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Flight Control & Guidance System
AIRBUS OPERATIONS SAS

Flight Control laws

January 2020

Summary

1 – Computers: Architecture and installation

2 – Flight control laws: Keys principles

3 – Displays

4 – Protection laws & Flight envelopes

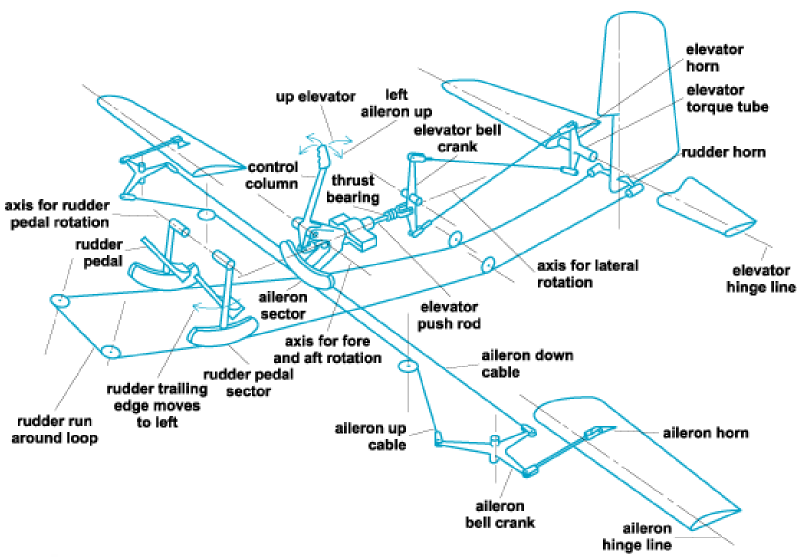
5 – Reconfiguration laws

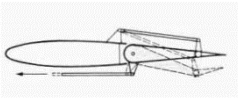
6 – Flight Control laws Robusteness

Questions at any time

Life in a design office at Airbus?

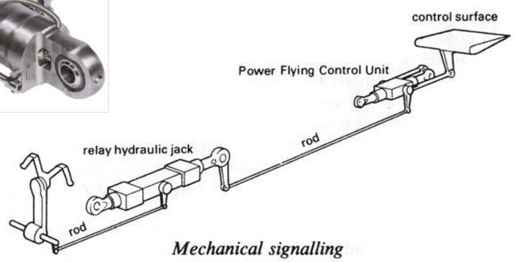
In the beginning there was direct mechanical flight controls



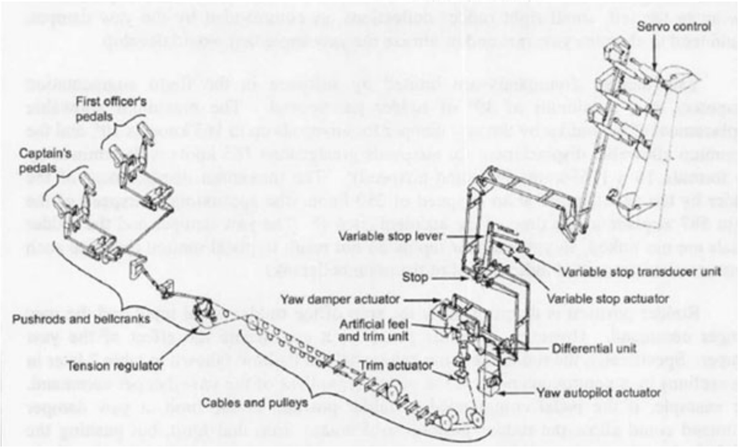


- Limited power ➔ “small” aircraft only
- Could be assisted by mechanical or aerodynamic devices (tabs)
- Very simple ➔ “light” maintenance

The second day they created mechanical flight controls with servo (… and they found it was good)

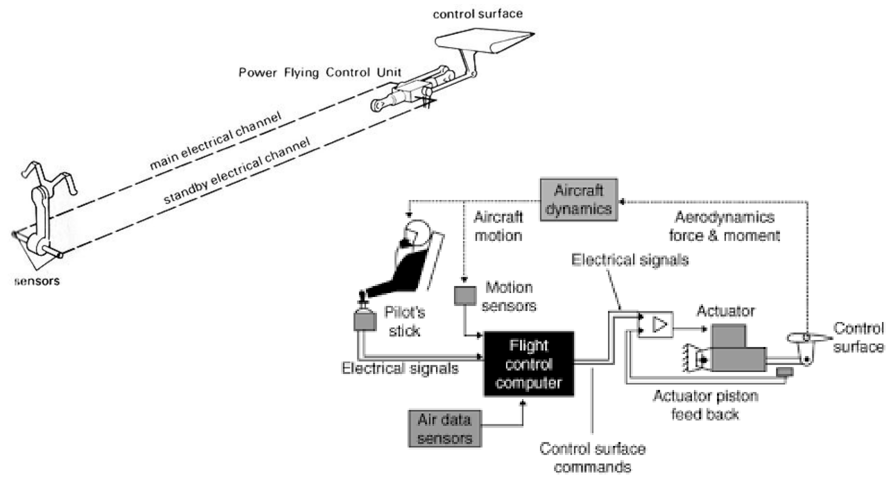


Mechanical signalling



- No power limitation➔ aircraft as large as you want !!
- Complexity ➔ high level of maintenance needed
- Not very precise (backlash, flexibility, …)

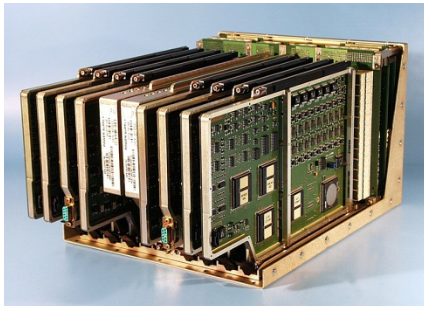
The third day appeared fly by wire



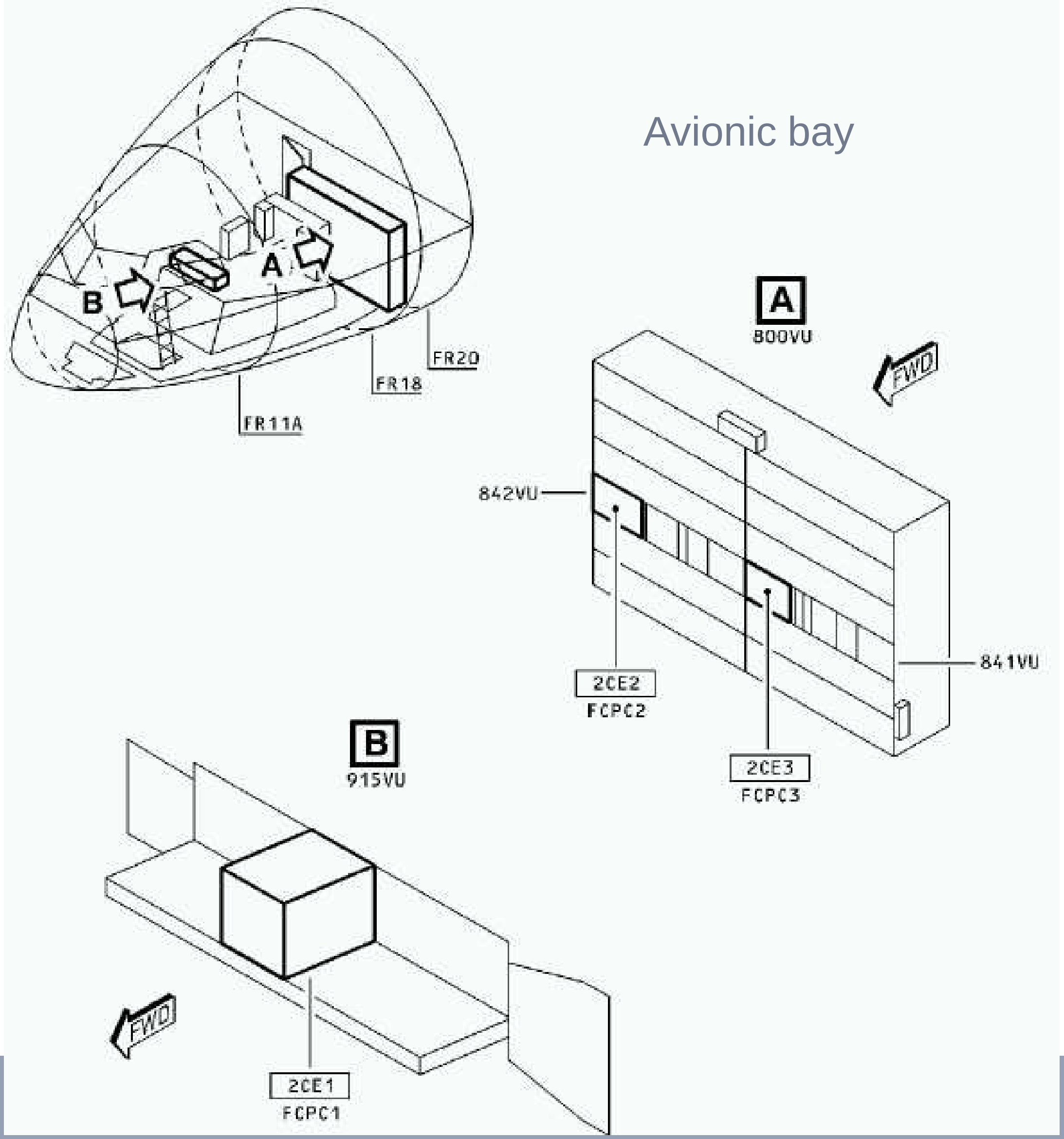
A study performed few years ago demonstrated that the business case for electrical flight control system is valid even for small and/or “basic” aircraft (weight, maintenance, …)

History : functional allocation

1 – Computers: Architecture and installation



Computers installation

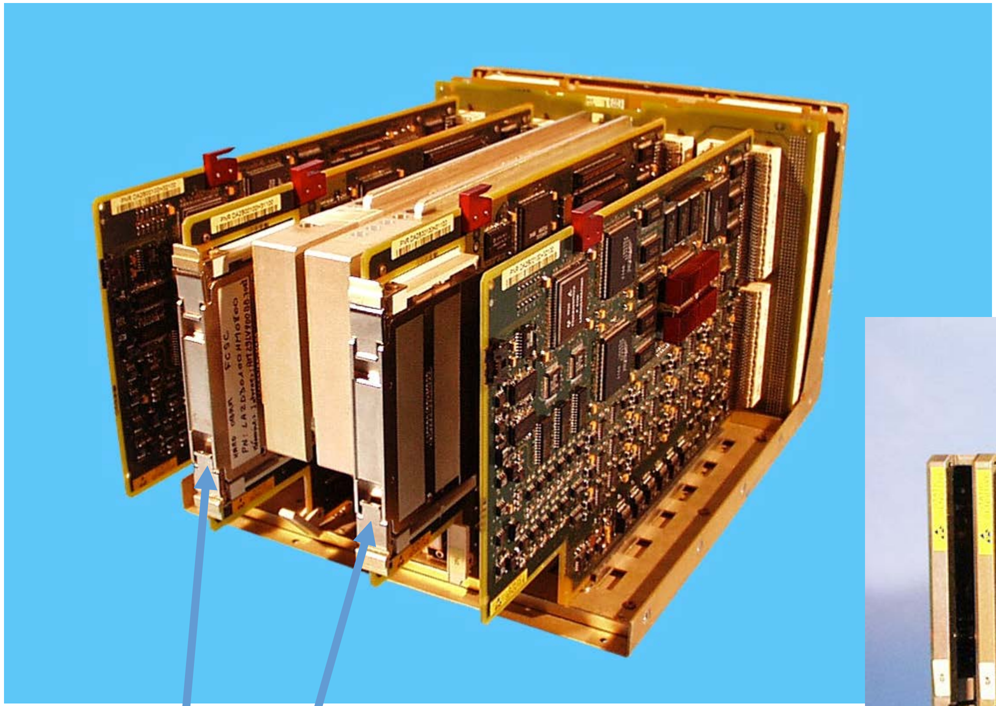


A340 computer: external view

OBRM
(On Board Removable Module)

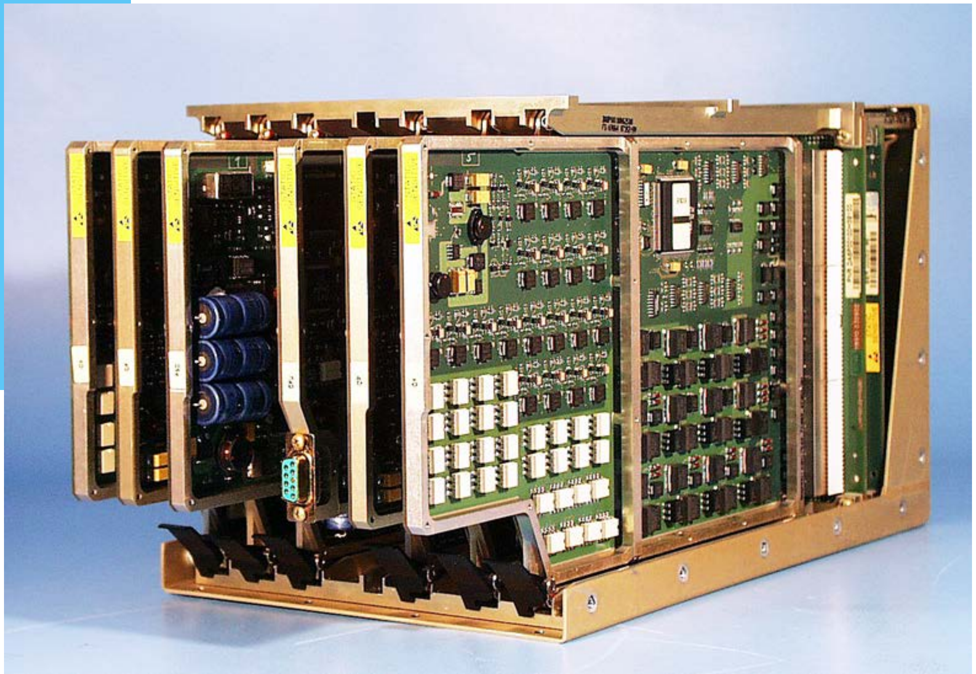
A340 computer: internal view

FCSC A340-600



OBRM
(On Board Removable
Module)

FCGU A380



Computers reconfiguration

- A single computer is the master one for a given function: e.g. left elevator control, engines control, ...

- Each computers has its own internal means:
  - to detect its own failures
  - to isolate the corresponding outputs
  - to provide its status to other computers (or functions)

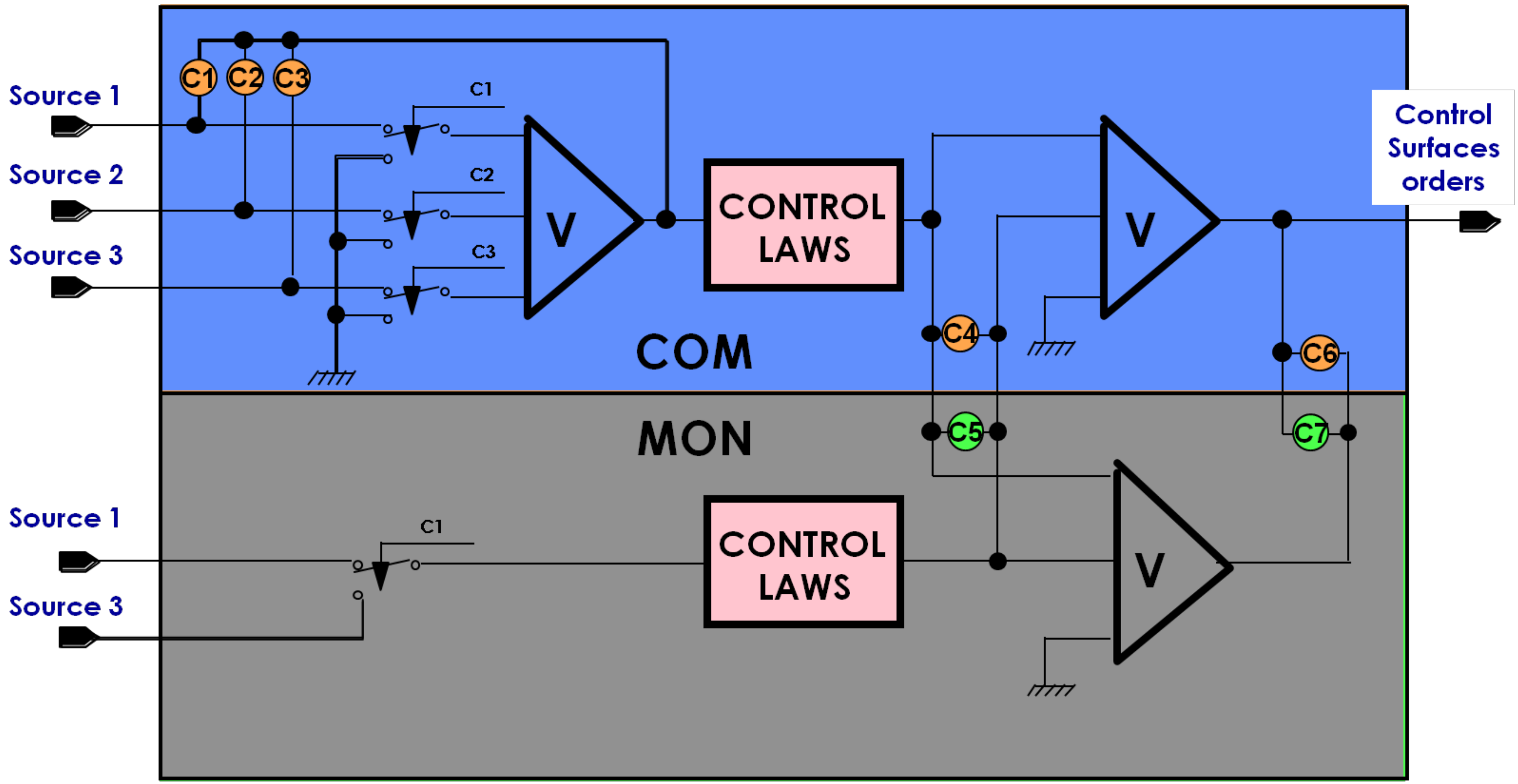
- Computers reconfiguration
  - is based on a pre defined priorities strategy for each function
  - Reconfiguration function is split between computers

- All computers perform their own computations all the time, to compare each together, and minimize "hidden failures"

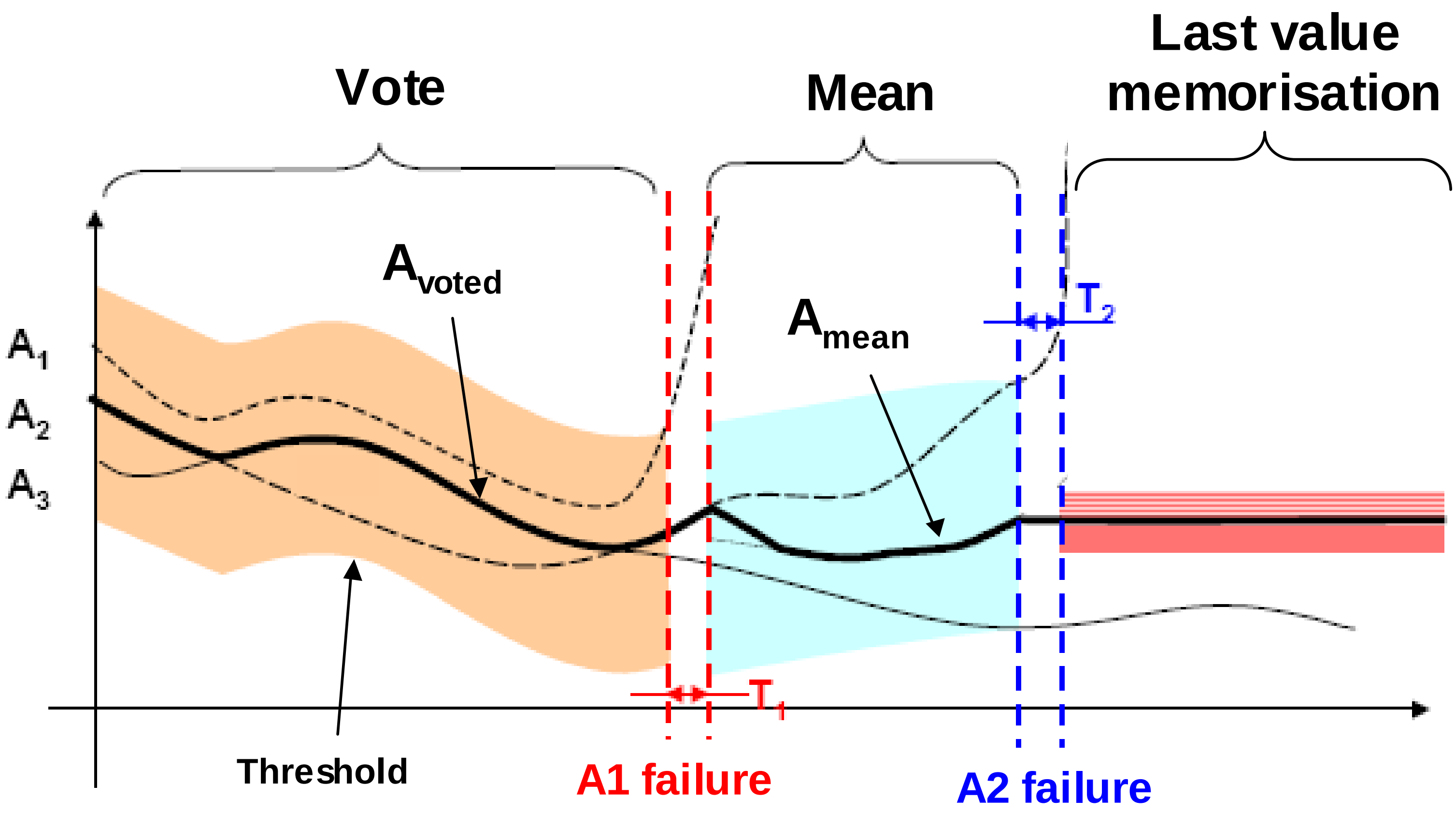
Computers: architecture and software dissimilarity

