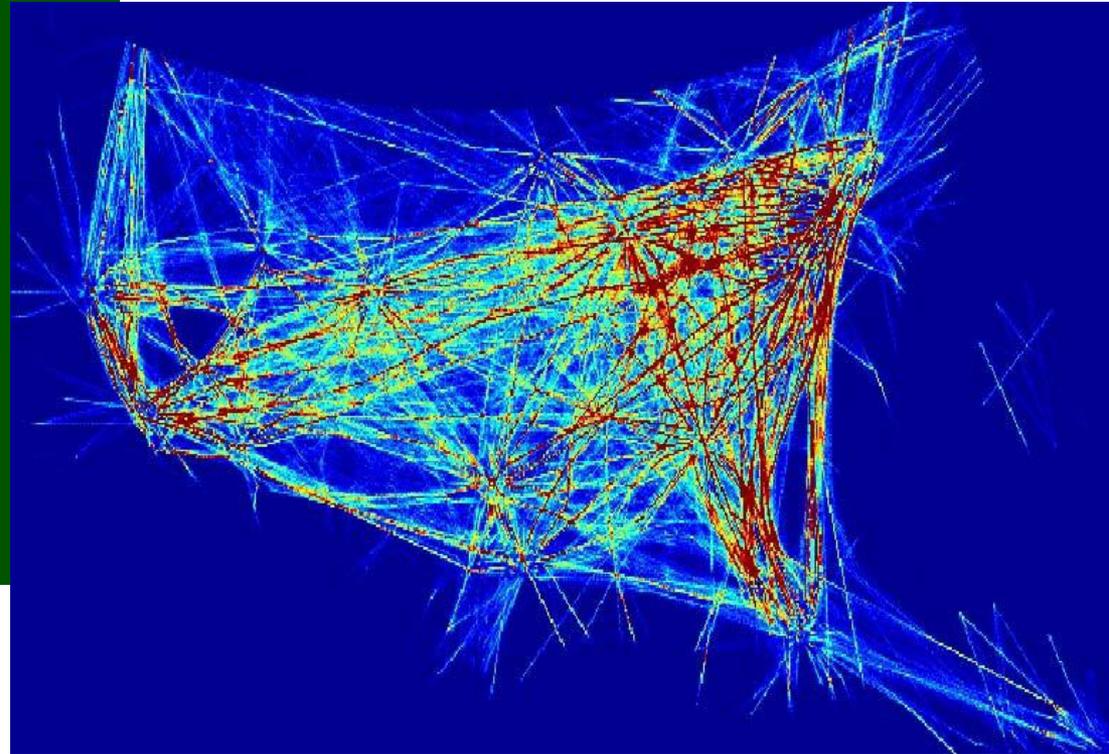
Designing Configuration Playbooks

- **Goal:** Identify good configurations corresponding to mined historical data scenarios
- **Rationale:** Certain traffic patterns may tend to repeat over different time intervals, in response to certain events (e.g., weather impact)
- What time intervals? What events?
- Clustering, mining trajectory data

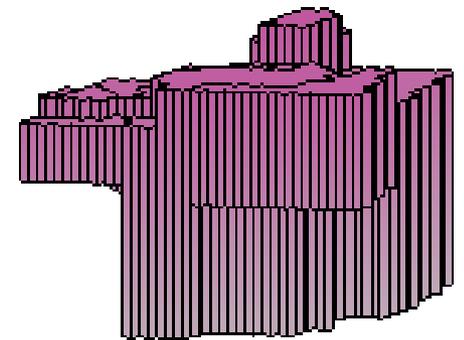
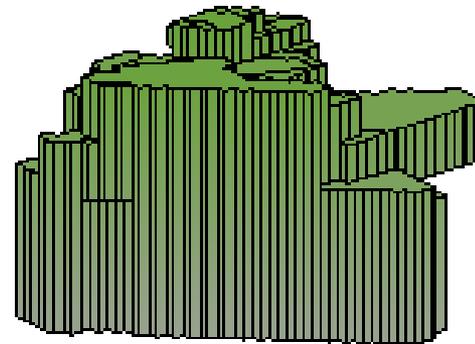
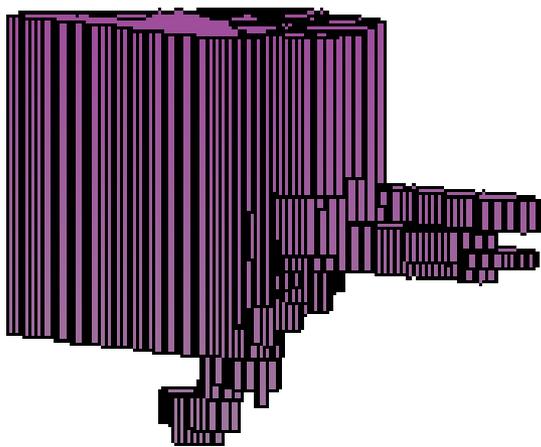
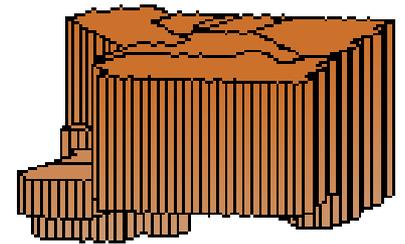
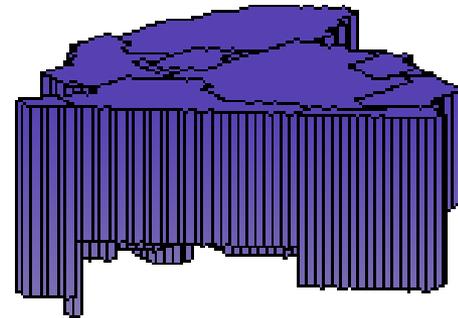
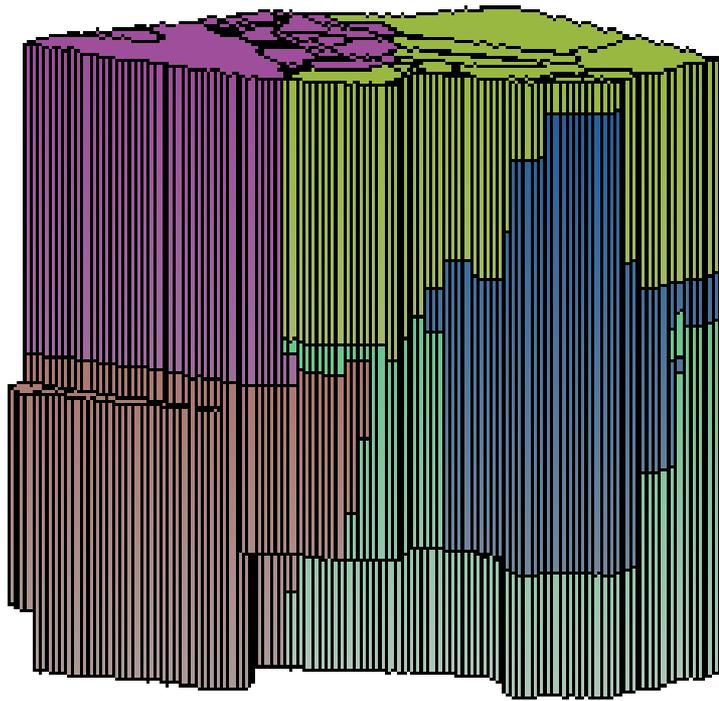
Clustering Trajectories: Discovering Dominant Flows



