AIR TRAFFIC MANAGEMENT AND ITS IMPACT ON THE ENVIRONMENT

MAE-AEROENV

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Outline

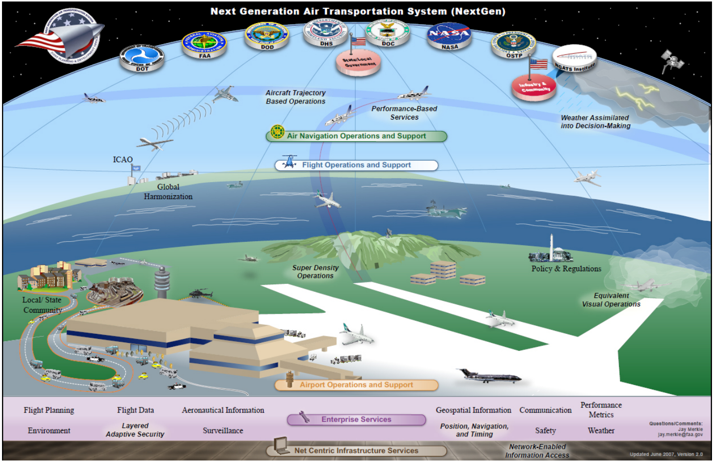
Air Transportation System

Air Transportation System

Air Transportation System is very complex system of the systems. The major components include:

- Air Traffic Management system,
- Airport system,
- Aircraft, and
- Airlines.

Air Transportation System



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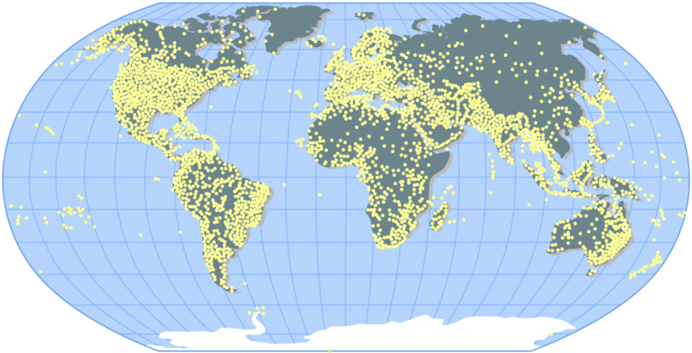
- major mean of long-distance travel
- significant economic impacts
- important role to improve environmental quality

Some key features of ATS

- Airports: $\simeq$50k
  - ATL, PEK, DXB, LAX, LHR, HND, CDG...
  - 5-800k operation per year at busiest airports
  - 100M passengers per year at busiest airports

Some key features of ATS



World airports

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  - 34Mds flown kms per year
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  - 355Mds liters of fuel consumption per year

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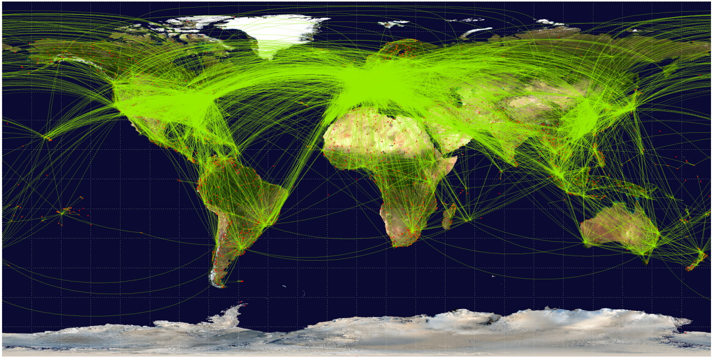

World airline routemap

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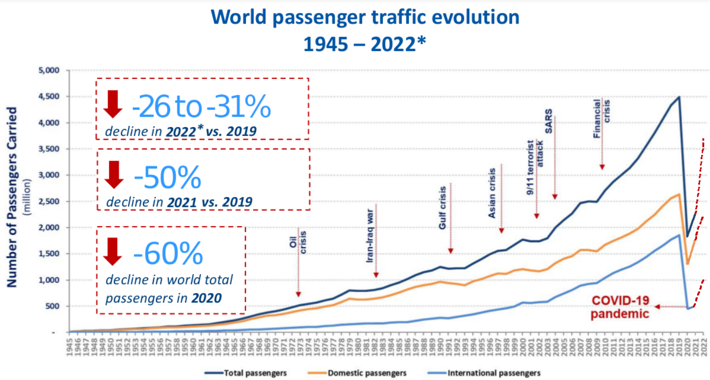

[Source: ICAO]

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- Turnover: $\sim$850Mds \$ (profit: $\sim$30Mds \$)

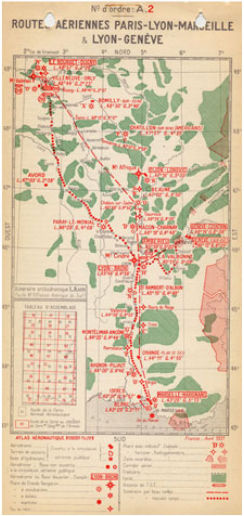
Air Transportation System

History of ATM

Beginning of air traffic control (1)

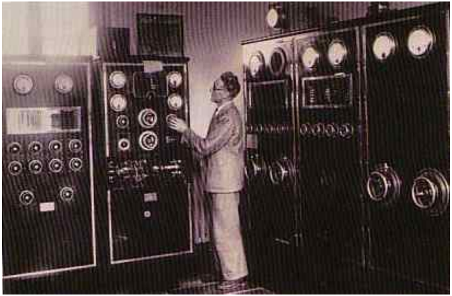
- Air traffic controllers monitor the arrival of the aircraft using binoculars (16 in 1924).
- In flight, pilots exit two flags: one to indicate the company, one for the flight ID.
- December 15, 1924, it is decided to establish two **segregated** one way routes between Paris and London.
- In 1925 building of a large network of navigation lights on the ground started.

First airways



Beginning of air traffic control (2)

- 1930 the first radio-equipped airport control room
- 1936 radio direction finding (the radio goniometry)



Emission Radio Station of Le Bourget airport

The beginning the the En-Route Control

By 1947 French airspace was divided into 3 Flight Information Regions.

Carte de zones de compétence des trois CCR de métropole (août 1947).

Procedural control (1)

- The aircraft were symbolised by magnets
- flight id, position and direction were **transmitted by the pilots**
- Morse Q (three-letter) code

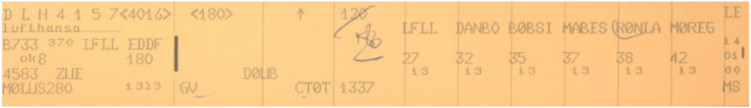
	Question ?	Answer or Advice
QAB	May I have clearance (for ...) from ... (*place*) to ... (*place*) at flight level/altitude ... ?	You are cleared (*or* ... is cleared) by ... from ... (*place*) to ... (*place*) at flight level/altitude ...
QAF	Will you advise me when you are (were) at (over) ... (*place*)?	I am (was) at (over) ... (*place*) (at ... hours) at flight level/altitude ...
QAK	Is there any risk of collision?	There is risk of collision.
QAM	What is the latest available meteorological observation for ... (*place*)?	Meteorological observation made at ... (*place*) at ... hours was as follows ...
QAN	What is the surface wind direction and speed at ... (*place*)?	The surface wind direction and speed at ... (*place*) at ... hours is ... (*direction*) ... (*speed*).
QBF	Are you flying in cloud?	I am flying in cloud at ... flight level/altitude ... [and I am ascending (descending) to flight level/altitude ...].
QCA	May I change my flight level/altitude from ... to ... ?	You may change your flight level/altitude from ... to ... *or* I am changing my flight level/altitude from ... to ...
QCH	May I taxi to ... (*place*)?	Cleared to taxi to ... (*place*).

Plotting table at Aix-en-Provence ACC

Salle de contrôle du CCR Sud-Est : le système plotting permet de déterminer la position de tous les avions circulant au-dessus d'une zone.

Procedural control (2)

- Radiotelephony
- ATS routes
- Time–distance diagram - paper strips, based on which controllers analyze the traffic situation and detect conflicts.
- Time-based separation - 15 minutes
- Stil in use in Oceanic airspace and countries without radar coverage.

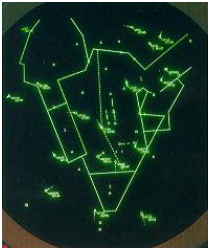


Control room at Aix-en-Provence ACC

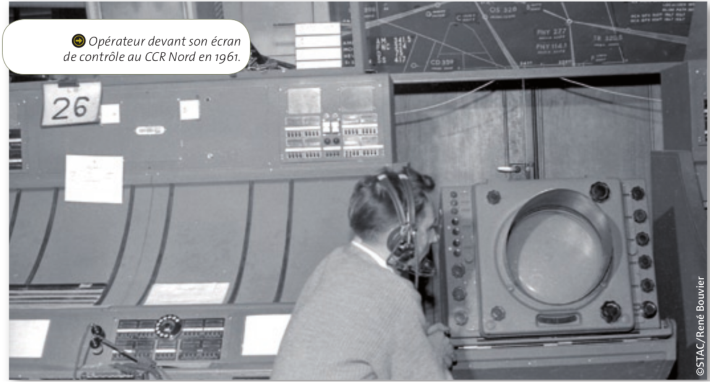
Salle de contrôle du Centre en-route de la Navigation aérienne Sud-Est en 1956.