- Each computer is split in two lanes: Command and Monitor
- COM et MON lanes both compute the same outputs (like surfaces desired position...), and COM lane sends the order to the actuators
- If an offset occurs between the 2 lanes, computers outputs are automatically inhibited, and status is provided to other computers
- COM and MON lanes (within a given computer) use the same hardware BUT software are different (“software dissimilarity“)
- This architecture is designed to guarantee that an undetected erroneous output leading to catastrophic effects is extremely improbable (probability <10-9/h)

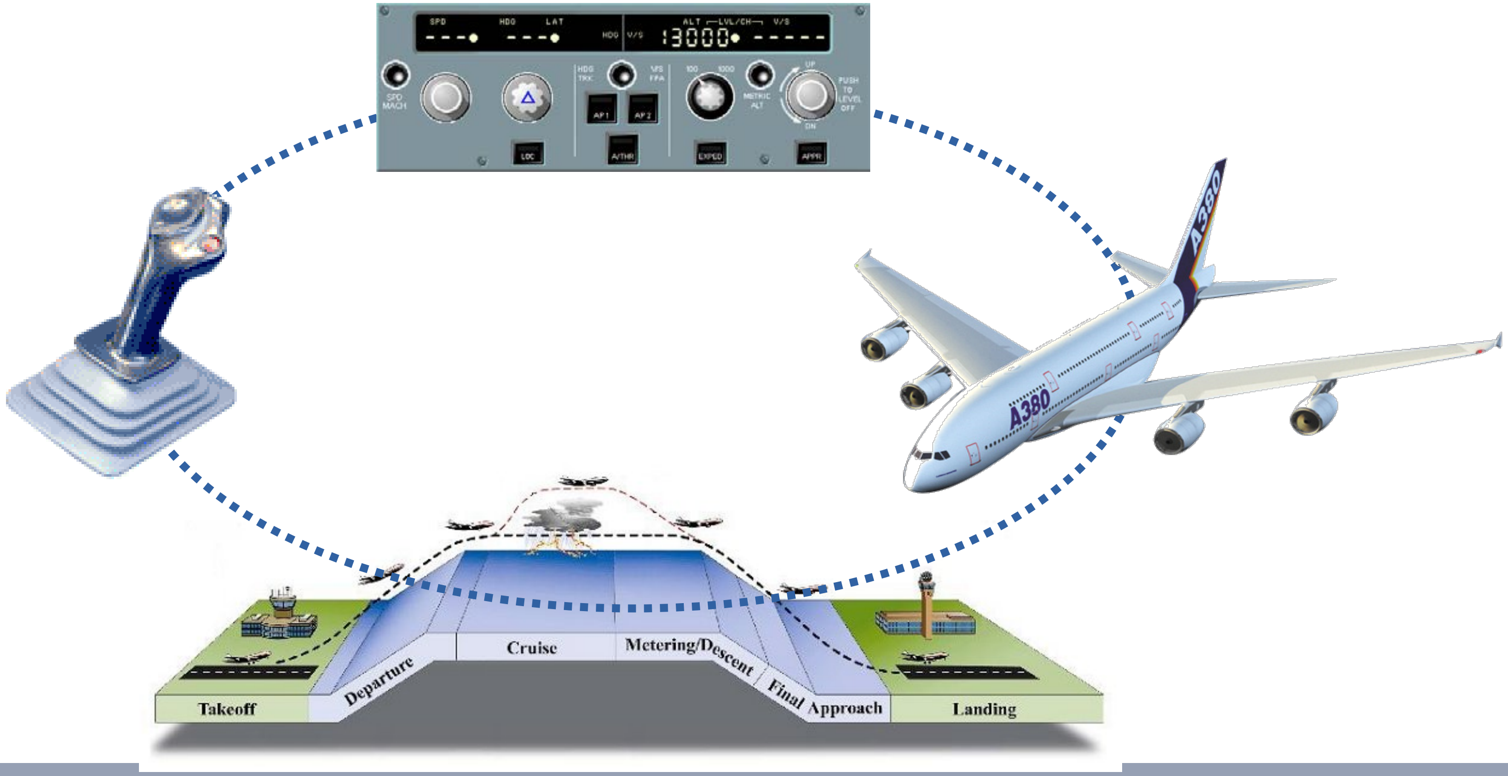
Computers: architecture and software dissimilarity



Example of an internal monitoring: a voter-based design

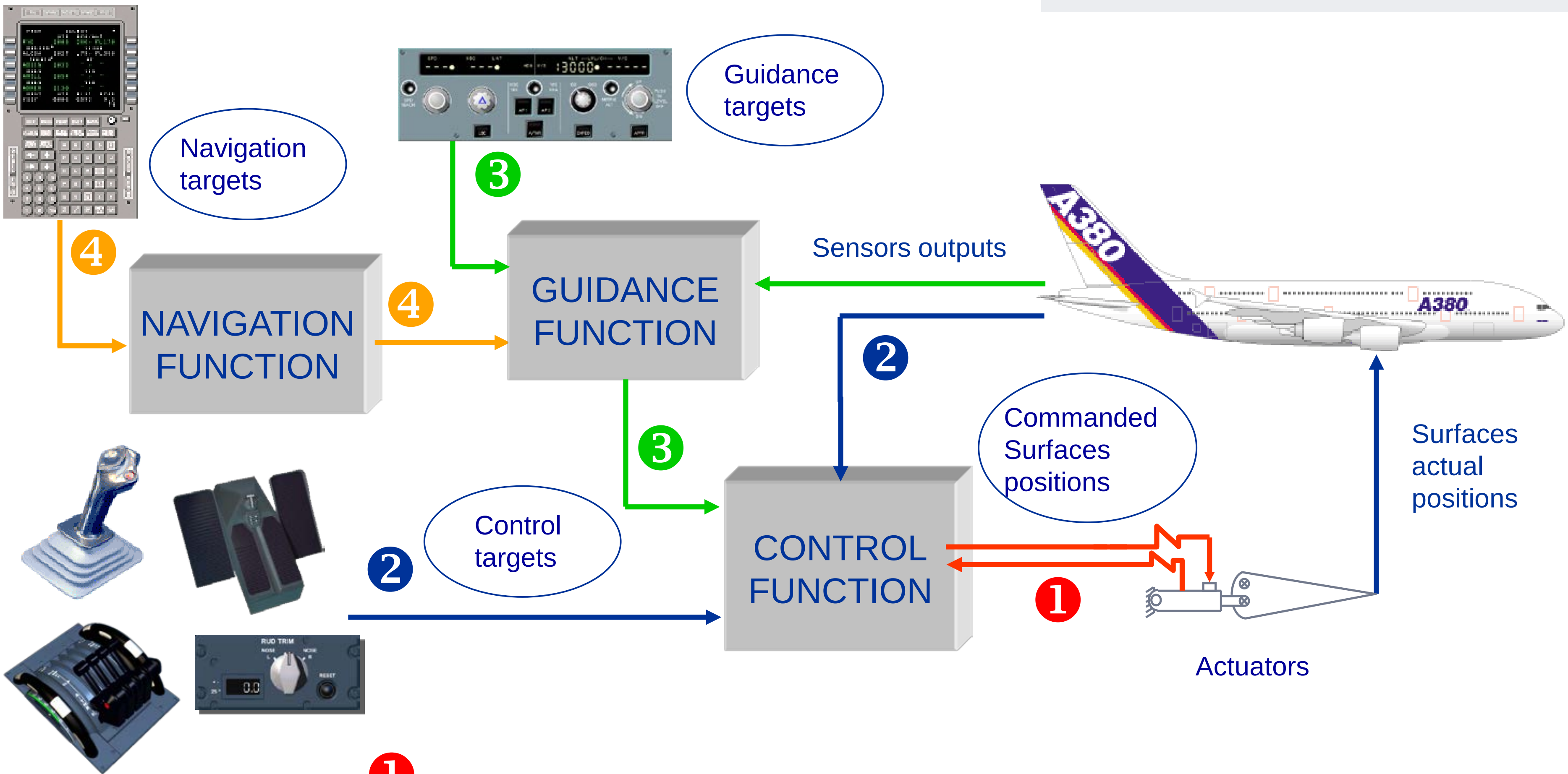


2 – Flight Control laws: keys principles



Guidance Navigation Control (GNC) loop

Important



1 = Actuators position control loop

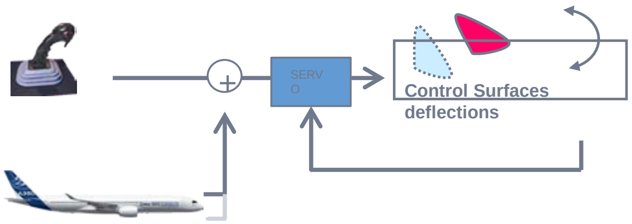
2 = Control loop: short term management (attitudes & accelerations control)

3 = Guidance loop: mid term management (trajectories, speed...)

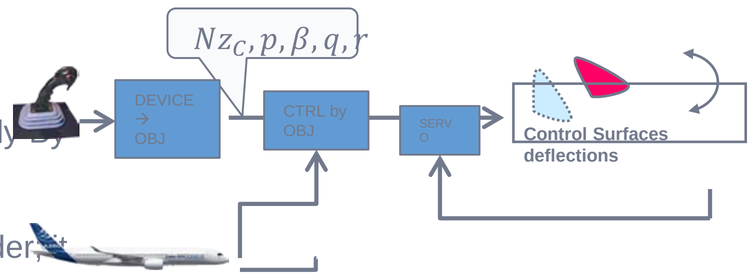
4 = Navigation loop : long term management (flight plan tracking)

BASIC DEFINITION OF A FLIGHT CONTROL LAW

- A flight control law is a system that brings a technical aid to the pilot, to reduce and/or simplify his workload.
  - As soon as the link between the control device and the actuator is more complex than a cable tie, we talk about a flight control law



- « real » direct law: direct link (cable or electric) between stick and surface deflection, or surface actuator.
- Actuators have their own control law, not considered in our definition
- Direct law: some damping feedbacks are usually added to the pilot order to damp (‘to smooth’) the aircraft behaviour (addition can be mechanical or digital)



- Advanced control law: several feedbacks modify the pilot order: damping ratio and frequency of the aircraft motion are shaped. (Fly By Wire opportunity)
- Control law by objective: the pilot input is no more a deflection order, it is translated into an objective, given to the control law, that calculates the deflection order to fulfill the objective.
  - Homogeneity – robustness – stability margins - sizing criteria

Objectives & Constraints

- **Objectives**
  - “Safety first”
  - Improve natural A/C handling qualities (for flight & ground)
  - Keep an intuitive aircraft handling
  - Decrease pilot workload
  - Fly in good comfort conditions
  - Allow a high maneuverability (by dynamic actions on control device), but without flying out of the safe flight envelope

- **Constraints**
  - Actuators capabilities (deflection rate, wear, fatigue cycles…)
  - Structural limits
  - Structural flexible modes (for comfort issues)
  - Human factors, HMI design rules (“situation awareness”…)
  - Continuity between “normal laws” and “degraded laws”

Control loop principles (1/2)

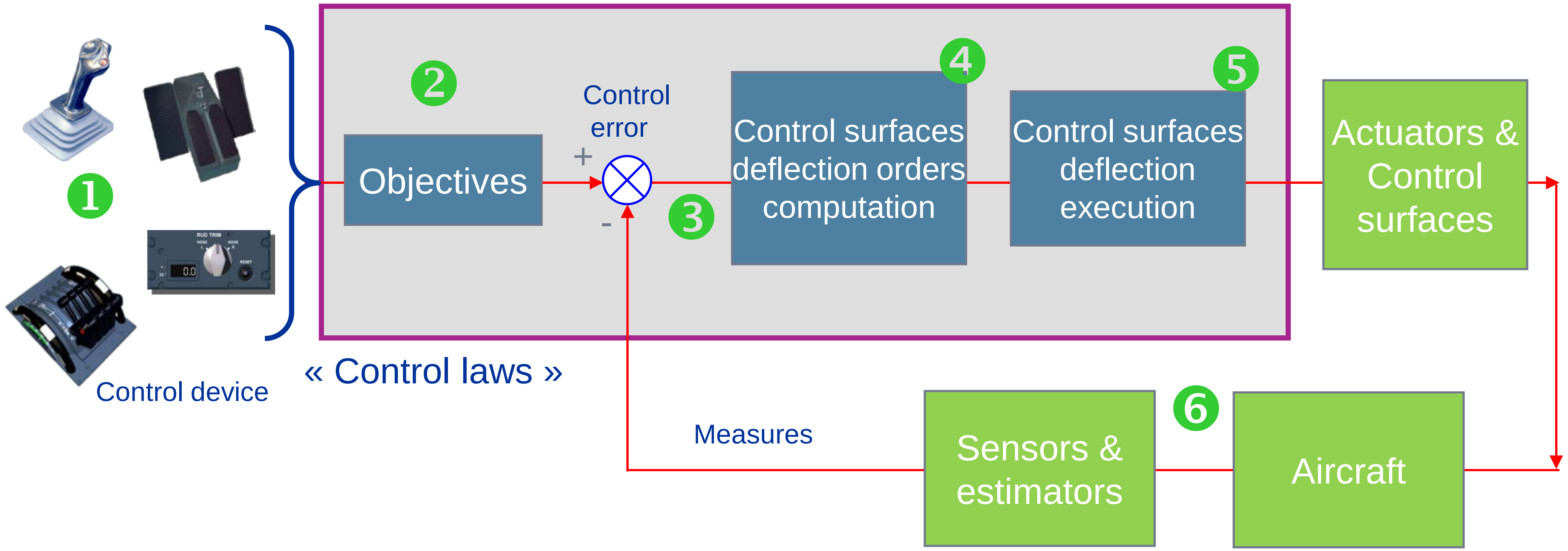
- Sidestick and pedals orders (measured by position sensors) and converted into flight control targets.
- These targets are then compared to aircraft current state (measured by inertial sensors, anemometric sensors…) to compute control surfaces position orders
- Target level:

Designation	Loop	Goal
Autopilot (“outer loop”)	Guidance loop	control targets provider
Flight Control Laws (“inner loop”)	Control loop	control targets capture & tracking

NB: On ground, control laws are generally “direct laws”: control surfaces deflections are “nearly” proportional to stick (or pedals) deflection

Control loop principles (2/2)

Important



time

1. Pilots deflects a control device
2. Pilot action is converted into a « high level » objective
3. Objective and actual measure are compared
4. Control Laws computes desired actuators positions
5. Control surfaces set to these desired positions
6. a/c moves, and motion is observed by sensors

Static stability

- For longitudinal control, stick deflection corresponds to a vertical load factor demand
  When the desired flight path is reached, the pilot releases the stick
  Then the flight path is kept constant (stick free)

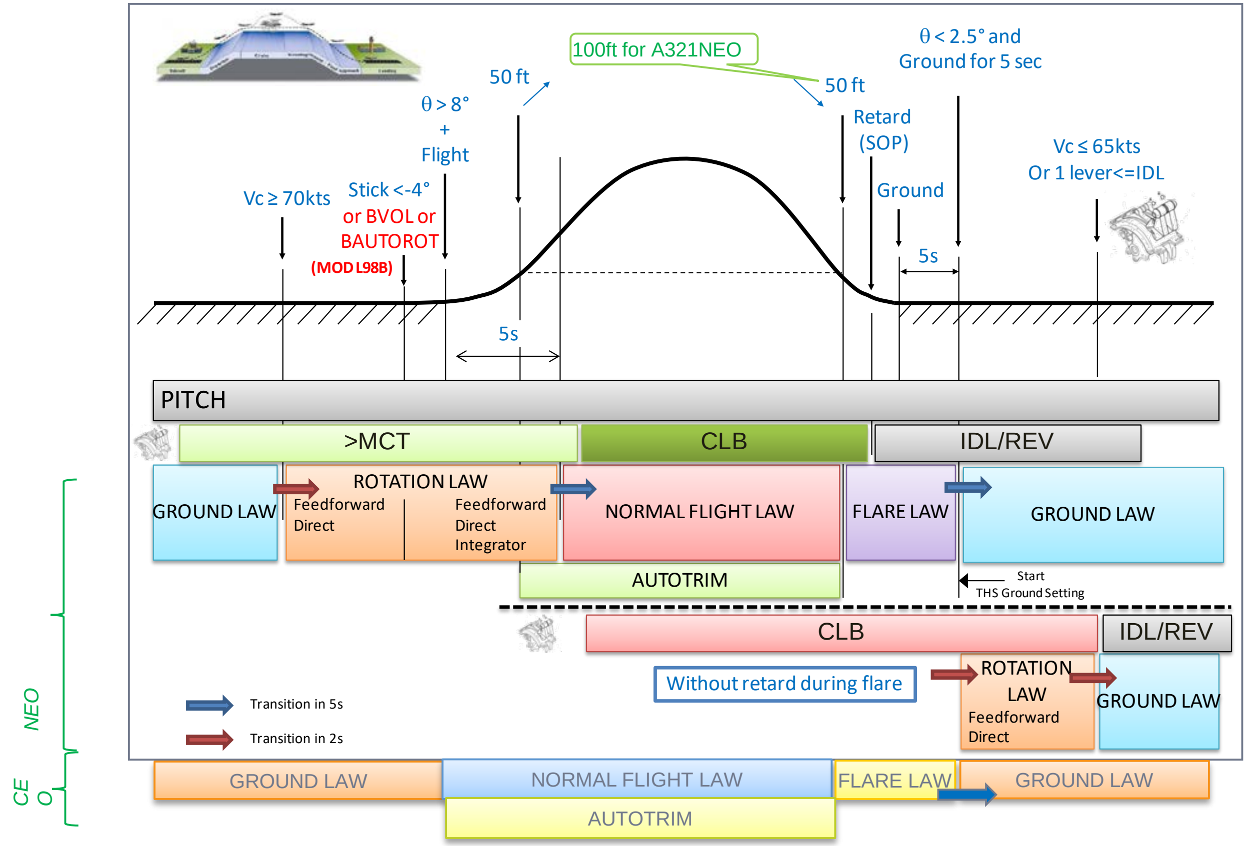
- For lateral control, a stick deflection in roll generates a bank angle variation demand (phi dot)
  When the desired bank angle is reached, the pilot releases the stick
  Then the bank angle is kept constant (stick free)

- This feature is called the “neutral static stability”

- So we can say that piloting is based on “pulses on the stick”
  This principle is intuitive, and reduces pilot workload.