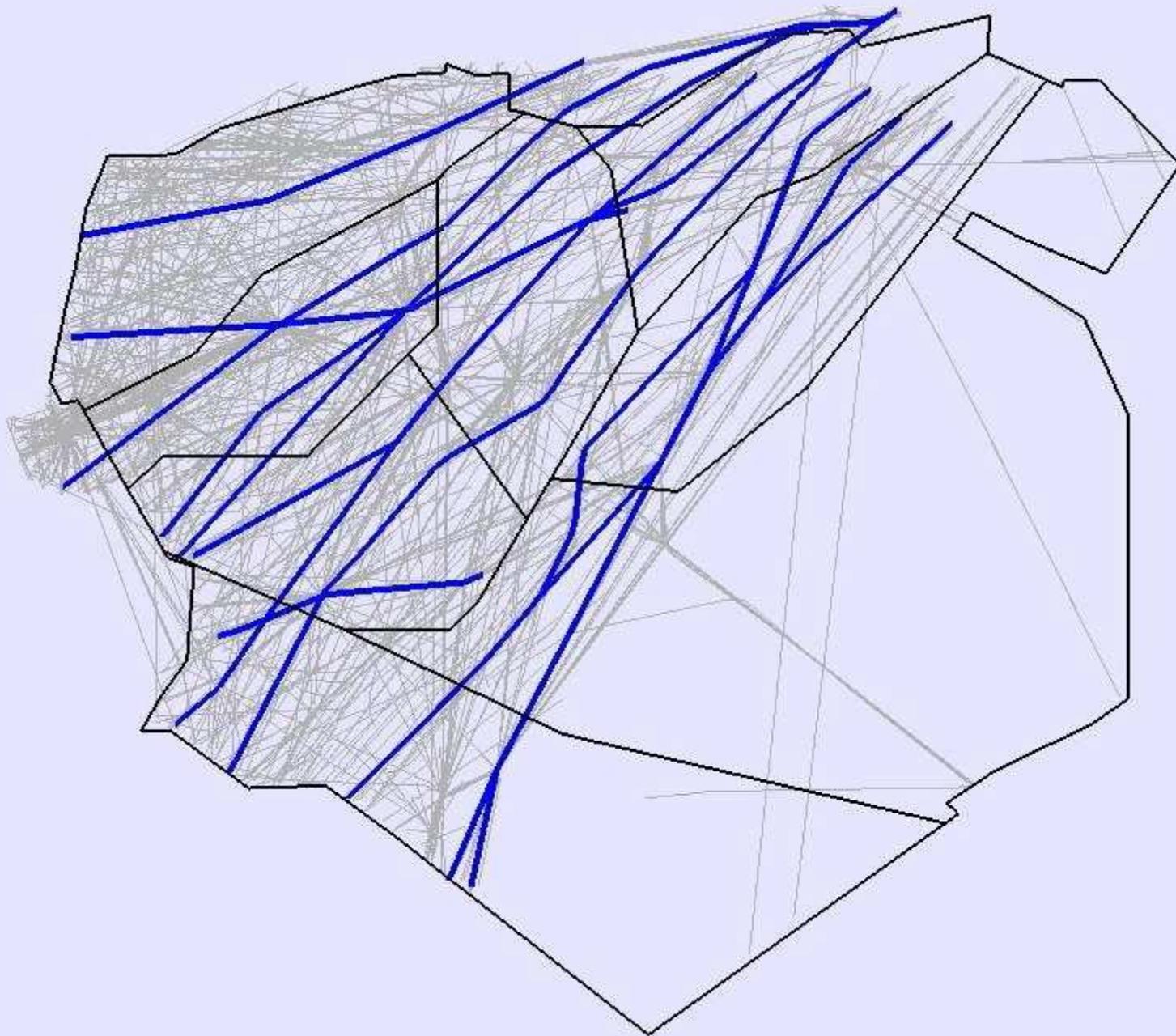
[A Weighted-Graph Approach
for Dynamic Airspace
Configuration 2007]



[Algorithmic Traffic Abstraction
and its Application to NextGen
Generic Airspace 2010]

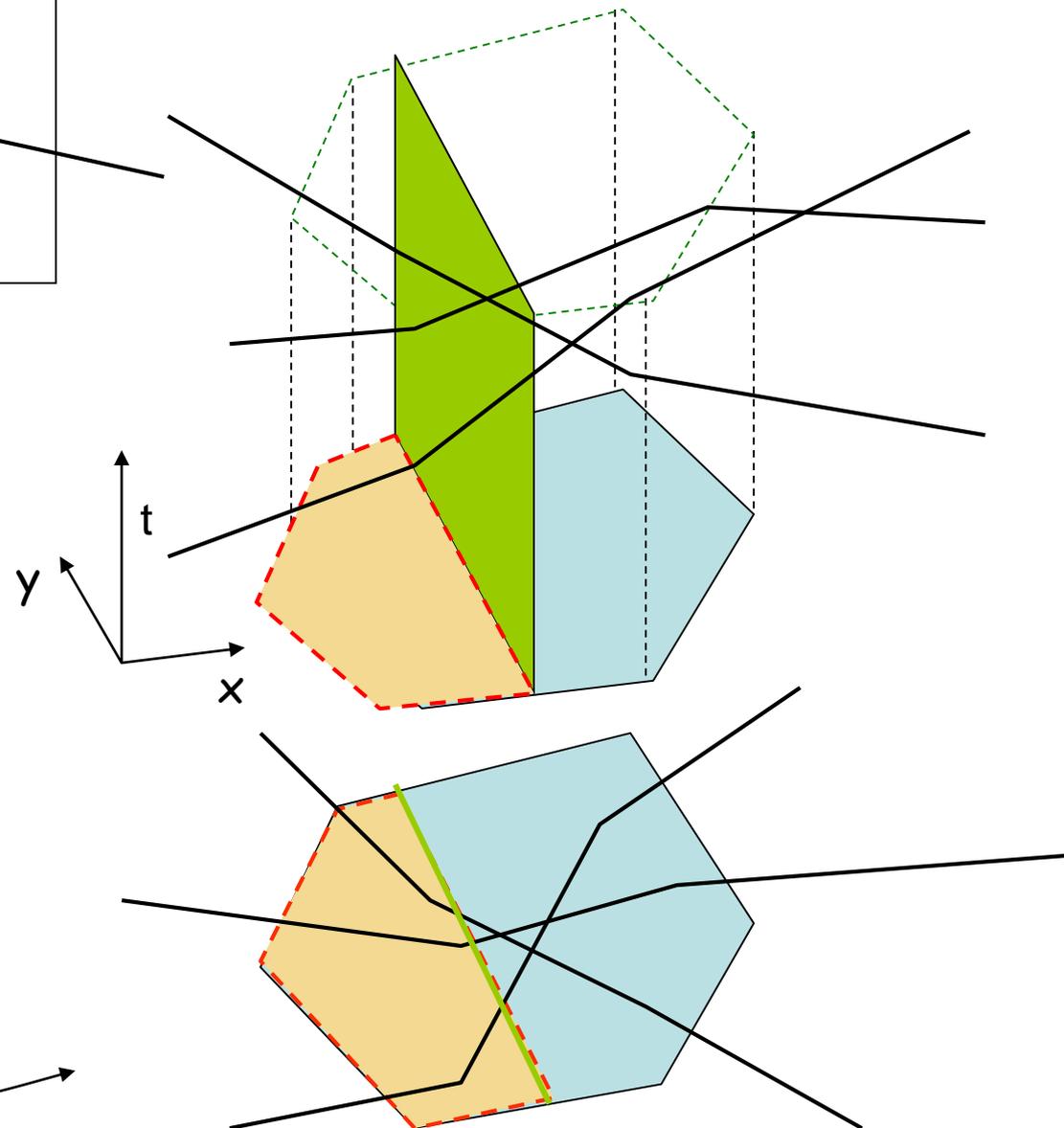
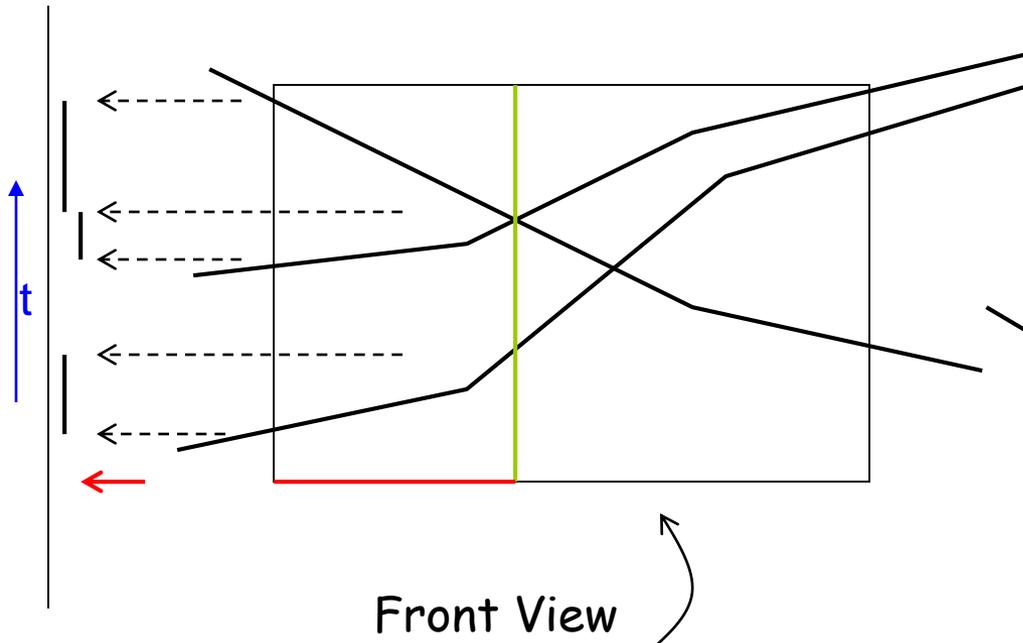


