Priteche VENILAL
Flight Control Laws
AIRBUS OPERATIONS SAS

AUTOFLIGHT

Deeper in flight control laws and autoland

Outlines

1 – Reminder of flight management, guidance and control functions

2 – Useful sensors

3 – AP/FD outer loops examples

4 – Flight control laws design

- Stability and performance requirements… and success criteria
- Flight control laws tuning issues
- Flight control laws development before and during flight tests

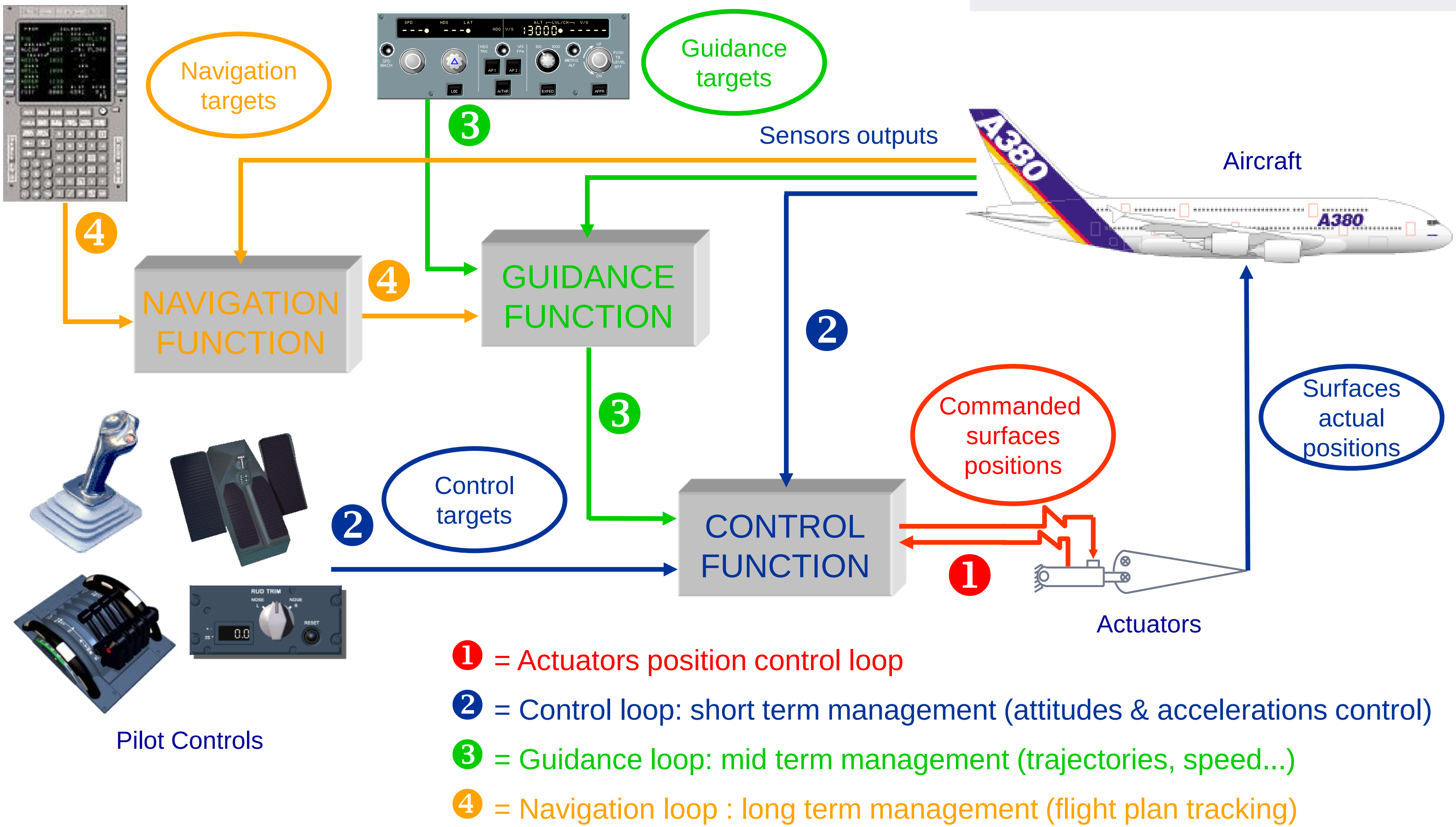
5 – Automatic landing (autoland) specificities

- Performances requirements and demonstration
- Performances robustness improvement based on estimators

AP: AutoPilot
ATHR: AutoTHRust
FD: Flight Director

1 – Reminder of flight management, guidance and control functions

Integration of navigation, guidance & control functions



Autoflight control laws principles

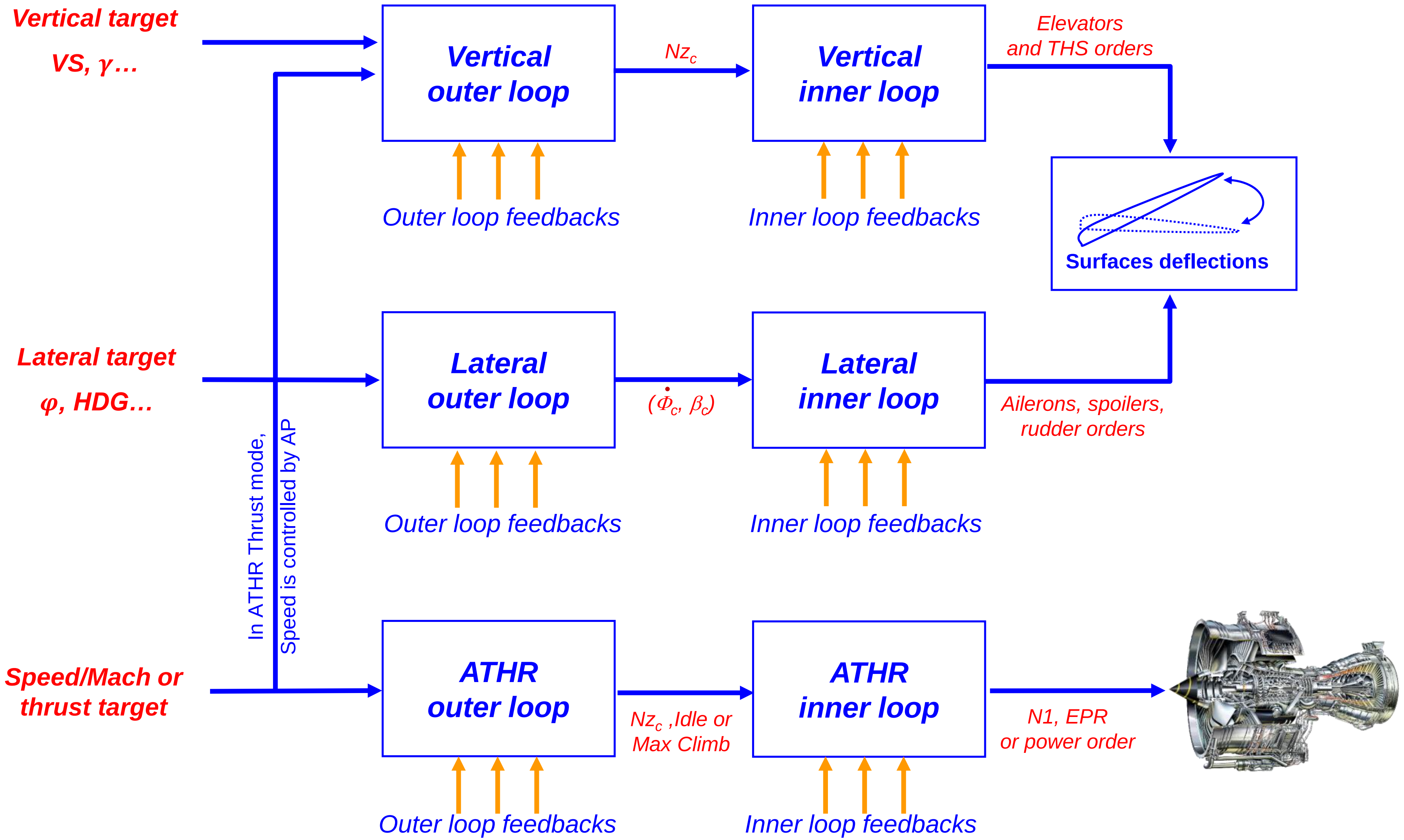
- The inner loop is dedicated to control
  - **Control the A/C attitude** (same scope as EFCS)
  - Limit the outer loop targets in amplitude and speed to limit the effects of a failure
  - Use A/C accelerations, attitude and attitude rates as main feedbacks
  - Compute orders: surfaces deflection

- The outer loop is dedicated to guidance
  - **Control the center of gravity position** to follow the flight plan
  - Limit FCU or FMS targets in amplitude and speed to limit the effects of a failure
  - Use A/C position and speed vector as main feedbacks to compute orders
  - Send them to the inner loop (AP) or displays (FD): load factor, bank angle