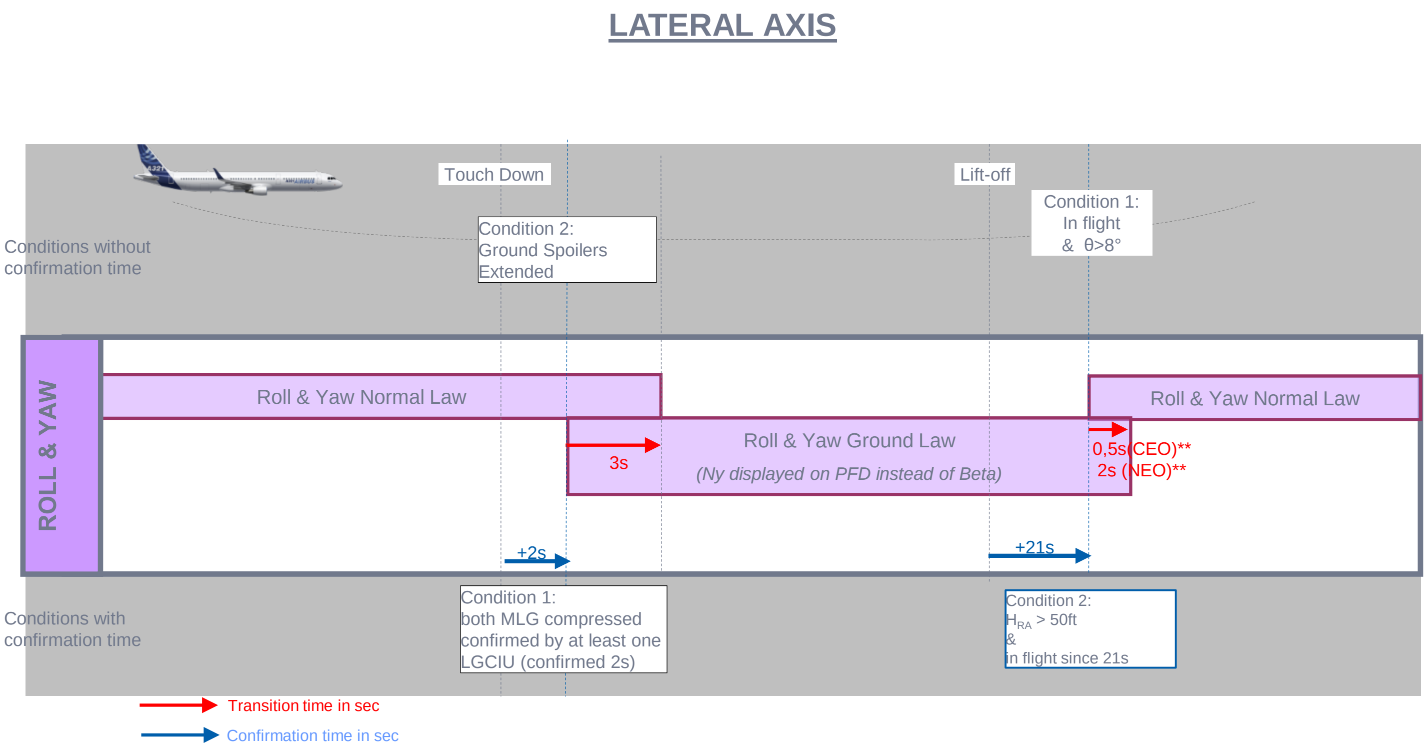
Recall of longitudinal control laws and transitions

- Extract of FCLD



Recall of lateral control laws and transitions

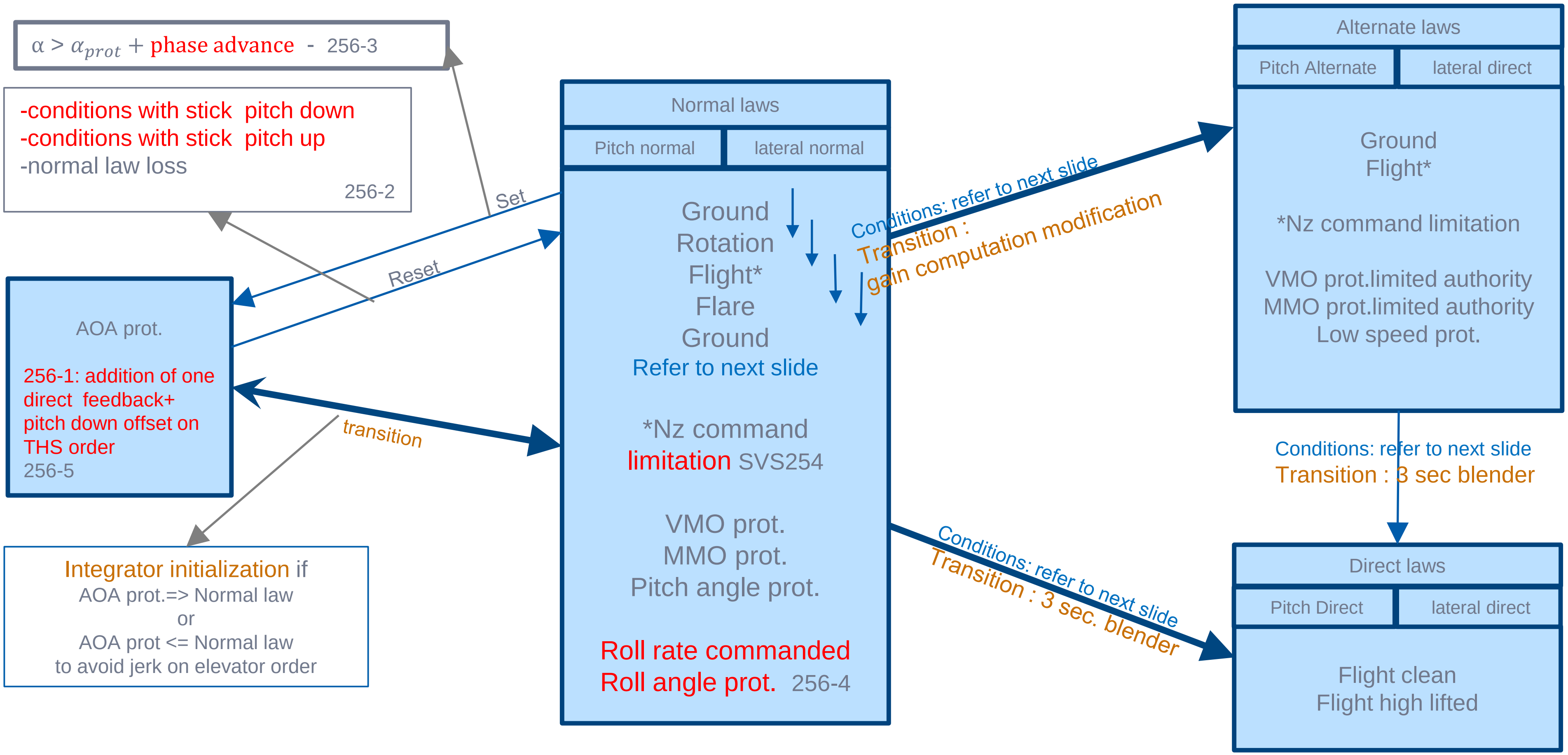
- Extract of the FCLD



(**) except for pedal induced roll order in normal law, which is introduced in 5s in NEO and in 0.5s in CEO

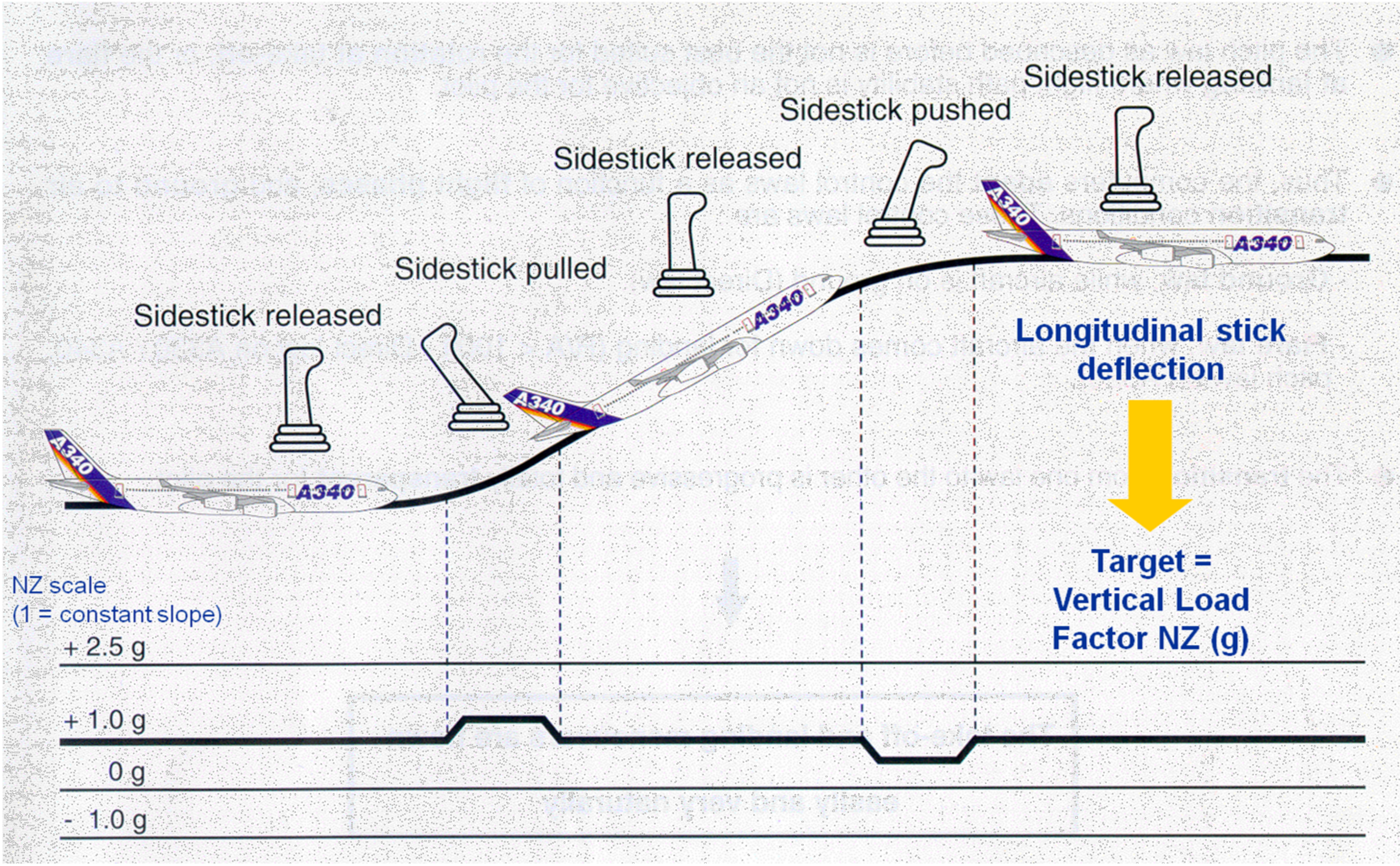
Manual mode – possible F/CTL laws modes and transitions

A319neo modifications in red



- Longitudinal control

A “pulse-based” control...



NZ LAW

- From a pilot point of view, C* offers
  - An homogeneous response
  - A good pitch attitude stability
  - An aircraft permanently in trim

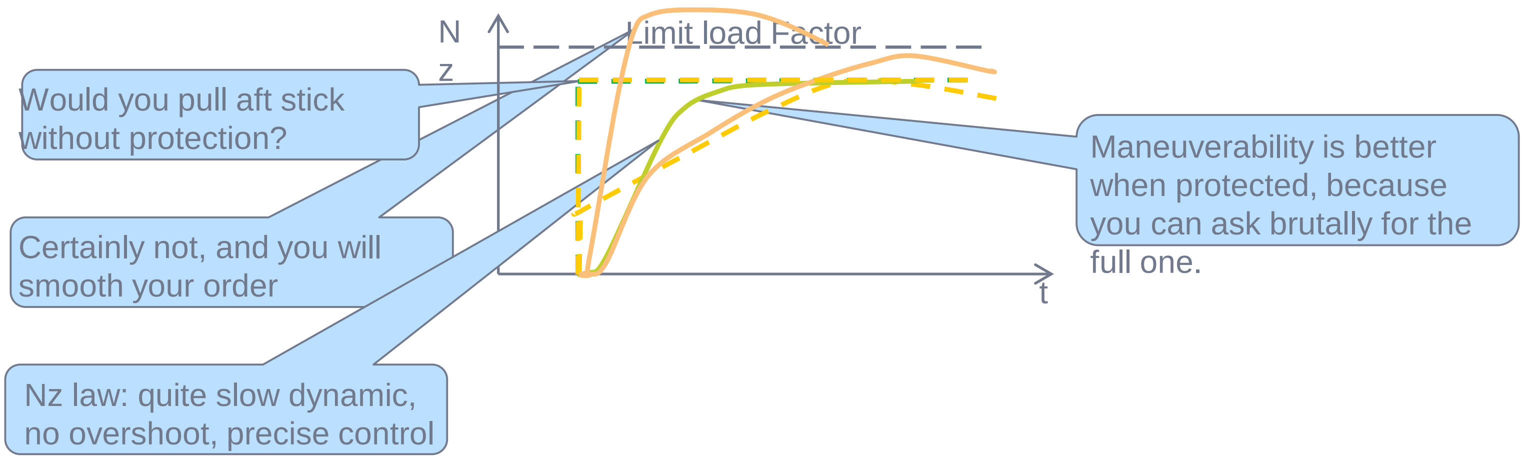
- C* is used on all Airbus Fly By Wire aircraft

- Boeing introduced C* on Boeing 777 and called it C*U
  - They added a feedback term as a function of the speed error between actual speed and a reference speed adjusted by the usual trim switches
  - By doing such, C*U provides artificial positive longitudinal static stability; B777 has to be re-trimmed like a conventionally controlled aircraft

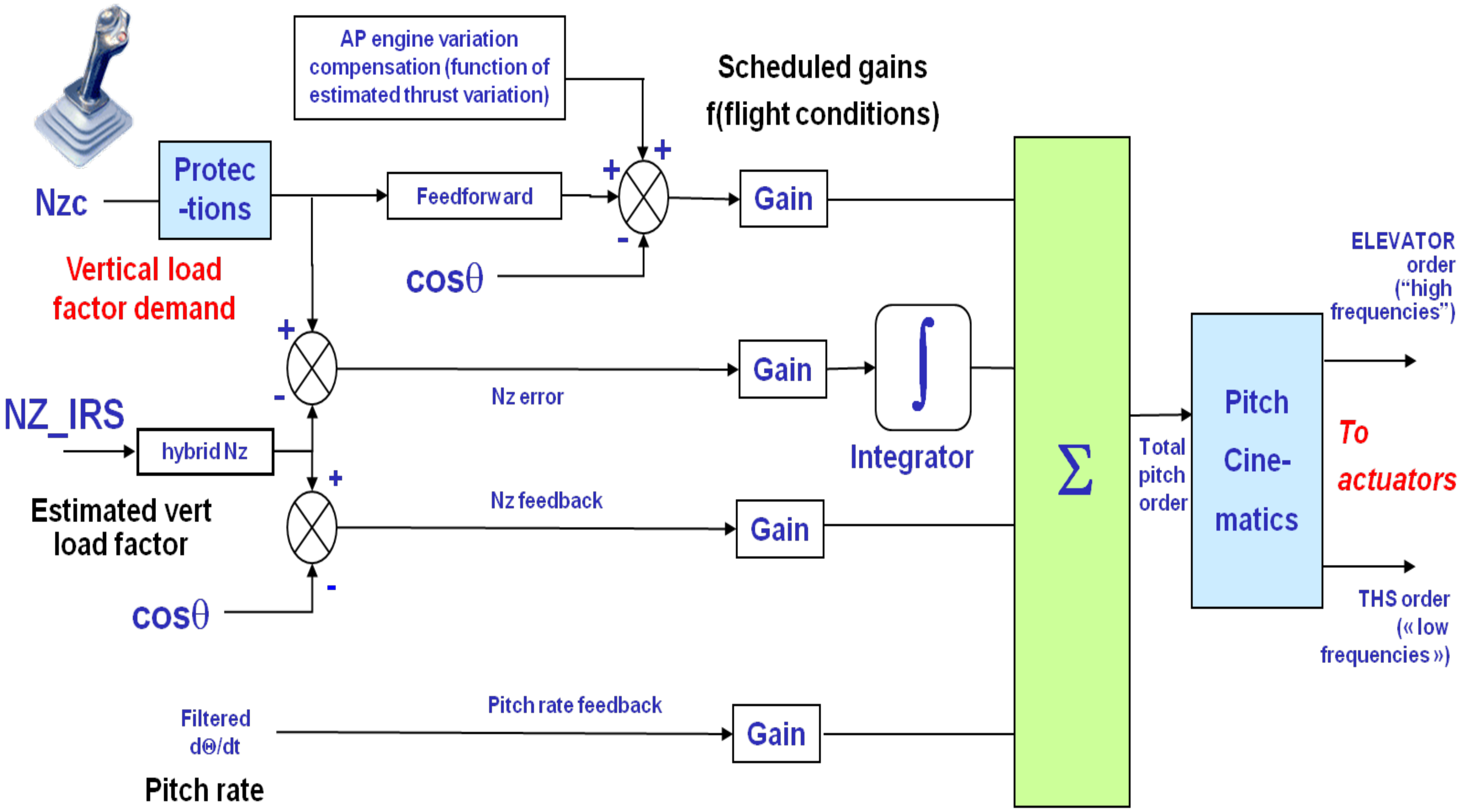
NZ LAW

- Maximum Vertical load factor sizes the structure:
  - ❑ $2{,}5/-1{,}0g$ in conf clean. Because $Nz_c < 0g$ in the cabin means “flying objects”, the $-1g$ load factor command needs to be confirmed by prolonged full nose down stick deflection
  - ❑ $2{,}0/0{,}0g$ in high lift configurations.

- Protections (Nz, α) gives confidence to the pilot to pull full aft stick instantaneously if needed. (AIRBUS philosophy since beginnings)



Longitudinal normal law architecture

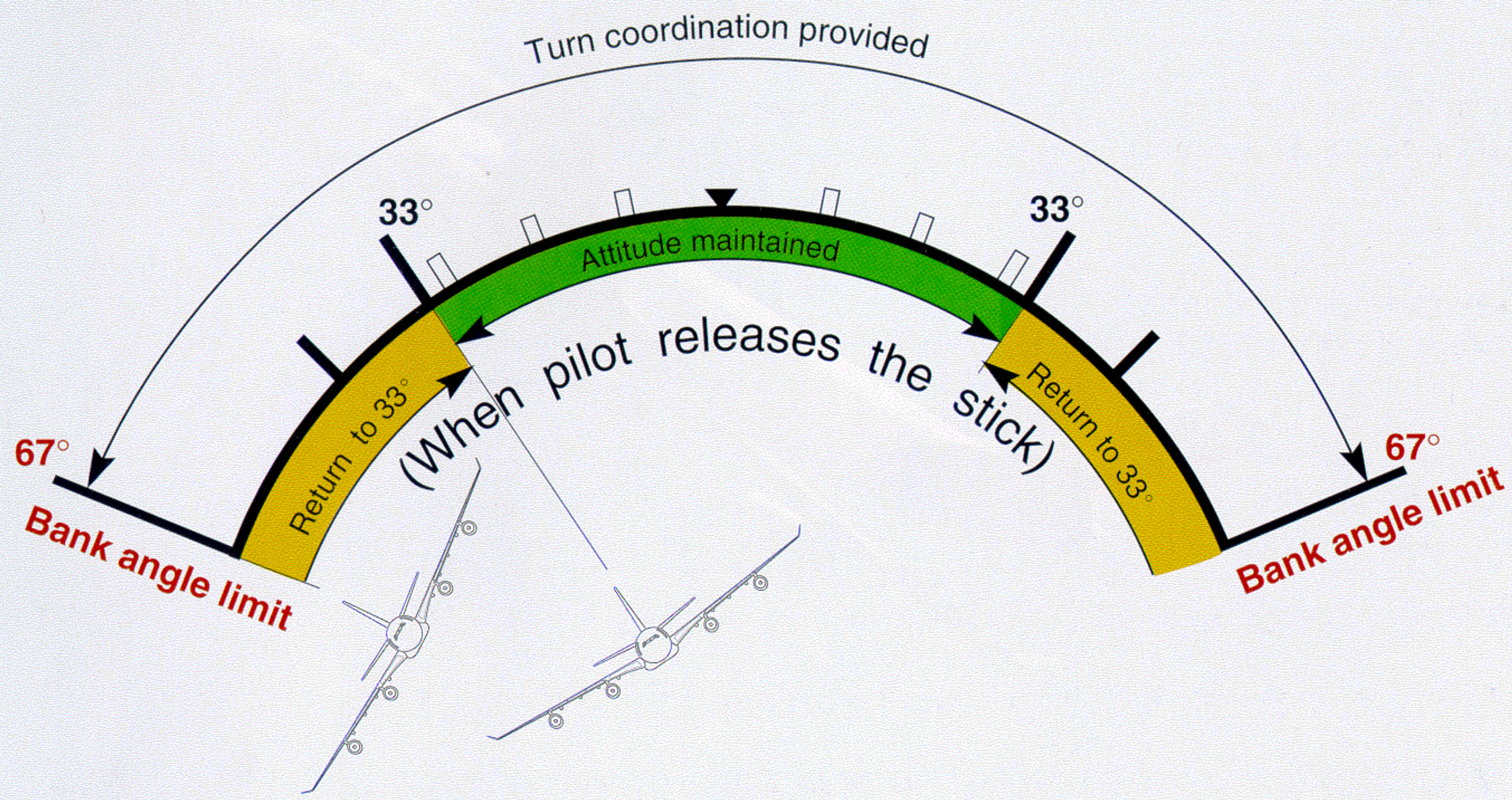


- Lateral control

Lateral control main features (1/2)

