AIRCRAFT VIRTUAL FLIGHT TEST AND CERTIFICATION TECHNOLOGY: VALIDATION AND APPLICATION EXPERIENCE

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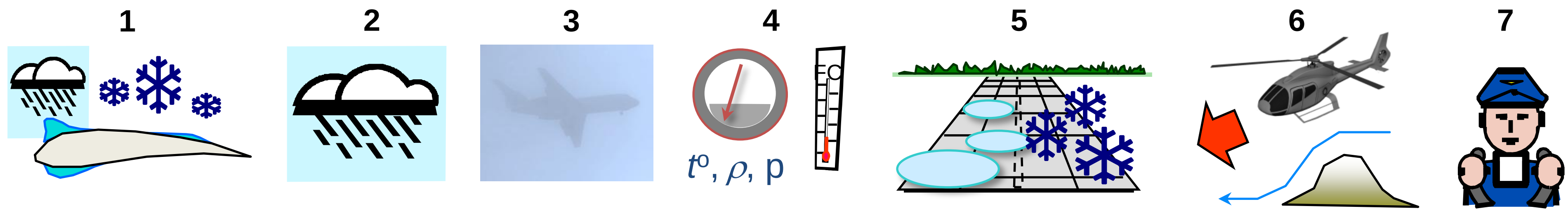
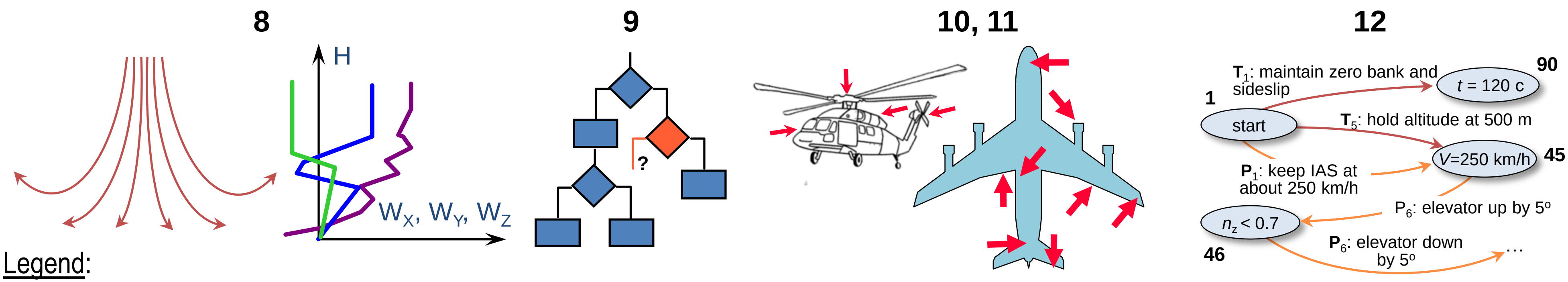
Flight Safety Risk Factors