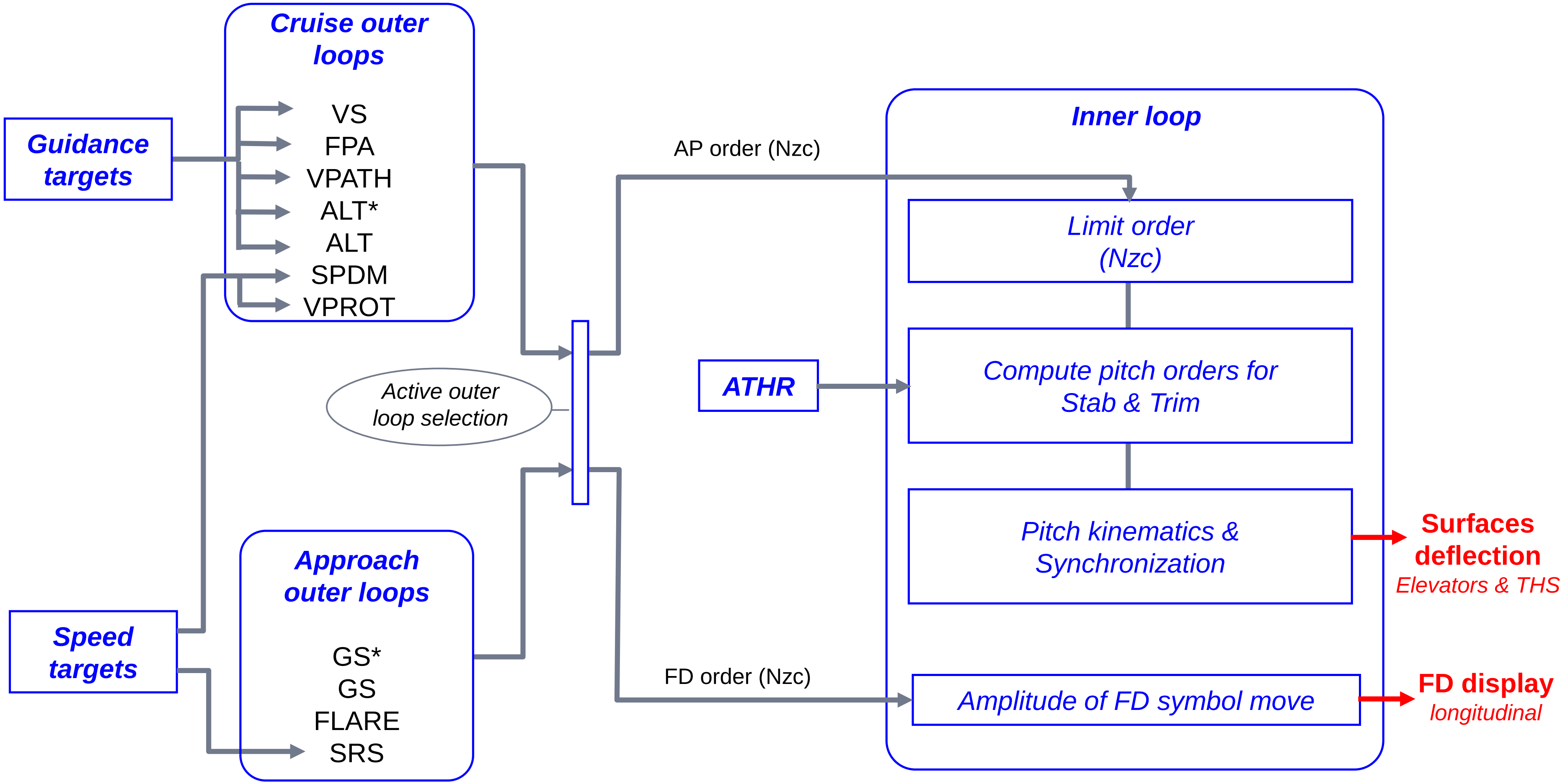
- A control law is associated to each mode
  - The link between modes and control laws is defined in « operational logic »
  - Different feedbacks are used at guidance level and control level

Autopilot orders are executed via inner loops, in charge of controlling the surfaces to their commanded deflections

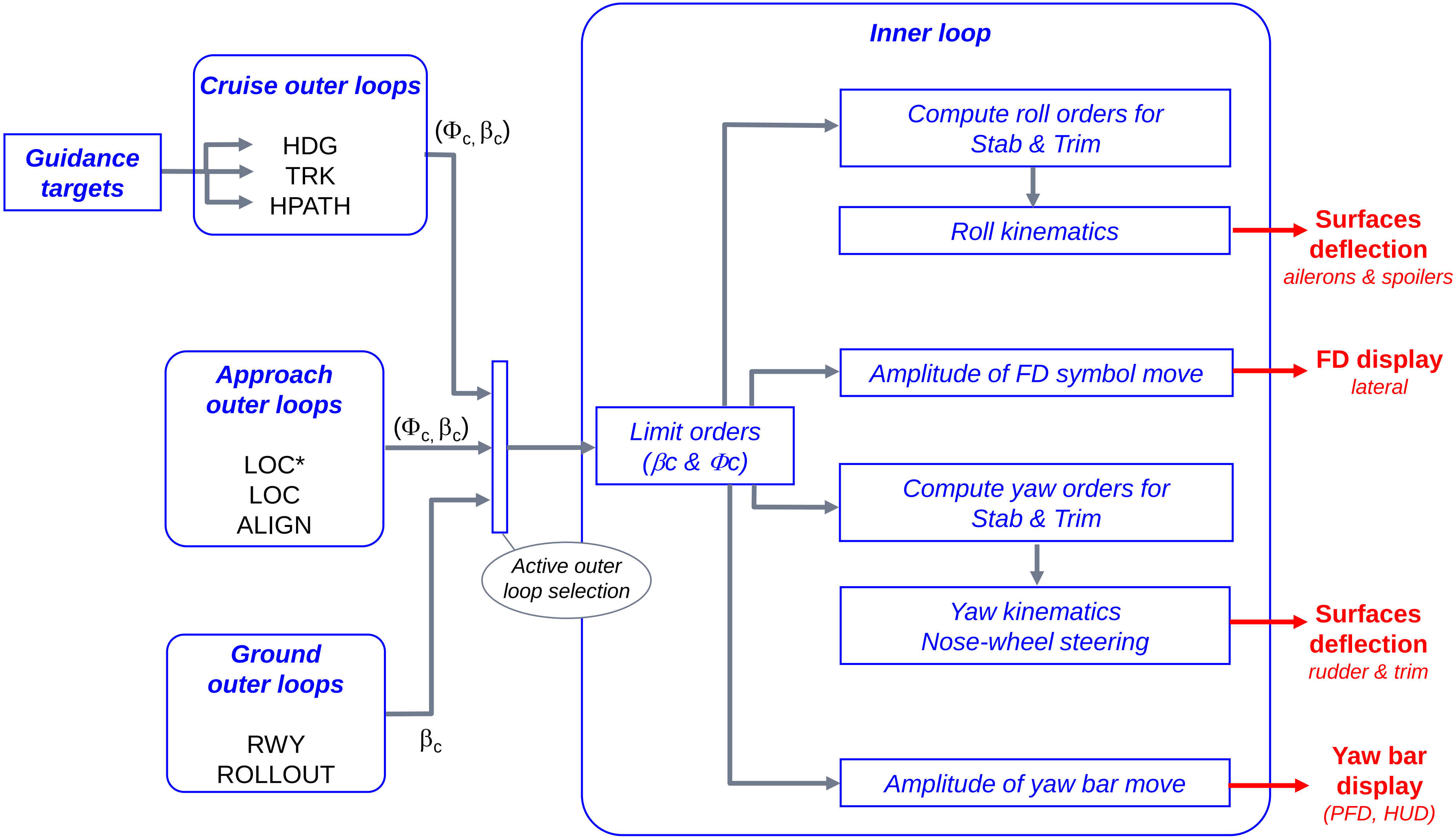
Functional breakdown of Flight Control Laws