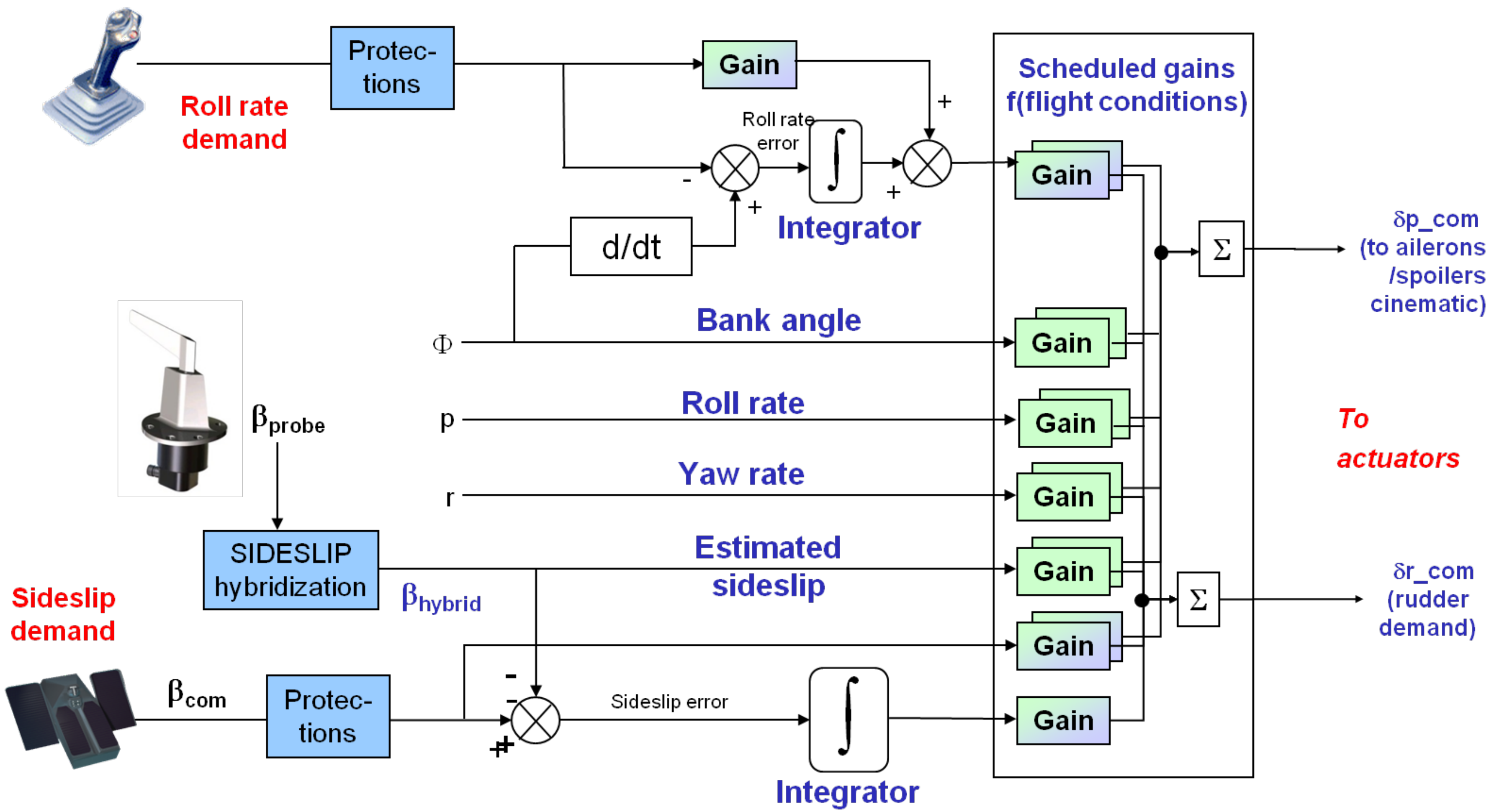
- Lateral control law is based on:
  - 2 control device: Stick & Pedals order
  - 2 control surfaces : Roll surfaces & rudder deflection.
- Spiral stability:
  - is neutral if bank angle remains lower than 33°
  - is positive if bank angle exceeds 33°
- The bank angle is limited to 66°
- Stick deflection generates a roll rate order (limited to 15°/sec) with a minimized sideslip (turn coordination).
- Pedals inputs generate a sideslip order (so pedals free = null sideslip)
  - To emulate a conventional aircraft, a light roll rate order is generally applied when a sideslip is commanded (to reproduce the dihedral effect)
- The lateral normal law damps the dutch roll mode

Lateral control main features (2/2)



If the aircraft exceeds the normal bank flight envelope, the pilot is immediately aware.

Lateral normal law architecture

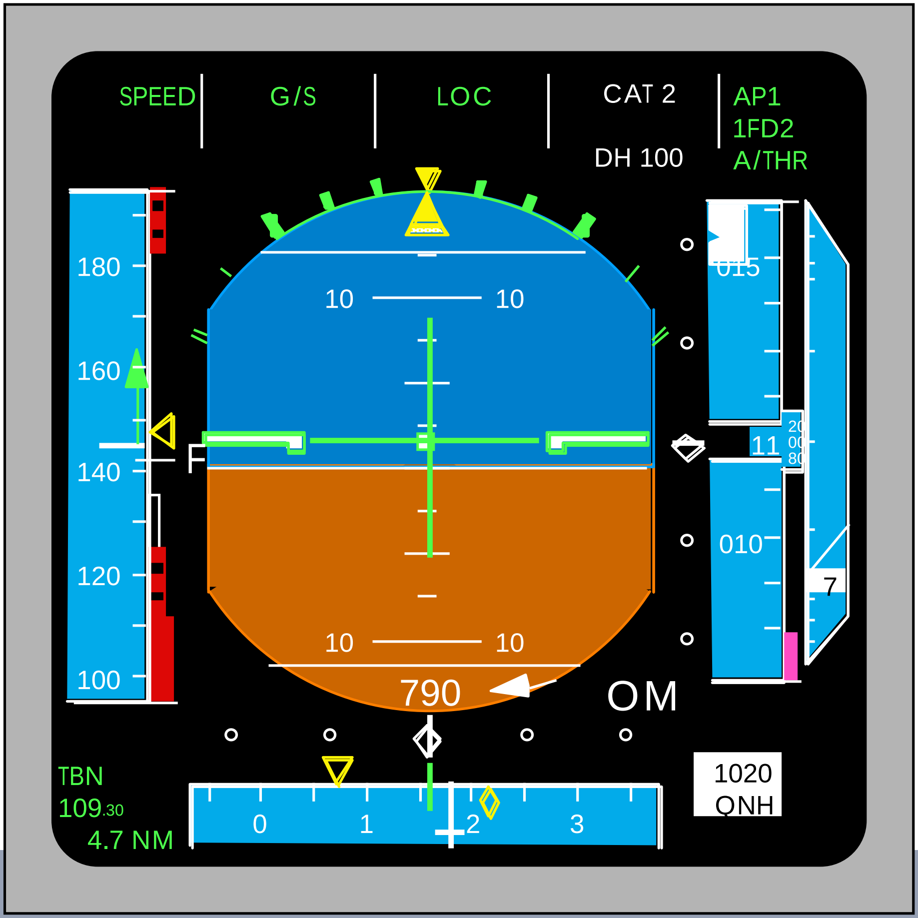


Engine Out case

- Short term aircraft response:
  - Engine failure is compensated by the lateral normal law: without pilot action, bank angle and sideslip variations are quite reduced, but still present. So they are sufficiently alerting for pilots, and close to short term conventional a/c response.
  - Heading moves slowly.

- Long term aircraft response :
  - The goal is to trim the aircraft so that performance penalty is minimized. So the steady state to be reached corresponds to minimum roll deflection (critical for take off or go around manoeuvres):
  - The sideslip corresponding to Engine Out + Null roll spoilers deflection is computed offline (from trimmed models).
  - This value ("Beta Target") is tracked either by the pilot (following a visual indicator on PFD), or automatically (A350).

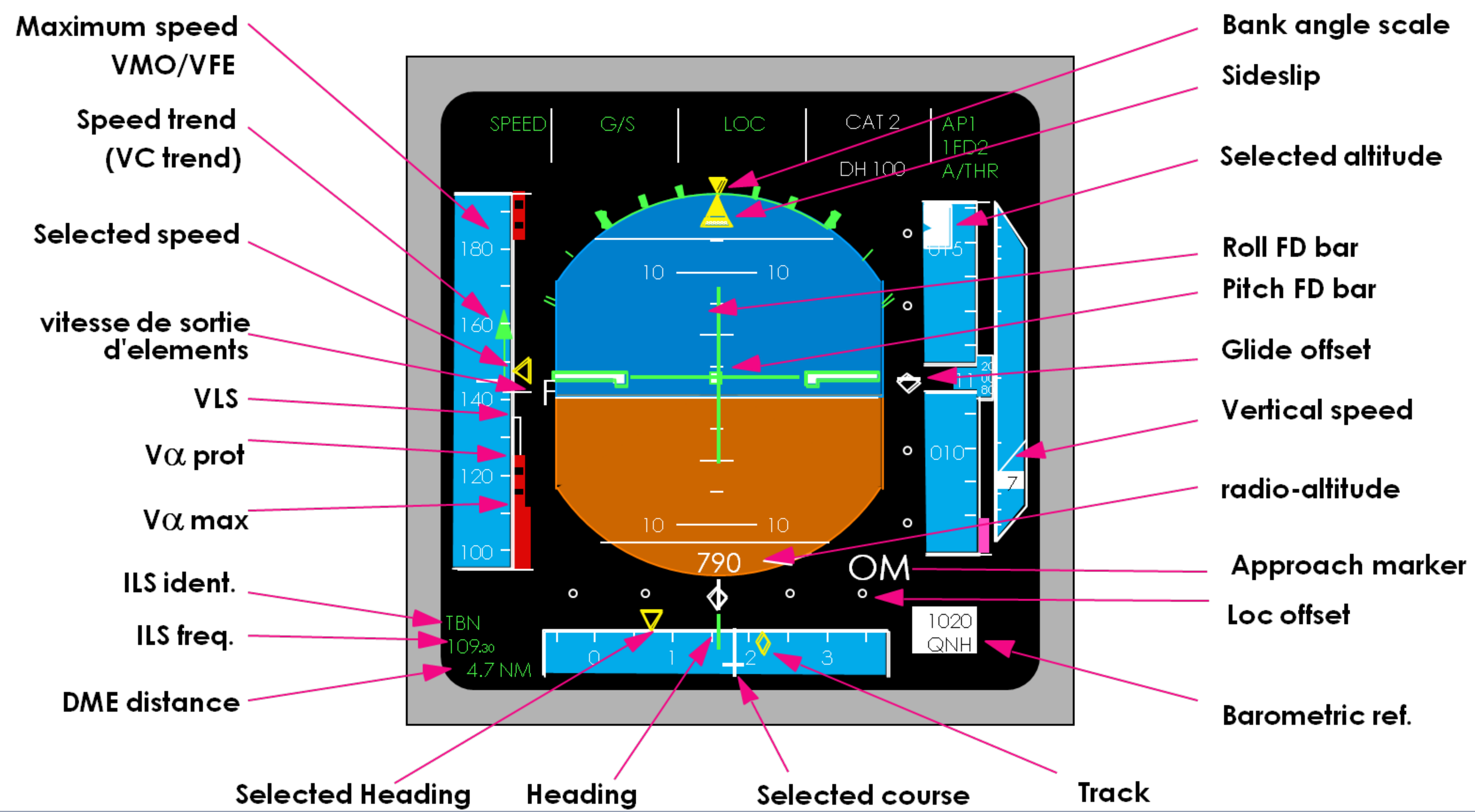
3 – Displays


SPEED
G/S
LOC
CAT 2
DH 100
AP1
1FD2
A/THR
180
160
140
120
100
F
10
10
10
10
790
OM
015
010
11
7
TBN
109.30
4.7 NM
0
1
2
3
1020
QNH

Important

Displays (1/2)

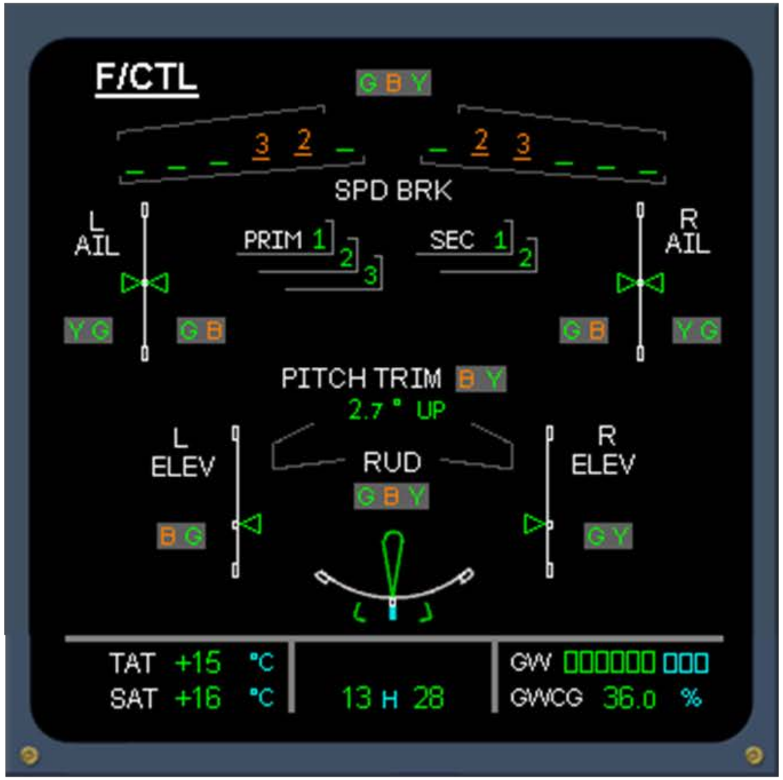
PFD (Primary Flight Display)



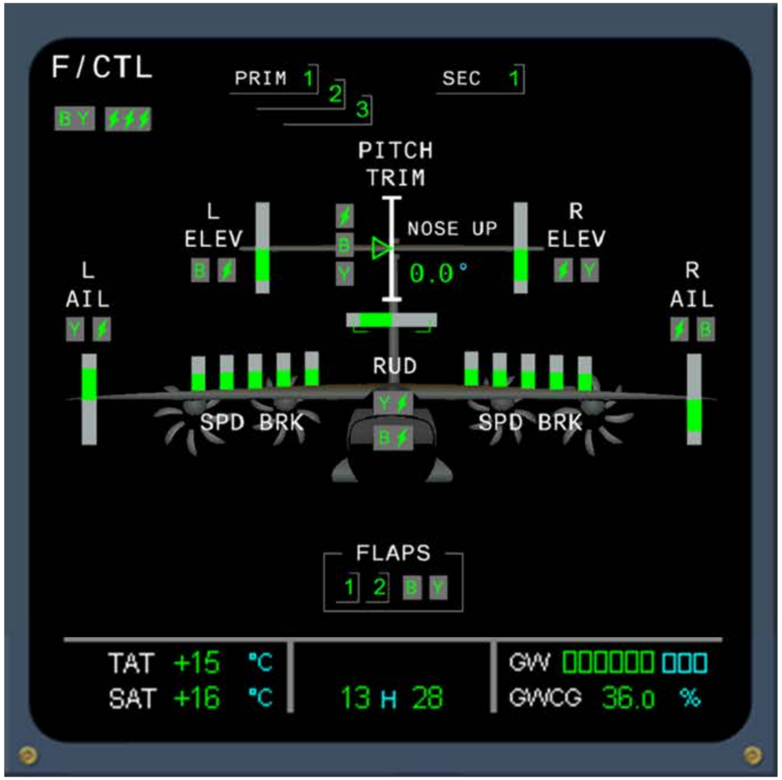
Displays (2/2)

SD (Systems Display): « Flight Controls Page »

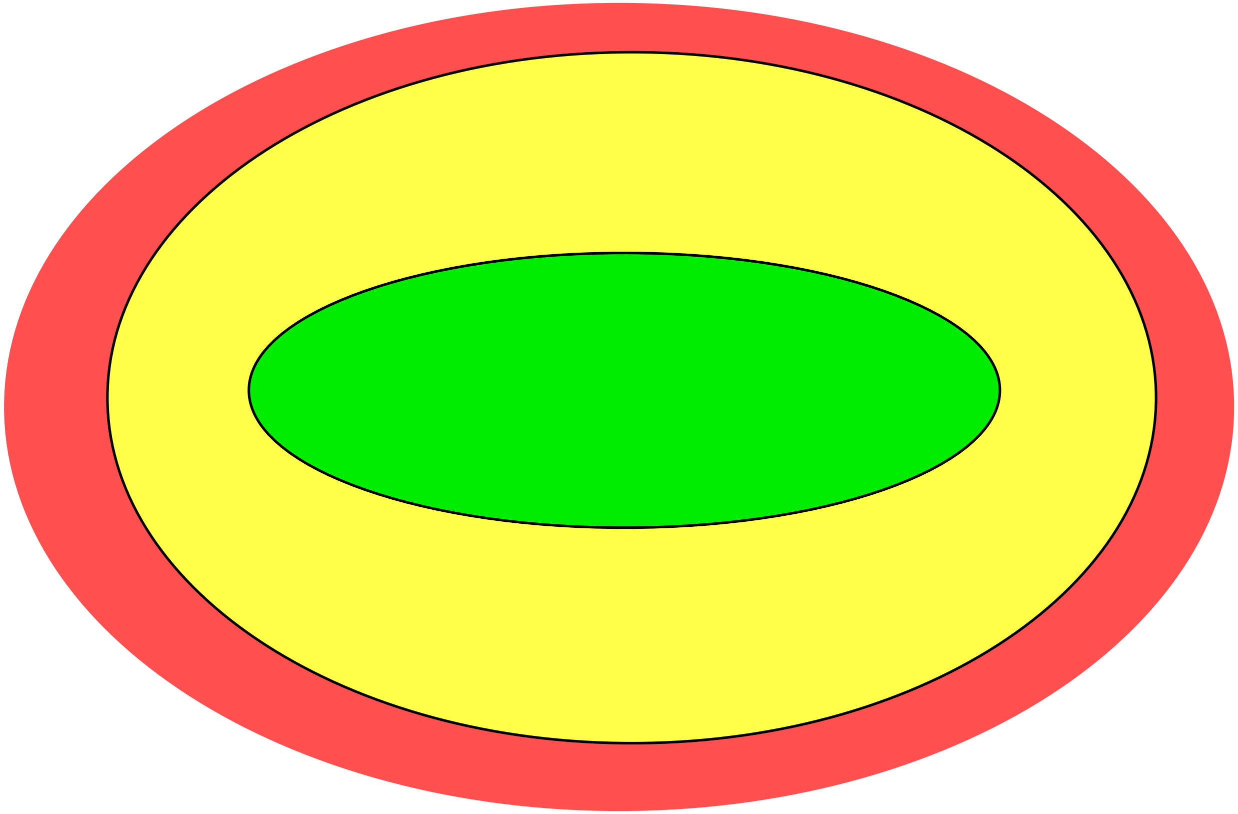
A330



A400M



4 – Protection laws & Flight envelopes

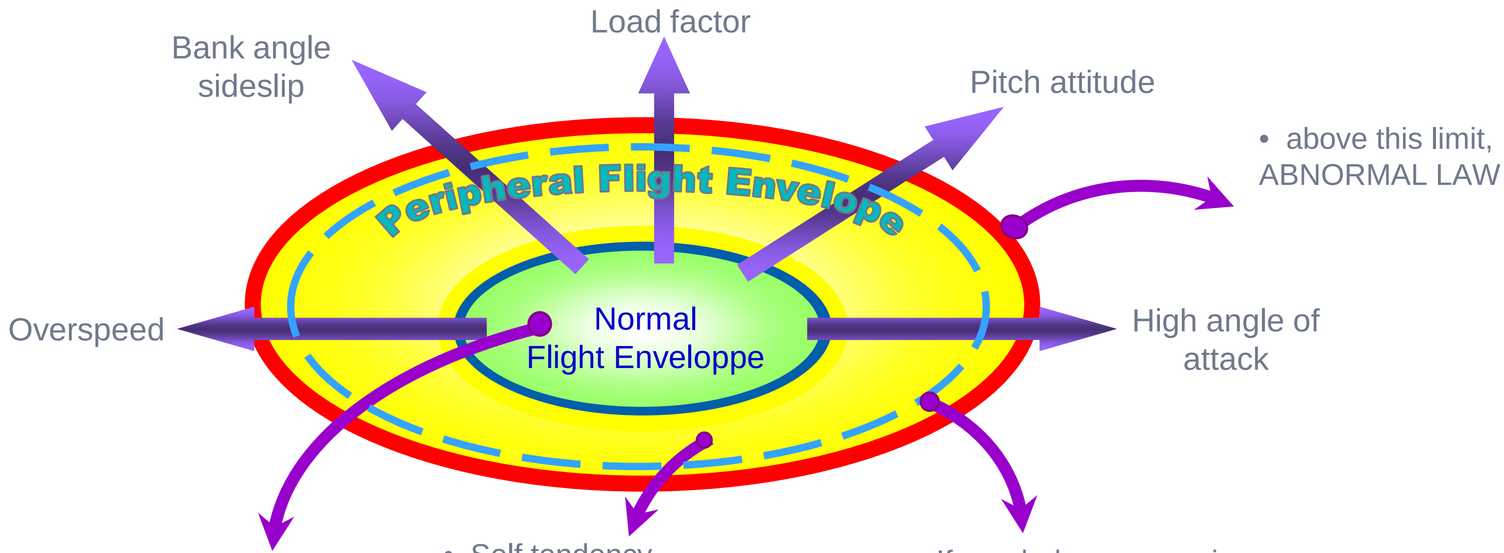


WHY NORMAL PROTECTIONS ?