The Revolution : The RADAR

- Invented by the British during the WWII
- Dec. 16, 1954 the first radar implemented
- Separation norm reduction: 80-45 NM $\rightarrow$ 20 NM, 10 NM and 5 NM
- 1961 Secondary Radar



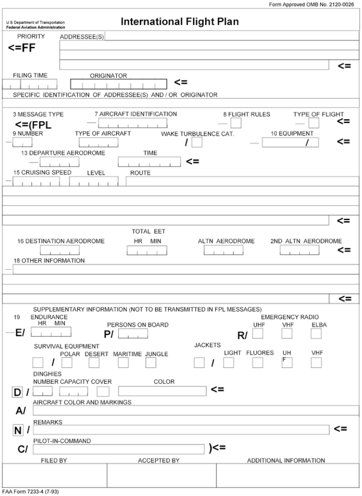
Radar control room at Paris ACC



Air Transportation System

ATM of today

International flight plan


Form Approved OMB No. 2120-0026

U S Department of Transportation
Federal Aviation Administration

International Flight Plan

PRIORITY <=FF ADDRESSEE(S) <=

FILING TIME ORIGINATOR <=

SPECIFIC IDENTIFICATION OF ADDRESSEE(S) AND / OR ORIGINATOR

3 MESSAGE TYPE <=(FPL — 7 AIRCRAFT IDENTIFICATION — 8 FLIGHT RULES TYPE OF FLIGHT <=

9 NUMBER TYPE OF AIRCRAFT WAKE TURBULENCE CAT. / — 10 EQUIPMENT / <=

— 13 DEPARTURE AERODROME TIME <=

— 15 CRUISING SPEED LEVEL ROUTE

<=

16 DESTINATION AERODROME TOTAL EET HR MIN ALTN AERODROME 2ND ALTN AERODROME <=

18 OTHER INFORMATION

<=

SUPPLEMENTARY INFORMATION (NOT TO BE TRANSMITTED IN FPL MESSAGES)

19 ENDURANCE HR MIN — E/ PERSONS ON BOARD P/ EMERGENCY RADIO R/ UHF VHF ELBA

SURVIVAL EQUIPMENT / POLAR DESERT MARITIME JUNGLE JACKETS / LIGHT FLUORES UH VHF

DINGHIES NUMBER CAPACITY COVER COLOR D / <=

AIRCRAFT COLOR AND MARKINGS A/

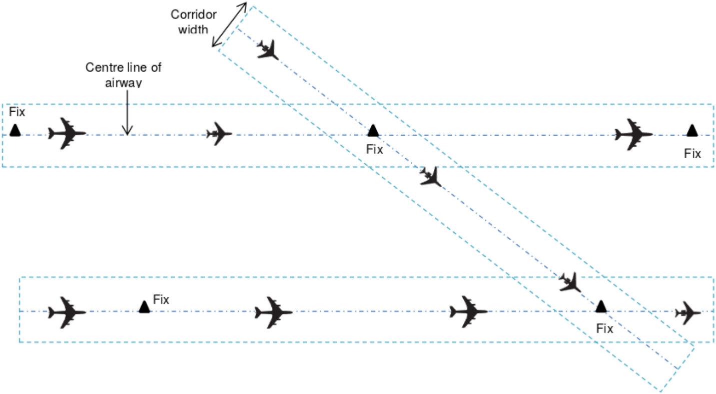
REMARKS N / <=

PILOT-IN-COMMAND C/)<=

FILED BY ACCEPTED BY ADDITIONAL INFORMATION

FAA Form 7233-4 (7-93)

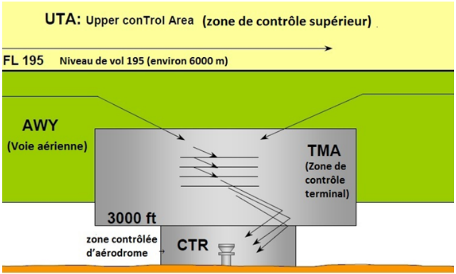
ATS route



Air Traffic Control

There are three types of control:

- Airport control (taxi, takeoff, landing)
- Approach control (departure and arrival paths (SID-STAR), sequencing and merging)
- En-Route control (continental, oceanic)



En-Route control

CRNA Est - Reims control position

ATM $\neq$ ATC

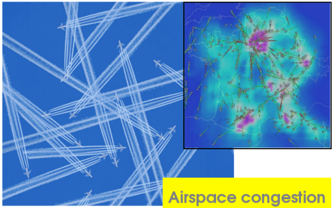
ATM include other services beside ATC, like Air Traffic Flow Management:

- Optimises the air traffic flows according to declared airspace capacities
- Allocates: departure slots, re-routings, alternative flight profiles
- make the best use of the available capacity

to be continued...

Aviation impact

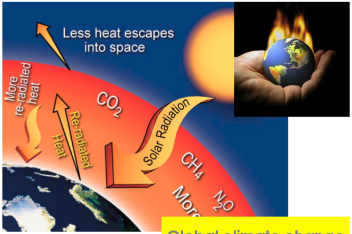
Aviation impacts



Airspace congestion

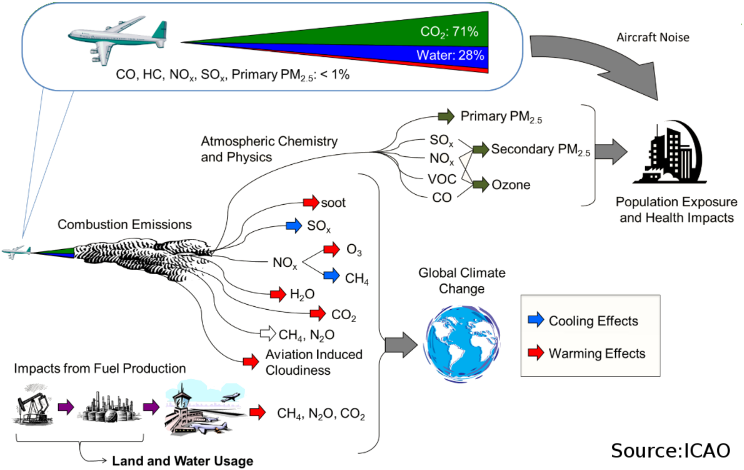
Airport congestion

Noise polution



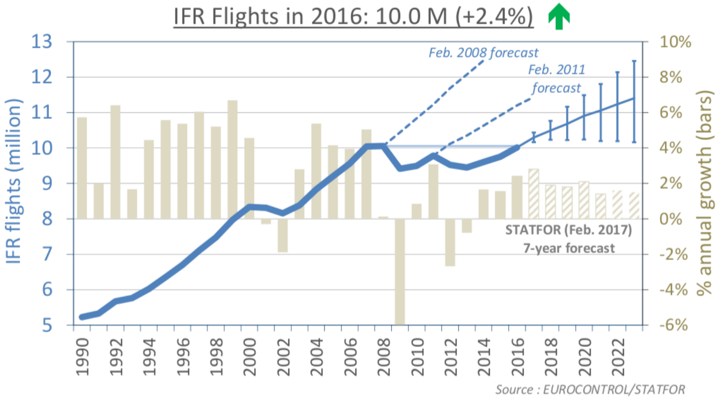
Global climate change

Aviation environmental impacts



Source:ICAO

European air traffic evolution (1)