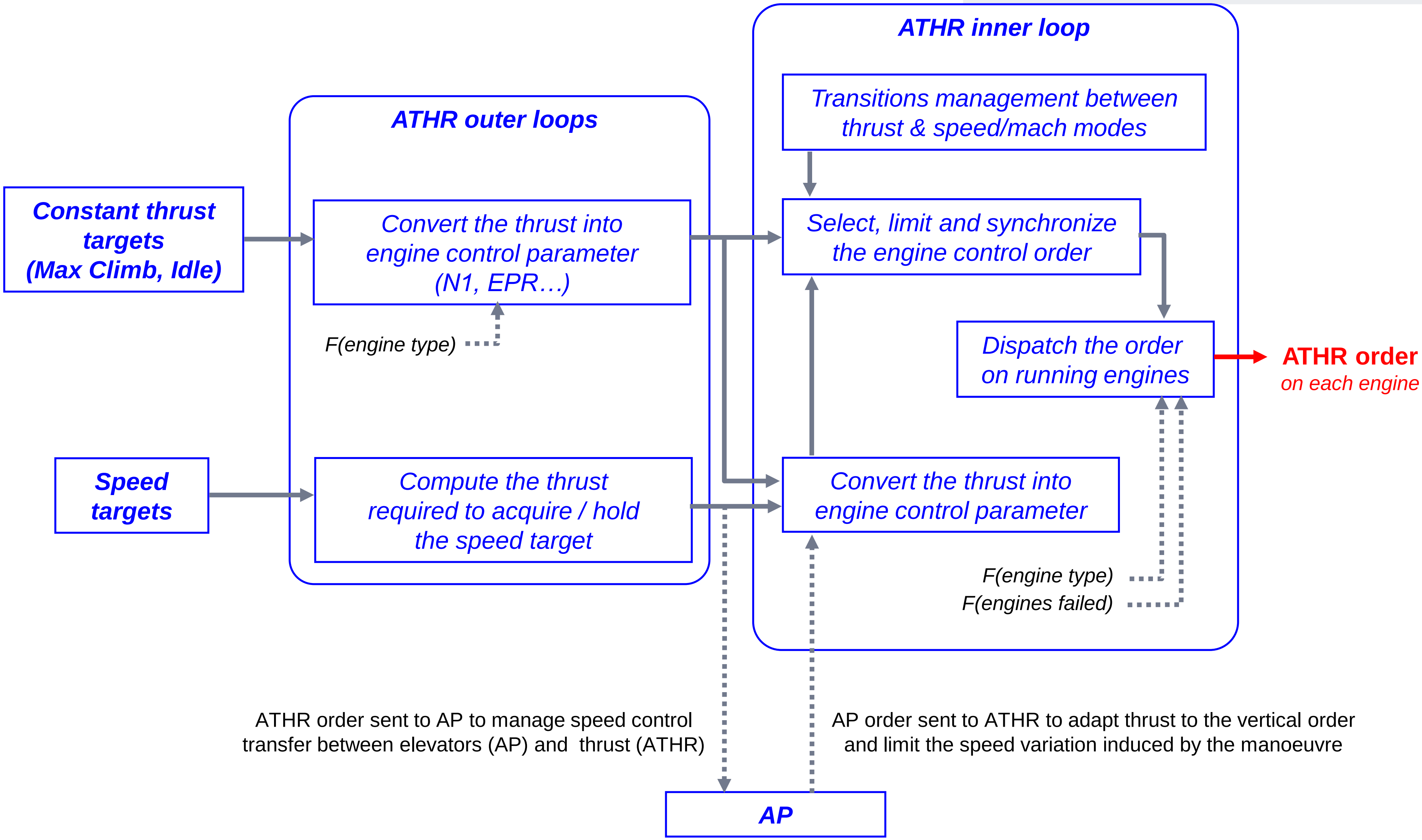
Vertical control laws breakdown



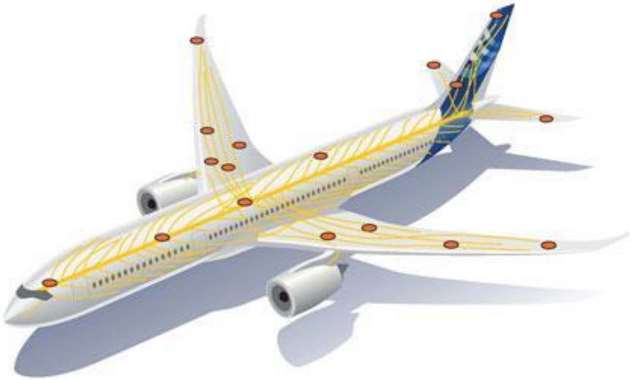
Lateral control laws breakdown

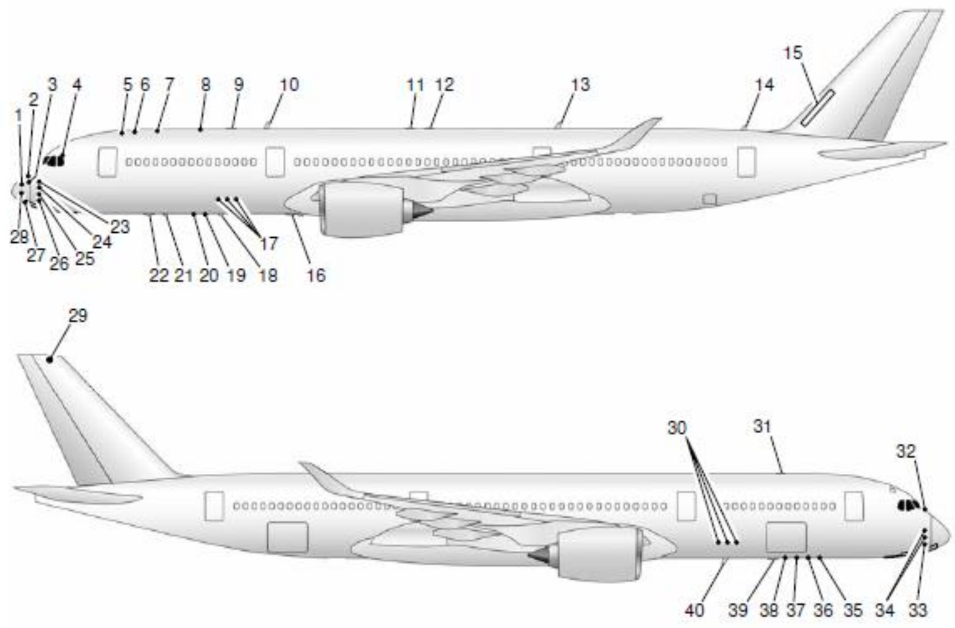


Thrust control laws breakdown



2 – Useful sensors





Sensors needed: ADIRU

Calibrated airspeed CAS
True airspeed TAS
Mach number M

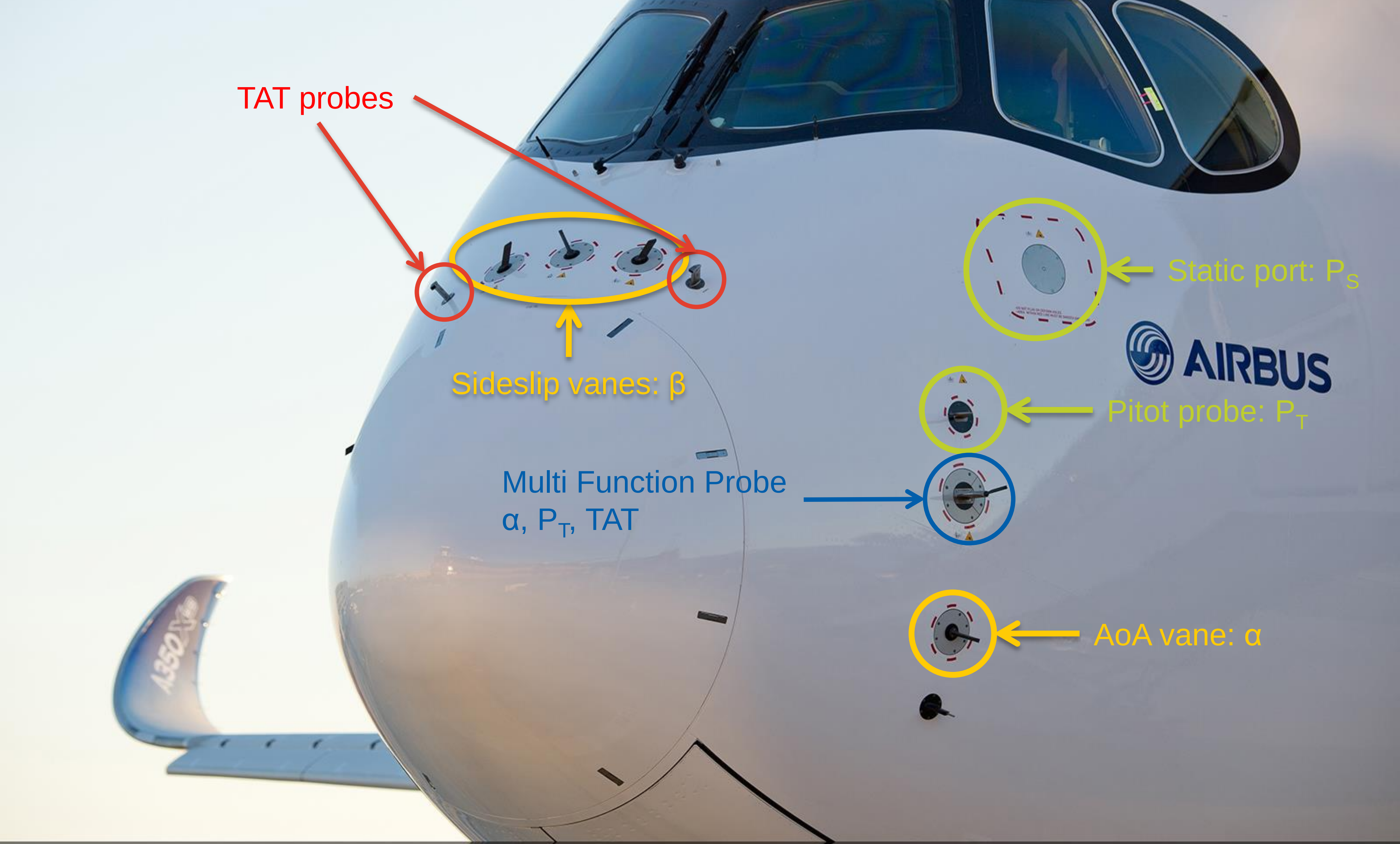
Baro-inertial vertical speed V_{ZBI}
Baro-inertial altitude Z_{BI}

Sensor	Measurement	Notation	Unit	What for?
Air Data Reference	Static pressure	P_S	mbar	Computation of airspeed
	Total pressure	P_T	mbar	
	Total air temperature	TAT	°C	
	Angle of attack	α	deg	α protection
	Angle of sideslip	β	deg	Lateral inner loop
Inertial Reference System	Accelerations	N_X, N_Y, N_Z	g	Longitudinal & lateral inner loops
	Rotation rates	p, q, r	deg/s	
	Attitudes	θ, φ, ψ	deg	
	Ground speed	V_{GND}	kts	Speed control laws
	Track angle	TRK	deg	Track control law

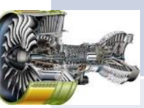
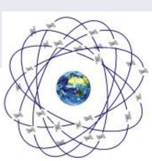
Flight path angle γ

ADIRU: Air Data Inertial Reference Unit

Sensors location



Sensors needed

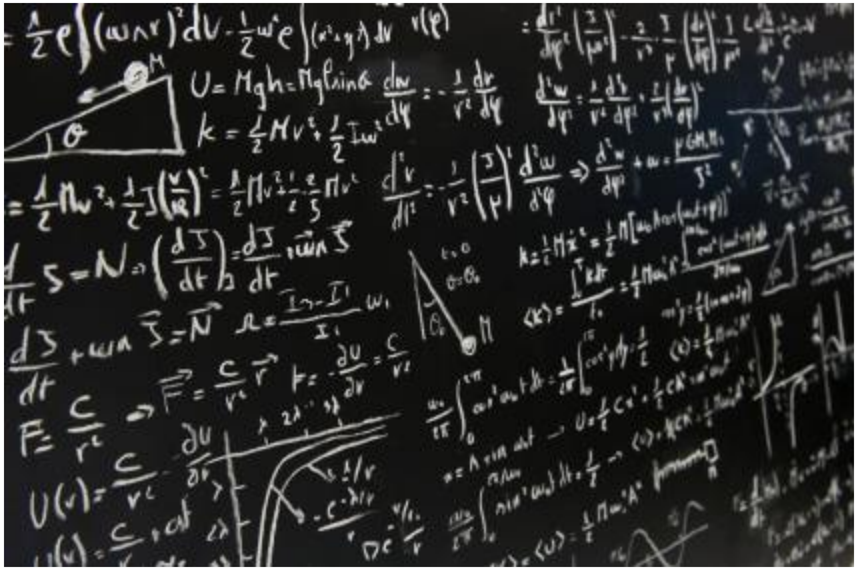
Sensor	Measurement	Notation	Unit	What for?
 Radio altimeter	Radio altitude height	HRA	ft	Approach and flare Anti tail strike
Multi Mode Receiver	ILS deviations	GS_{DEV}, LOC_{DEV}	µA	Take-off roll (LOC only) Approach, align & rollout
Tanks, fuel flow, flight mechanics equations…	A/C weight	WGT	T	Longitudinal & lateral inner loops
	CG position	CG	%	
Position sensors	Primary and secondary control surfaces	THS, ELEV, AIL, SP, RUD, S/F	deg	Longitudinal & lateral inner loops
	Landing gear position		up or down	
 Engine	Engine control parameter	N1 EPR	% wu	Auto thrust control
GPS 	Ground speed	$V_{GND\ GPS}$	kts	Backup display
	Altitude	Z_{GPS}	ft	
	Track angle	TRK_{GPS}	deg	