- The best level, available in nominal conditions. AP available. all protections available

- Loss of control is still responsible for accidents/serious incidents
  - May result from
    - stall
    - spin (combination of excessive incidence/excessive sideslip)
    - overspeed (flutter)
    - overstress
    - excessive bank
  - But fear of loss of control may also cause accidents
    - Controlled Flight Into Terrain (CFIT)
    - mid-air collision
    - loss of control from one parameter by fear of loss of control from another parameter
  - Objective of Flight Envelope Protections is double
    - protect against loss of control by providing more robustness towards either crew mishandling/errors or even lack of awareness/ monitoring of flight parameters
    - Increase crew confidence in exceptional circumstances by providing instant access to enhanced escape manoeuvres.

NORMAL CONTROL LAWS



- Instinctive piloting
- Facilitated technique
- Reduced workload
- Better trajectory
control

- Self tendency
  to return to normal
  Flight envelope
- Flight possible but indicated
  by permanent forces
- Error tolerance and improved
  situation awareness

- If needed, maneuvering
  possible at this safe limit
  with control on the stops

•Easy, quick, reproducible

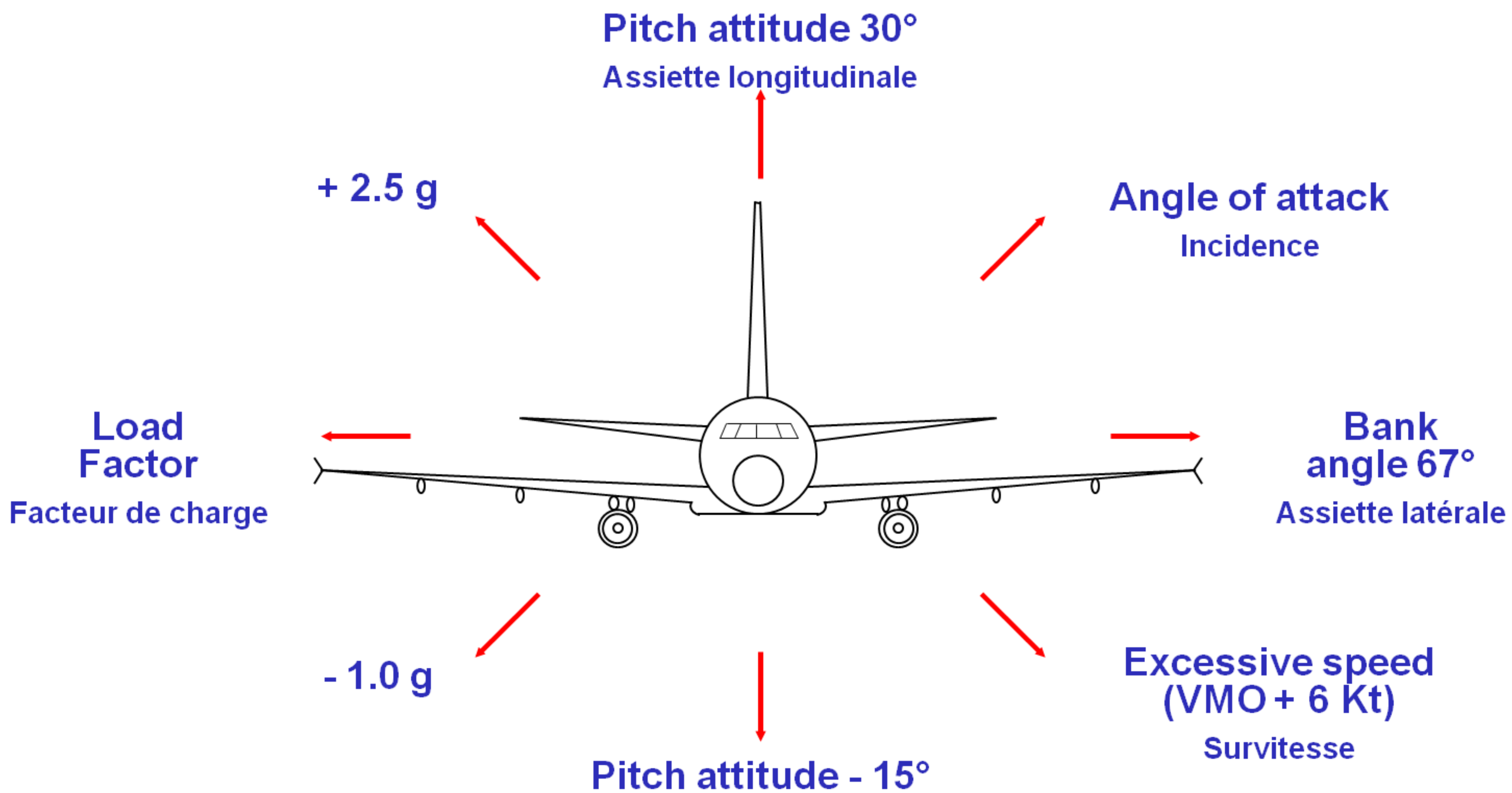
HARD/SOFT PROTECTIONS

- Definition :
  - hard protections **(AIRBUS PHILOSOPHY)** : with pilot controls on their stop, flight parameters will be limited to a safe value ; bigger values are never available.
  - soft protections **(BOEING PHILOSOPHY** until 787**)** : with pilot controls on their stops, flight parameters are authorized to penetrate into the ‘loss of control’ domain ; the pilot is deterred to do so by appropriately scheduled non-linearities in the force feedbacks.
- Stakes :
  - hard protection must not runaway (needs architecture precautions)
  - hard protection must carefully set the margin between the limit of the protection and the limit of the dangerous domain
  - soft protection relies on “deterrent” force levels which are questionable in stress situations
  - soft protection does not provide the confidence to order full devices deflection.

Flight Envelope Protections (1/2)

- Objective :
  - Allow a maximum manoeuvrability in the whole flight envelope
  - but prevent the pilot from flying out of the safe flight envelope or perform a quick return to flight envelope if aircraft goes out.
- Load factor protection : Protection built–in in longitudinal normal law.
- High Speed protection : Beyond a threshold, (VMO + 6 Kts) speed is limited to VMO + 16 Kts (full forward stick)
- AoA protection :Beyond a threshold (alpha prot), a dedicated protection law prevents from overshooting Alpha max.
- Pitch attitude protection : Helps AoA protection. Protects from up and down pitch attitudes
- Bank angle protection : Protection built–in in lateral normal law.

Flight Envelope Protections (2/2)



HIGH ANGLE OF ATTACK PROTECTION

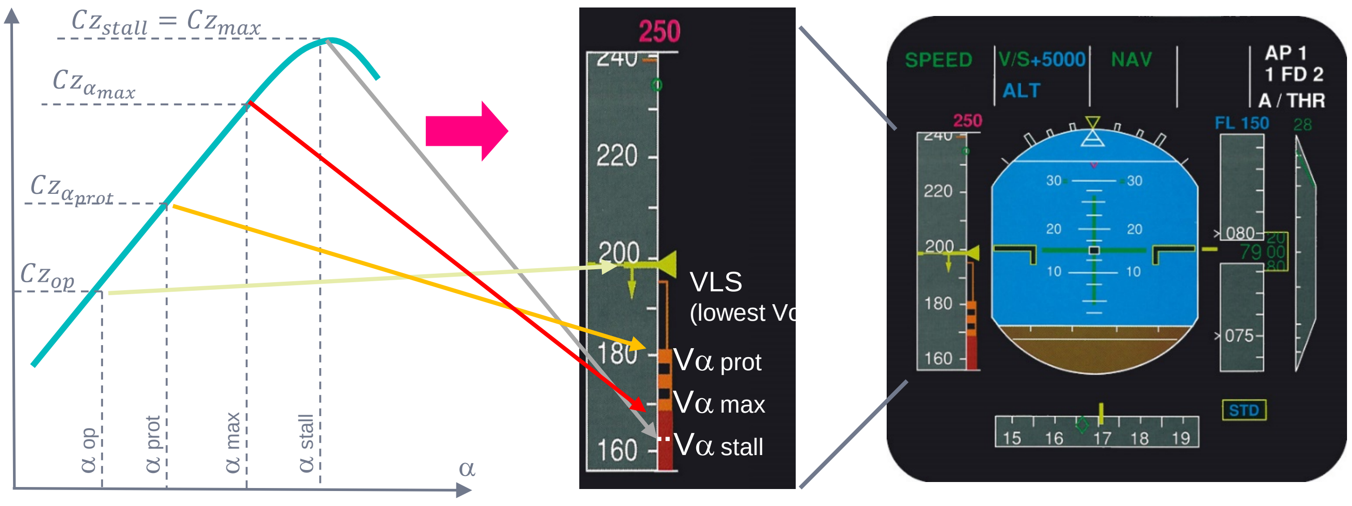
- PFD Speeds Indication:

$$Nz.weight = \frac{1}{2}\rho S V^2 Cz_\alpha(\alpha - \alpha_0)$$

Then ,we have dynamically $\frac{1}{2}\rho S V^2 Cz_\alpha(\alpha - \alpha_0) = \frac{1}{2}\rho S V_{max}^2 Cz_\alpha(\alpha_{max} - \alpha_0)$

and:

$$V_{max/prot} = \boxed{V\sqrt{\frac{\alpha - \alpha_0}{\alpha_{max/prot} - \alpha_0}}}$$



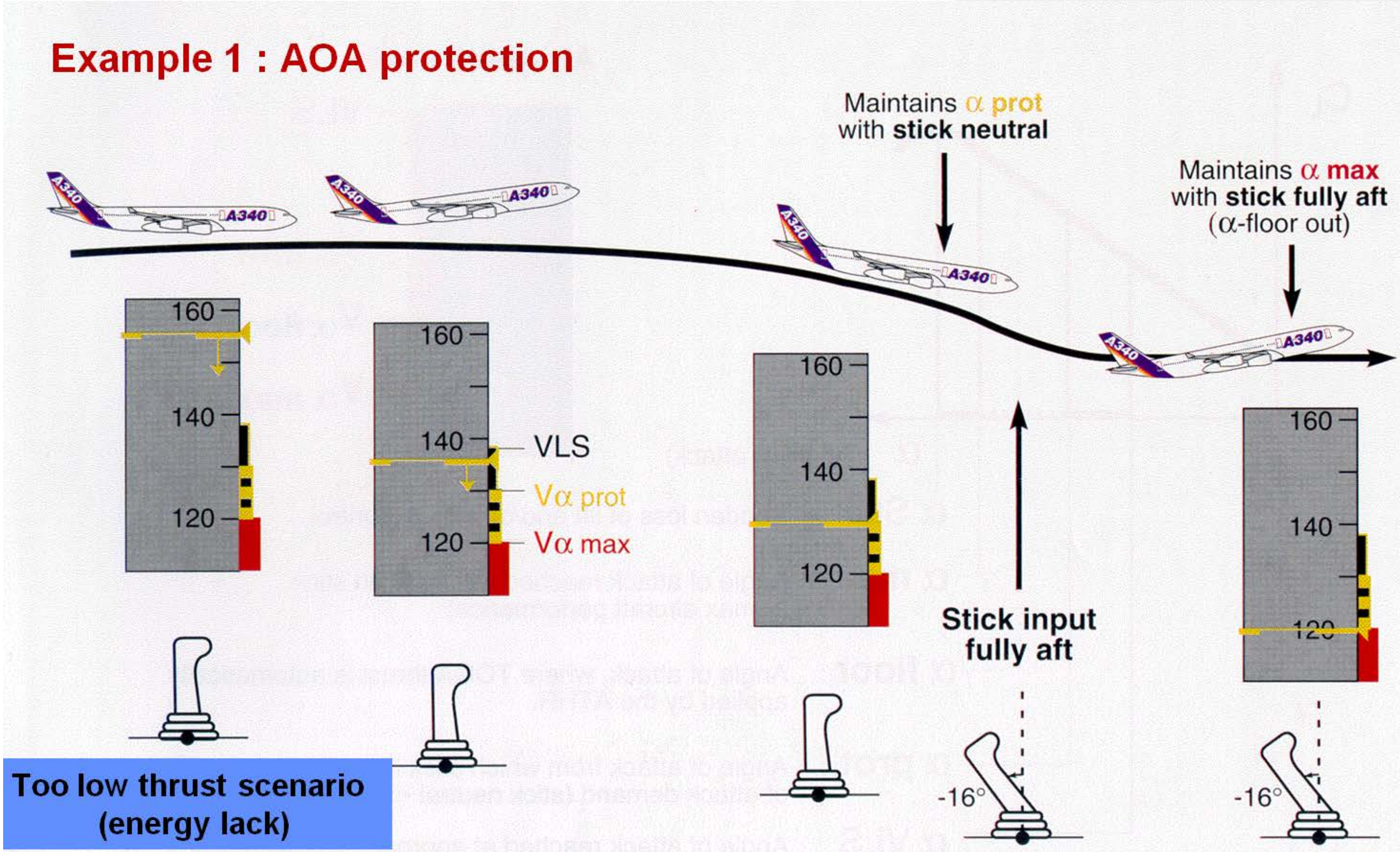
HIGH ANGLE OF ATTACK PROTECTION

- Protects against stall
- Compensates lack of positive static stability in high incidence region
- When α becomes greater than a given AoA (called α_{prot}):
  - C* law “changed” to alpha command law
  - Stick to neutral commands α_{prot}. Stick on the stop commands α_{max} (maximum allowed AoA)
- α_{prot} is set outside the normal operating range
- α_{max} is set few degrees (typically 2 to 3) below stall angle (allowing for some overshoots in dynamic manoeuvers). Overshoot is however challenged for loads purposes.
- Pure alpha command leads to uncontrolled phugoid motion ; it is avoided by adding pitch-attitude and speed damping terms.
- Difficult compromise between robustness and dynamics.
- The way to switch from C* to protα has evolved
  - Logics on SA, LR - difficulties to cover well all scenarios
  - Since A380, Vote between pilot and protections objectives -continuity of orders is guaranteed

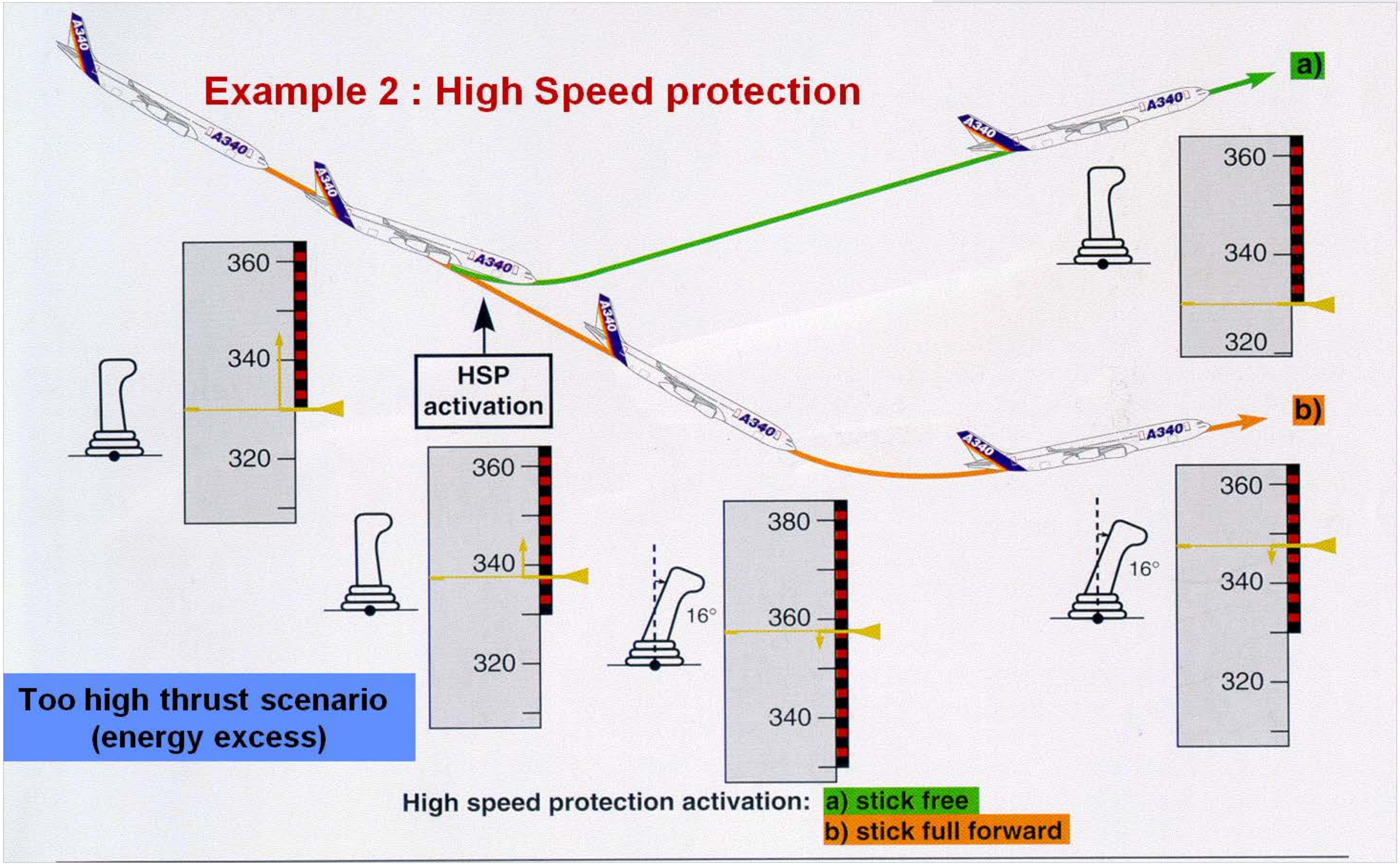
Prot alpha – Longi

Prot alpha – Escape

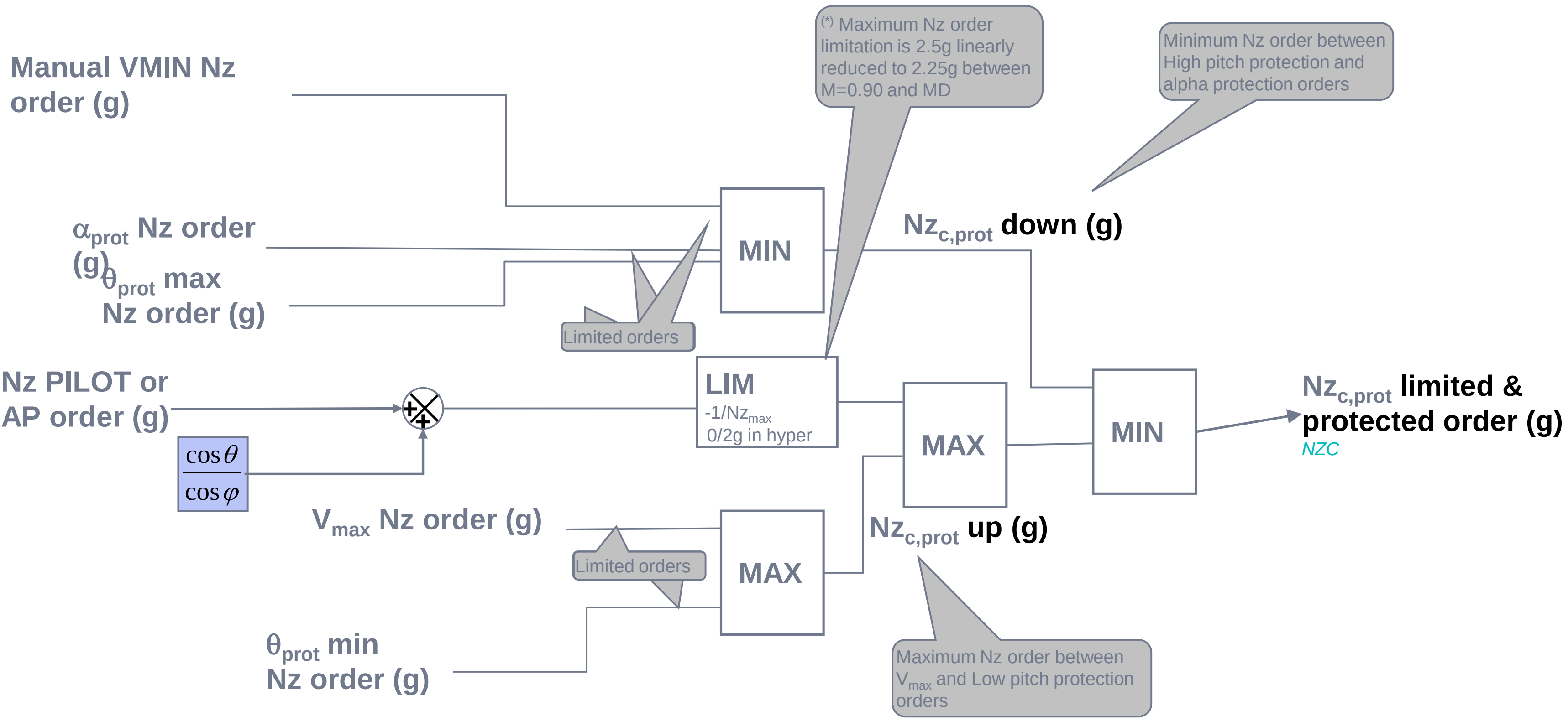
Angle of Attack (AoA) Protection (2/3)