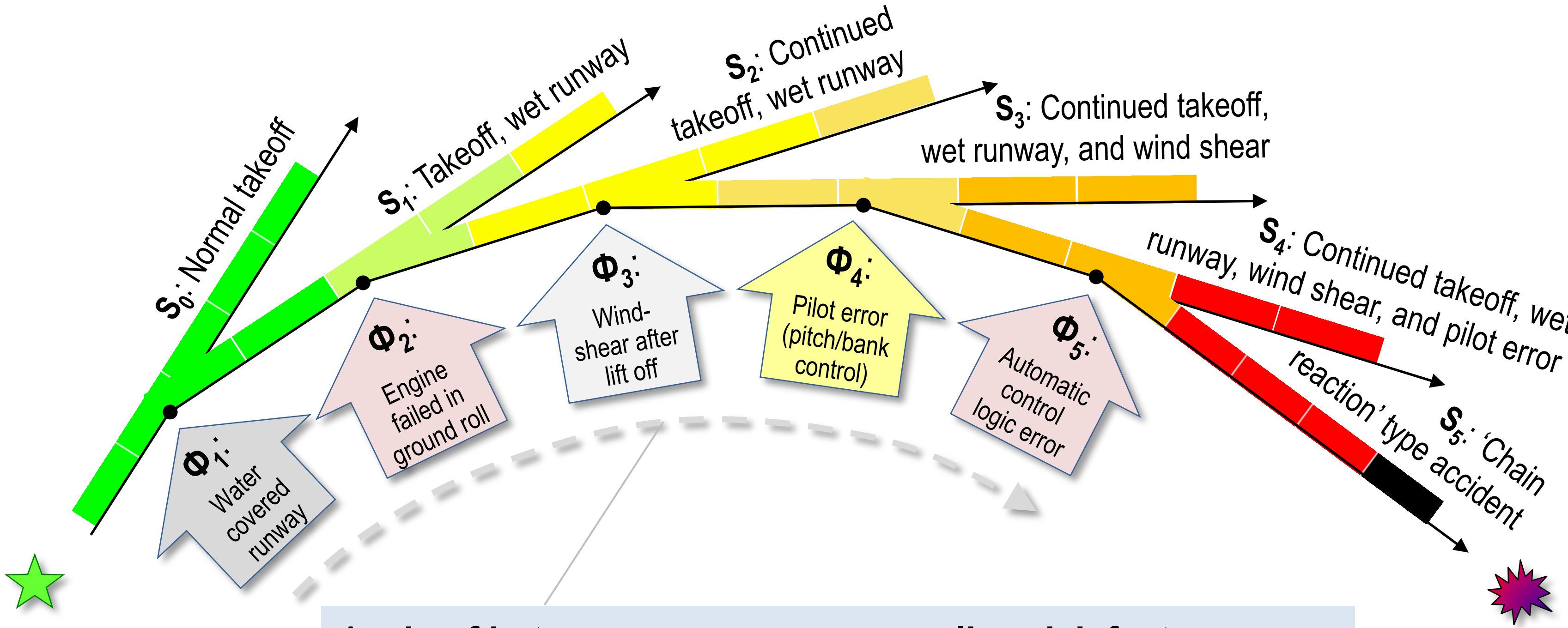
Legend:

1 – **icing** (effect on aerodynamics of wing, fuselage and tail).
2 – **rain** (effect on aircraft aerodynamics and dynamics).
3 – poor visibility, **fog**, nighttime,
4 – non-standard **atmospheric conditions** (temperature, pressure).
5 – demanding **runway conditions** (wet, ice-/snow-covered), uneven geometry, dynamics.
6 – **obstacles** (moving, stationary) or other kinetic threats.
7 – human **pilot errors**, inattention, terrorist-/ inadequate-/ sick-type tactics (objectives, observers, gains, delays, etc.).

8 – **wind** (any 2D/ 3D profile: gust, crosswind, headwind, tailwind, wind-shear, 'microburst', rotor, lee wave, wake), atmospheric **turbulence**.
9 – onboard **flight automation software logic or/ and data errors**.
10 – onboard **hardware mechanical failures** (engines, controls, actuators, undercarriage, etc.).
11 – variations of aircraft **aerodynamic configuration**, weight, center of gravity and moments of inertia.
12 – variations of **flight control scenario**, Pilot's Manual errors/ ambiguities.

Irreversible cause-and-effect composites of several risk factors are **in charge for many accidents**.

Build-up Mechanism of ‘Chain-Reaction’ Accident In Multifactor Situations – Takeoff Example



initial state (safe)