And many others, especially estimated parameters from raw data…

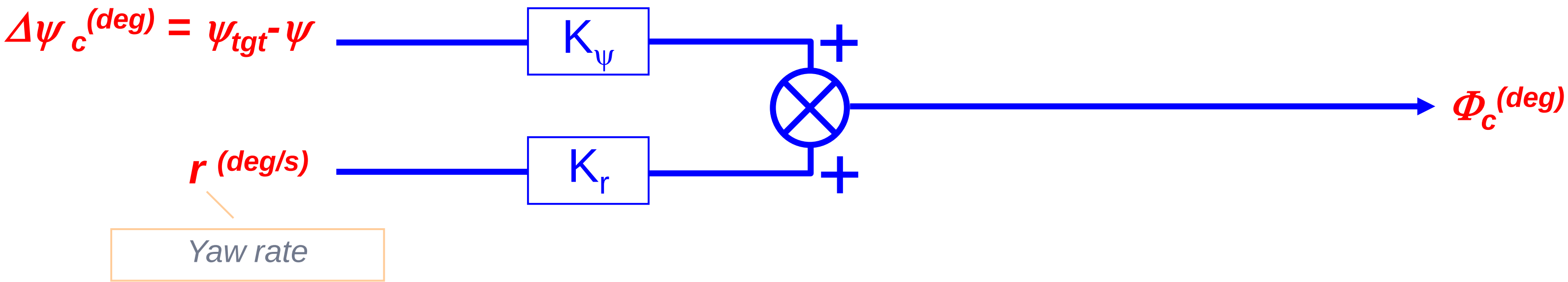
N1: Rotation speed of the engine fans

EPR: Engine Pressure Ratio (=output pressure / input pressure)

3 – AP/FD outer loops examples



Example 1: Acquire & hold a track angle target



- Considering a unique feedback (K_r=0)

$$\phi_c^{(deg)} = K_\psi \cdot \Delta\psi^{(deg)}$$

- Assuming a first order dynamics for inner loop

$$\frac{\phi}{\phi_c} = \frac{1}{1+\tau_\phi p}$$

- And simplified flight dynamics equations

$$\phi = \frac{V_{ground}^{(m/s)} \; \dot{\psi}^{(deg/s)}}{g}$$

- Comes the transfer function

$$\frac{\psi}{\psi_c} = \frac{1}{\left(\frac{\tau_\phi \cdot V_{ground}}{K_\psi \cdot g}\right) \cdot p^2 + \left(\frac{V_{ground}}{K_\psi \cdot g}\right) \cdot p + 1}$$

Example 2 : Acquire & hold a flight path angle target

$$\Delta\gamma_c^{(deg)} = \gamma_{tgt} - \gamma \longrightarrow \boxed{K_\gamma} \longrightarrow Nz_c^{(g)}$$

- Considering a unique feedback

$$Nz_c^{(g)} = K_\gamma \cdot \Delta\gamma^{(\mathrm{deg})}$$

- Assuming a first order dynamics for inner loop

$$\frac{Nz}{Nz_c} = \frac{1}{1 + \tau_{Nz}\, p}$$

- And simplified flight dynamics equations

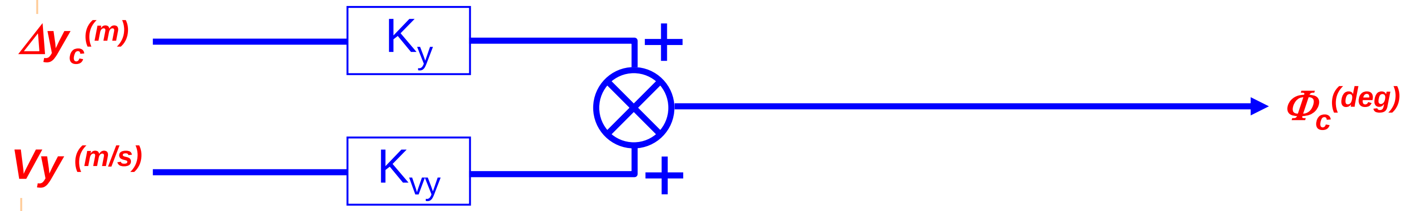
$$Nz^{(g)} = \frac{V_{inertial}^{(m/s)} \cdot \pi \cdot \dot{\gamma}^{\text{(deg/s)}}}{g \cdot 180}$$

- Comes the transfer function

$$\frac{\gamma}{\gamma_c} = \frac{1}{\left(\dfrac{\tau_{Nz} \cdot V_{inertial}}{K_\gamma \cdot g \cdot 57.3}\right) \cdot p^2 + \left(\dfrac{V_{inertial}}{K_\gamma \cdot g \cdot 57.3}\right) \cdot p + 1}$$

Example 3: Acquire & hold a horizontal path target

Lateral deviation between the A/C and the path, estimated from sensors (GPS, IRS, ILS…)



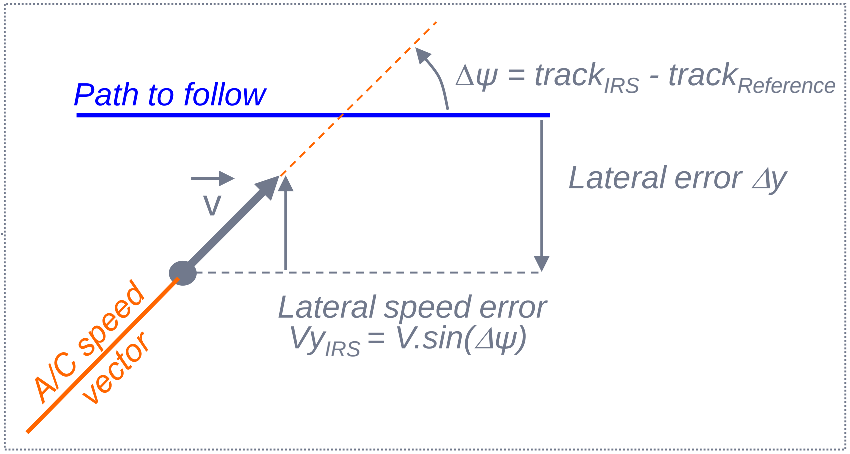
Estimated lateral speed error

- Lateral speed error estimation (Vy)
  - From inertial data

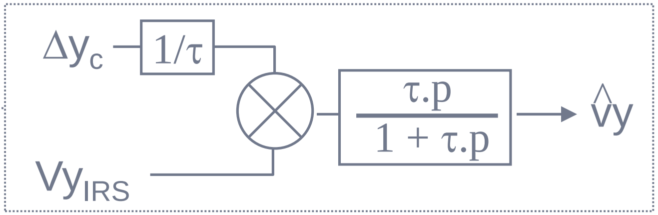
    … possible bias due to IRS drift

  - From measured lateral deviation

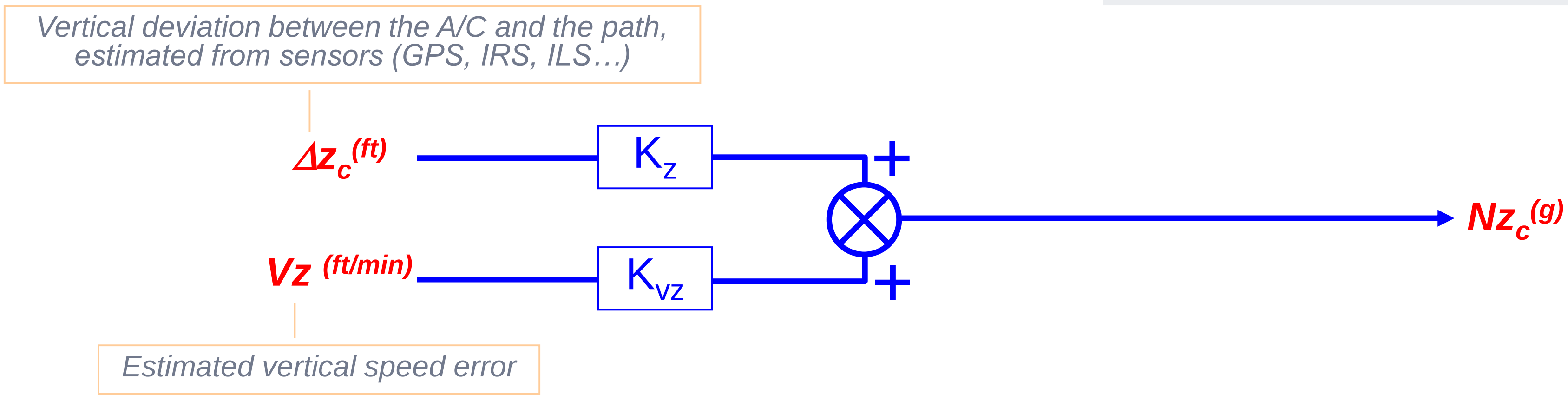
    … poor result when deriving a noisy signal



Complementary filter combining both



Example 4: Acquire & hold a vertical path target



- Vertical speed error estimation (Vz)
  - From inertial data

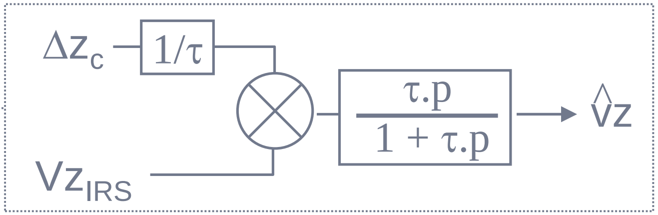
    … possible bias if reference is inaccurate