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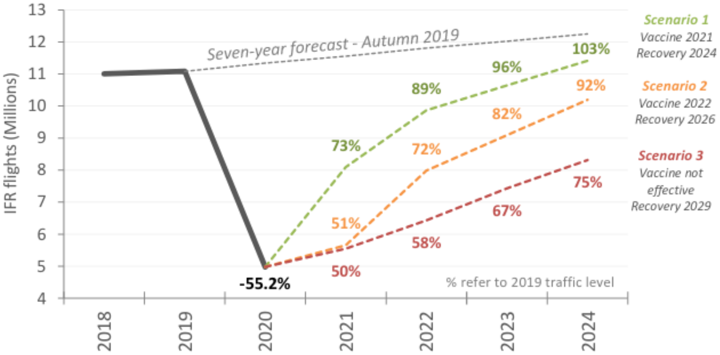
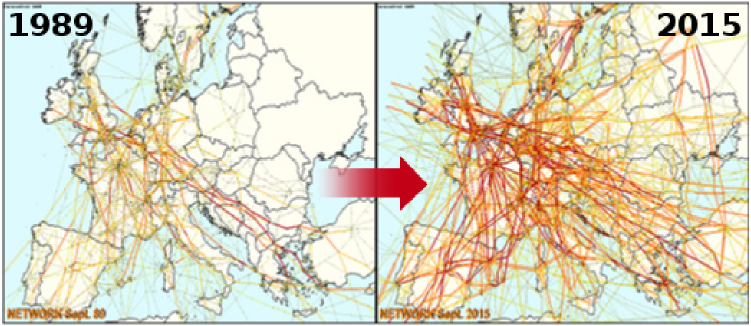
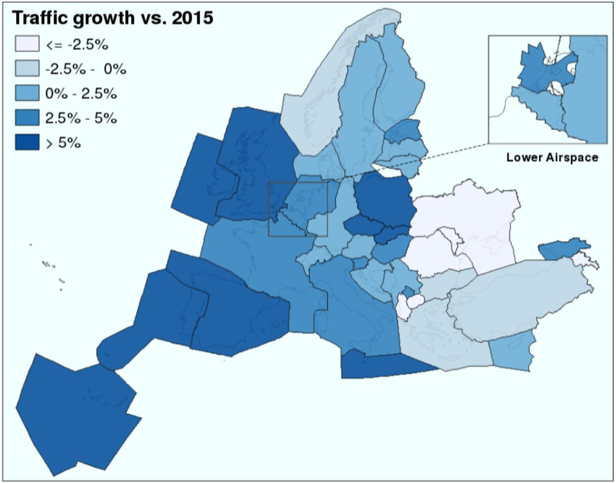


European air traffic evolution (2)



European air traffic evolution (3)



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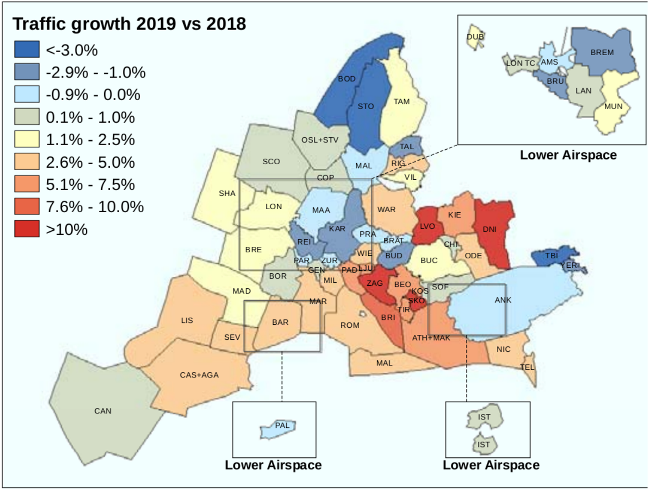
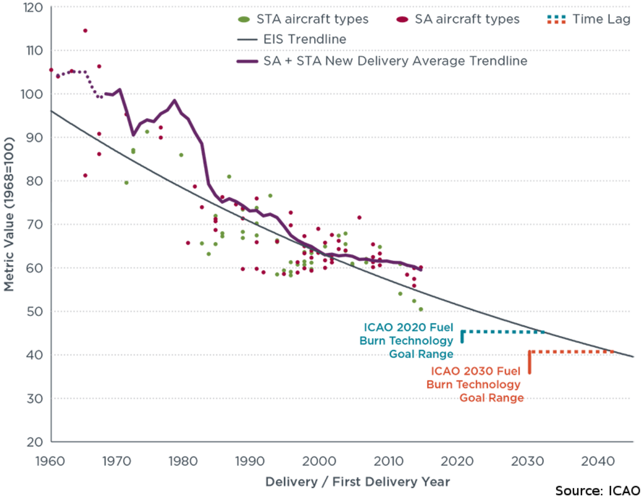


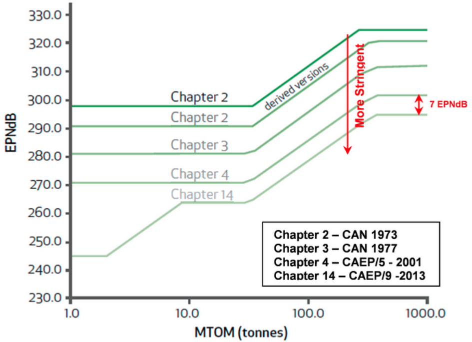
Aircraft fuel efficiency evolution



Source: ICAO

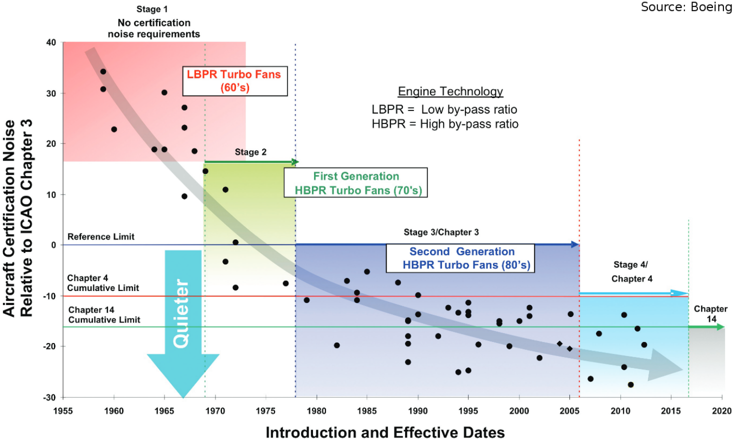
Aircraft noise evolution (1)

- Reduction of Noise at Source
- Aircraft Noise Management
- Annex 16 - noise limits for aircraft certification
- Ensures implementation of the latest technologies

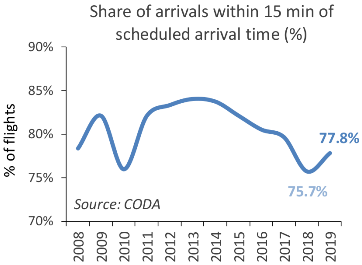


Aircraft noise evolution (2)

Source: Boeing



Aviation impact facts (1)



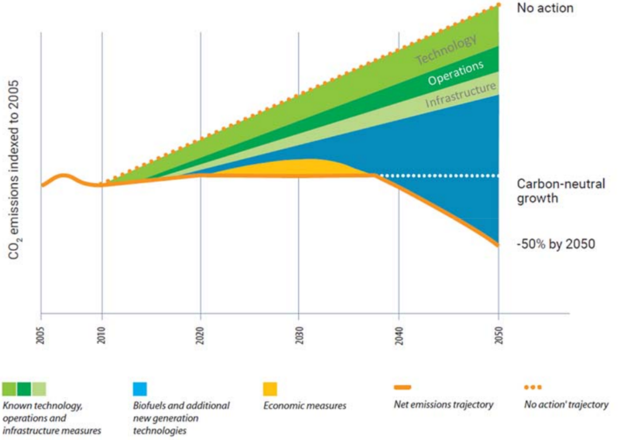
- $>$2M flights delayed
- 13 min/flight of delay
- $>$50% ATC related
- 1Md euros of costs

Aviation impacts facts (2)

- $\triangle$ Number of flight increased by 80% 1990-2014
- $\triangle$ CO_2 emissions have equally increased
- $\triangle$ NO_X emissions have doubled in the same period
- $\triangle$ 2.5 million people were exposed to noise in 2014
- $\triangledown$ Aircraft noise level reduced by 2-4 dB/decade
- $\triangledown$ Aircraft engine emissions continuously improves

[Source: EEA, EASA, EUROCONTROL - European Aviation Environmental Report 2016]

Aviation basket of measures



[Source: ICAO, EUROCONTROL]

Flight Efficiency Plan

Agreed by IATA, CANSO and EUROCONTROL in 2008
FEP contains five action points:

- Enhancing European en-route airspace design
- Improving airspace utilization and route network availability
- Efficient TMA design and utilization
- Optimizing airport operations
- Improving awareness of performance

Current ATM

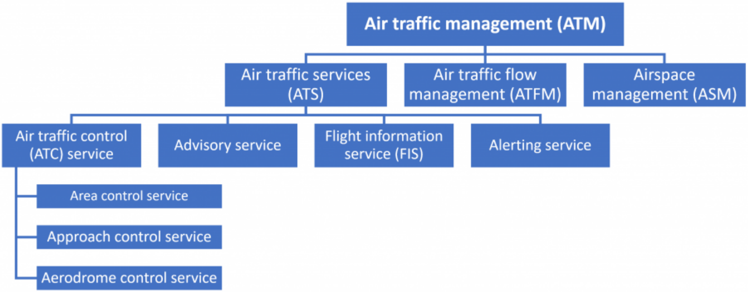
Air Traffic Management

ATM aims at ensuring safe, efficient, and expeditious aircraft movement and it is composed of the following services:

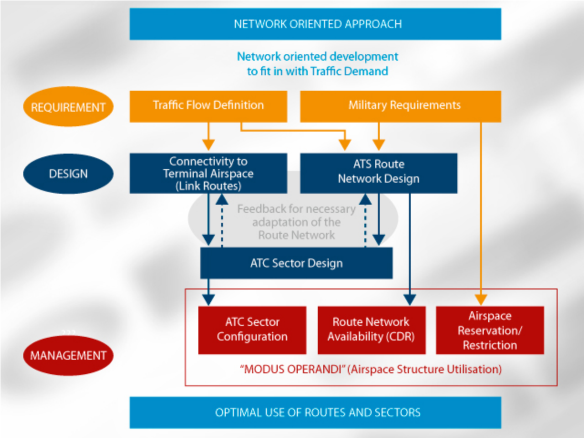
- Airspace Management (ASM)
- Air Traffic Flow Management (ATFM)
- Air Traffic Service

ATC is responsible for safe flow of air traffic.
ATCO monitors the traffic and ensures minimum safety separation between aircraft.