High Speed protection



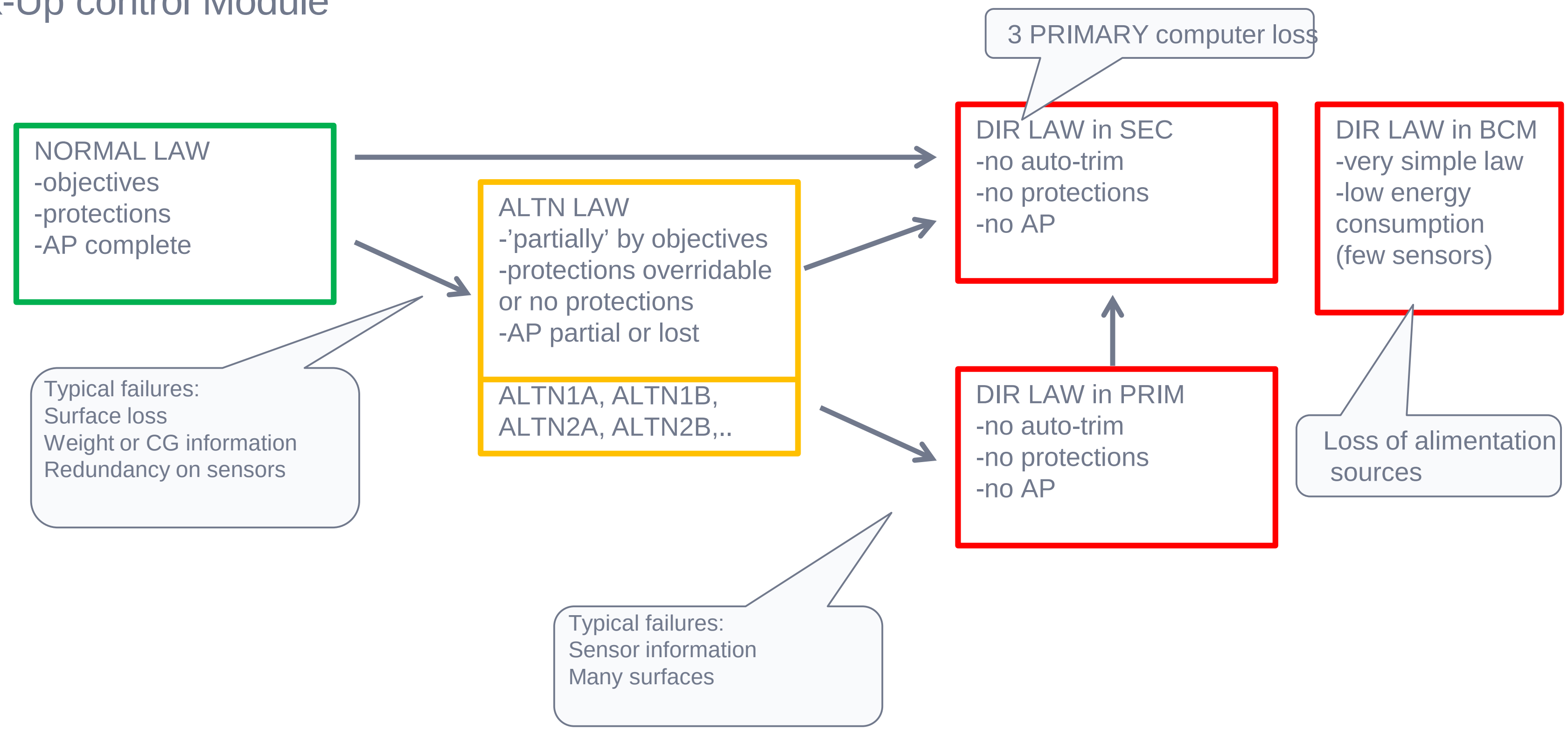
VOTERS PRINCIPLE



5 – Laws Reconfiguration

RECONFIGURATION PRINCIPLE

- All nominal: NORMAL LAW ,with AP and all protections
- Depending on failure, ALTN law, loss of AP, loss of protections (not-overridable ones)
- Lot of failure → DIRECT law
- Loss of PRIMARY computer chain →DIRECT law on SECONDARY chain
- Back-Up control Module



RECONFIGURATION PRINCIPLE

- BEFORE A350:
  - Numerous level of laws (ALT1A, ALT1B, ALT1C, ALT2A, ALT2B..)
  - Loss of AP linked to the reconfiguration level

- On A350, improvement of:
  - Sensors availability (redundancy, estimators…)
  - Validation means (failure cases assessment)
  - Control laws efficiency and simplification

→ Reconfiguration scheme is drastically simplified

NORMAL LAW → ALTN LAW → DIR LAW in PRIM → DIR LAW in SEC

NORMAL LAW: All functions available

ALTN LAW: All functions available
Only DISPLAY is changed

DIR LAW in PRIM: No AP
No protections

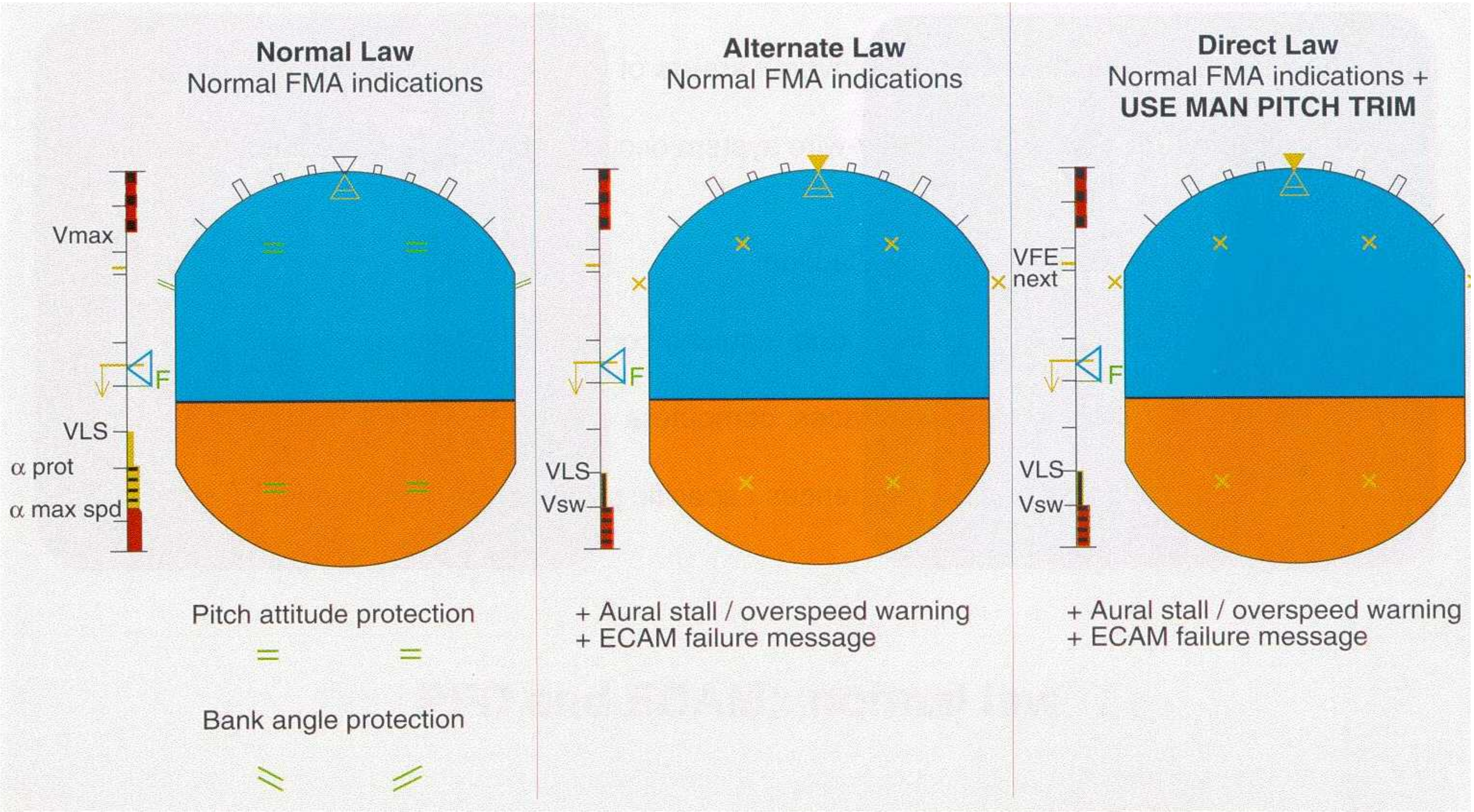
Mainly Surfaces loss

All other failures
$P < 10^{-8}/fh$

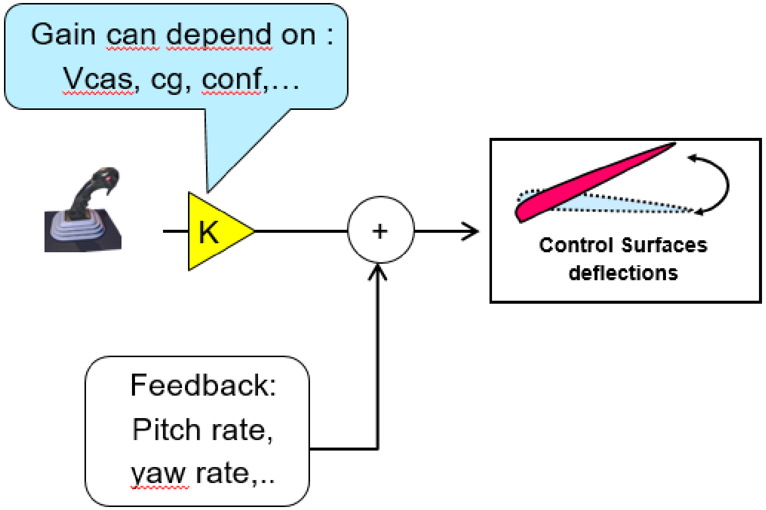
3 PRIMs loss
$P = 10^{-7}/fh$
(fixed price)

In the immediate future:
AP available in DIR law
Some protections also

Specific PFD indications



DIRECT CONTROL LAW PRINCIPLE



A common issue with direct type of control law is the selection of the max control authority (elevator deflection corresponding to full stick deflection)

On Airbus Fly By Wire aircraft, this type of control law is used on ground and following failures in flight

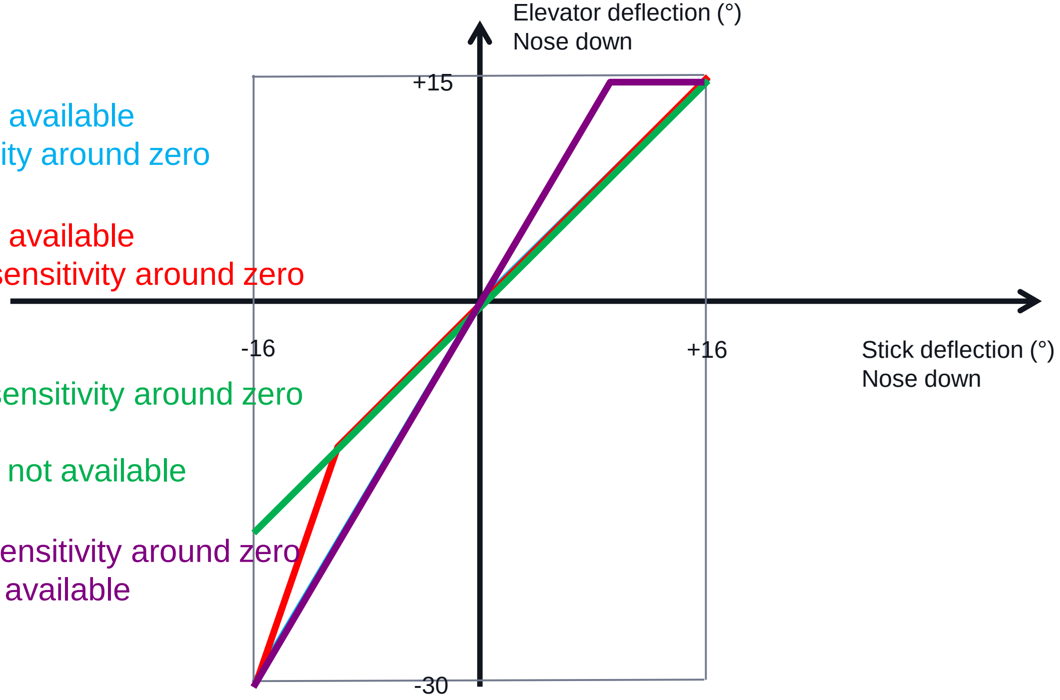
DIRECT CONTROL LAW PRINCIPLE

Full deflection available
But non linearity around zero

Full deflection available
Symmetrical sensitivity around zero
Non-linearity

Symmetrical sensitivity around zero
Linearity
Full deflection not available

Symmetrical sensitivity around zero
Full deflection available
Dead zone

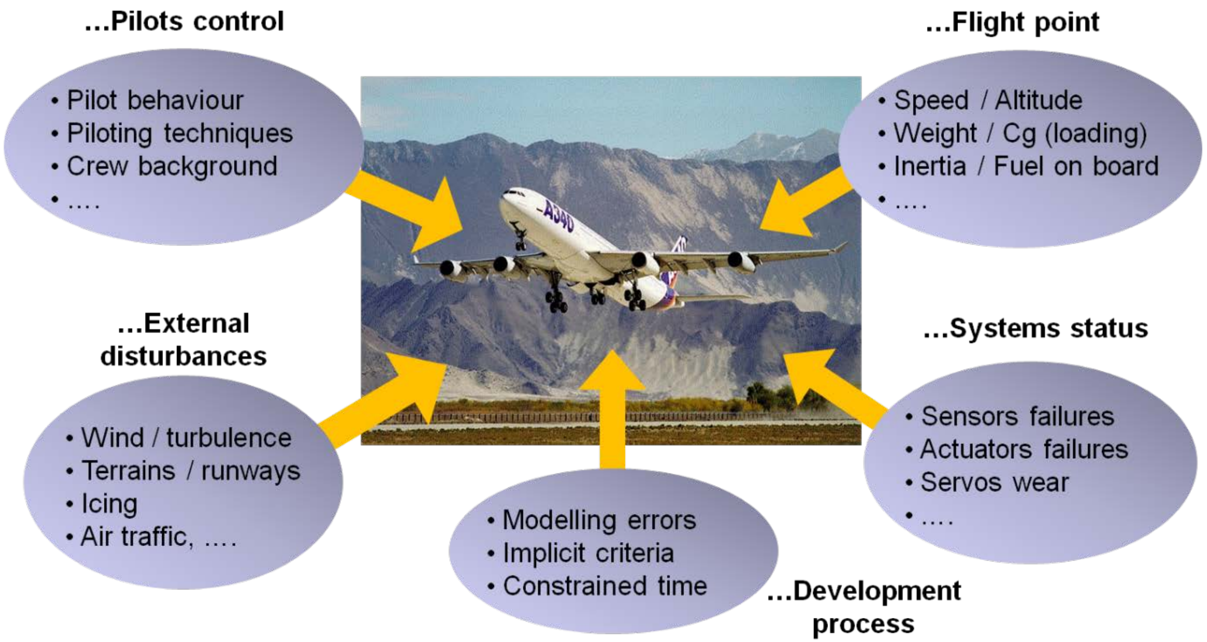


RECONFIGURATION PRINCIPLE: WHAT'S NEXT?

- 4 computers (IFCC architecture) instead of 3 PRIMs + 3 SECs
- NORMAL law (or ALTN==NOR) always available
- AP always available
- Protections always available
- Automatic recovery

→ Toward 1 single pilot in the loop

6 – Flight control laws Robustness



Robustness challenge

…Pilots control

- Pilot behaviour
- Piloting techniques
- Crew background
- ….

…Flight point

- Speed / Altitude
- Weight / Cg (loading)
- Inertia / Fuel on board
- ….

…External disturbances

- Wind / turbulence
- Terrains / runways
- Icing
- Air traffic, ….

…Systems status

- Sensors failures
- Actuators failures
- Servos wear
- ….

…Development process

- Modelling errors
- Implicit criteria
- Constrained time

Structural constraints

- A320 / A340 in service experience has showed that structural constraints (loads in turbulence, loads on manoeuvres, aero elasticity....) should be considered at the very beginning of control functions design, because control strategy has direct (and strong) impacts on stress levels on a/c structural parts, on their sizing, and consequently on aircraft weight.

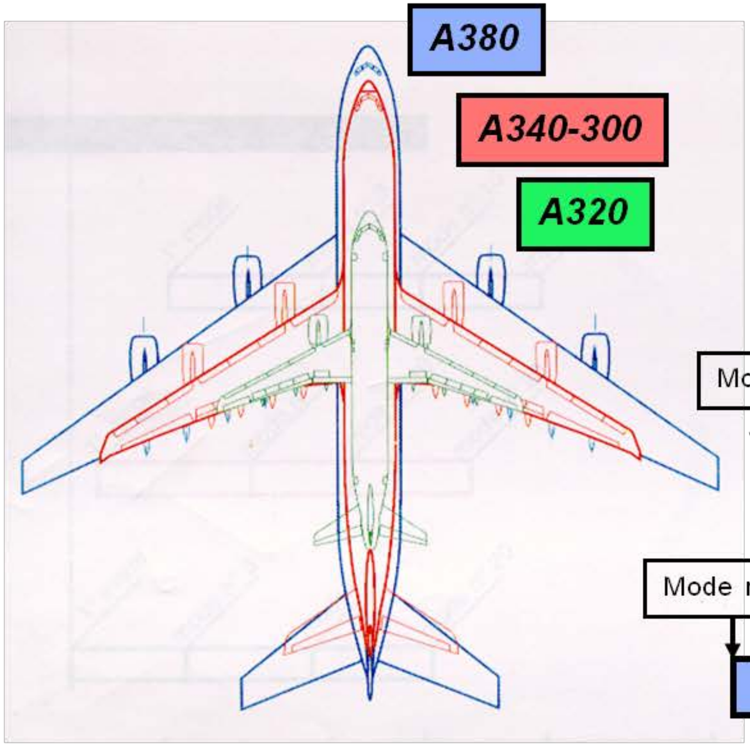
- So several loads reduction device has been implemented in Flight Controls, since A320:

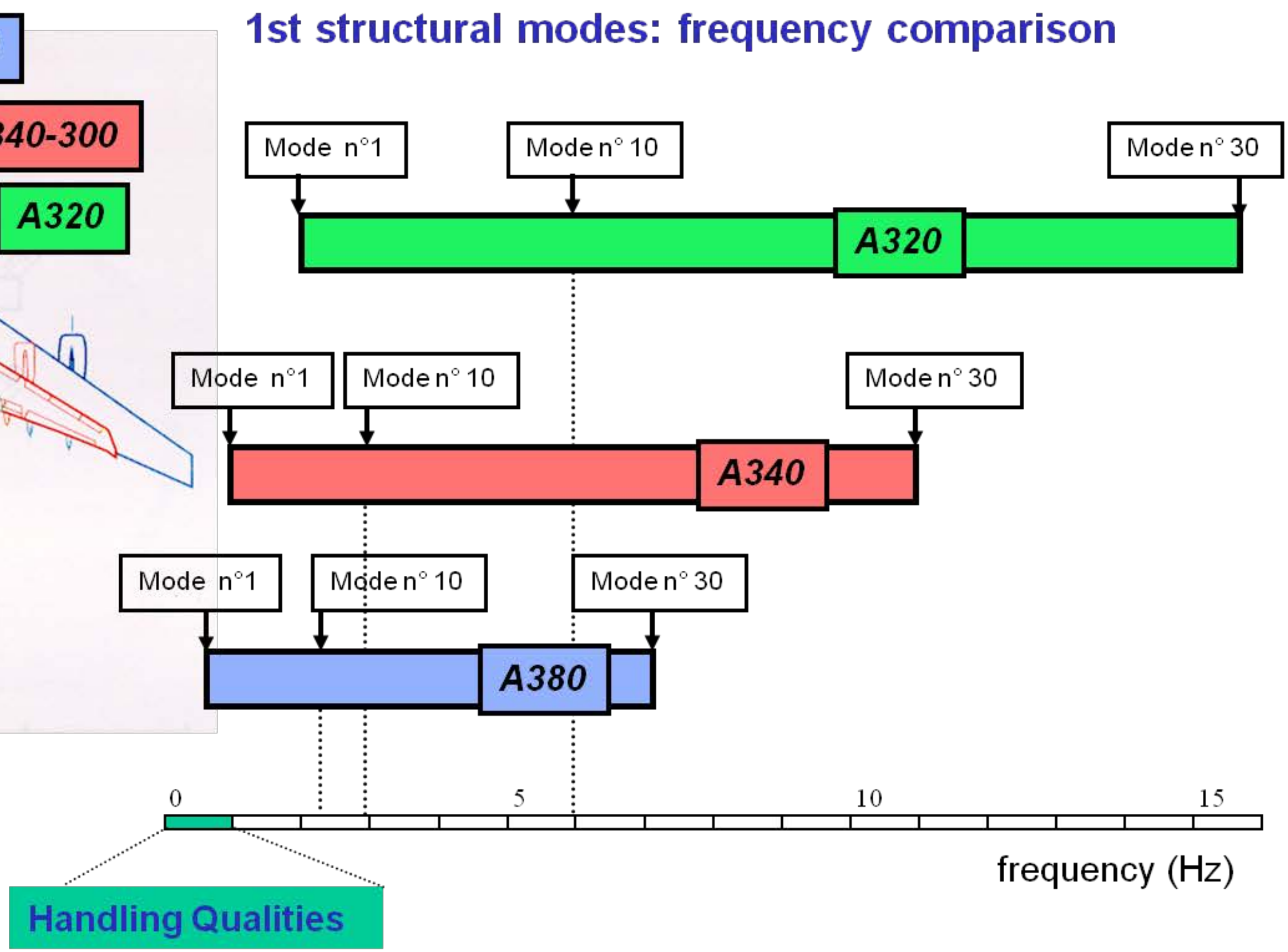
- Loads reduction on wind bursts and in turbulence (LAF, Load Alleviation Function GLA, Gust Load Alleviation).