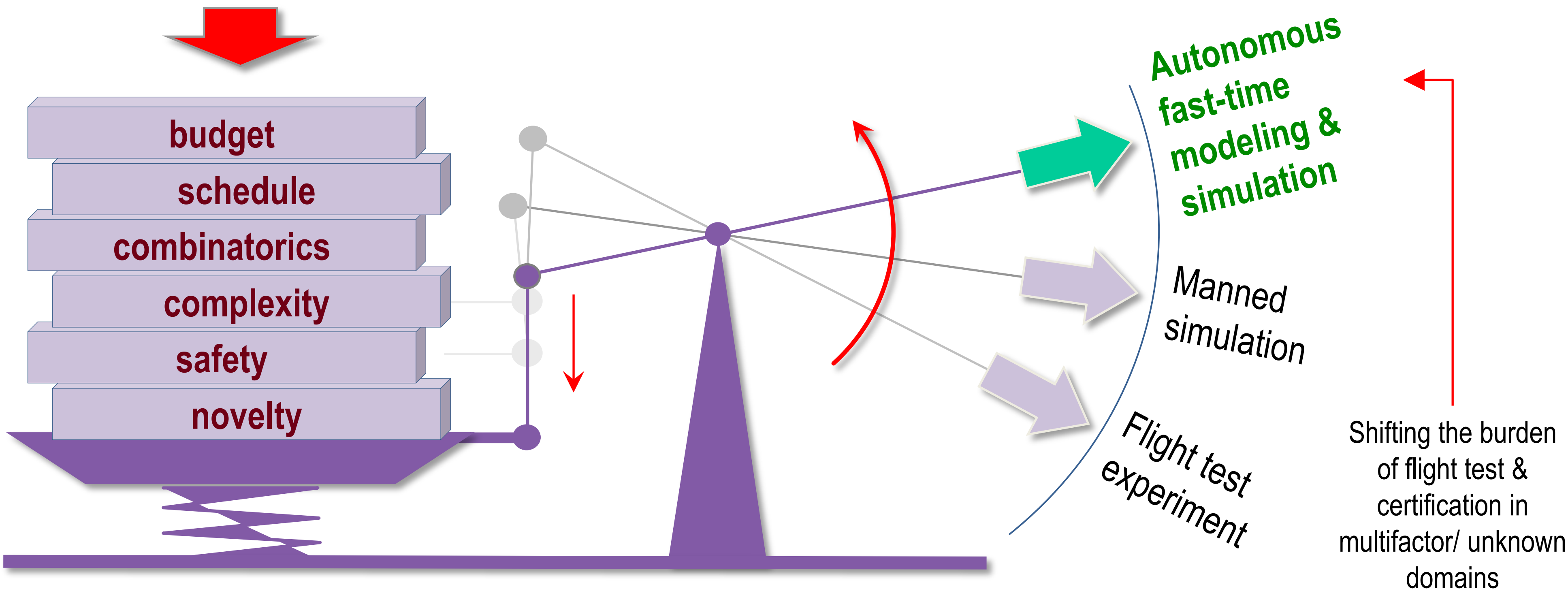
A **mix of heterogeneous cross-coupling risk factors** can spontaneously trigger a ‘chain reaction’ accident. Such scenarios are extremely rare (‘theoretically improbable’), but quickly propagate and often unknown to engineers and pilots.

final state (catastrophic)

Legend: – time axis of an ‘alternative future’ (a ‘what-if’ situation). – a situational tree of ‘alternative futures’ – ‘what-if’ takeoff situations. Φ – a risk factor embedded into a ’what-if’ hypothesis to ‘plant’ a multifactor situational tree of VFT&C domain. • – an event when a new (additional) risk factor is ‘grafted’ into the situational tree. $\mathbf{S}_0$, …, $\mathbf{S}_5$ – alternative scenarios in the order of increasing complexity and risk: $\mathbf{S}_0$ – normal (benign, no risk) scenario, …, $\mathbf{S}_5$ – highly complex catastrophe-prone (five-factor) scenario. – safety colors.

Why Autonomous Fast-Time Flight Modeling and Simulation for Aircraft Test & Certification?

By using classic flight research techniques, the behavior of the 'pilot – automaton – aircraft – operating environment' system in multifactor situations **cannot be examined for safety – proactively and exhaustively** – due to the following pressures:

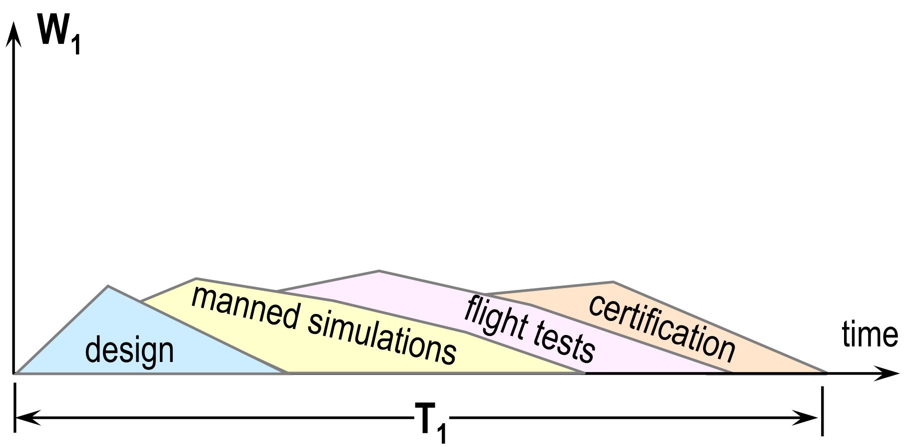


The problem is a **lack of affordable and efficient technologies** for examining multifactor operational domains of flight for safety. 'Virtualization' of aircraft flight test and certification in multifactor conditions based on autonomous fast-time M&S emerges as an **natural affordable solution** to this problem.

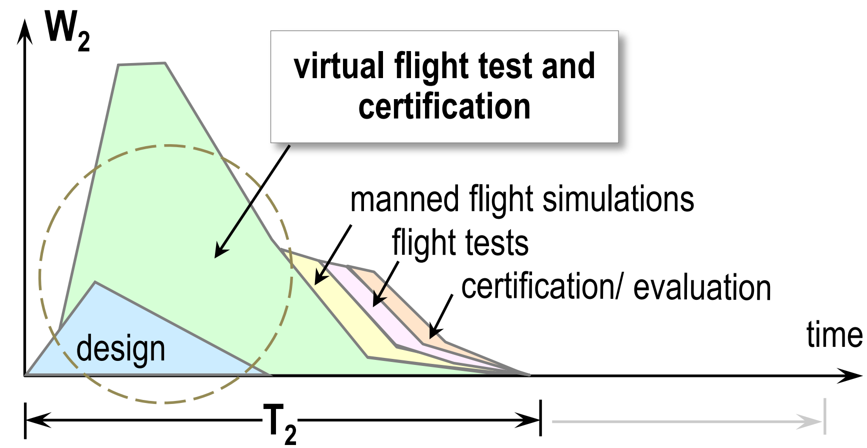
Classic vs. Enhanced Design, Flight Test & Certification Cycle

1. Research Task Formulation

Classic cycle – extensive and less integrated

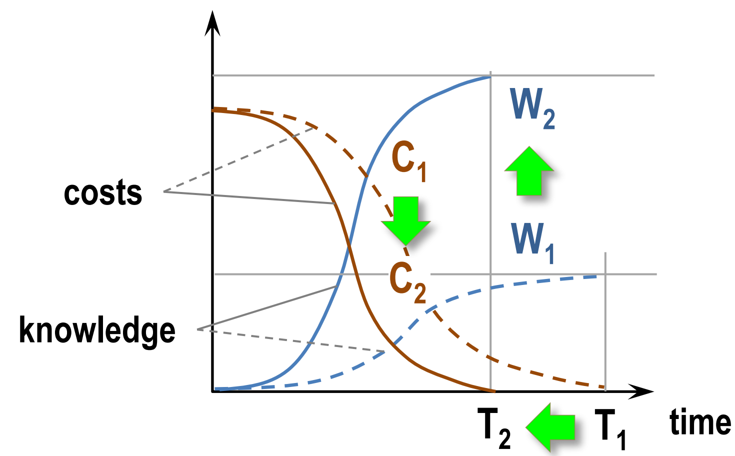


Fast-time flight M&S based cycle – intensive and integrated



The goal of virtualization ('dematerialization') of flight research **into multifactor domains** is three-fold:

- $W_2 >> W_1$ – **gain much more predictive knowledge** on the system performance & safety earlier in the lifecycle.
- $C_2 << C_1$ - **cut cost** of design, flight test & certification.
- $T_2 < T_1$ - **shorten** 'design - T&C' **schedule**.



Legend: **W** – knowledge gained on aircraft flight performance & safety. **C** – flight test & certification (evaluation) costs. **T** – cycle duration time.

Demand for Virtualization ('De-Materialization') of Multifactor/ Unknown Scenario Accidents

'As with most aircraft accidents, **there were several 'ifs'** that might seem **relatively benign when taken separately but together conspired to inflict substantial damage**… and present a hazard to … people aboard. **If** the approach speed had been a few knots lower, **if** the touchdown has been a few meters shorter, **if** the runway had been dry and just a bit longer, **if** the pilots had considered a go-around a few seconds earlier, **if** the thrust reverser system had not malfunctioned, or **if** the concrete base for an approach light had not protruded from the ground off the runway, the … accident … might not have happened'.