Air Traffic Management



Airspace Management (ASM)

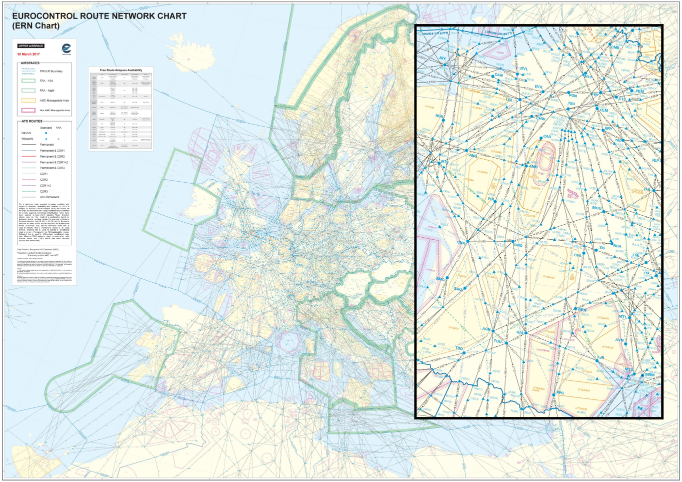


Current ATM
Airspace design

Airspace infrastructure design

- Two confronted objectives:
  - efficiency - AU may chose preferred trajectories
  - capacity/safety - Airspace may accommodate demand
- Two stage iterative process:
  - ATS route network design - adapt routes to major flows; direct segments
  - Airspace sectorization - determine geometric form of sectors

ATS Route Network chart



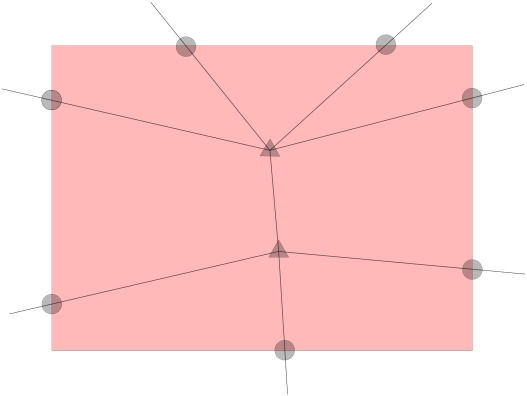
Free Route Airspace (FRA)

FRA is a specified airspace within users can freely plan a route between a defined entry and exit point
(or by an intermediate point) without reference to the ATS route network.

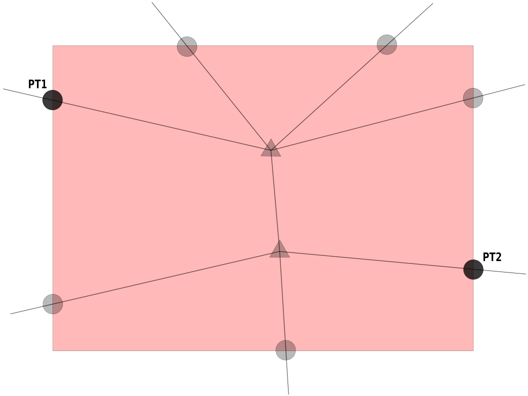
FRA aims at enhancing enroute flight efficiency with subsequent benefits for airspace users, environment and ATM as whole.

- It is subject to availability
    - During period of light traffic e.g. night
    - Upper airspace above airspace with ATS routes
- Flights remain subject to ATC

FRA vs. ATS routes



FRA vs. ATS routes



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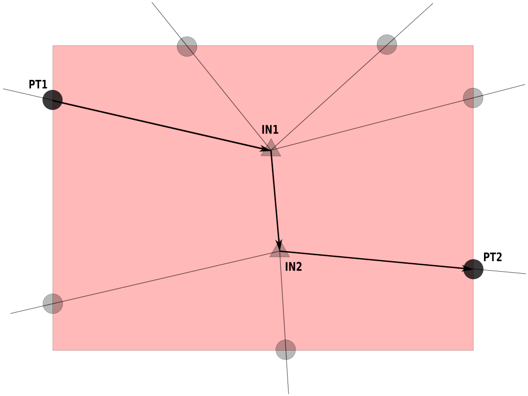

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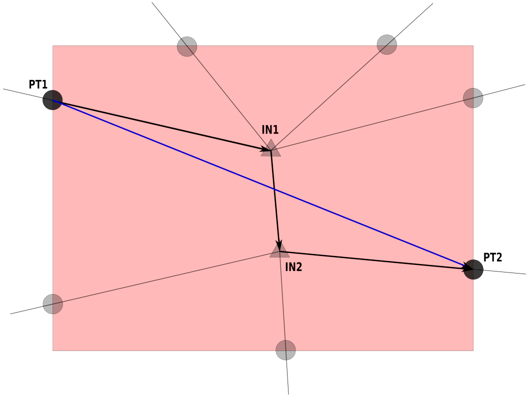
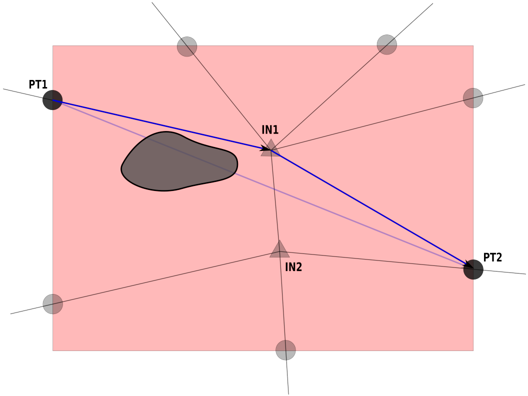
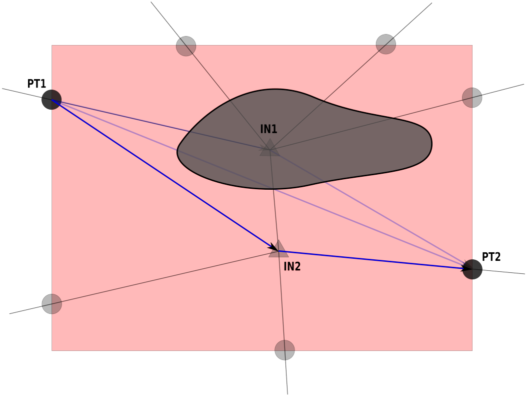


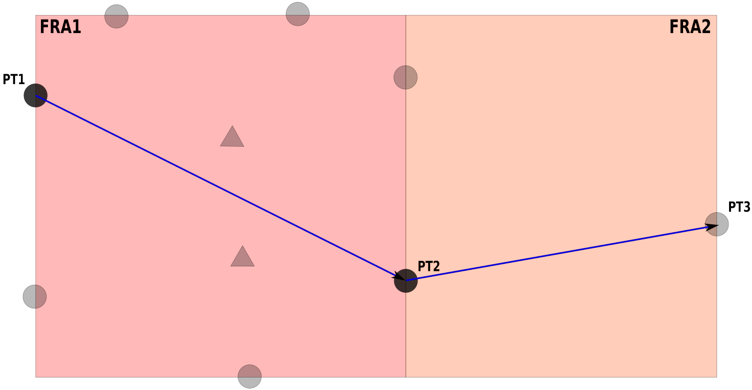
FRA vs. ATS routes



FRA vs. ATS routes



Cross-Border FRA



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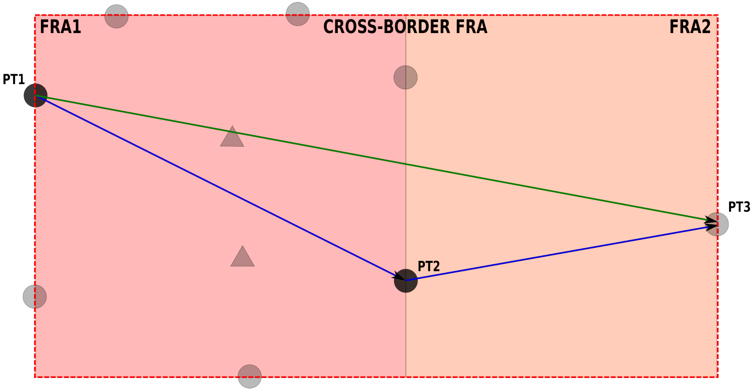


FRA benefits

Operational efficiency $\implies$ environmental sustainability
FRA is a way of overcoming the efficiency, capacity and environmental problems.