[Airspace Sectorisation using Constraint-Based Local Search 2013]



[Flow conforming operational airspace sector design 2010]

State of the art

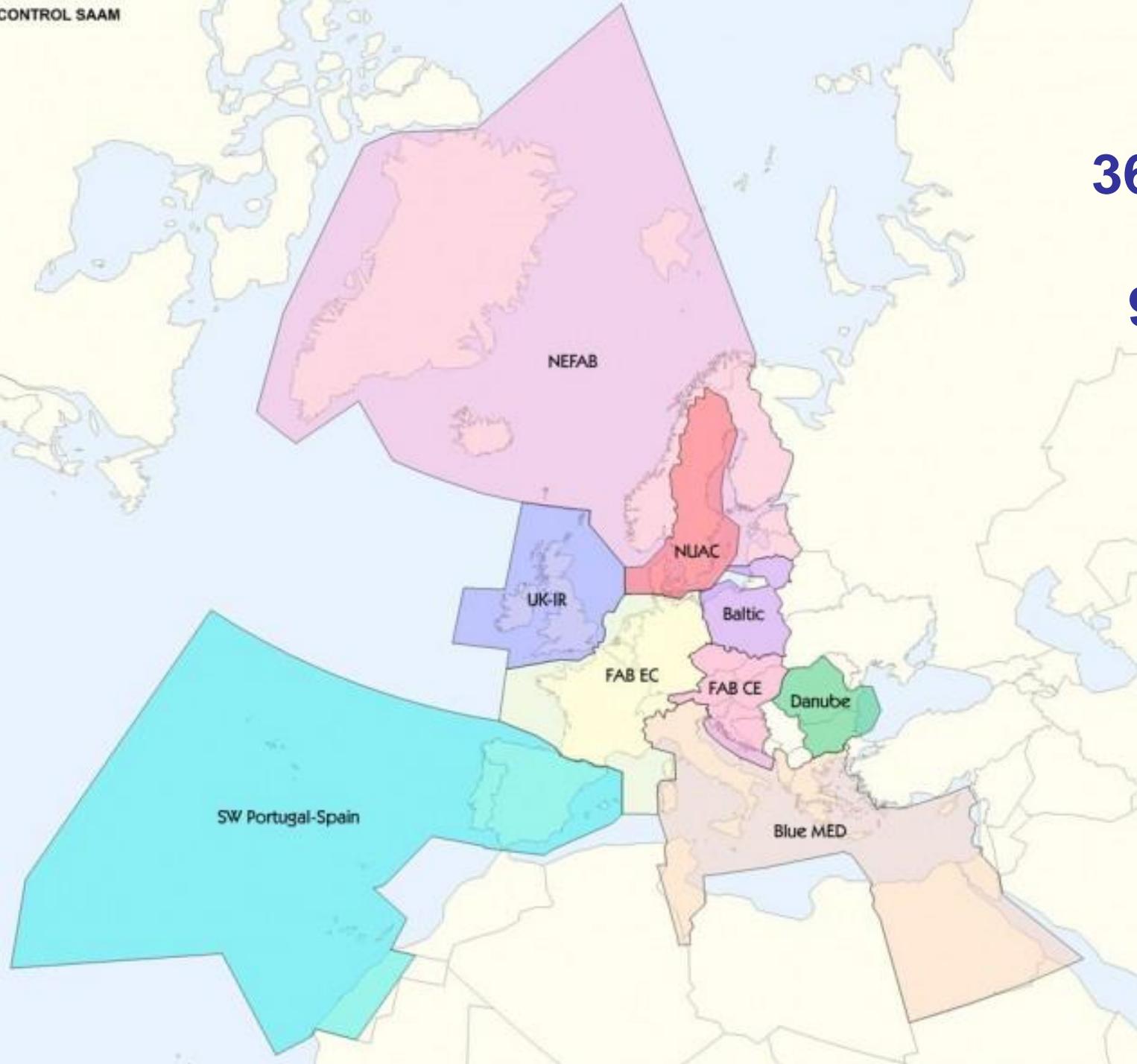


EU:

36 ANSPs



9 FABs



EU: establishing FABs is more of political decision than RnD Q

DK-SE FAB assessment @ Entry Point North air traffic services Academy, Sturup

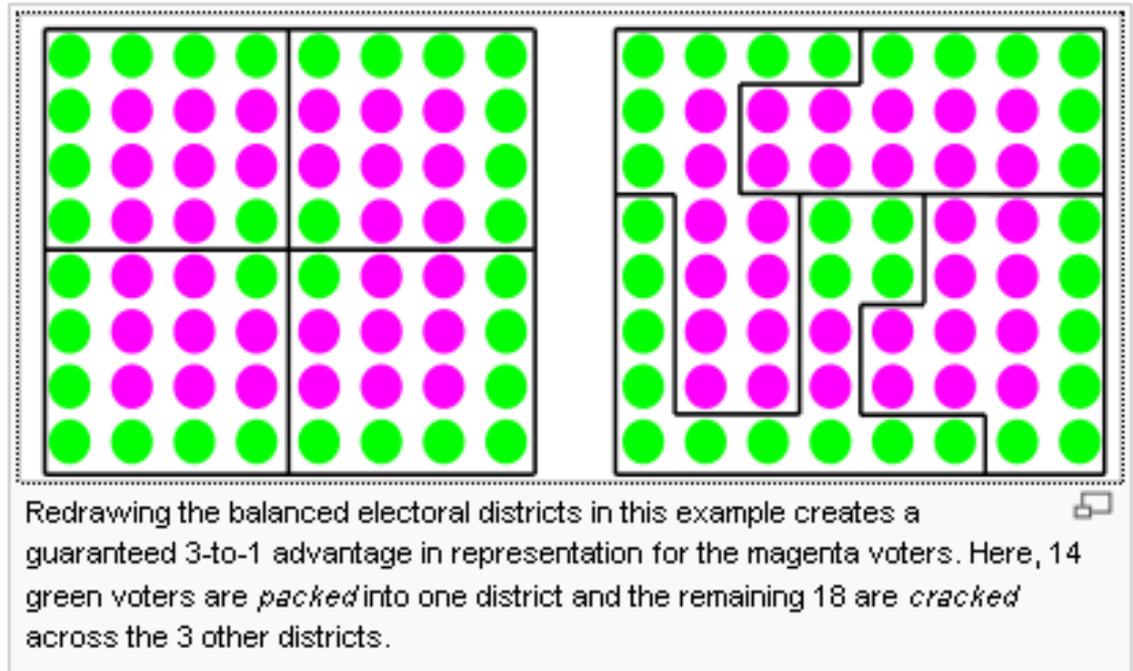
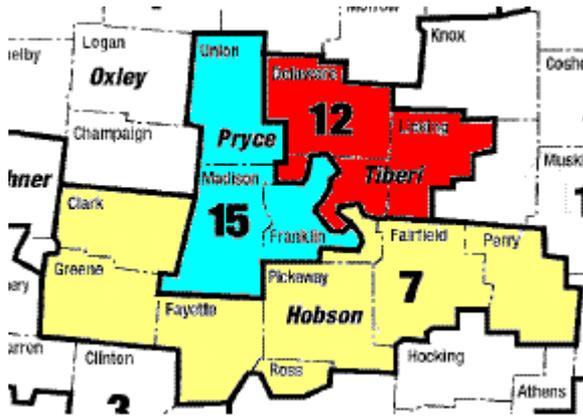
Conclusions

- Not much benefits (no harm either 😊)
- DK-SE: good cooperation before FAB
- Improvements visible where things are **bad** ?
 - “Bring competence to the European level” lol

Resectorization

- US: Dynamic Airspace Configuration (DAC)
- EU: dynamic Demand & Capacity Balancing (dDCB) <http://www.youtube.com/watch?v=RH6ZXdKsQbM>

Related: Election Districting



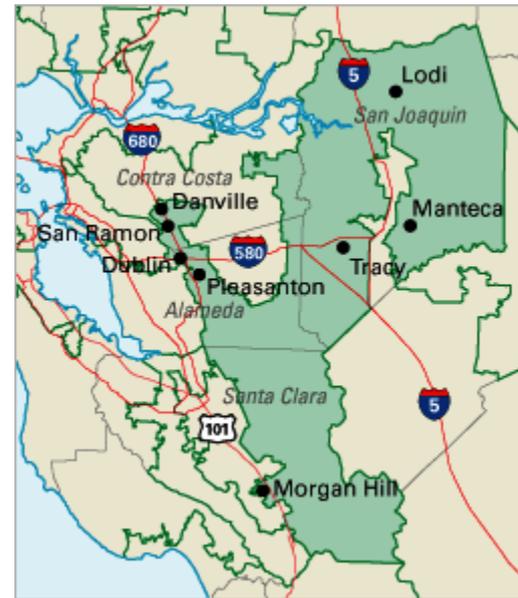
An example of "cracking" style Gerrymandering; where the urban (and mostly liberal) concentration of Columbus, Ohio is split into thirds and then each segment outweighed by attachment to largely conservative suburbs.