*[Mark Lacagnina, '**A Matter of Meters**', AeroSafety World, The Journal of Flight Safety Foundation, April 2012, pp. 16-19].*

'The European Aviation Vision 2050… **The European certification process, based on virtual simulation** tools **is widely applied** at both component and product level and is **streamlined, efficient and low cost.** … Comprehensive and consolidated test, demonstration and validation infrastructures are harmonised, interoperable and available across Europe to support the **transition to automated, autonomous and integrated systems** and beyond. **They include modeling, fast- and real-time simulation and flight-trial systems.** These capabilities integrate the ground and airborne validation and certification processes. **Education and training for controllers, pilots and engineers** are incorporated into the system **supported by training and simulation tools…**'.

*[**Flightpath 2050**. Europe's Vision for Aviation. Report of the High Level Group on Aviation Research, European Commission, Directorate General for Mobility and Transport, Luxembourg, EC, 2011, 21 pp.].*

There is a strong public and professional demand for **'dematerialization' of dangerous multifactor flying experience** through the entire lifecycle - from design to operations.

Virtual Flight Test & Certification (VFT&C) Technology

Virtual Flight Test & Certification (VFT&C) Technology

Intelligent Situational Awareness & Forecasting Environment (ISAFE) methodology

Virtual Autonomous Test & Evaluation Simulator (VATES tool), its prototypes and derivative tools

Application case studies: design, flight T&C, accident analysis, research/student projects

KEY COMPONENTS

Theory of multifactor flight domains (**).

'Pilot - automaton - aircraft - operating environment' **system dynamics model.**

Human pilot model - Prof. Totiashvili model (*).

'Events-processes' language for scripting flight situation scenarios.

Generalized **model of a complex flight situation**.

Techniques for safety **knowledge 'mining' & mapping (**).**

Generalized computational algorithms and data structures (**).

Standardized and automated process of autonomous fast-time flight M&S (**).

Techniques for **automatic exploration of multifactor operational domain** and automatic generation of safety knowledge maps (**).

Software tool for **automatic generation of software modules** for calculating aircraft input characteristics based on its 'parametric definition'.

Flight test & certification: **Experimental WIG, BURAN Aerospace Plane, Ilyushin-86/ -114/ -96-300/ -76/ -96T, Sukhoi-80GP, Tupolev-154M/ -204/ -214/ -334.**

Flight operations and accident investigation: **Antonov-28, Beriev-103, Boeing-737-300, Let L-610, Ilyushin-62M/ -86 / -76, Kamov-32, Mil-26/ -8, Tupolev-134A/ B, Tupolev-154/ -154M, Yakovlev-40.**

Flight dynamics, piloting and safety research (incl. MSc, PhD, DSc) projects, CD/ PD: **FLA F-93A, Hypersonic Maneuvering Vehicle, Notional 4++ Gen Highly-Maneuverable (TVC) Jet, Cessna Citation X, Concorde, HSCT, SSBJ, Sukhoi-38/ -49, Tupolev-136, XV-15.**

Legend: (*) – the pilot model is a part of the system dynamics model. (**) – VATES v.7, 8.

VFT&C technology resides on three pillars: a generalized **methodology**, a validated **software** tool and many **application case studies** for various aircraft types and operational domains.

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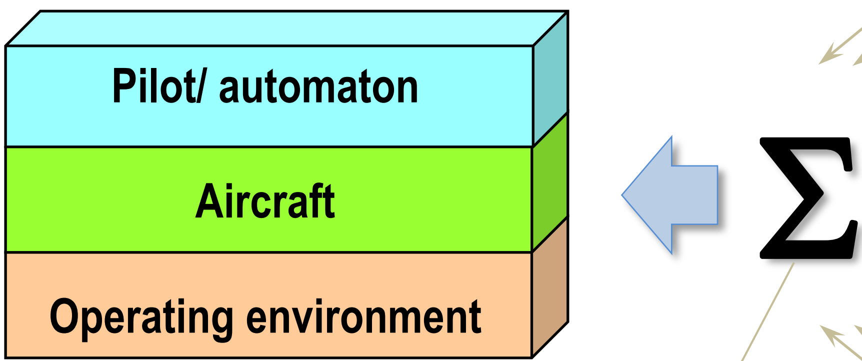
ISAFE Methodology: Theoretical Basis