- Loads reduction on manoeuvres (MLA, Manœuvre Load Alleviation).

- Comfort optimization in turbulence (CIT, Comfort In Turbulence).

Structural modes overview

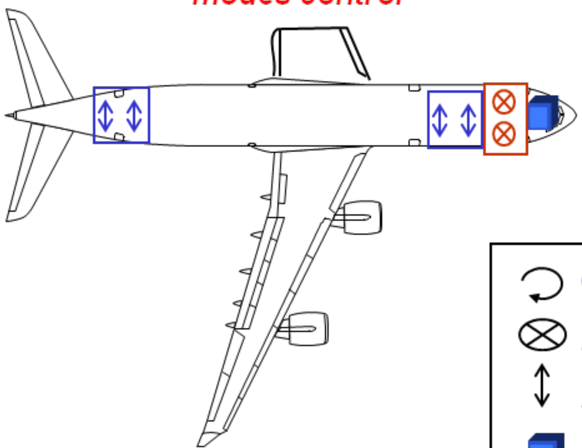




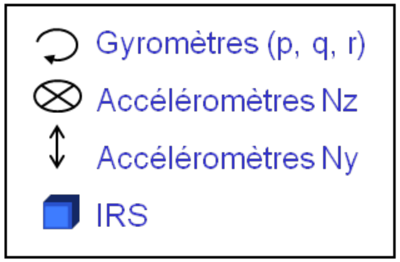
Structural modes sensing

A340-300

IRS used for rigid modes control
Specific sensors used for Comfort / Flexible modes control

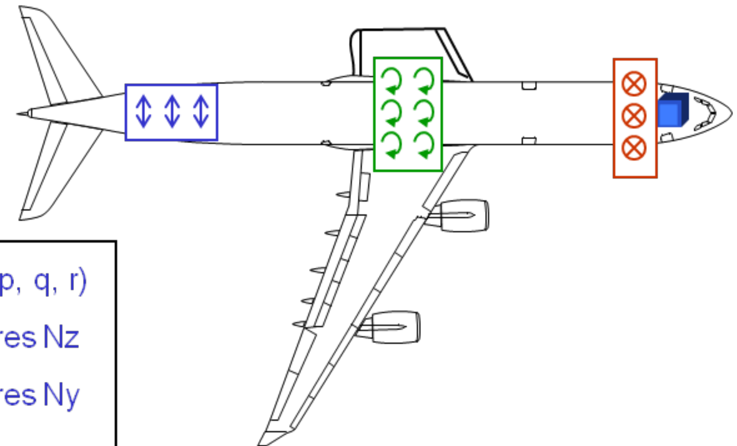


- 2 accelero Nz at nose
- 2 accelero Ny at nose
- 2 accelero Ny at rear fuselage



A340-500/600

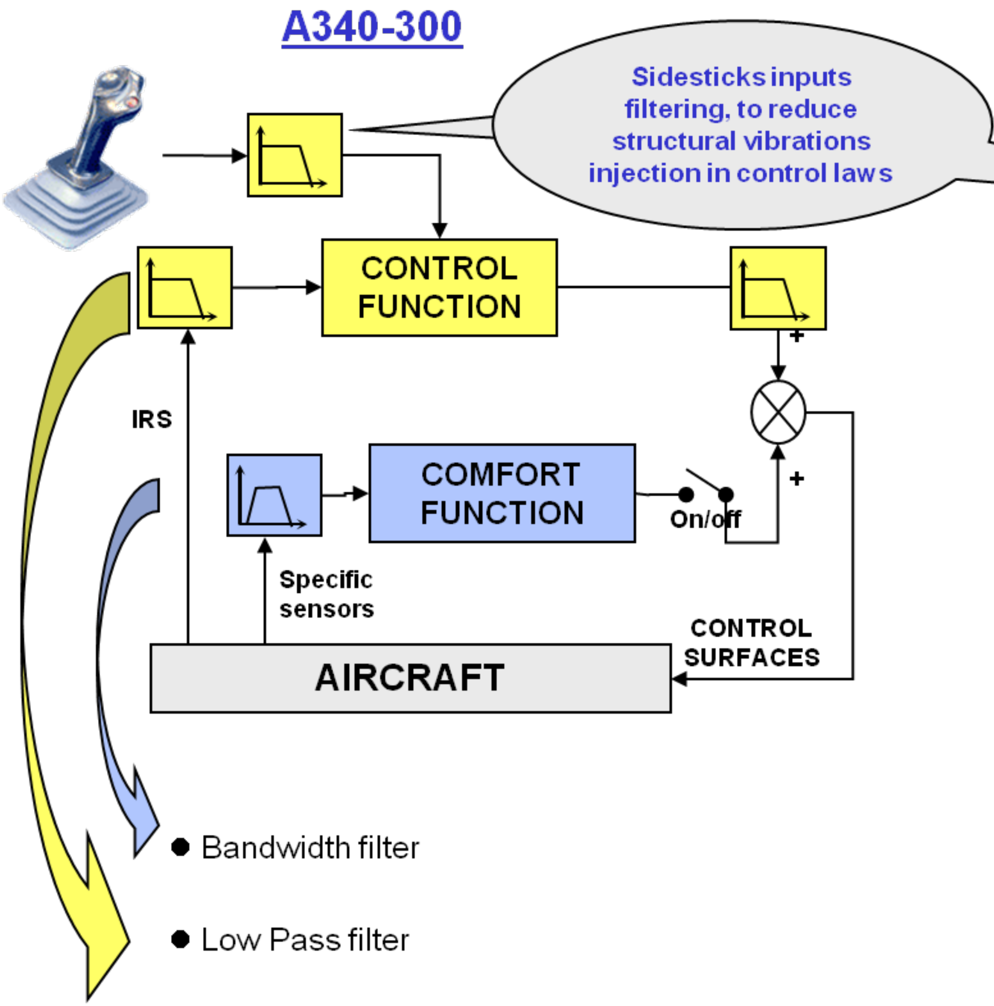
IRS & specific sensors are used for both rigid and flexible modes control



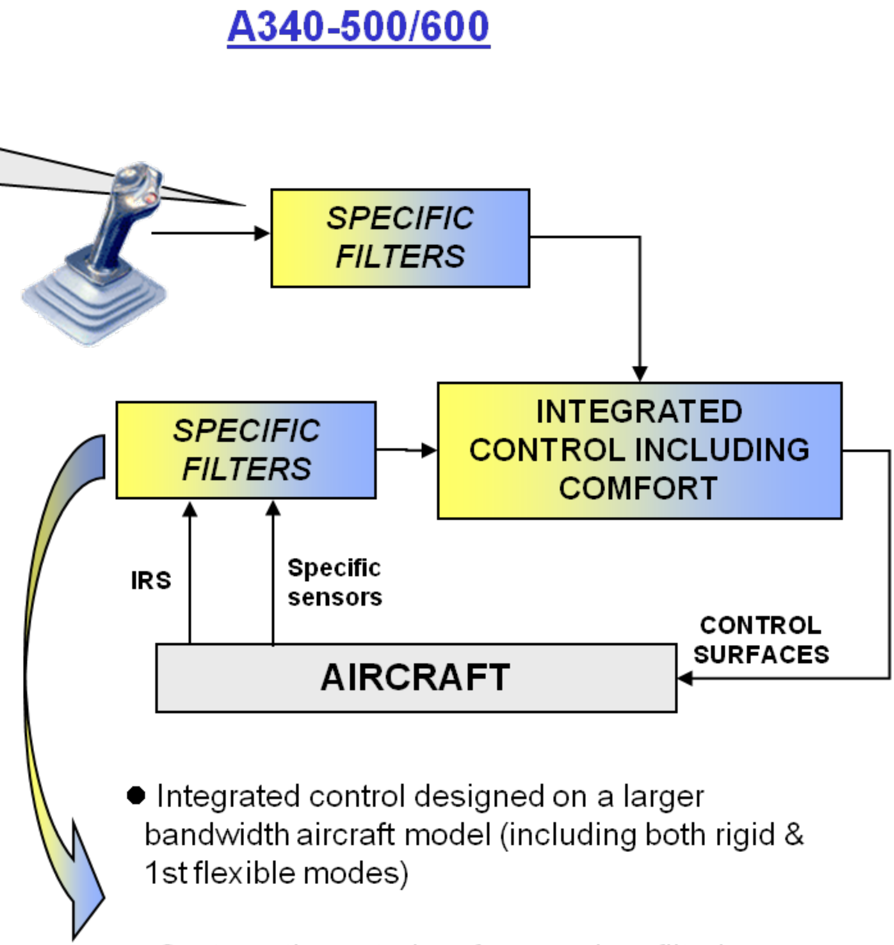
- 3 accelero Nz at nose
- 3 accelero Ny at rear fuselage
- 6 gyro meters at mid fuselage

- ***Specific sensors are located close to nodes and antinodes of flexible modes***
- ***They are directly connected to Flight Control Computers, to minimize time delays***

Structural modes control



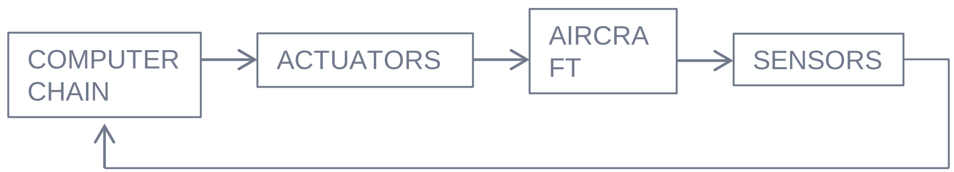
- Bandwidth filter
- Low Pass filter



- Integrated control designed on a larger bandwidth aircraft model (including both rigid & 1st flexible modes)
- Systematic control surfaces orders filtering cancelled

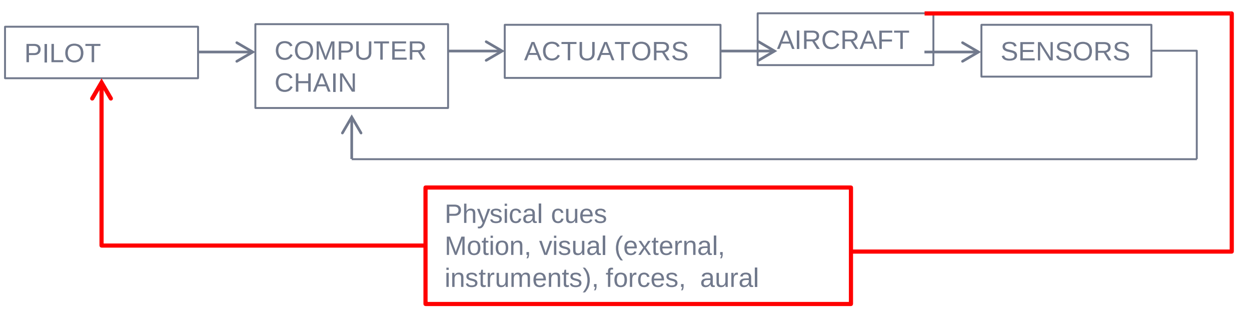
COUPLING BETWEEN PILOT AND AIRCRAFT

The stability of flight control laws may concern the loop



Adequate stability margins during control loop design

But also this one:



Loop closed by a variable human filter: gain, lag, inputs selectivity

Flight Controls robustness example : the PIO

Background

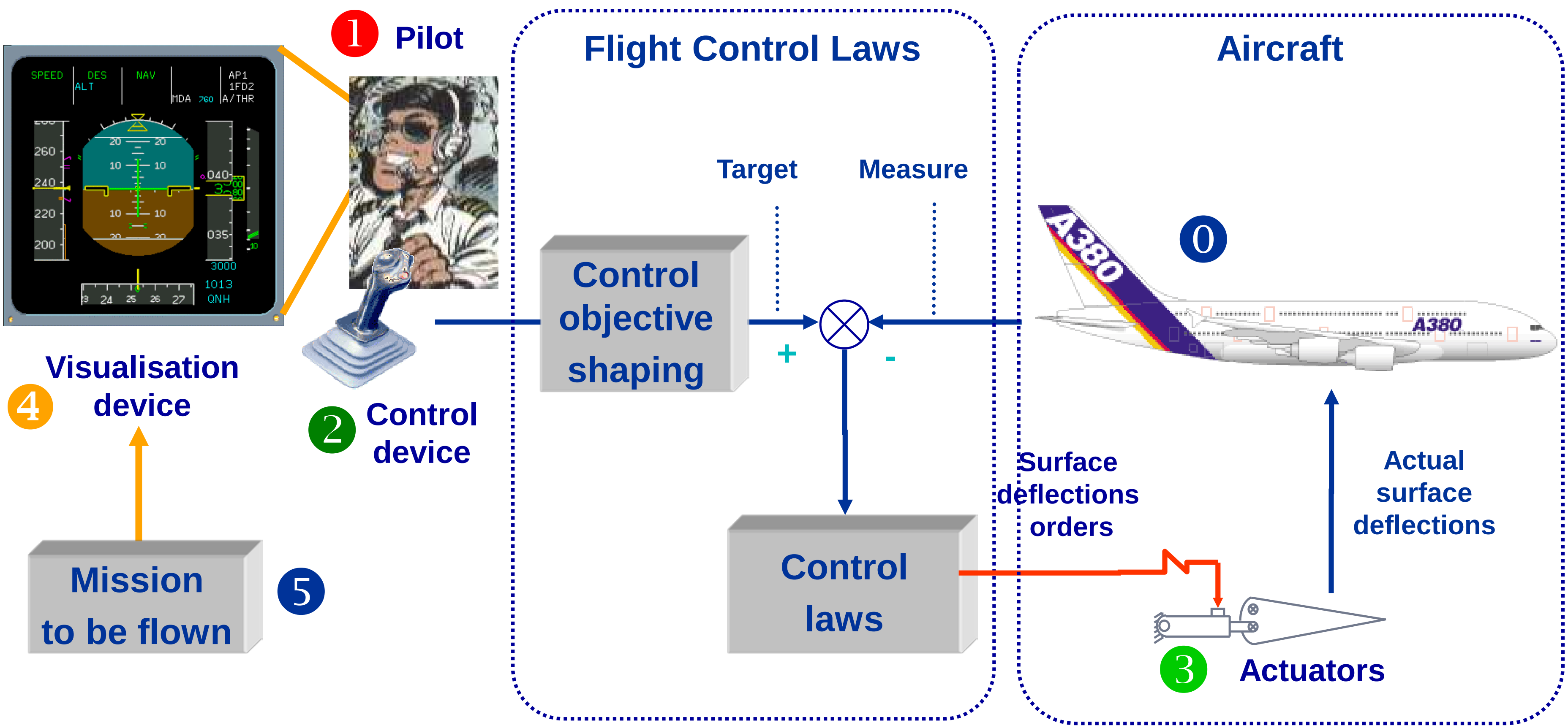
- What's PIO ?
  - **PIO = Pilot Induced Oscillations** = Aircraft / Pilot coupling
  - Practical effects: loss of aircraft control, on one or several axis
  - From automatic control point of view: **unpredicted stability margins reduction**

- Potential causes
  - **Linear causes**: pilot gain increase (stress, bang bang control…), two high dynamics in the control loops, aerodynamic modifications (iced wing…)
  - **Non linear causes:** extra delays, limited commanded signals (in magnitude, or in rate), hydraulic failures (out of phase controlled surfaces…)

- Illustrative videos
  - Airbus A321 at landing
  - YF16 roll PIO at Take Off
  - Boeing V22 convertible

PIO / Contributors in the Flight Loop

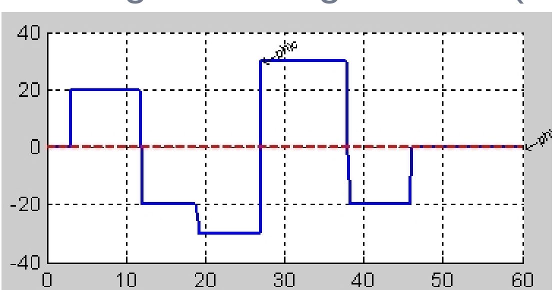
PIO potential contributors:
- Pilot & assigned mission
- HMI (control device + visual cues)
- Control loop (a/c dynamic + control laws + actuation device)



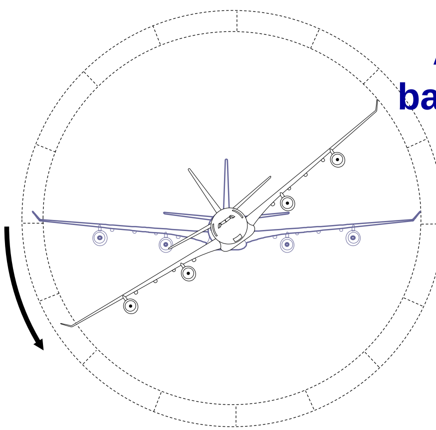
PIO demo / Mission to be flown

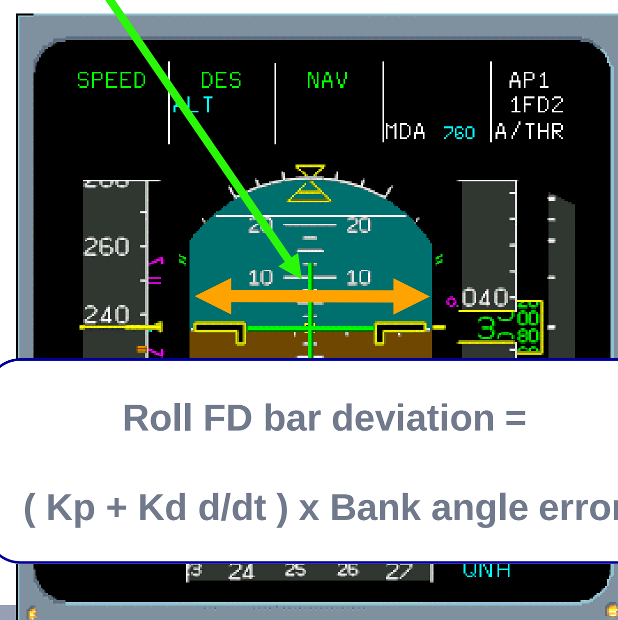
- **Flight Phase & Aircraft**
  - Landing configuration (Full)
  - Approach speed
  - AP OFF – A/THR ON – FD ON
  - Typical Long Range behaviour

- **Simulated mission (control task)**
  - Bank angle tracking mission (multi steps)



  - Try to maintain altitude (roughly)
  - Mission displayed on Flight Director
  - Roll FD Bar deviation = bank angle error