Source: Wikipedia

Gerrymandering



Image: The Gerry-Mander.png



A gerrymandered Congressional District, the 11th CD of CA (now occupied by Democrat [Jerry McNerney](#)), drawn to favor Republican [Richard Pombo](#). While the Danville area is a traditional Republican stronghold, Morgan Hill is not, and that largely Democratic district was added to obtain the proper population numbers for the 11th after [Livermore](#) was assigned to the 10th at the behest of the incumbent Democrat ([Ellen Tauscher](#)), since it contains the [Lawrence Livermore National Laboratory](#) (located near the "580" shield) and she sits in the House Energy Committee. The 10th CD is immediately north of the 11th in Contra Costa and Solano Counties. See the [California 11th congressional district election, 2006](#) for an unexpected result that overcame this gerrymander.

Challenges

- **Volume**
- **Safety**
- **Complexity**
- **Uncertainty**



Separation assurance

Human-in-the-loop

Contingency plans

Modeling: Experts interaction

TOP 5 ATM OPERATIONAL SAFETY PRIORITIES FOR 2013:



1. RISK OF OPERATIONS WITHOUT TRANSPONDER OR WITH A DYSFUNCTIONAL ONE

Operations without transponder or with a dysfunctional one constitute a single threat with a potential of “passing” through all the existing safety barriers up to “see and avoid”.



2. LANDING WITHOUT CLEARANCE

For various reasons, aircraft sometimes land without ATC clearance resulting in Runway Incursions that are often only resolved by ‘providence’.



3. DETECTION OF OCCUPIED RUNWAY

Some Runway Incursion incidents could have been prevented if controllers had had better means to detect that the runway was occupied at the time of issuing clearance to the next aircraft to use the runway.



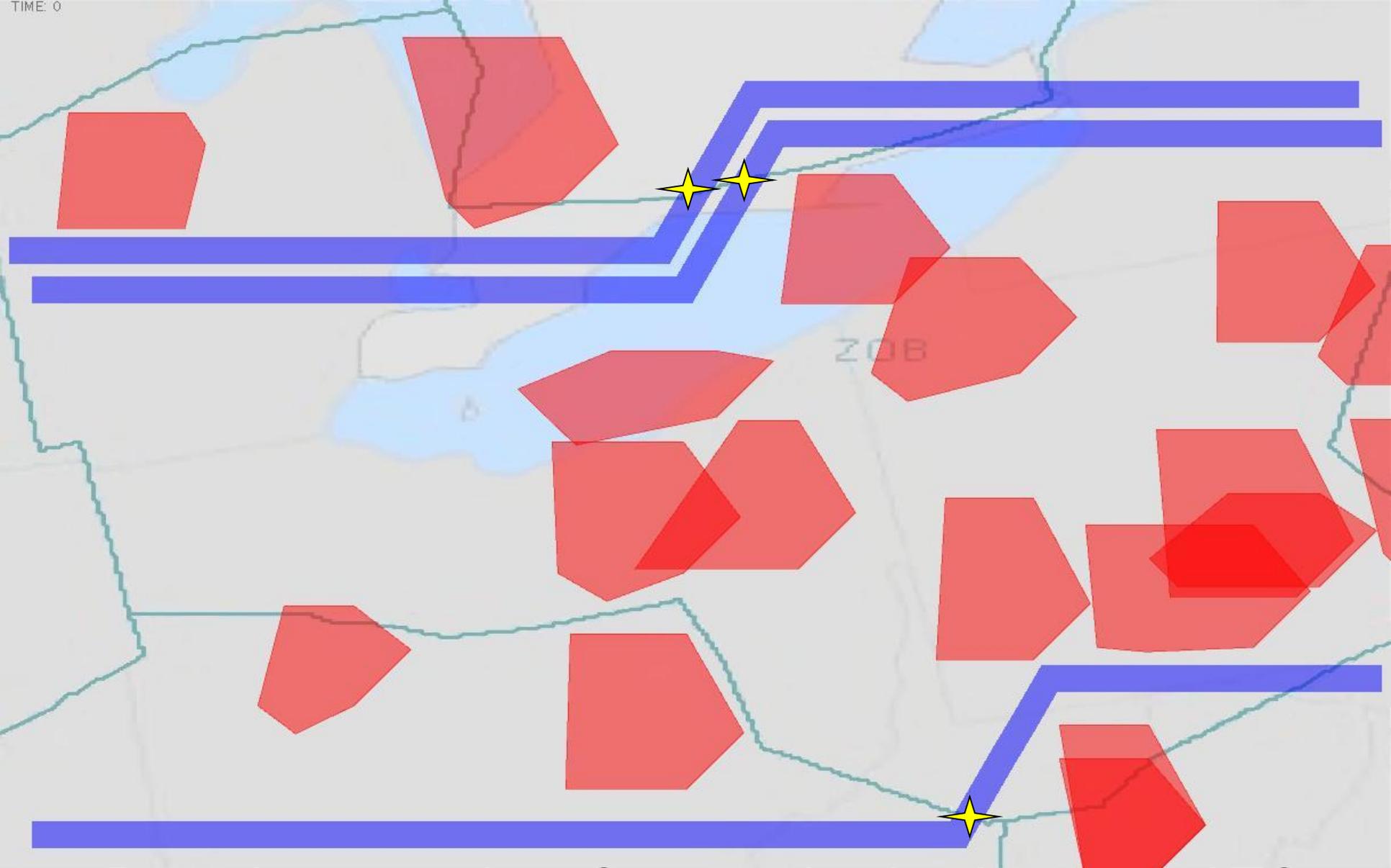
4. “BLIND SPOT” – INEFFICIENT CONFLICT DETECTION WITH THE CLOSEST AIRCRAFT

Loss of separation “Blind Spot” events are typically characterised by the controller not detecting a conflict with the closest aircraft. They usually occur after a descent clearance and in the context of a rapidly developing situation – often when the conflicting aircraft are 1000ft and 15 nm apart.