System Dynamics Model



- Flight mechanics
- Aerodynamics
- Propulsion
- Flight control principles
- Graph theory
- Modeling & simulation
- Algorithms & data structures
- Numerical methods
- Design of experiments
- Pilot's decision making models
- Scenario scripting language
- Situational control
- Knowledge mining & mapping
- AI, L-systems, etc.

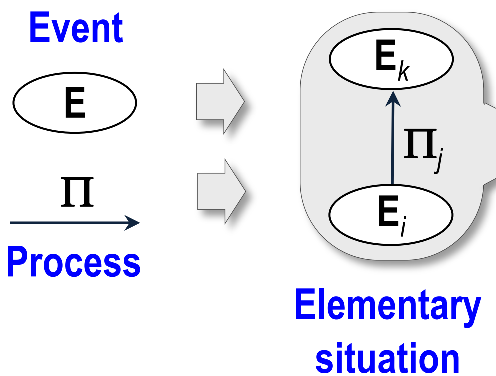
The model is a synergy of **classic** and **innovative** techniques.

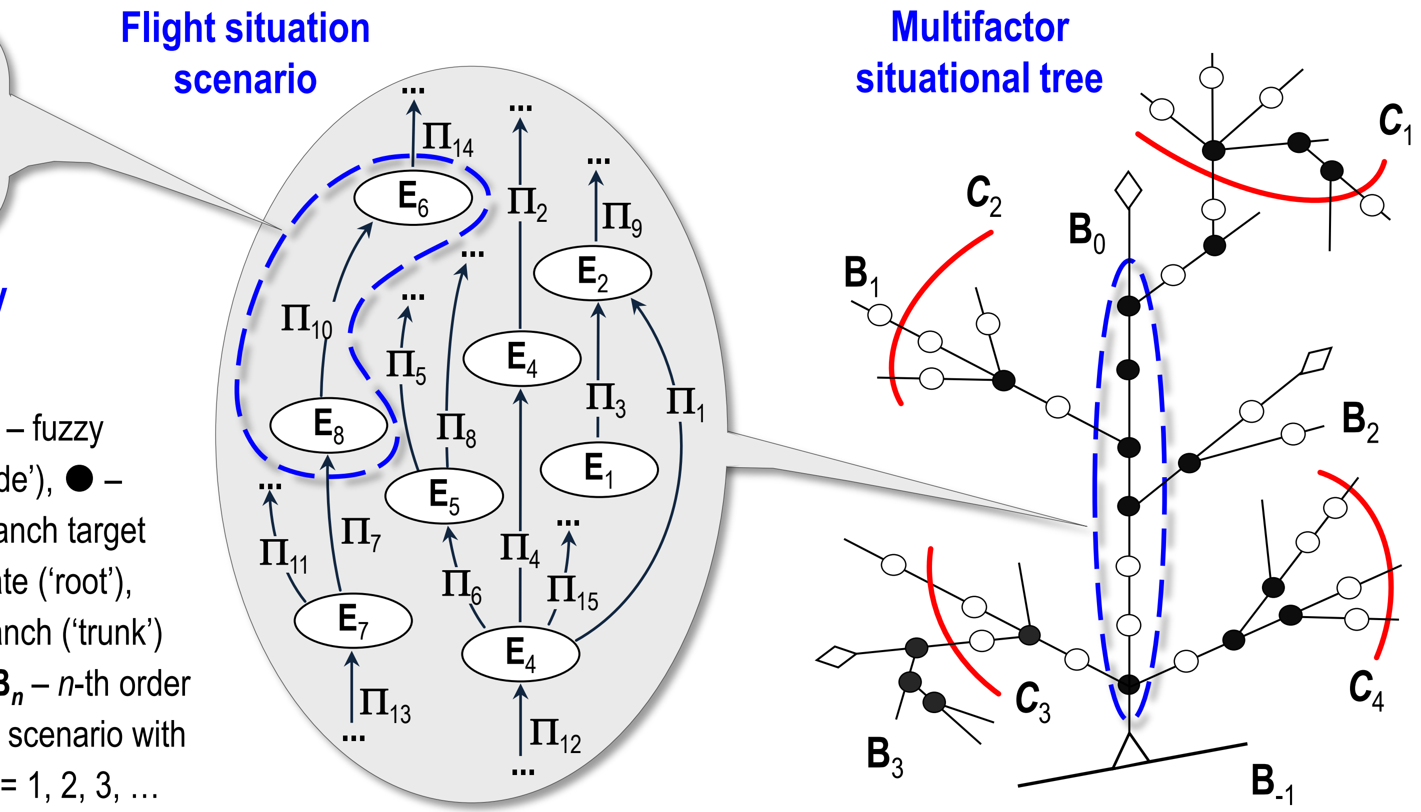
The system dynamics model is a **high-fidelity mathematical description** of the behavior of the 'pilot – automaton – aircraft – operating environment' system in **multifactor** flight situations.