- Choice of preferred (shortest) route for the AU
- Wind-optimal routes
- Improved traffic predictability
- More efficient use of conflict detection tools
- Increased capacity
- No major implementation issues

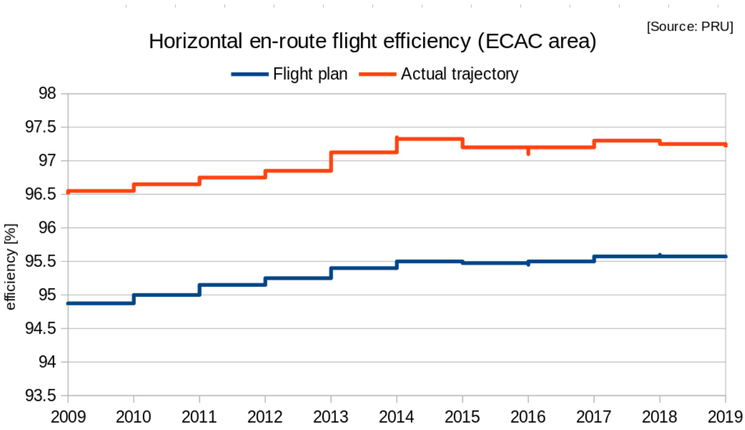
FRA benefit estimates

Initial annual estimates (source EUROCONTROL):

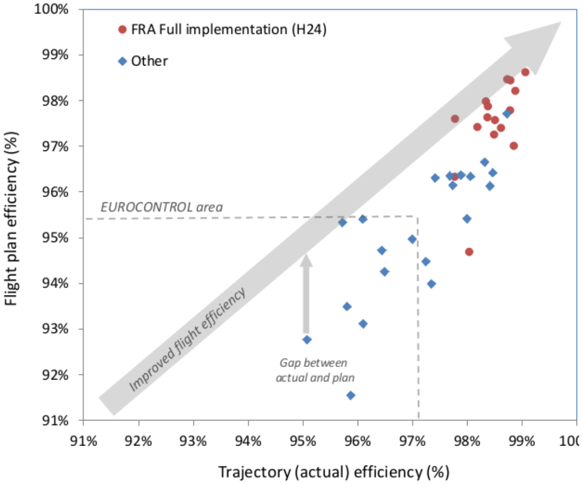
- $\bigtriangledown$ 7.5M NM in flight distance
- $\bigtriangledown$ 45k tonnes of fuel
- $\bigtriangledown$ 37M euros of fuel costs
- $\bigtriangledown$ 150k tonnes of CO_2

By 2019/2020 additional savings of 60-75 kNM/day

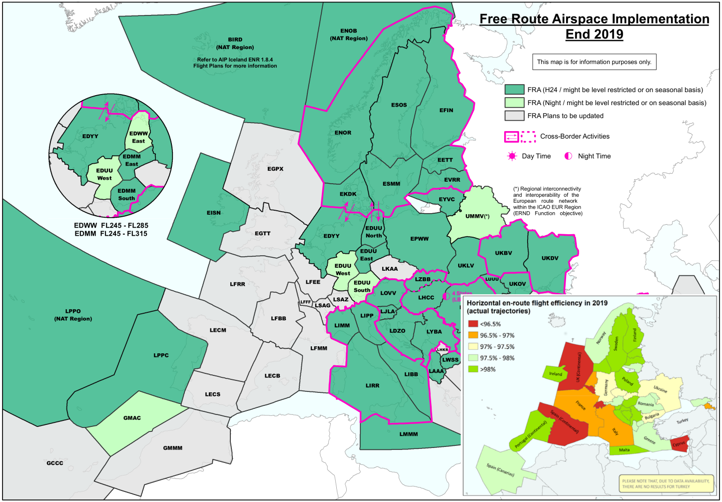
FRA benefit facts (1)



FRA benefit facts (2)



FRA implementation 2019



Noise Abatement Procedures

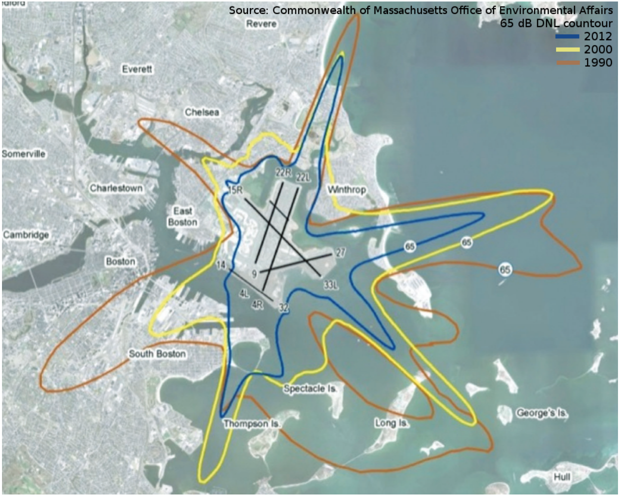
Procedures being employed to provide noise relief to communities around airports.

- Noise abatement flight procedures
  - Continuous Descent Approach (CDA)
  - Noise Abatement Departure Procedures (NADP)
  - Modified approach angles, displaced thresholds
  - Low power/low drag approach profiles
- Spatial management
  - Noise preferred arrival and departure routes
  - Noise preferred runways
- Ground management
  - APU management
  - Taxi and queue management

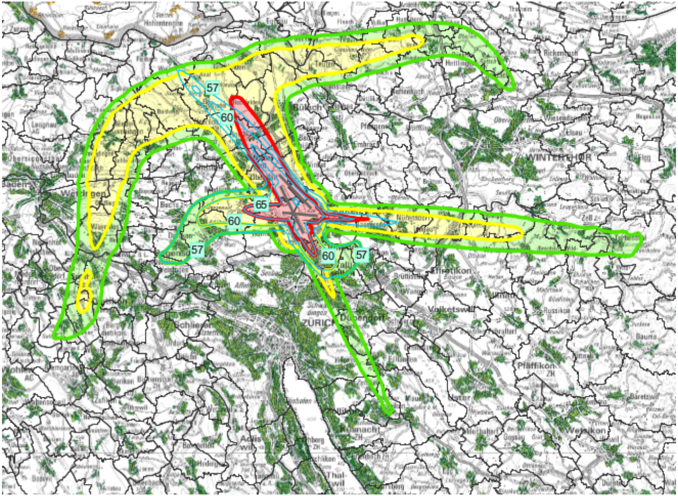
Noise Abatement Procedures difficulties

- Lack of harmonising guidance
- Capacity requirements
- Aircraft/Airport equipage
- Pilot and air traffic controller acceptance
- Economic constraints
- Trade off between noise and emissions
- Terrain and obstacles

Noise footprint at Boston Logan airport

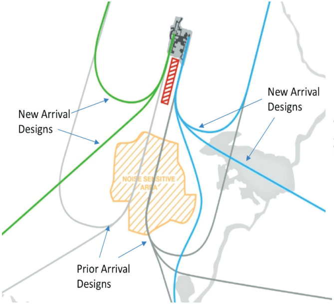


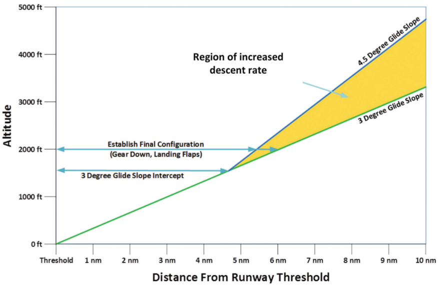
Noise footprint at Zurich airport



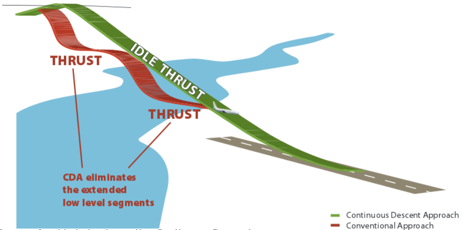
Tailored Arrivals

- Increased Angle Approaches
- Two-Segment Approaches
- Displaced Threshold
- Advanced Arrival Procedures - PBN





Continuous Descent Approach (CDA)



Source: A guide to implementing Continuous Descent

"Continuous Descent Approach is an aircraft operating technique in which an arriving aircraft descends from an optimal position with minimum thrust and avoids level flight to the extent permitted by the safe operation of the aircraft and compliance with published procedures and ATC instructions".