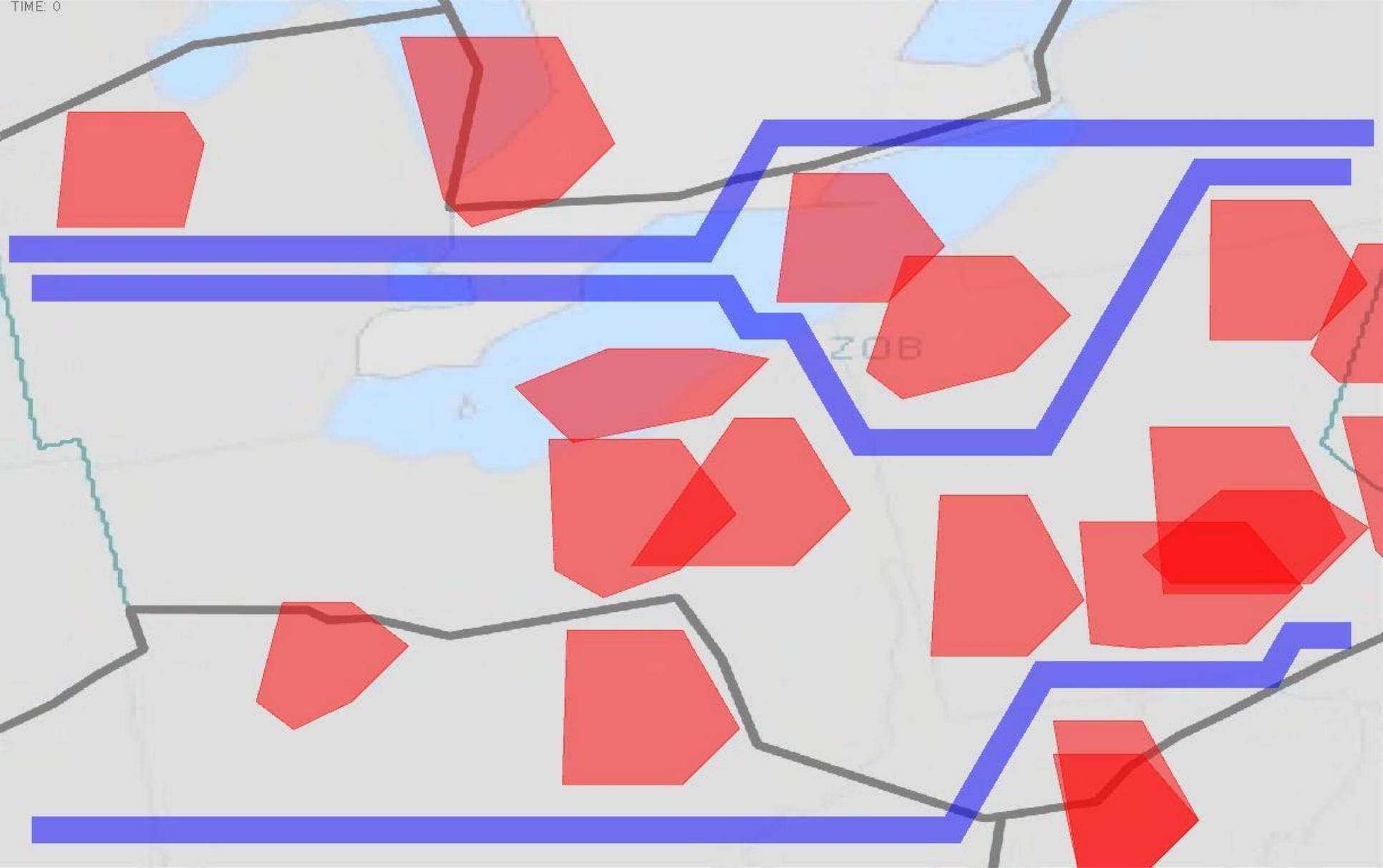


5. CONFLICT DETECTION WITH ADJACENT SECTORS

Losses of Separation in the En-Route environment sometimes involve “inadequate coordination” of clearance with an adjacent sector. These typically involve either an early (premature) transfer of control to or from the neighbouring sector.



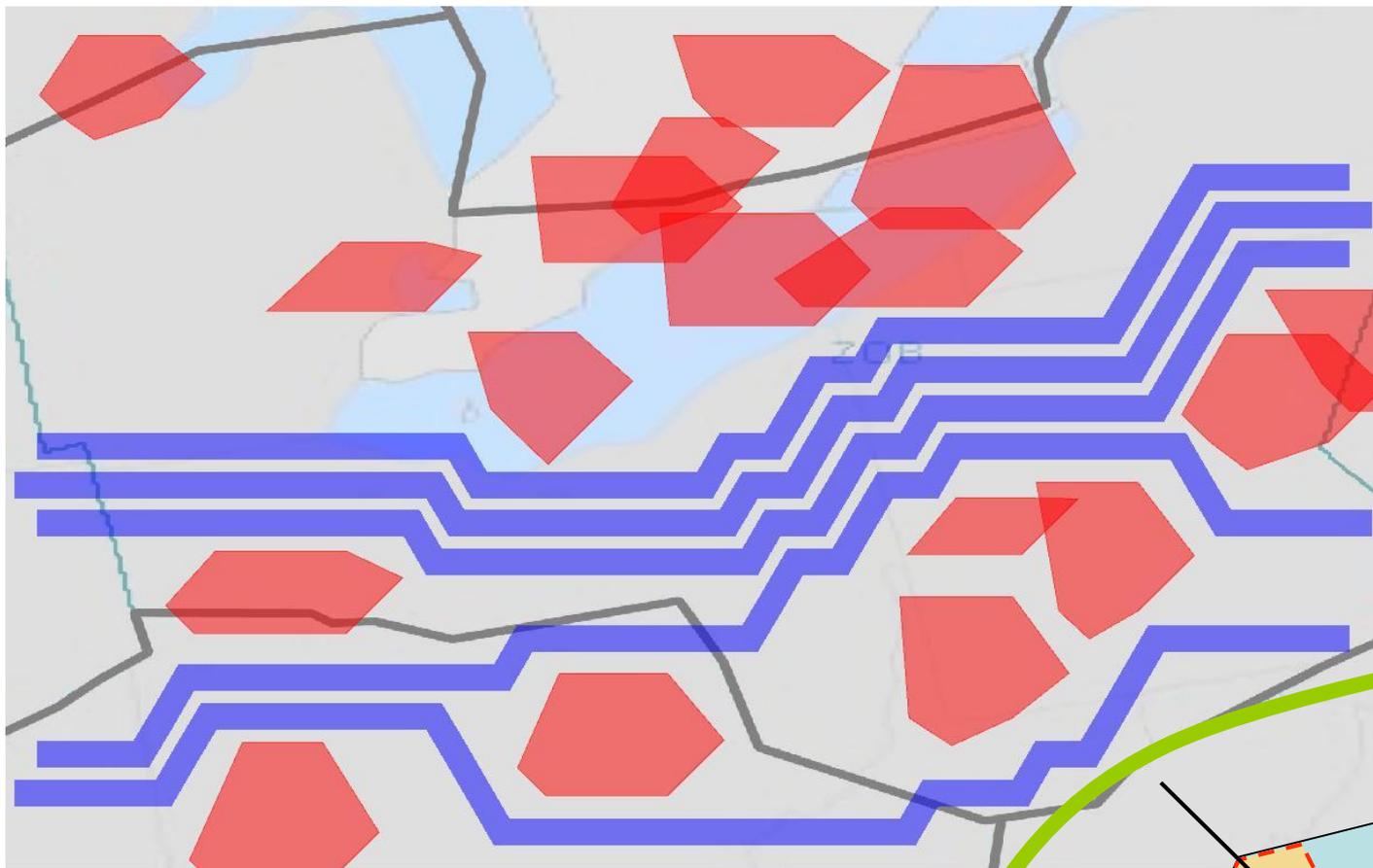
Boundary crossing: Communication between ATCs





Boundary crossing: Communication between ATCs

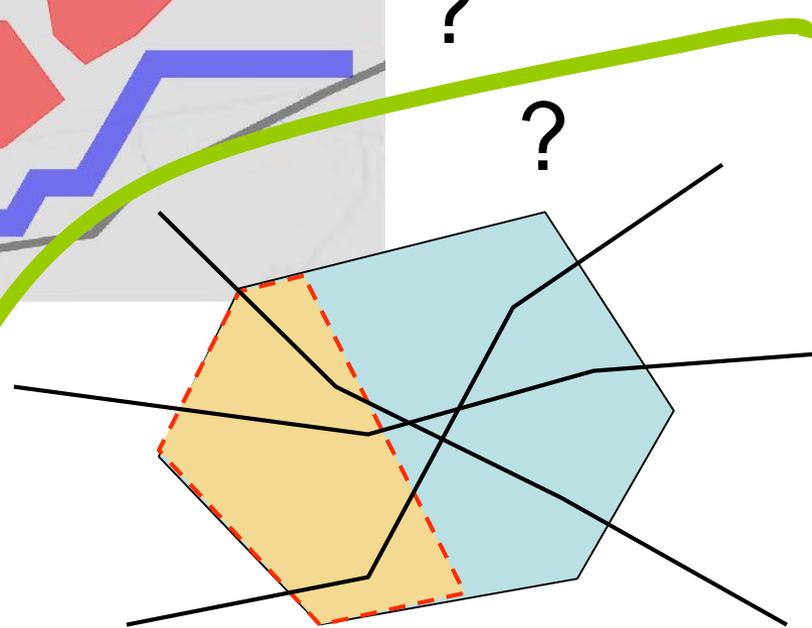
Conforming flow



?

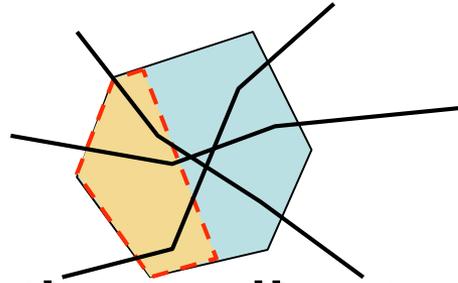
?