Two-Level Knowledge Model of Complex Flight Domain

2. System Dynamics Model

Basic formal elements	‘Micro-structure’ of flight (Level 1)	‘Macro-structure’ of flight (Level 2)





Legend: **E**$_i$ – event, Π_j – process, ***C*** – fuzzy constraint, ○ – reference state (‘node’), ● – branch grafting state (‘bud’), ◇ – branch target state (‘leaf’), △ – branch source state (‘root’), **B**$_{-1}$ – parental branch, **B**$_0$ – main branch (‘trunk’) – baseline flight situation scenario, **B**$_n$ – *n*-th order derivative branch, complex situation scenario with *n* contributing operational factors, *n* = 1, 2, 3, …

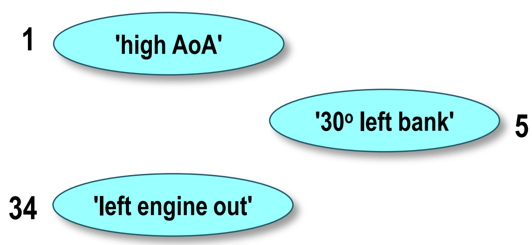
Using this generalized two-level knowledge structure, **realistically complex multifactor operational domains** of flight can be modeled and screened - in depth and breadth - in advance.

Flight Situation Scenario Scripting Language: Discrete-Continuous Formalism

Flight event (E)

The **flight event** is a special state of the system which is important to the pilot/designer in terms of flight control 'switching' logic and stands for a substantial change in the flight situation. Examples:

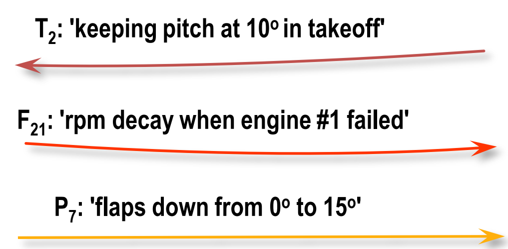
- **'inner left-hand engine out'**
- **'speed VR achieved'**
- **'altitude 360 ft and IAS 180 kt'**
- **'on the runway'**
- **'high angle of attack'**
- **'go-around decision'**



Flight process (Π)

The **flight process** is a time-history of one or several flight parameters which characterize a continuous aspect of the 'pilot (automaton) – aircraft – operating environment' system behavior (dynamics, control, weather, etc.). Examples:

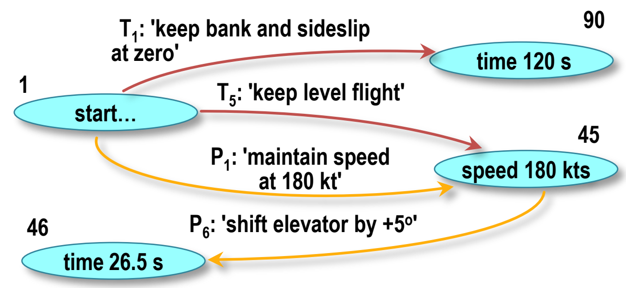
- **'steer runway's centerline'**
- **'keep pitch at 10° in initial climb'**
- **'wind shear (10 ft/s at H = 30 ft)'**
- **'extend flaps from 0° to 15°'**
- **'turn at 10° bank and 0° sideslip'**
- **'wet runway condition (μ_D = 0.3)'**