Continuous Descent Approach (CDA)

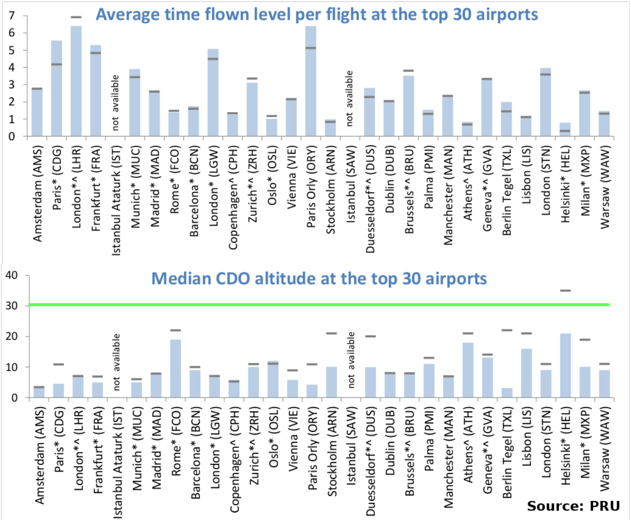
- CDA delivers major environmental and economic benefits without any adverse affect on safety.
- ToD $\rightarrow$ touchdown
- low engine trust
- low drag configuration (where possible)
- delayed final flap selection!!!
- minimum level flight segments only to decelerate, change configuration or intercept ILS
- priority: noise impact, fuel efficiency, emission reduction

CDA benefits

Annual estimates for ECAC (source EUROCONTROL):

- $\bigtriangledown$ 150k tonnes of fuel
- $\bigtriangledown$ 100M euros of fuel costs
- $\bigtriangledown$ 500k tonnes of CO_2
- $\bigtriangledown$ 2-5 dB per flight

CDA benefit facts



Functional Airspace Block (FAB)

Current ATM

Airspace management

Flexible Use of Airspace (FUA)

The FUA Concept provides the Air Traffic Management (ATM) system with the potential to increase capacity and flight efficiency.

Concept of FUA is that:

- Airspace is continuum, not "civil" or "military"
- Necessary airspace segregation is temporary
- Not constrained by national boundaries.

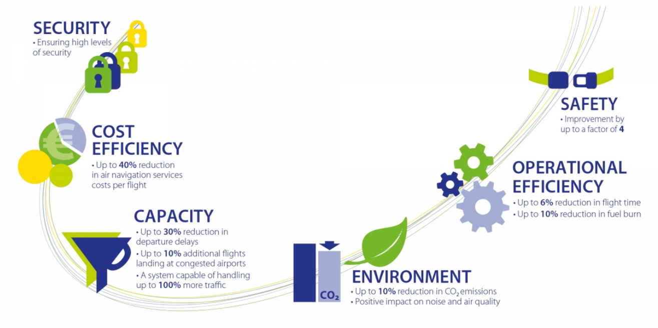
FUA benefits

- Increased flight economy
- Reduced environmental impact
- Enchanced ATS route (CDR) and sectorization (TSA, CBA)
- Enchanced real-time civil/military co-ordination
- Reduced airspace segregation

Future ATM

Need for change

- Incremental changes not sufficient
- ICAO - Global Air Navigation Operational Concept
- Underway projects: SESAR, NextGen, CARATS



Fundamental changes

Paradigm shift from Airspace-centric ATM to Trajectory-centric ATM requires:

- Modernisation of ATM technologies
- **Higher level of automation**
- **System-wide share of information**
- Fusion of the flight planning and execution processes into **Trajectory Based Operations (TBO)**

4D Trajectory Management

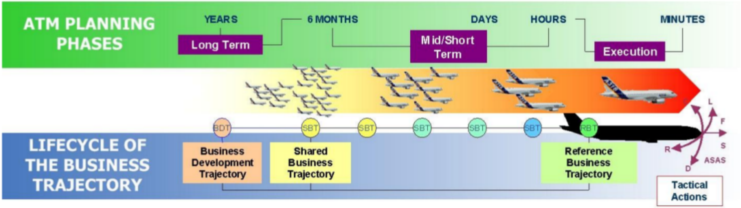
Trajectory Based Operations (TBO)

Trajectory Based Operation facilitates a fundamental shift away from the management of flights through tactical intervention towards a more strategic focus on planning and intervention by exception.

4D Trajectory Management

Trajectory management is the process by which the Business or Mission Trajectory of the aircraft is planned, agreed, updated and revised. It is achieved through Collaborative Decision Making (CDM) processes between Airspace users and ATM Service Providers (ANSP, Airports, Network Manager).

The Business Trajectory Lifecycle

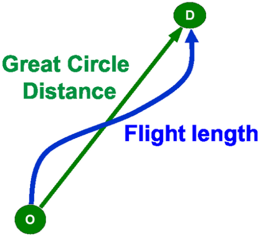


BDT - Airspace user preferences
SBT - Shared trajectory with ATM partners
RBT - Agreed trajectory

Measuring ATM efficiency

Horizontal Flight Efficiency

- Do current distance-based indicators properly capture ATM inefficiency ?
- EU Regulation No 691/2010 and 390/2013
- EUROCONTROL Performance Review Unit



- $HFE[\%] = \frac{FL-GCD}{GCD}$
- 40 Nm around a/p excluded
- Two versions : KEP and KEA

Horizontal Flight Efficiency

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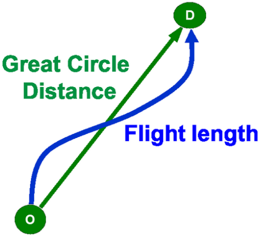
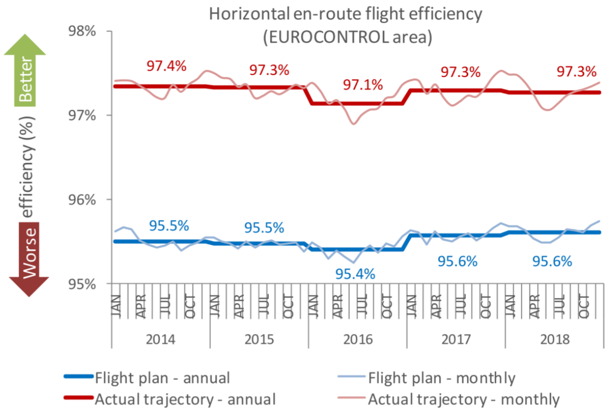


- $HFE[\%] = \frac{FL - GCD}{GCD}$
- 40 Nm around a/p excluded
- Two versions : KEP and KEA
- $+$ simplicity
- $-$ proxy
- $-$ vertical/speed profile neglected

HFE High level picture



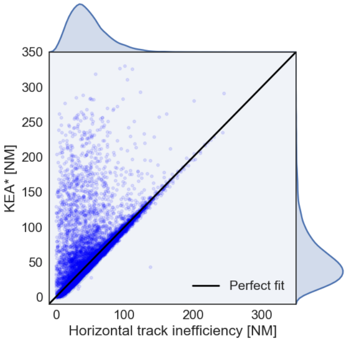
New distance-based metric

- SESAR ER The APACHE project
- Weather optimal trajectory as a reference
  - Using realistic weather condition
  - Free-route airspace
  - Maximum range operations (Cost Index $= 0$)
- Extension is calculated as $|FL - WOD|$

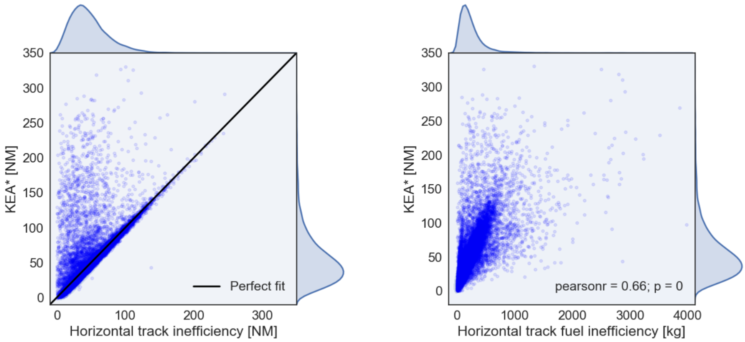
New distance-based metric

- SESAR ER The APACHE project
- Weather optimal trajectory as a reference
  - Using realistic weather condition
  - Free-route airspace
  - Maximum range operations (Cost Index $= 0$)
- Extension is calculated as $|FL - WOD|$
- $+$ better baseline
- $-$ require weather data
- $-$ require optimization algorithms
- $-$ more difficult to express per state

Result comparison



Result comparison

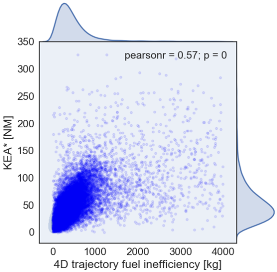


New fuel-based metric

Weather optimal trajectory + optimal vertical/speed profile

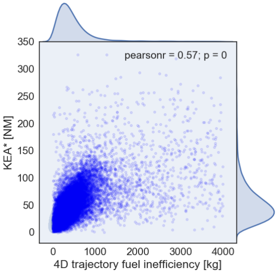
New fuel-based metric

Weather optimal trajectory + optimal vertical/speed profile



New fuel-based metric

Weather optimal trajectory + optimal vertical/speed profile



- + best possible baseline
- + consider vertical/speed inefficiency
- – require fuel estimation models

Conclusion on KEP and KEA

Key Performance Environment Indicators

- Current indicators is not good proxy
- It is as good as taking any random value
- Cheap improvement possible
- Ultimate solution requires important change in methodology: usage of fuel estimation models, optimization models

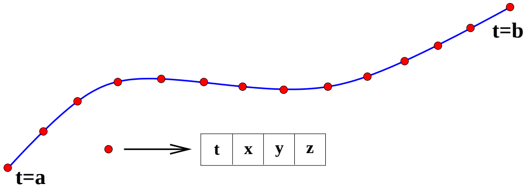
Trajectory optimisation

Trajectory optimisation

Trajectory features

Classical trajectory representation

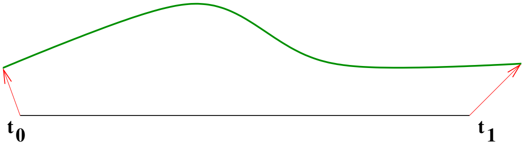
Trajectory is expressed as an ordered list of trajectory samples (plots) containing time, position and possibly speed vector.