    $$Vz_{IRS} = V_{3D}.\sin(slope_{IRS} - slope_{Reference})$$

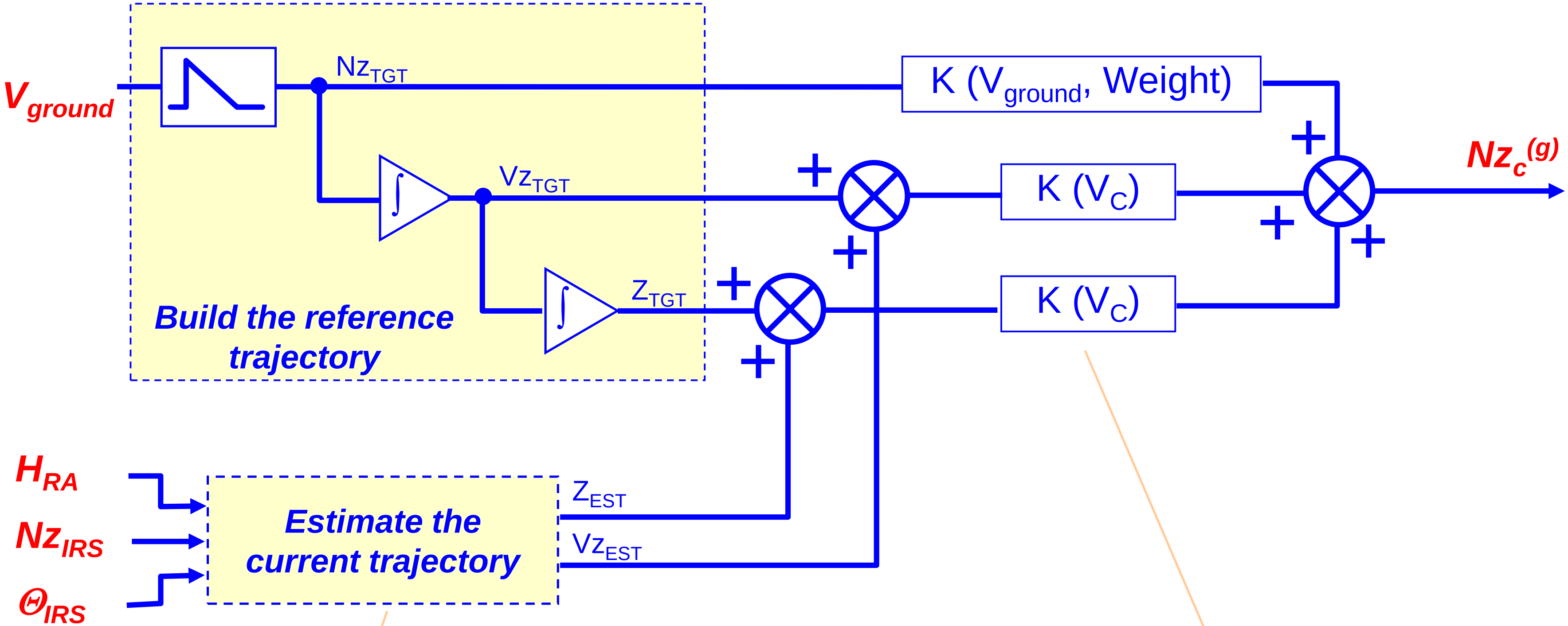
  - From measured vertical deviation

    … poor result when deriving a noisy signal

Complementary filter combining both



Example 5: Flare outer loop dedicated to autoland function



Estimator requirements:

- *Remove noisy / biased part of measured data*
- *Feed outer loop with accurate position & speed*

Outer loop requirements:

- *Pitch stability and no elevators oscillations*
- *Initial pitch up similar to a manual flare*
- *Performances in terms of touch down charateristics*

3 – Flight control laws design

Flight Control Laws requirements

- Based on **stability**, **performance**, **comfort** and **safety** objectives

- Nominal performance
  - Expected **within** the operational flight envelope and **out of failures**
  - Objective: **robustness** with respect to every day disturbances
    - Wind & turbulence
    - Sensors characteristics : biases and noise
    - Known events from in-service fleet or previous flight tests campaigns
      - Wind gradient, ILS beam noises, particular terrain profiles

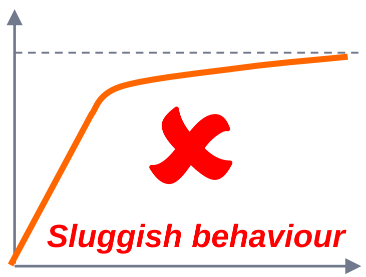
- Marginal performance
  - Objective: reassuring behaviour further to severe disturbances
    - **Outside** the operational flight envelope of the system
    - Abnormal procedures
    - **Failures**: engine, sensor or control surface
    - Severe gusts or turbulence

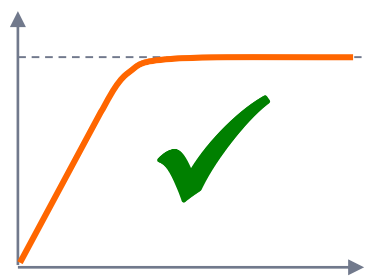
… so that the crew can analyse the situation before potentially take over

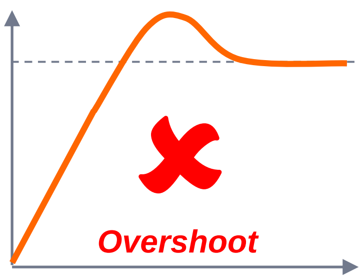
Performance criteria

- General criteria in stabilized phase and in manœuvre
  - Lateral axis: focused on sideslip, bank angle & lateral load factor Ny
  - Vertical axis: focused on normal load factor Nz, pitch angle & pitch rate

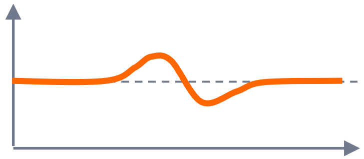
- Criteria specific to each control law
  - Capture dynamics following a **target change**







  - Target recovery dynamics after **disturbances**
    - Wind gradients and turbulence
    - Change in configuration (gears, speedbrakes, slats/flaps)
    - Failures



Flight control laws tuning issues (1)

- **Knowledge of the aircraft** and representativeness of its models
  - Aerodynamics: needs a good identification from wind tunnel and flight tests
  - Actuators & sensors: needs accurate data from suppliers

- **Loads & aeroelasticity** constraints
  - Limit loads in manœuvre or in turbulence $\Rightarrow$ limit gains
  - Avoid exciting structural modes (flutter) $\Rightarrow$ filter, limit gains

- **Sensors** contraints
  - Process noisy or biased signals $\Rightarrow$ filter, merge data (complementary filter)
  - Limit the effects of failures $\Rightarrow$ limit and rate-limit FCL orders
  - Manage the signal loss $\Rightarrow$ **reconfigure** on a different source, data or law

Flight control laws tuning issues (2)

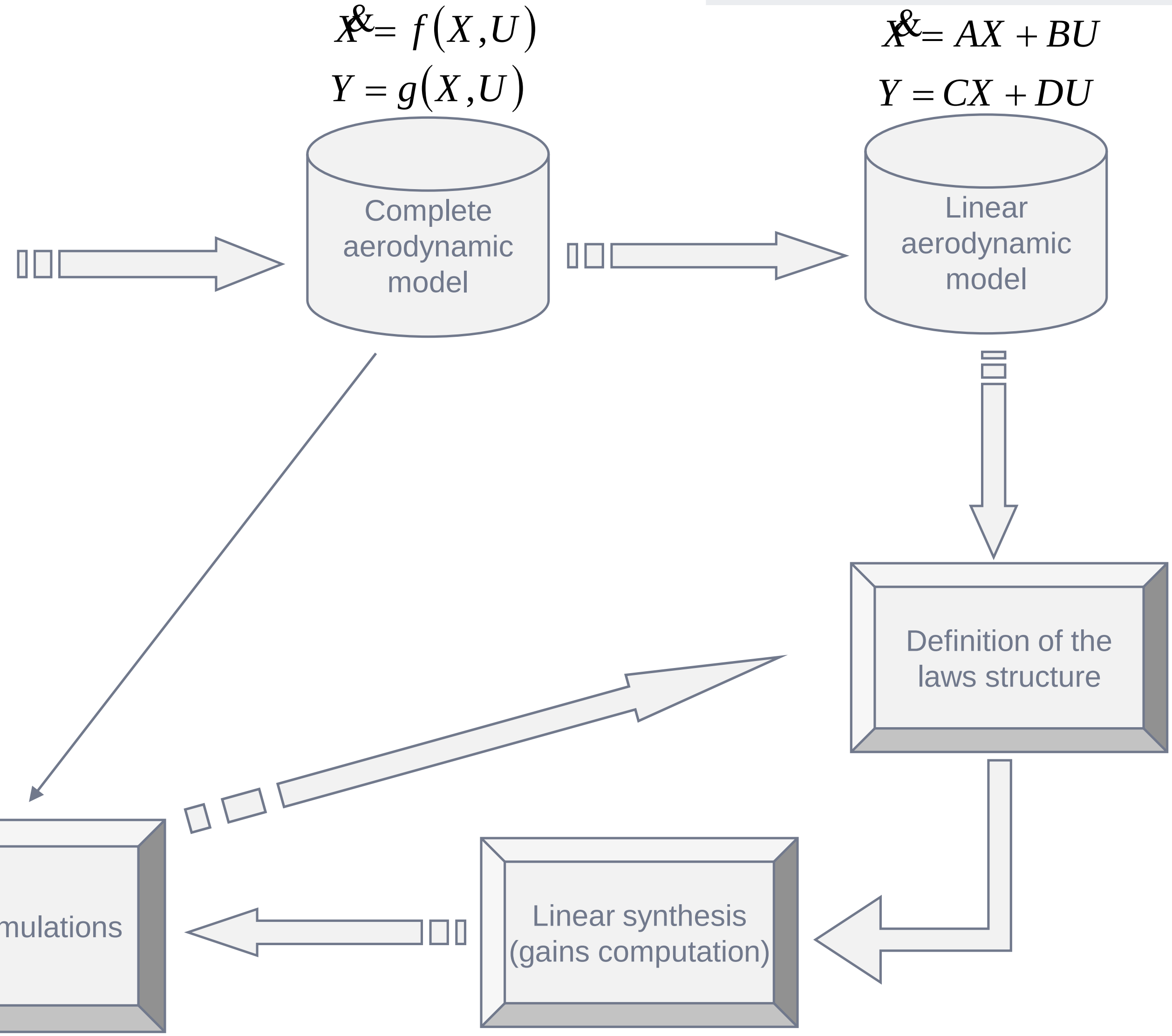
- **Actuators** constraints
  - Set a time response of control loop compatible with actuators' one
    - Make sure that our orders can be followed by the actuators
  - Find an appropriate **trade-off** between fatigue and performance

- **Architecture** constraints
  - Consider the **global delay**: own delay of each system, acquisition/emission…