But wait a minute...

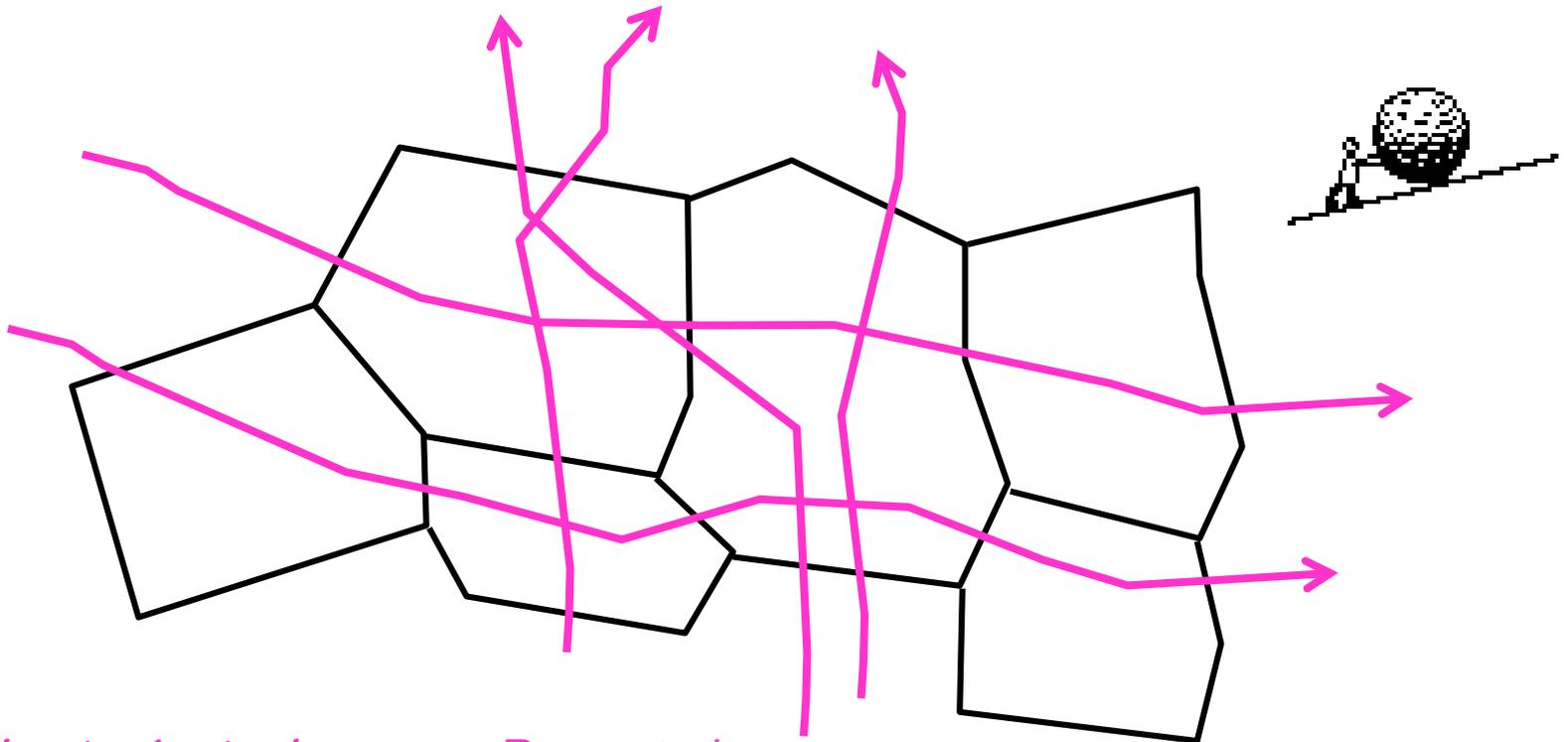


Q: What is rigid: routes or sectors?

A: None!



Feedback loop: Iterative adjustment of routes to sectors and sectors to routes



Conforming trajectories → *Re-sectorize*

Flexible Use of Airspace (FUA):

conditional routes, temporary areas,...

ATM systems

- Airspace management
 - design skyways
- ATFCM
 - flight plans
 - available capacity
- ATC
 - lead through

dDCB,
DAC

Non-rigid
sectors

FUA: ATFCM → Flow Management

Non-rigid
network

FF,
FRA,
Direct
routes

Are we ready,
algorithmically?

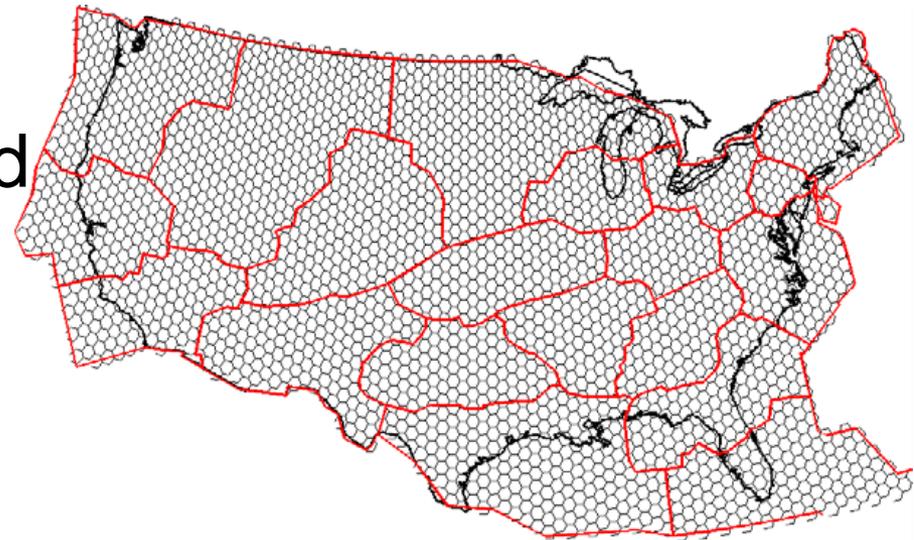
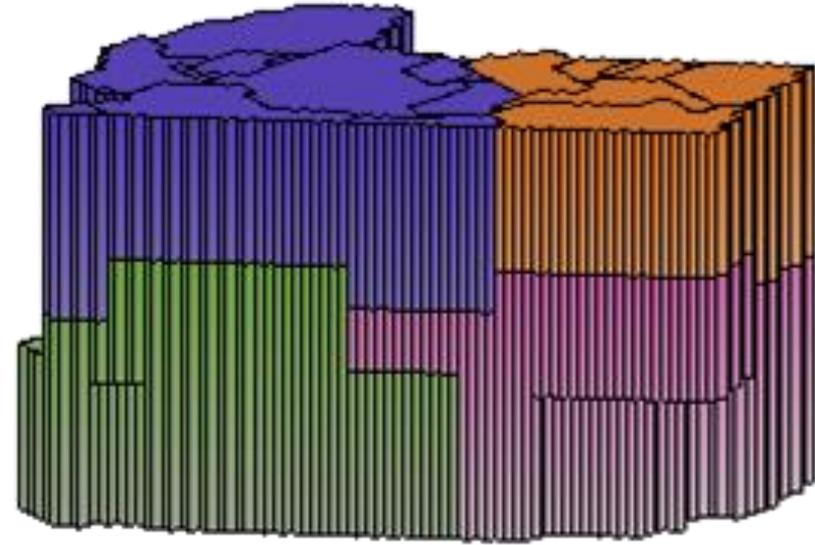
NO 

Research so far:

State-of-the-art techniques for
2 separate problems

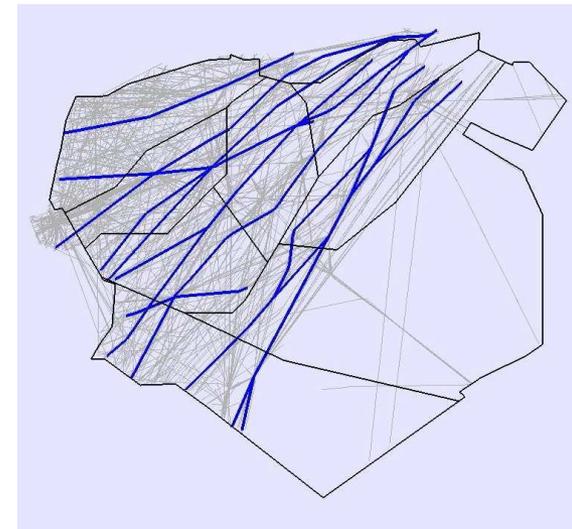
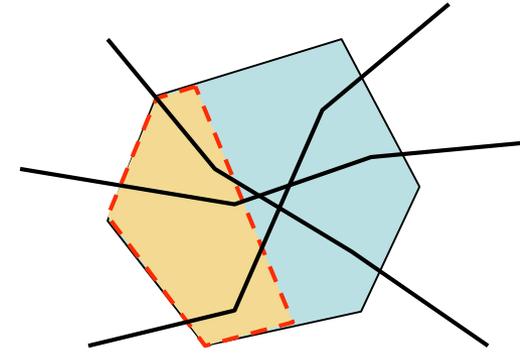
Problem 1. Sectorization

- Flener and Pearson '13, Automatic Airspace Sectorisation: A Survey
- Yousefi and Donohue '04, Temporal and spatial distribution of airspace complexity for air traffic controller workload-based sectorization
- ...