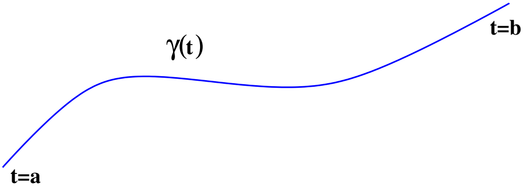
No aircraft dynamics in such representation.

Trajectory as functional data

Trajectory is described as mappings from a time interval $[t_0, t_1]$ to a state space E belong either $\mathbb{R}^3$ or $\mathbb{R}^6$ depending on whether speed is assumed to be part of aircraft state or not.



Trajectory features



- Trajectory $\vec{\gamma} : \vec{\gamma}[a, b] \rightarrow E$
- $\gamma(\vec{a})$ and $\gamma(\vec{b})$ being end points.
- Trajectory is at least continuously differential (C^1)
- Trajectory length $l(\vec{\gamma}) = \int_a^b \|\vec{\gamma}'(t)\| dt$
- Smoothness assumptions are made for aircraft trajectories belonging to C^2.

Trajectory optimisation

Trajectory models

Trajectory models

- Dimension Reduction Approaches
- Front Propagation Approaches
- Optimal Control Approaches

Lagrangian Interpolation

Given $n+1$ real numbers y_i , $0 \leq i \leq n$, and $n+1$ distinct real numbers $x_0 < x_1 < \ldots < x_n$, *Lagrange polynomial* associated with $\{x_i\}$ and $\{y_i\}$ is a polynomial of degree n solving the interpolation problem :

$$L_n(x_i) = y_i, \quad 0 \leq i \leq n$$

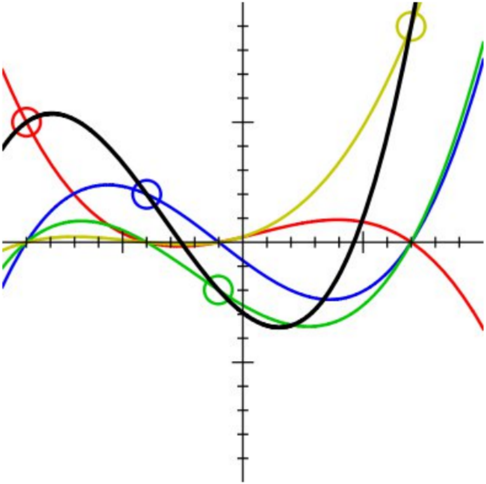
Solution :

$$L_n(x) = \sum_{i=0}^{n} y_i \; l_i(x)$$

where

$$l_i(x) = \prod_{j \neq i} \frac{(x - x_j)}{(x_i - x_j)}$$

Lagrangian Interpolation example

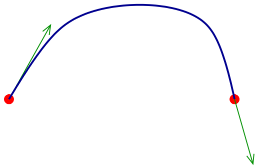


Hermite Interpolation

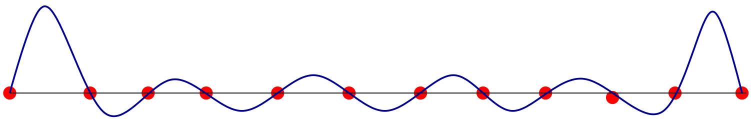
Hermite interpolation generalizes Lagrange interpolation by fitting a polynomial to a function f that not only interpolates f at each knot but also interpolates a given number of consecutive derivatives of f at each knot.

$$\left[\frac{\partial^j H(x)}{\partial x^j}\right]_{x=x_i} = \left[\frac{\partial^j f(x)}{\partial x^j}\right]_{x=x_i}$$

for all $j = 0, 1, ..., m$ and $i = 1, 2, ..., k$



Runge phenomenon



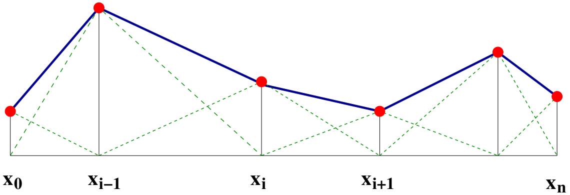
Interpolation with high degree polynomial is risky...

Solution: Piecewise interpolation

Piecewise Linear Interpolation

Given $n+1$ real numbers $y_i, 0 \leq i \leq n$, and $n+1$ distinct real numbers $x_0 < x_1 < \ldots < x_n$, we consider the n linear curves $l_i(x) = a_i x + b_i$ on the intervals $[x_i, x_{i+1}]$ for $i = 0, \ldots n-1$. Where each $l_i(x)$ has to connect two points $\{(x_i, y_i), (x_{i+1}, y_{i+1})\}$

$$y_i = a_i x_i + b_i x_i \quad y_{i+1} = a_i x_{i+1} + b_i x_{i+1}$$



Piecewise Quadratic Interpolation

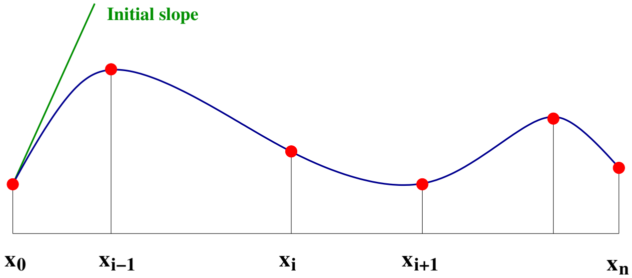
We consider the n quadratic curves $q_i(x) = a_i x^2 + b_i x + c_i$ on the intervals $[x_i, x_{i+1}]$ for $i = 0, \ldots n-1$.
Where each $q_i(x)$ has to connect two points $((x_i, y_i),(x_{i+1}, y_{i+1})$

$$y_i = a_i x_i^2 + b_i x_i + c_i \quad y_{i+1} = a_i x_{i+1}^2 + b_i x_{i+1} + c_i$$

And on each point, except the first one, the derivative of the previous quadratic has to be equal to the derivative of the next one.

$$2a_i + b_i = 2a_{i-1} + b_{i-1}$$

Piecewise Quadratic Interpolation



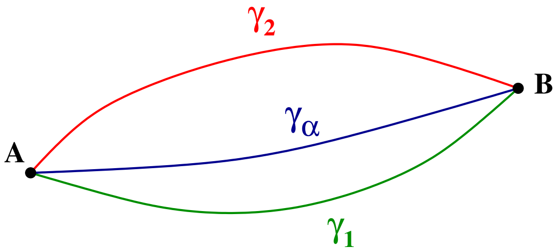
Small change in only one way point may totally change the shape of the interpolating curve.

Piecewise cubic interpolation, B-Splines...

Homotopy Trajectory Design

If we consider two (or more) references trajectories $(\gamma_1(t), \gamma_2(t))$ joining the same origin destination pair (e.g. past flown trajectories), one can create a new trajectory $\gamma(\alpha, t)$ by using an homotopy :

$$\gamma(\alpha, t) = (1 - \alpha)\gamma_1(t) + \alpha\gamma_2(t)$$



Trajectory models

- Dimension Reduction Approaches
- Front Propagation Approaches
- Optimal Control Approaches

Front Propagation Approaches

Methods introduced by J.A. Sethian.

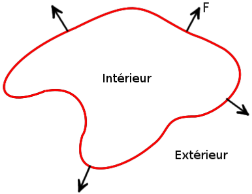


Figure: Curve propagating with speed F in normal direction.

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.

Trajectory models

- Dimension Reduction Approaches
- Front Propagation Approaches
- Optimal Control Approaches

Optimal Control Approaches

- Mainly used for time-parameterized of shapes.
- Generating *time-parameterized* paths requires the incorporation of the aircraft dynamics.
- The objective of optimal control theory is to determine the control input(s) that will cause a process to satisfy the physical constraints, while, at the same time, minimize (or maximize) some performance criterion.
- Feasibility of the trajectories is automatically ensured using this approach.

Trajectory optimisation

Applications

Wind Optimal Trajectory Design
Front Propagation Approach
ENAC - Cap Gemini

What are our objectives ?