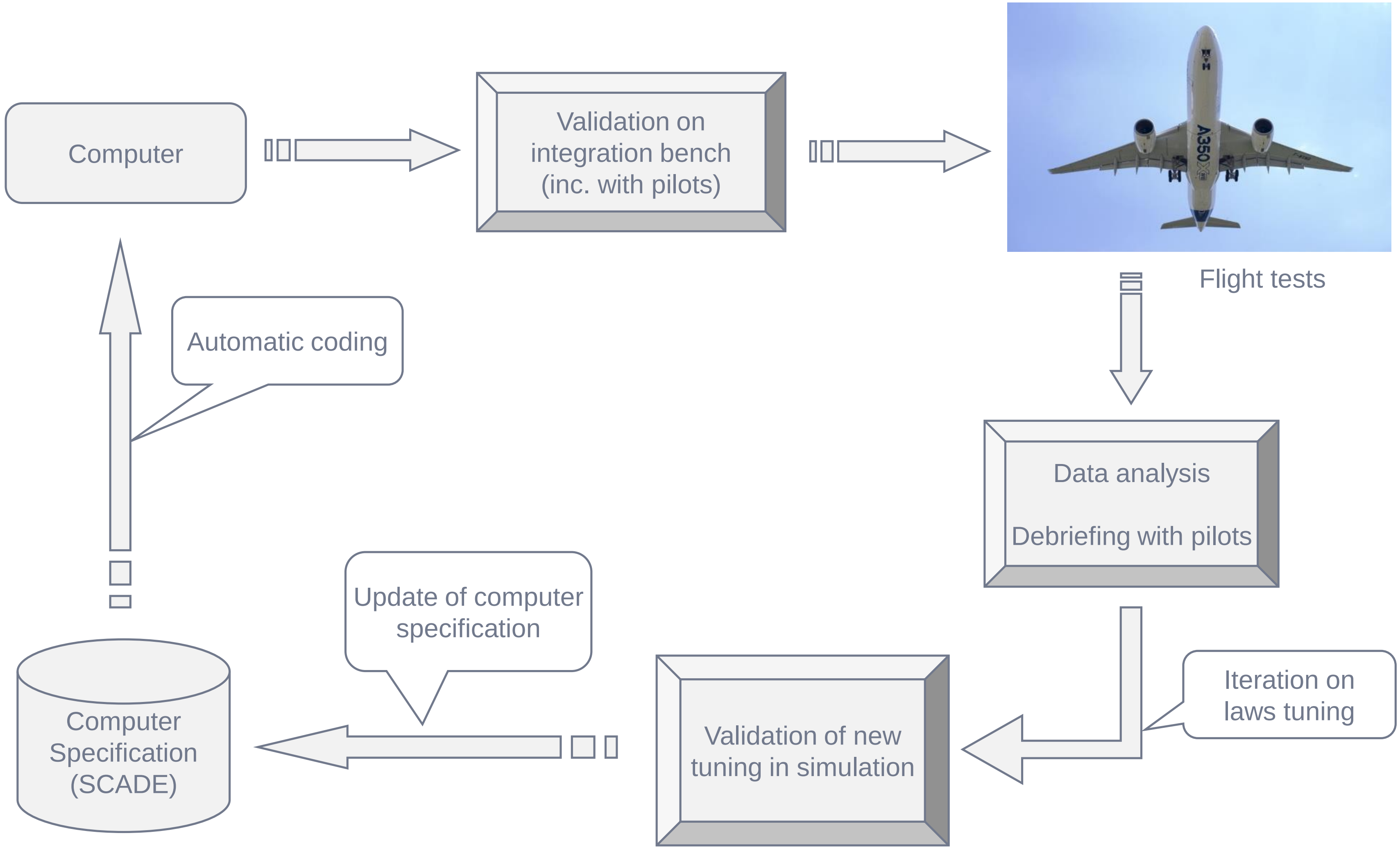
- **Pilot** constraints
  - Make autoflight behaviour close to what a pilot would do
  - Converge towards a FD satisfying a heterogeneous pilots community
    - For a given FD demand, pilots actions on the sidestick can be very different
  - Find an appropriate **trade-off** between comfort and performance

Flight control laws (FCL) development before the first flight

Wind tunnel tests



FCL development during the flight tests campaign

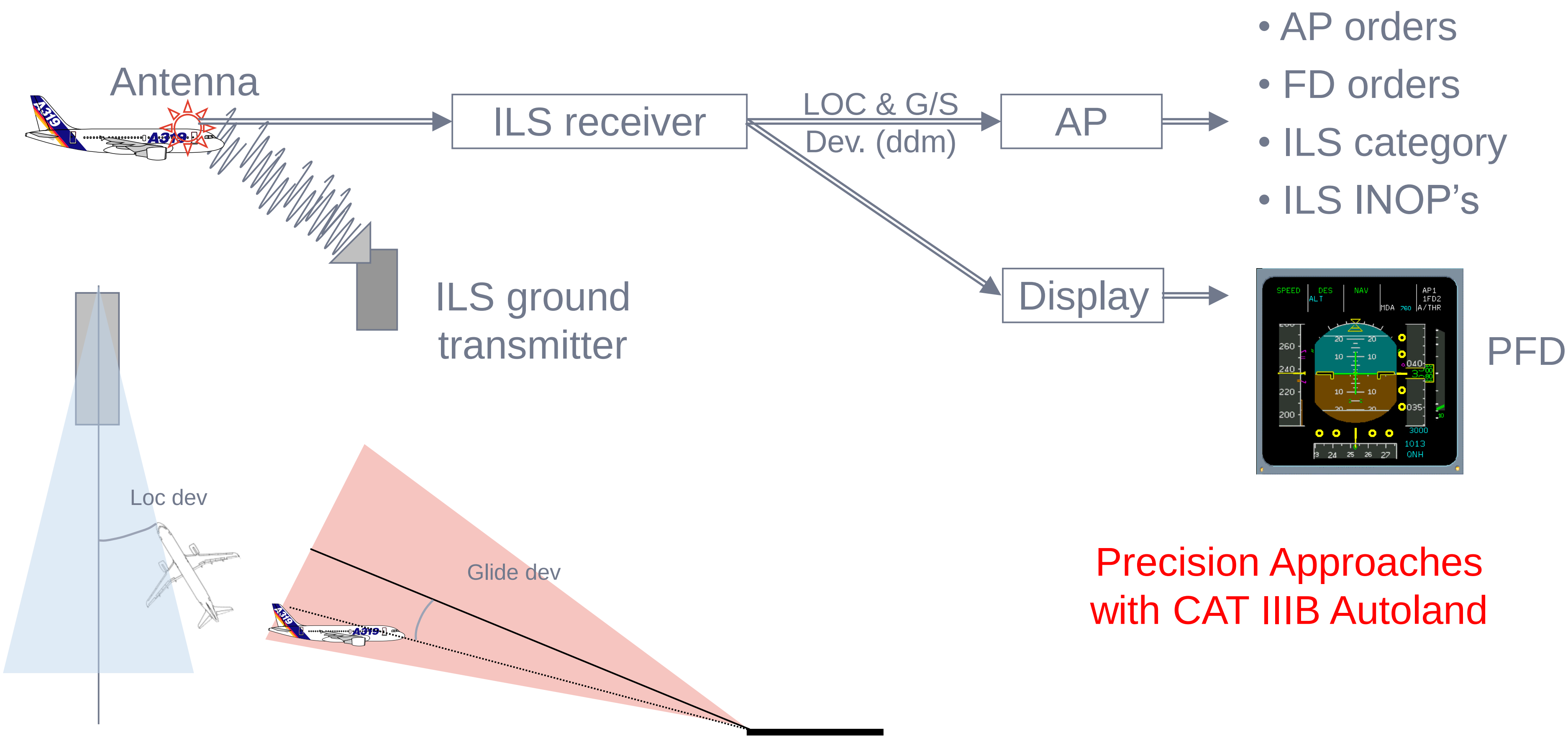


4 – Automatic landing specificities

Autoland guidance references (1/2)

1 – ILS: Instruments Landing System

“Historical” mean



Autoland guidance references (2/2)

2 – GLS: GNSS Landing System based on GPS & DGPS

Use of satellites and ground stations

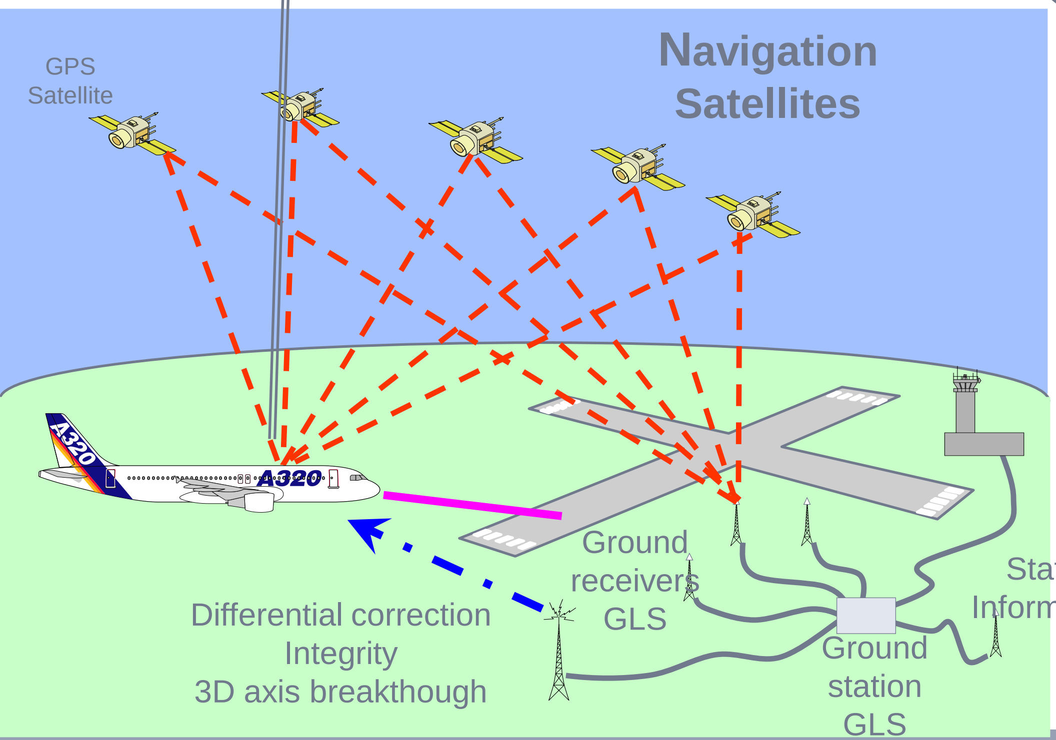
MMR
Multi Modes Receiver

GLS mode
LOC & G/S
Dev. (ddm)