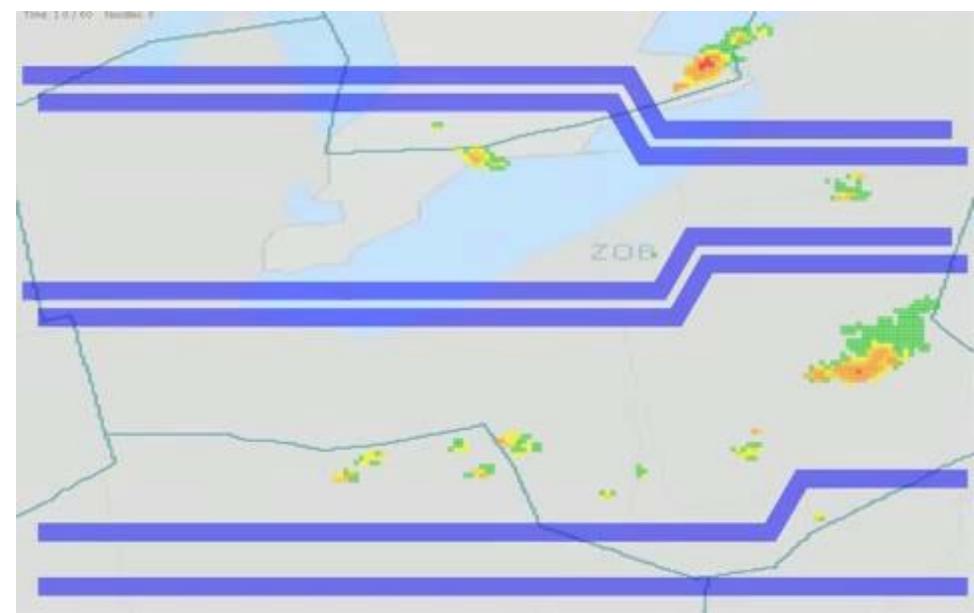
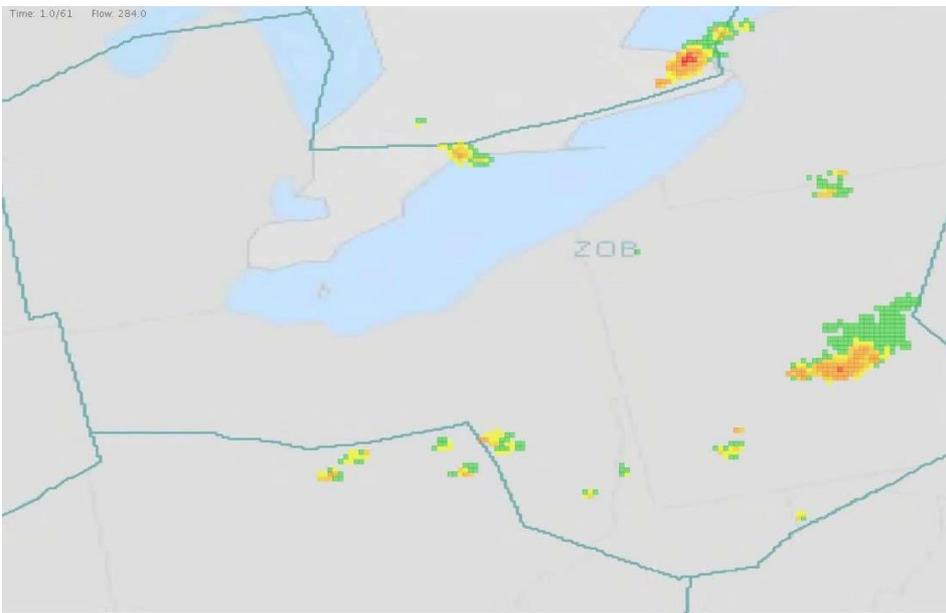
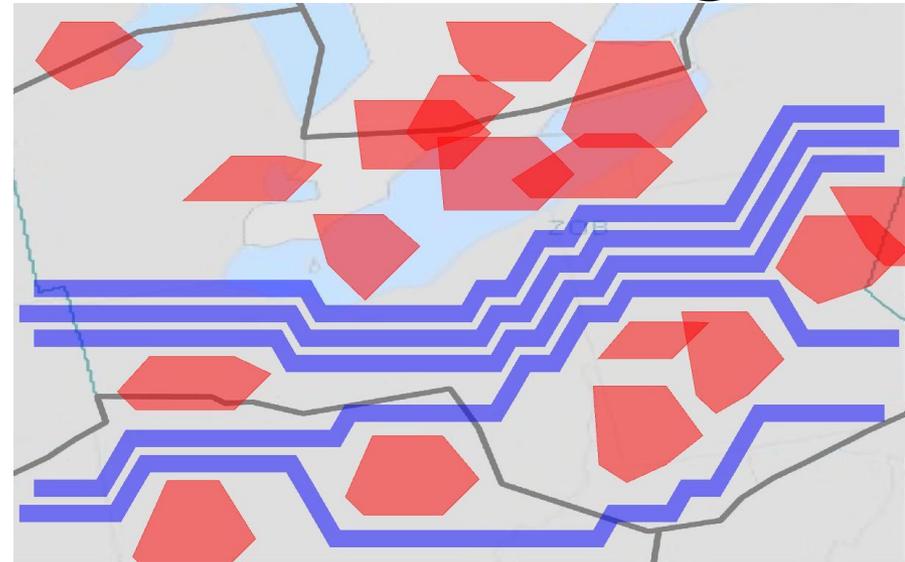
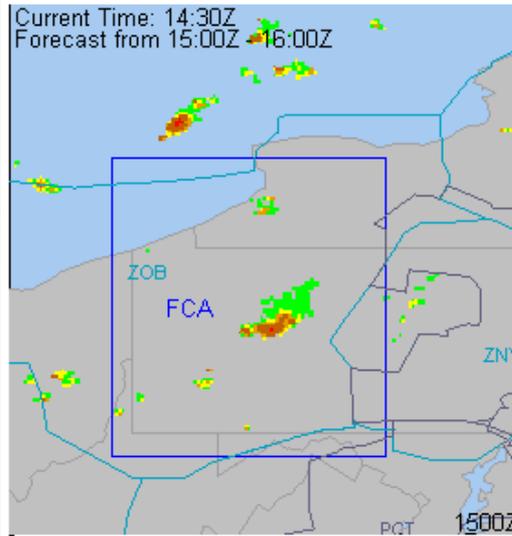
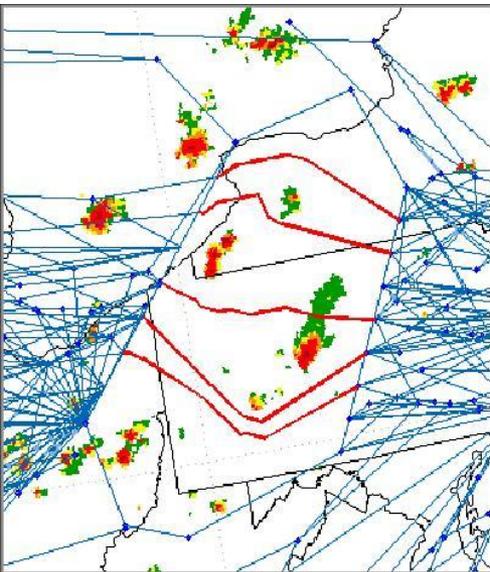


Problem 1 (cont.):

- Geometric Algorithms for Optimal Airspace Design and Air Traffic Controller Workload Balancing [ALENEX, ACM Journal on Experimental Algorithmics'09]
- Flow conforming operational airspace sector design [ATIO'10]
- Balanced Partitioning of Polygonal Domains [PhD thesis'13]
- ...