Proposed approach : Wind optimal route design

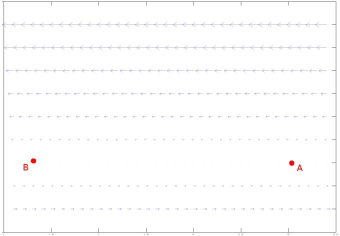
Optimization of aircraft trajectories based on wind data which avoid congestion areas, adverse weather, etc.

Criterion : Travel Time and/or Fuel Consumption

Statement of problem

Inputs

- Start point A
- End point B
- Constant speed
- Wind forecast
- Areas to avoid



Goal : Connect the point A to the point B minimizing criterion.

Statement of problem

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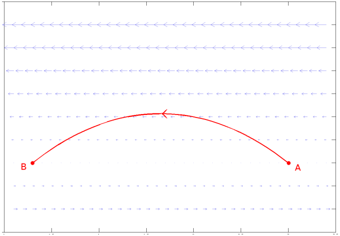


Goal : Connect the point A to the point B minimizing criterion.

Example with obstacles

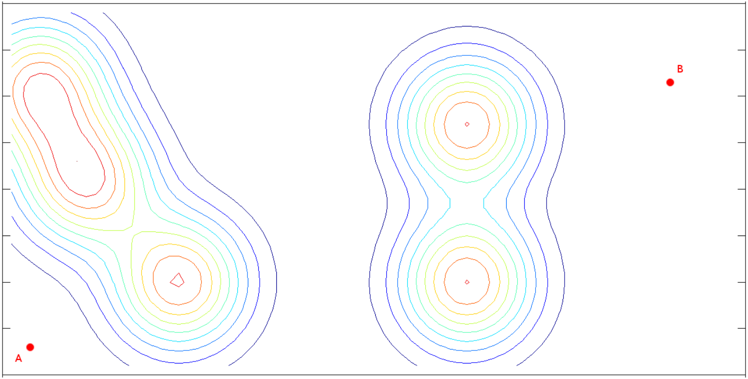


Figure: **Obstacles** (Forbidden areas then coefficient decreasing to 0.)

Example with obstacles

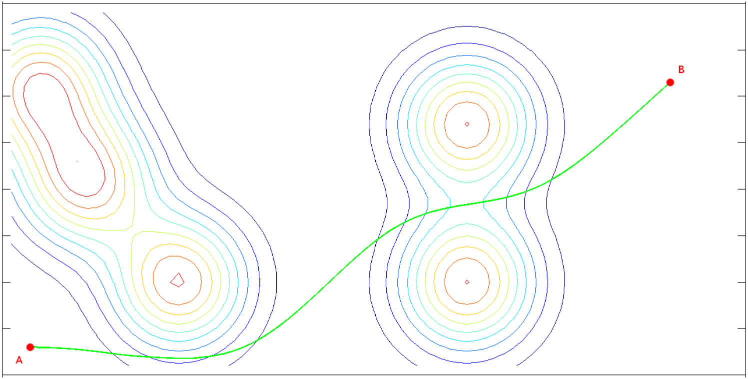


Figure: Optimal trajectory (green) without wind

Example with obstacles

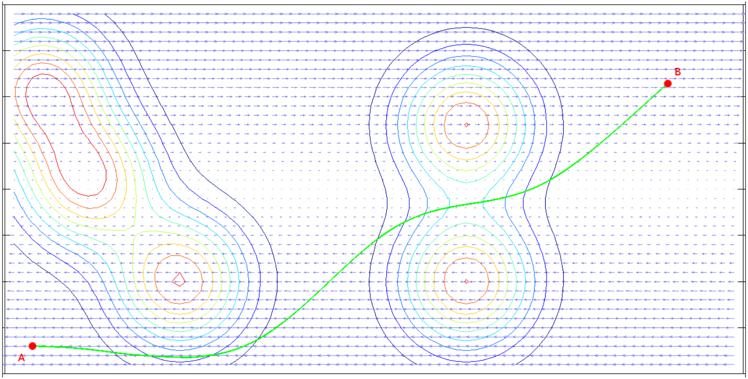


Figure: Wind

Example with obstacles

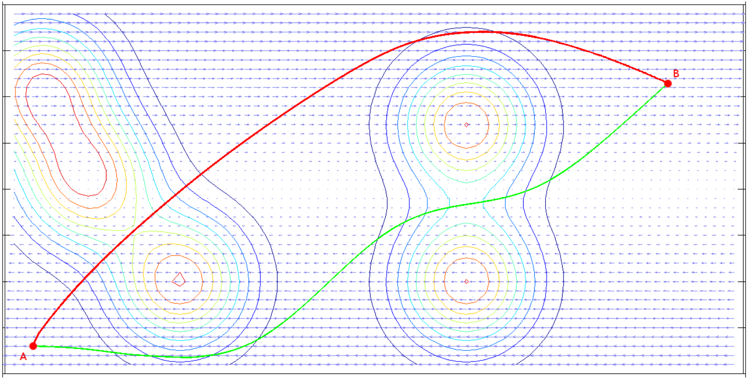


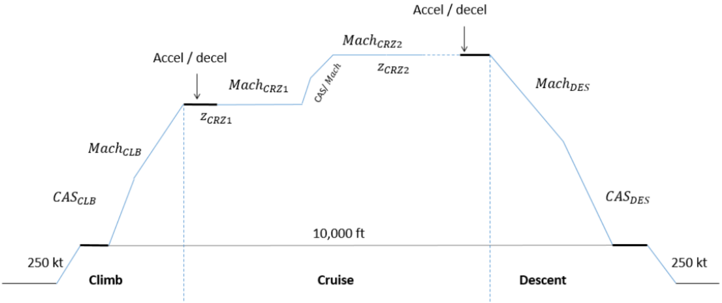
Figure: Optimal trajectories : with wind and without wind.

Trajectory vertical profile optimisation

Optimal control

ENAC - Airbus

Traditional mission profile

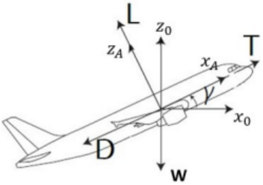


Mission separation into the phases is justified by:

- ATC procedures
- aircraft (engine regim, aerodynamic configurations)

Aircraft dynamics

$$
\begin{cases}
m\dot{v} & = & T - D - mg\sin(\gamma) \\
0 & = & L - mg\cos(\gamma) \\
\dot{x} & = & v\cos(\gamma) \\
\dot{z} & = & v\sin(\gamma) \\
\dot{m} & = & -\eta T
\end{cases}
$$



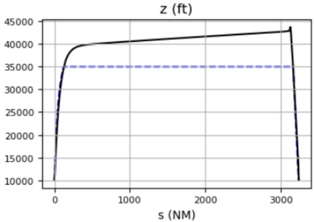
- z : altitude
- s : longitudinal distance
- v : airspeed
- γ : airslope
- m : aircraft masse
- w : aircraft weight
- D : drag
- L : lift
- T : trust
- η : specific consumption

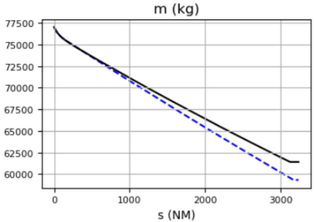
Optimal control formulation

$$\min_{\mathbf{u}} J(\mathbf{x},\mathbf{u}),$$

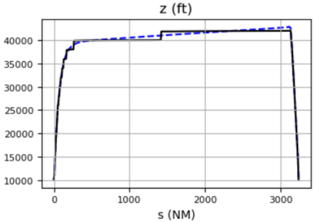
$$\text{s.t.}\ \left|\begin{array}{l}
\dfrac{dv}{ds}(\mathbf{u},\mathbf{x},s) = \dfrac{F_N}{mv\cos\gamma} - \dfrac{\frac{1}{2}\rho v S_{ref} C_x(C_z)}{m\cos\gamma} - \dfrac{g_0}{v}\tan\gamma \\
\dfrac{dm}{ds}(\mathbf{u},\mathbf{x},s) = -\dfrac{\eta F_N}{v\cos\gamma} \\
\dfrac{dz}{ds}(\mathbf{u},\mathbf{x},s) = \tan\gamma \\
\dfrac{dt}{ds}(\mathbf{u},\mathbf{x},s) = \dfrac{1}{v\cos\gamma} \\
\\
C_z \leq C_{z_{max}} \\
CAS(v,z) \leq VMO \\
MACH(v,z) \leq MMO \\
0 \leq \lambda \leq 1 \\
V_{z_{min}} \leq v\sin\gamma \leq V_{z_{max}} \\
\\
\mathbf{x}(s_0) = (v_0, m_0, z_0, t_0) \\
v(s_f) = v_0 \\
z(s_f) = z_0.
\end{array}\right.$$

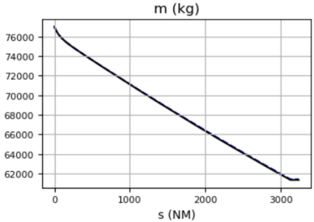
Continuous cruise climb solution





Cruise flight level solution





Thank you for attention!
Questions?

Andrija D. Vidosavljevic

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12 September 2022