AP

Display

- AP orders
- FD orders
- GLS category
- GLS INOP's



PFD

« ILS LOOK ALIKE » concept
Precision Approaches
for CAT I only & autoland

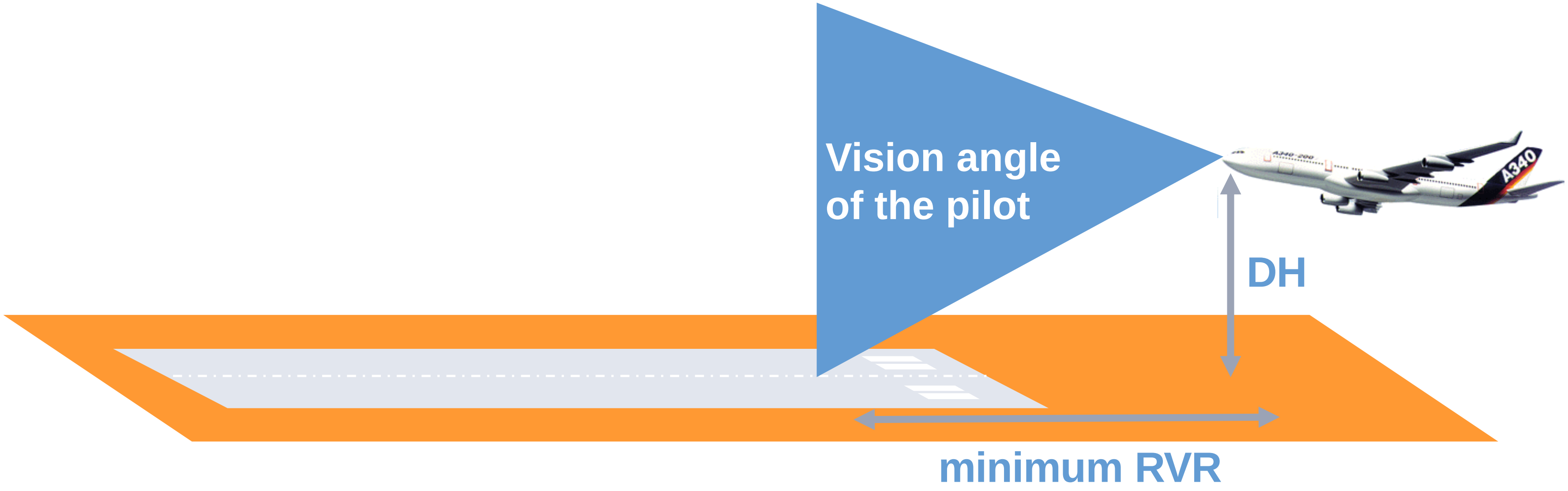
Autoland categories: definitions

- **DH**: **D**ecision **H**eight

  Height at which the pilot must have the **visual references** (runway, lights…)

  Else the approach must be interrupted and a **go-around** must be performed

- **RVR**: **R**unway **V**isual **R**ange (horizontal visibility)



Autoland categories: definitions

- **Fail passive** system

  The system **can not ensure its function** if a failure occurs but there will not induce a consequence on the flight safety (the failure is passivated).

  ➔ No significant effect on A/C trajectory

- **Fail operative** system

  The system keeps on ensuring its function after the 1st failure. It stays operational: the **safety and the performance are maintained**.

  ➔ Operations carried on normally (thanks to redundancy…)

Autoland categories

<table>
<tr><th>Categories</th><th>Navigation means</th><th>Operational Limitations (DH, RVR)</th><th>Automatic guidance modes required</th><th>Failures effect</th></tr>
<tr><td>I</td><td>RNAV
ILS CAT I</td><td>DH > 200 ft</td><td>Display of ILS signals
(no automatic guidance required)</td><td rowspan="3">Fail Passive</td></tr>
<tr><td>II</td><td>ILS CAT II</td><td>DH > 100 ft</td><td>⊕
Fail passive automatic approach & go-around</td></tr>
<tr><td>III A</td><td rowspan="3">ILS CAT III</td><td>DH < 100 ft or « no DH »
& RVR > 200 m</td><td>⊕
Autoland
Automatic thrust control</td></tr>
<tr><td>III B</td><td>DH < 50 ft or « no DH »
& RVR > 50 m</td><td>⊕
Fail operative autoland
Fail passive rollout</td><td rowspan="2">Fail Operative</td></tr>
<tr><td>III C</td><td>« no DH » & « no RVR »</td><td>⊕
Fail operative rollout</td></tr>
</table>

Performances demonstration: simulations & flight tests

- Simulation performance
  - **Reduction** of the volume of certification flight tests
    - Wide range of autoland conditions can be covered by simulation
  - Performances must be **compliant** with the regulations
    - Results to be compared to certification requirements
  - Methods & means must be **approved** by airworthiness authorities
    - Simulation means, wind models, results processing…
  - Simulation representativeness demonstrated by **flight test matching**

- Flight tests performance
  - **Touch down**: 100 autolands in various conditions, for certification only
    - Aircraft loading envelope (WGT & CG)
    - Wind conditions (calm or windy: head, cross, tail)
    - Runway profiles: specific profiles and high altitude terrain
  - **Roll-out**: 20 autolands where the AP is kept engaged after touchdown
  - **Go-around**: ~10 go-arounds, with or without engine failure

Flight tests matching with the simulation

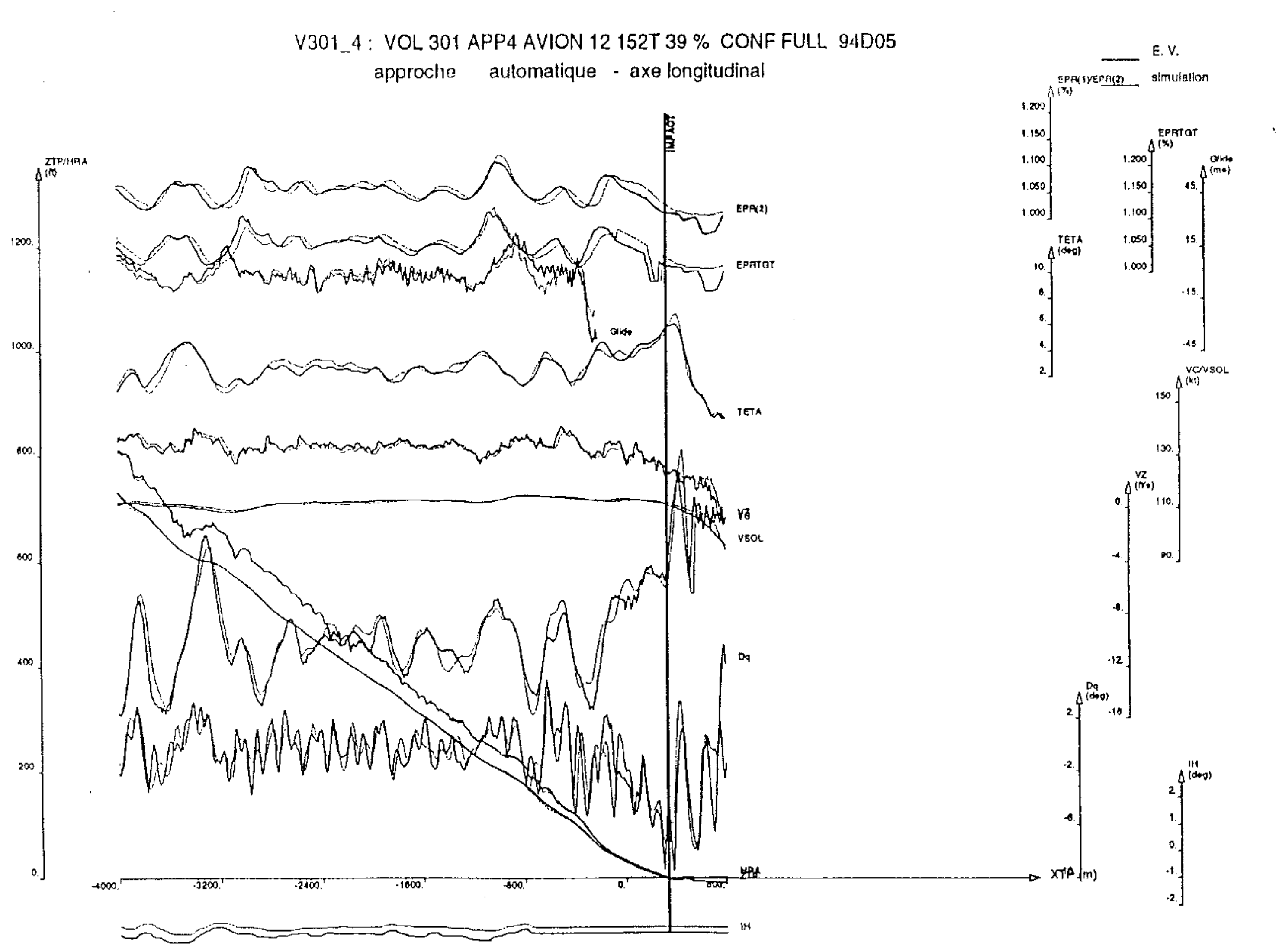


figure 1-3 Flight 301/4 - a/c 12 - Longitudinal axis

Touch down performance: statistical demonstration (1)

- Assess the **probability of occurrence** of some events
  - Landing too short, too long, too far from the runway centre line
  - Structural damages (hard landings)
  - Runway exit during the roll-out

- Considering **various approach conditions**
  - Aircraft parameters: weight, CG position, configuration…
  - Atmospheric parameters: wind and turbulence
  - Airport parameters: temperature, terrain elevation, runway profile, runway state (wet/dry), ILS slope, noise…

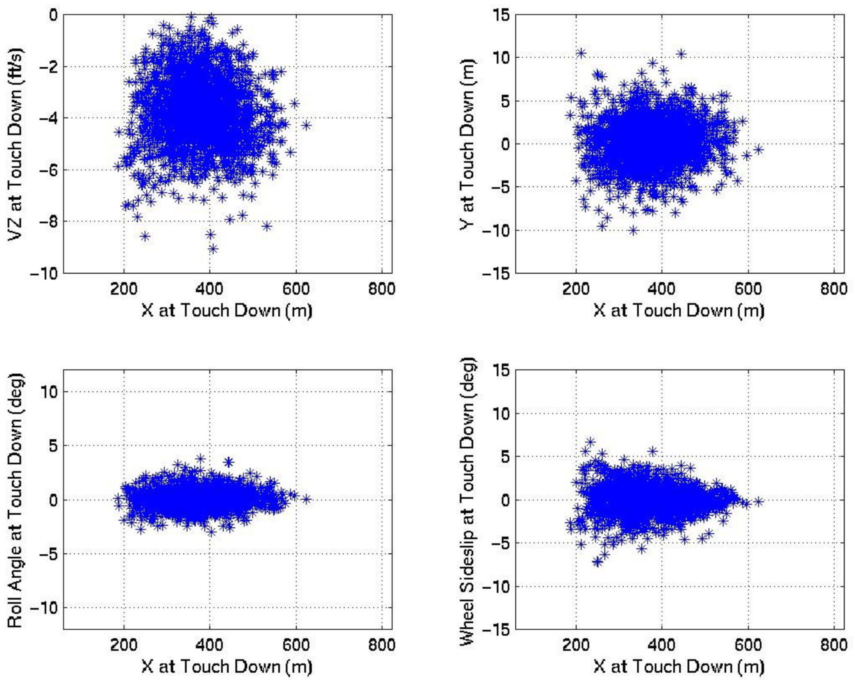
- To **demonstrate** the compliance with the regulations
  - Average risk: all parameters are distributed (random process)
  - Limit risks: one of them is set to its most adverse value
    - Limit probability of occurrence is then relaxed
    - Examples of limit risks: max crosswind, heaviest weight, one engine failed…