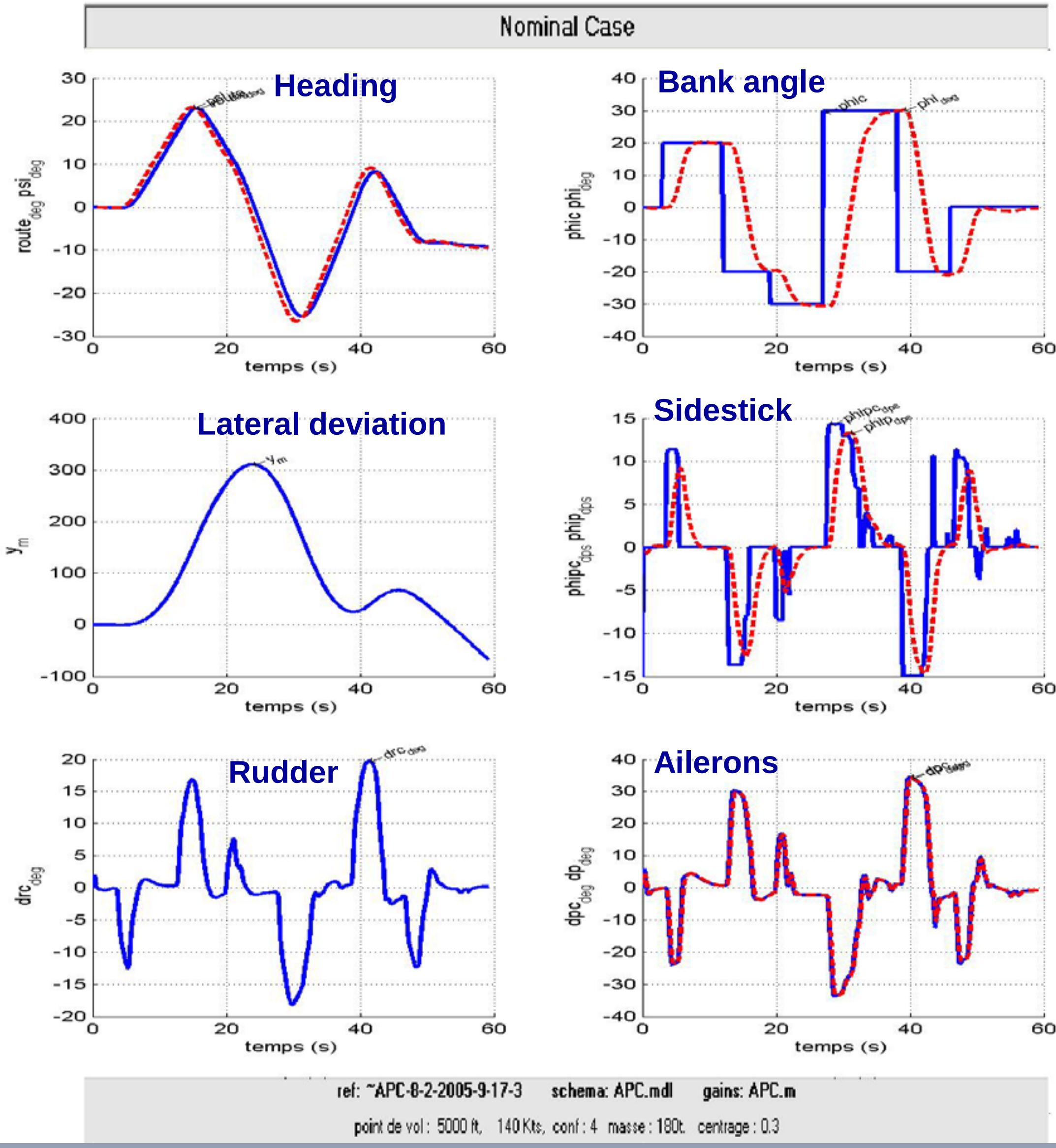




Roll FD bar deviation =

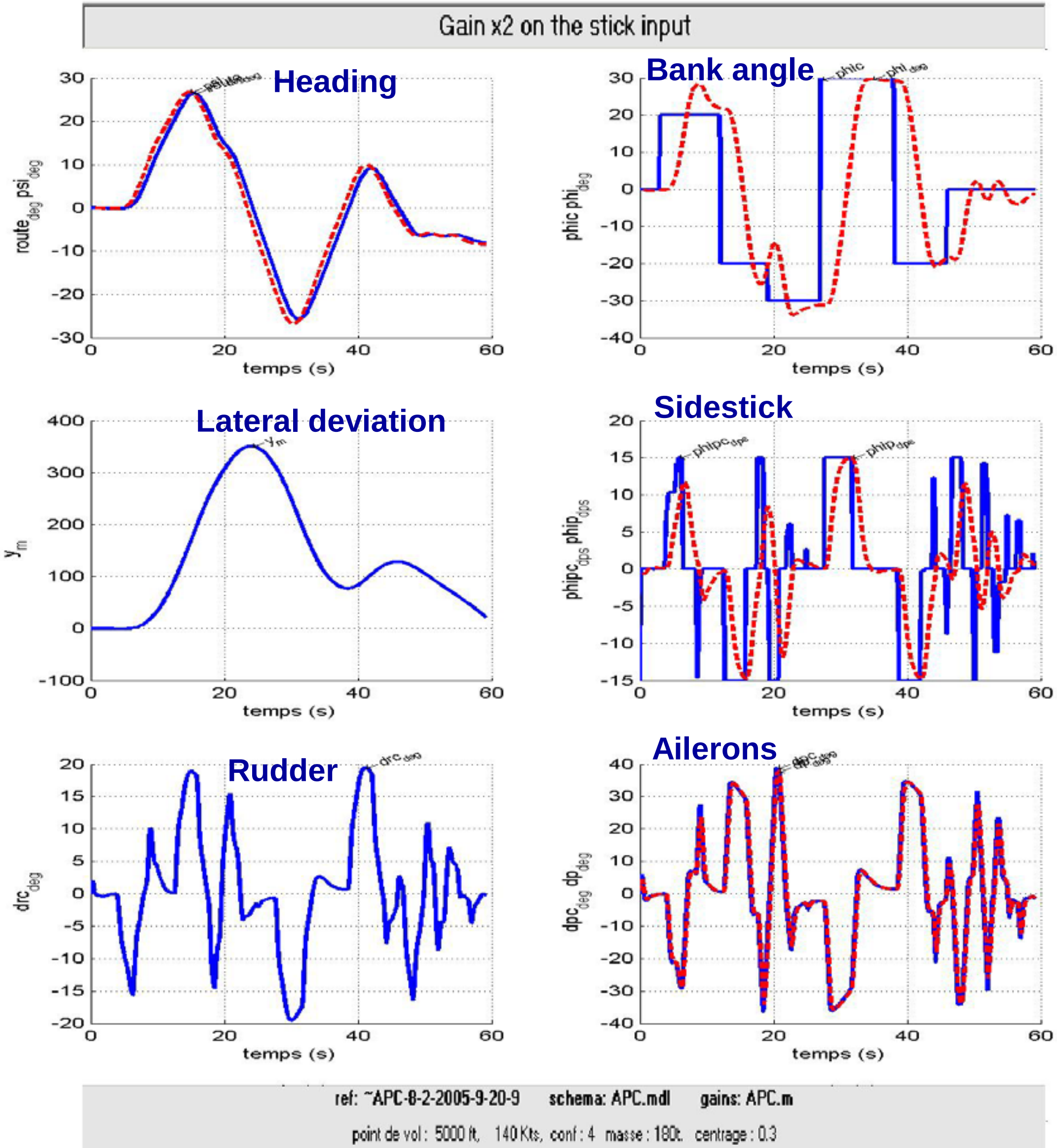
(Kp + Kd d/dt) x Bank angle error

PIO demo / Nominal case



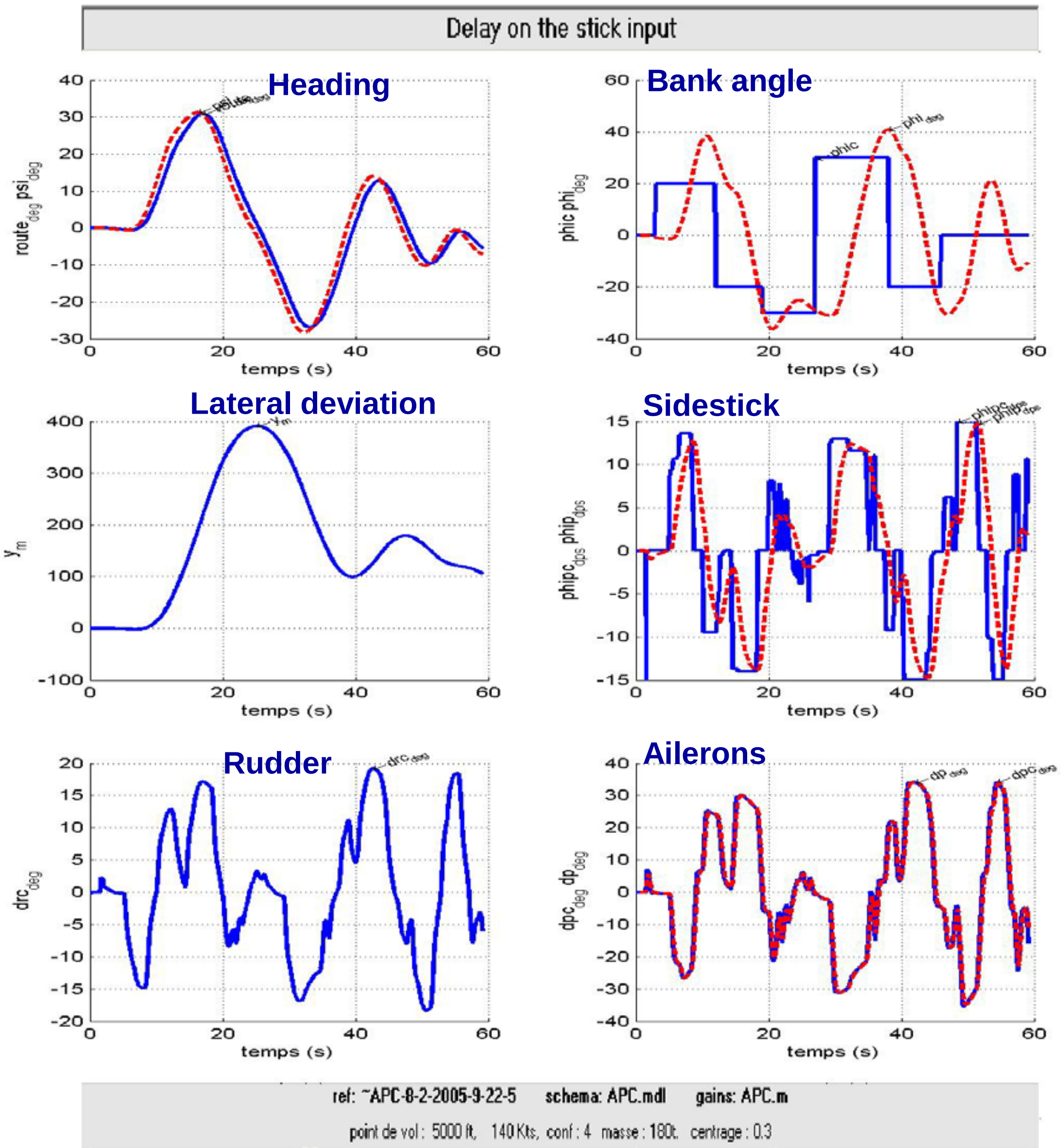
- **Nominal case**
  - Well tuned control laws
  - Correct sidestick cinematics
  - Well tuned Roll FD bar (tracking task visualisation)
  - No failure
- **Task management**
  - Precise
  - Easy
  - Low activity on stick

PIO demo / Too sensitive sidestick



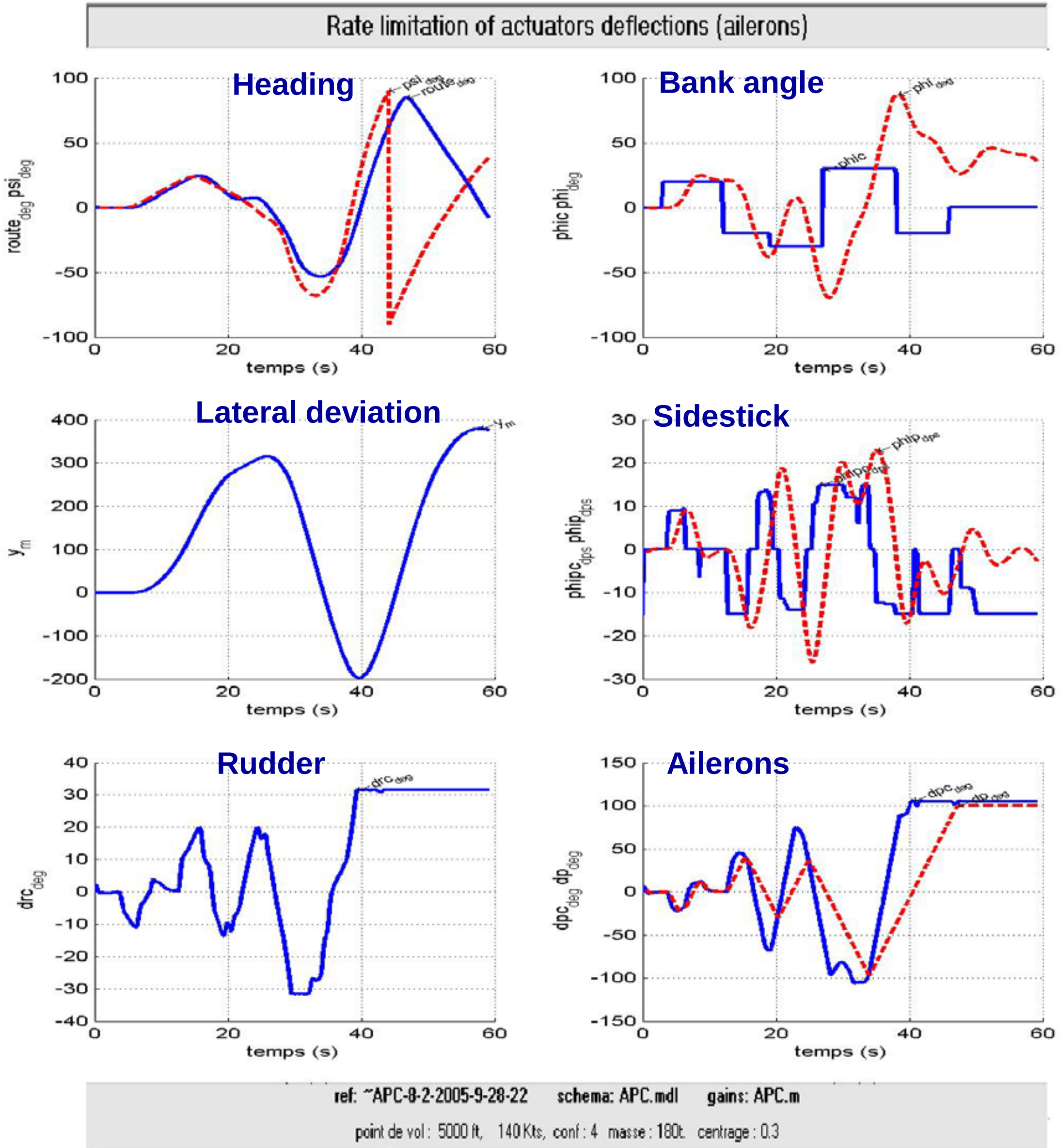
- **Control loop disturbance**
  - Modified sidestick cinematics (stick too sensitive)
- **Task management**
  - Less precise control
  - More difficult
  - Increased activity on stick
  - No severe PIO
  - Pilot can self-calibrate

PIO demo / Delayed sidestick input



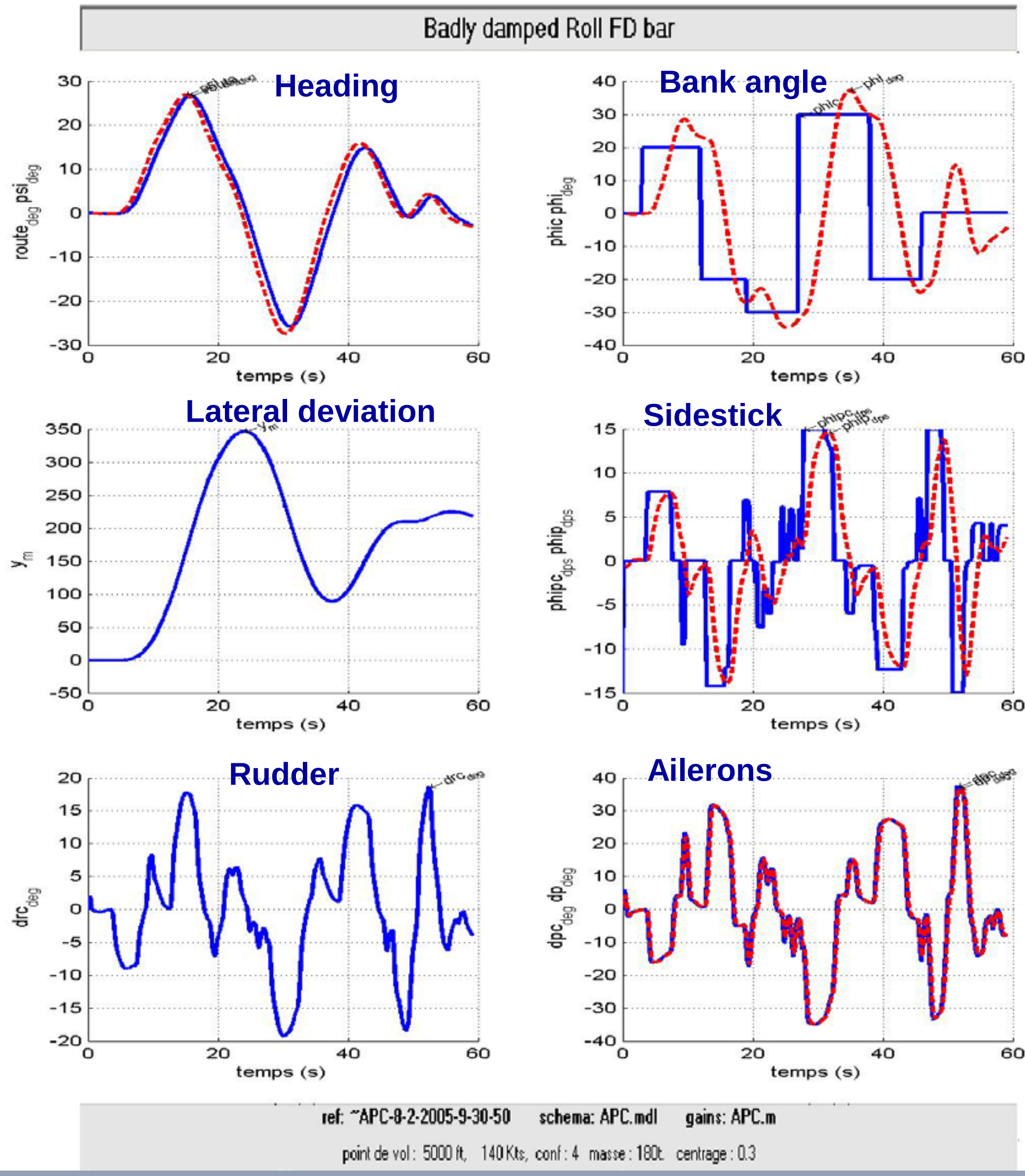
- **Control loop disturbance**
  - Modified sidestick cinematics (large delay added to pilot action)
- **Task management**
  - Less precise control
  - Bad bank angle tracking
  - Increased activity on stick
  - Severe PIO

PIO demo / Ailerons failure



- **Control loop disturbance**
  - Failure case simulation: loss of hydraulic circuits
  - Effect: ailerons actuators speed reduced from 40°/s to 10°/s
- **Task management**
  - Loss of control (transient, then steady state)
  - Wrong phase between pilot action and aircraft response
  - Severe PIO

PIO demo / Badly damped display



- **Control loop disturbance**
  - Modified Roll FD bar deflection computation (no more damping)
  - Effet: needs too much phase advance from the pilot
- **Task management**
  - Less precise control
  - Bad bank angle tracking
  - Increased activity on stick
  - Severe PIO

PIO demo / Observations summary

The global control loop controllability depends on ...

Pilot behaviour

- From high gain pilot to lazy pilot … difficult to modelize !
(gain, delay, non linearities, limit cycles…)
- Nota : pilots « learn » the mission => difficulties to assess flight controls robustness wrt PIO

Control task & HMI

- Calibrated missions may be used
- Control devices have a clear effect (stick sensitivity, stick filtering, FD bar dynamic…)
- PIO occurs mainly at low speed, TO & Landing (high gain tasks)

Control laws & actuation dynamics

- Drastic effects of rate limitations on actuators (bad sizing, failures…)
- Caution with high aircraft dynamic & delays in the control loop