Problem 2. Traffic flow planning



Problem 2 (cont.). Theory

Paths and flows in polygonal domains:

MaxFlow/MinCut

[Mitchell, SoCG'89]

Flow decomposition

[Mitchell, P, SoCG'07]

Menger's Thm, Disjoint paths

[Arkin, Mitchell, P, SoCG'08]

MinCost (monotone) flow

[Eriksson-Bique, P, Sysikaski, SoCG'14]

Kth shortest path

[Eriksson-Bique, Hershberger, P, Speckmann, Suri, Talvitie, Verbeek, Yıldız, SoDA'15]

The Grand Challenge

Simultaneous optimization

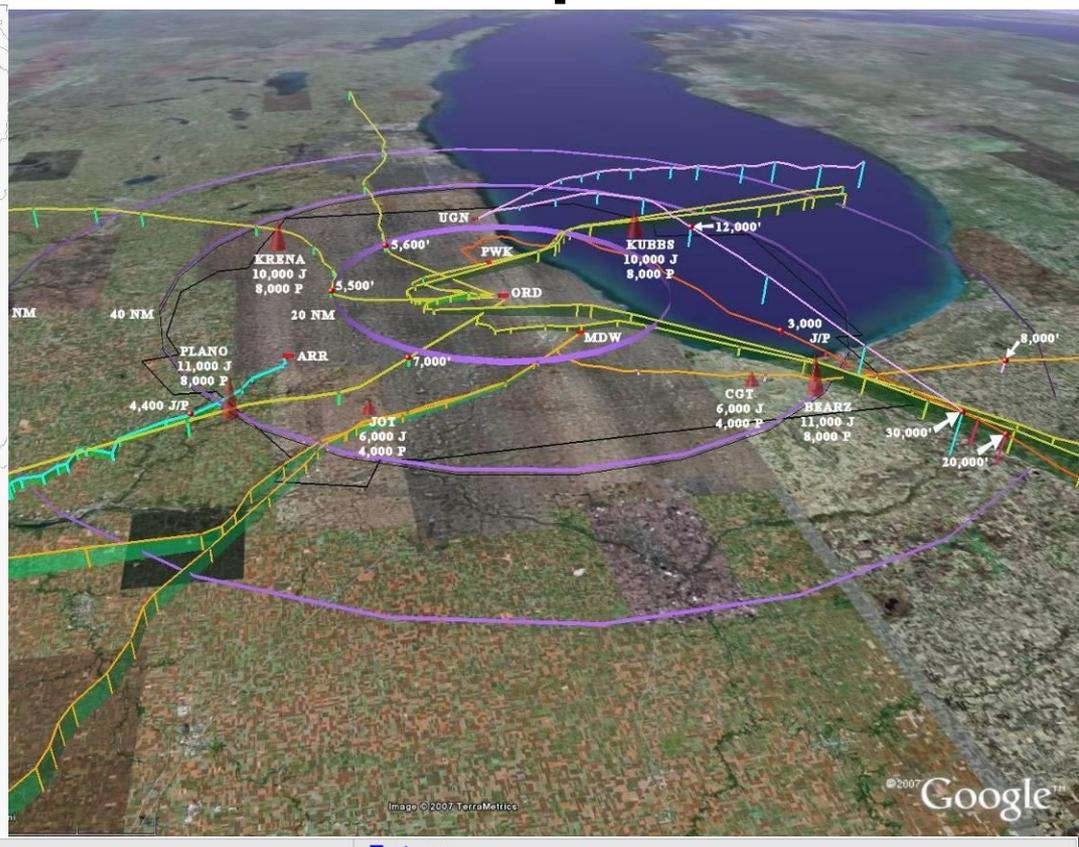
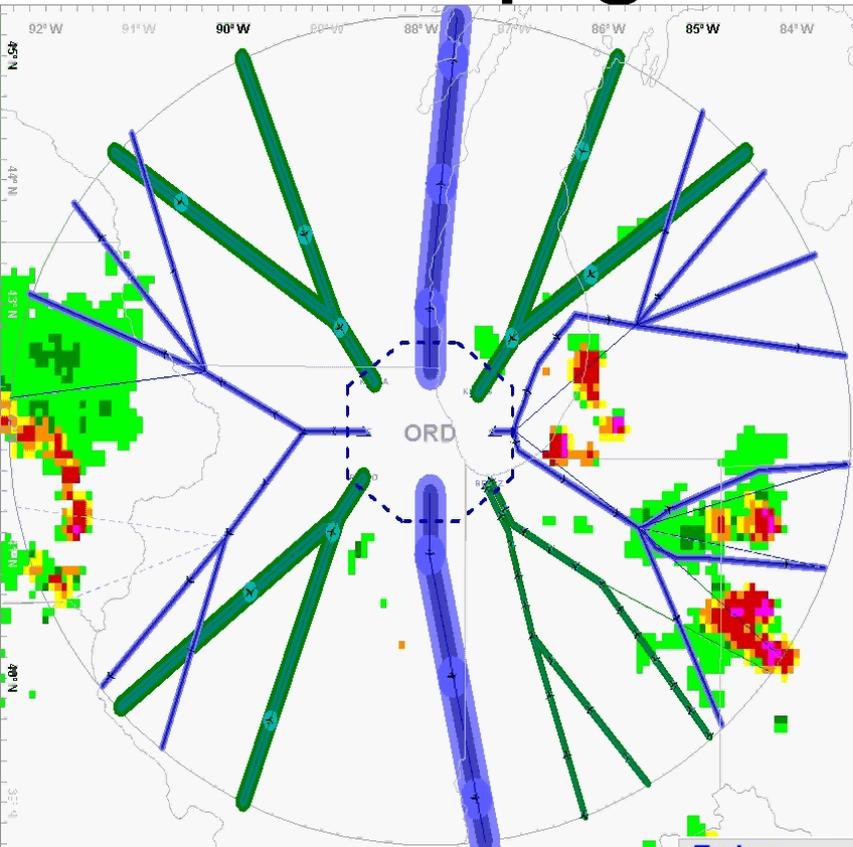
Sectors

+

Traffic flows

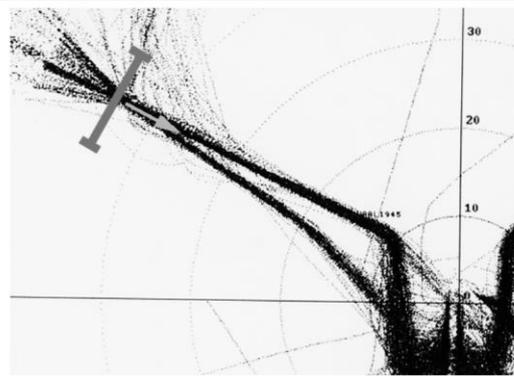
Solve both Problems 1 and 2

Guinea pig: Terminal airspace



Arrival/departure trees
Sectors

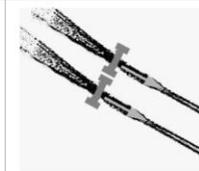
Today



Future



Single Fix;
Variance of incoming flow reduced by FD precision guidance



Double Fix;
Two non-intersecting flows arrive at the metering fix location; requires precision guidance



Triple Fix;
Three non-intersecting flows arrive at the metering fix location; requires precision guidance

State of the art: Modeling

Why one airspace configuration
is better than another?

Objective criteria (even subjective hard to express)



[Kostitsyna, Löffler, P. 7th Intl Conf on Fun with Algorithms'14
Optimizing airspace closure with respect to politicians' egos]

THE PROBLEM

*"Aircraft arrivals get
delayed by
unscheduled airspace
closure."*





Linköping University

ODESTA Project



AIR NAVIGATION SERVICES OF SWEDEN

- Optimal DESign of Terminal Airspace

- Linköping University +
LFV (Luftfartsverket)
+ reference group



EUROCONTROL



TRANSPORT
STYRELSEN



TRAFIKVERKET



swedavia
SWEDISH AIRPORTS

- Funding for 2015--2018
– Swedish Gov. Agency for
Innovation Systems



PhD position

- Linköping University
- 2015--2018
- Skills: Optimization, data handling
 - Air traffic management expertise: in-house
- ***Practice-oriented***
 - Theory @ nights & weekends