Touch down performance: statistical demonstration (2)

Limit probabilities set by the regulations

		Risks	
		Average	*Limit*
Main landing gear position at touch down			
XTP	Less than 60m beyond runway threshold	10^{-6}	10^{-5}
XTP	More than 823m beyond runway threshold	10^{-6}	10^{-5}
YTP	More than 21m from centre line (outer wheel)	10^{-6}	10^{-5}
Structural limits			
VZ_{IMP}	Sink rate beyond the maximum value	10^{-6}	10^{-5}
β_{NW}	Wheel sideslip beyond the maximum value	10^{-6}	10^{-5}
φ	Bank angle beyond the maximum value	10^{-8}	10^{-7}
Maximum lateral deviation during the roll-out			
YTP	More than 21m from centre line (outer wheel)	10^{-6}	10^{-5}

Touch down performance: example



	Average	***Std deviation***	***Min***	***Max***
XTP (m)	378	71	186	624
VZTP (ft/s)	-3.7	1.3	-9.1	0.3
YTP (m)	0.1	2.5	-10.1	10.5
PHI (deg)	0	0.8	-3	3.8
BETA (deg)	-0.1	1.4	-7.2	6.7

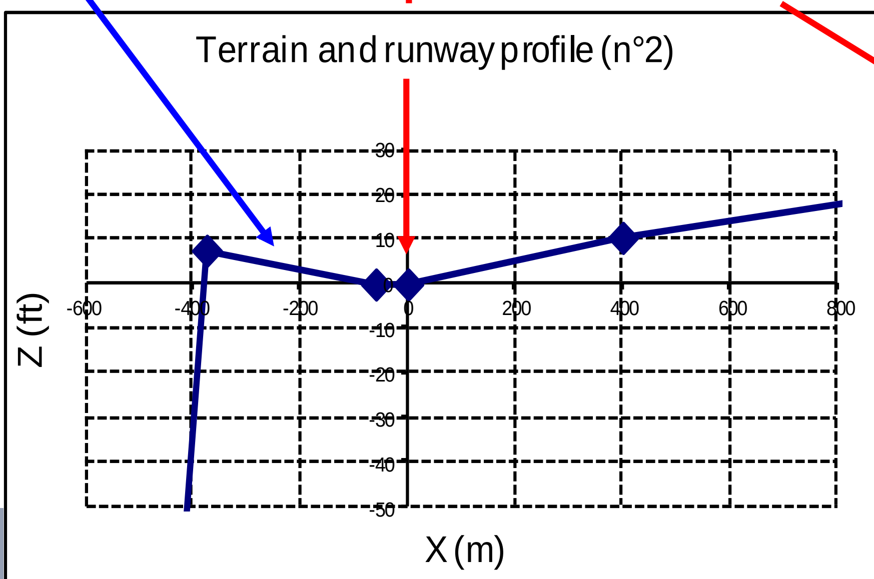
Performance robustness to runway profiles

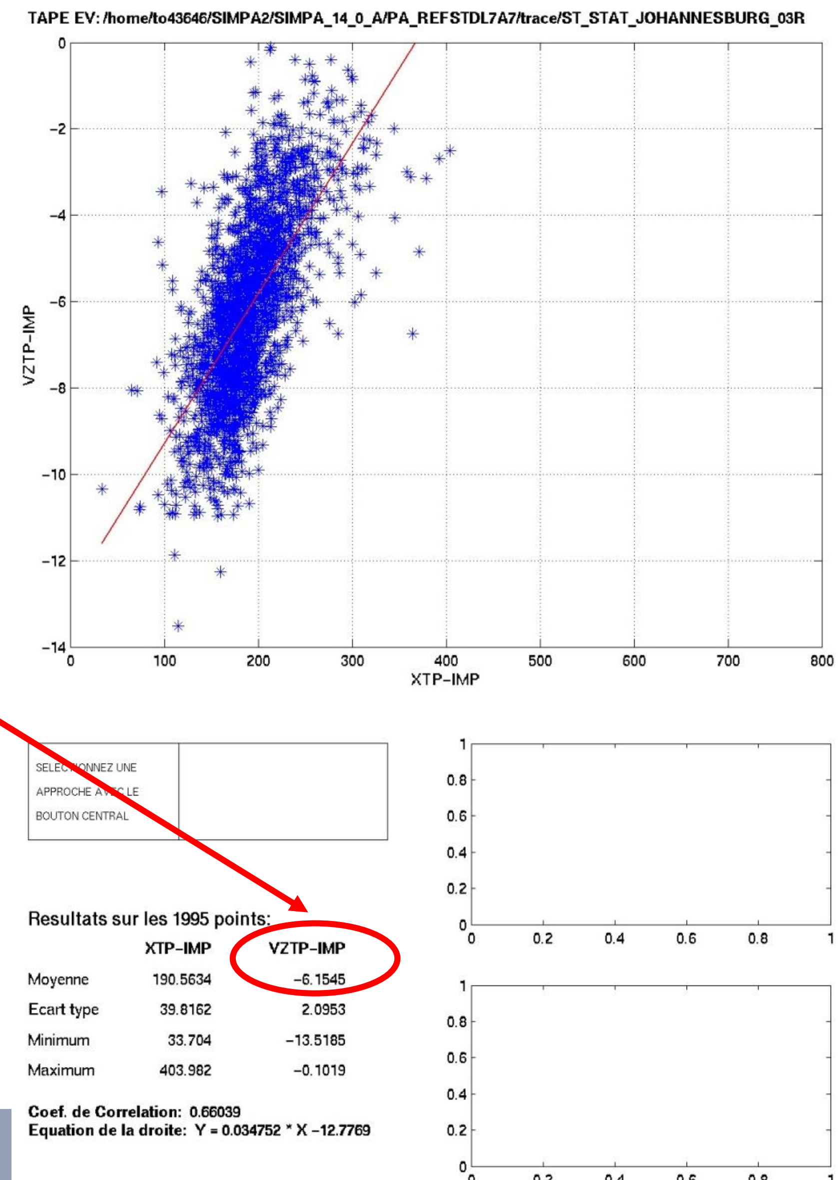
Autoland performances analysis on other « exotic » runways.

Nose down order commanded by AP due to the descending profile (Johannesburg)

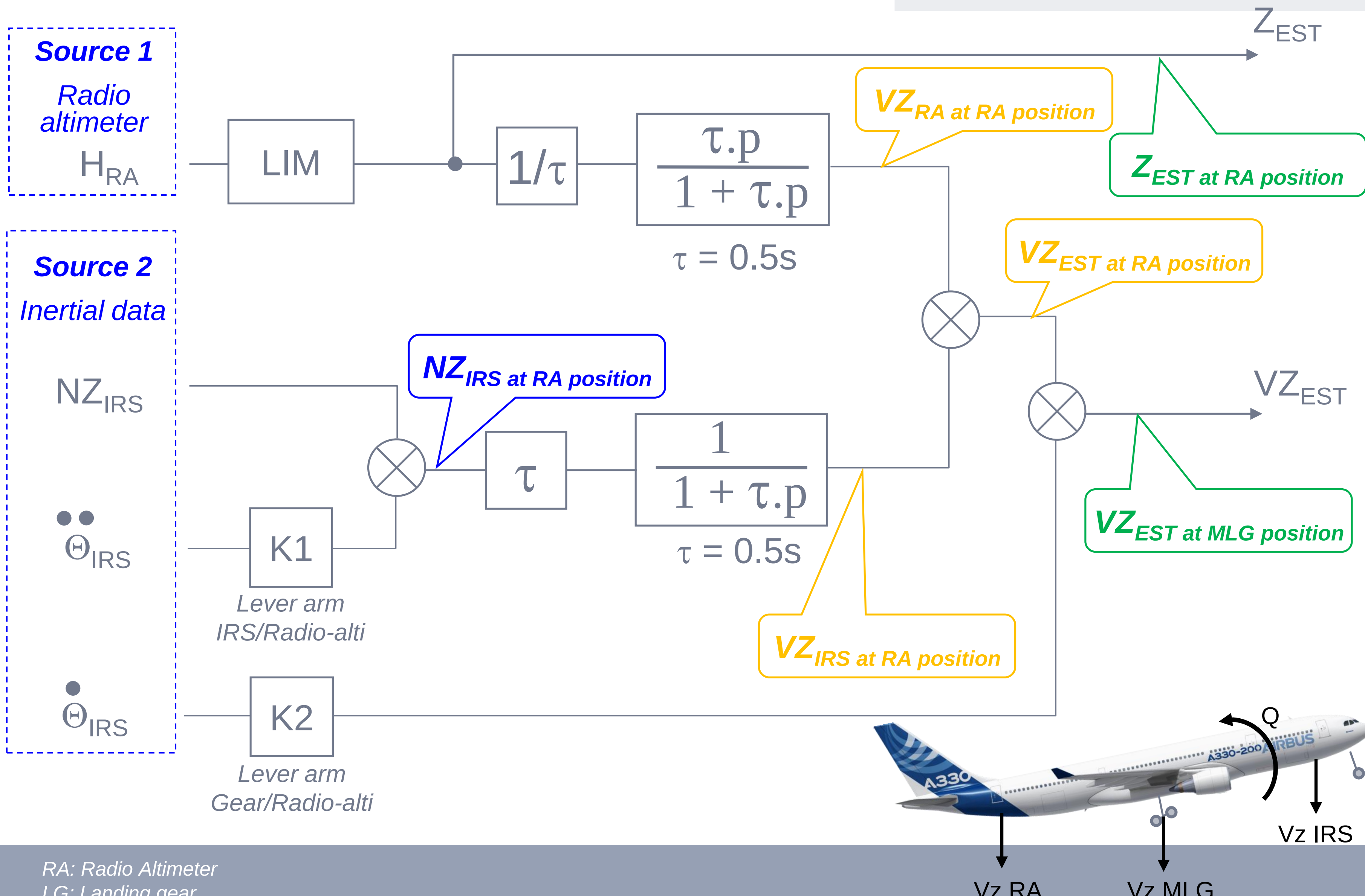
Slope inversion near the runway threshold

⇒ Hard landing





Lack of robustness due to the trajectory estimator in Flare



RA: Radio Altimeter
LG: Landing gear

THE END!

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