Flight scenario (S)

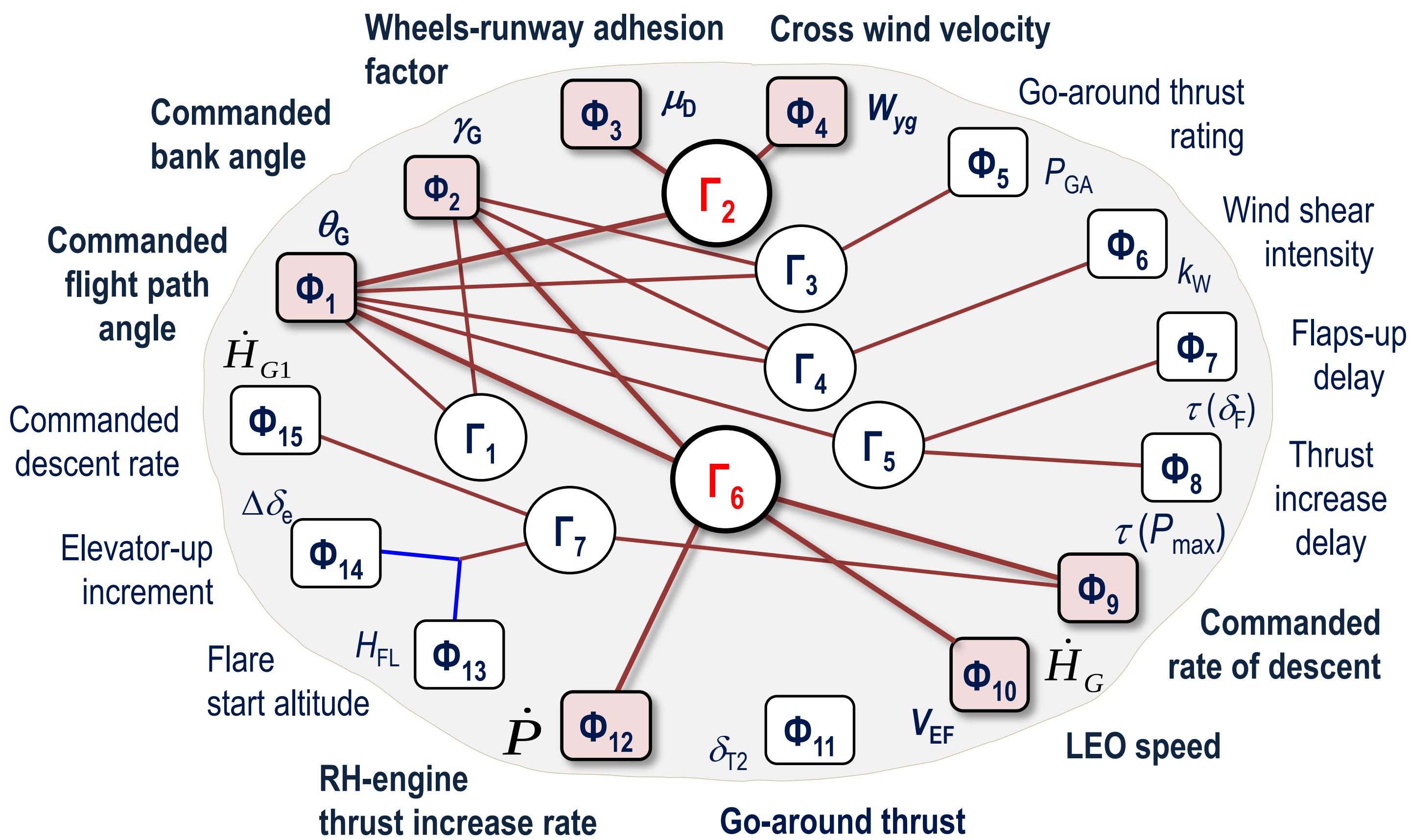
The **flight situation scenario** is a concise plan of a flight situation. It specifies the content and the logic of flight in this situation. A flight scenario is depicted as a directed graph or a matrix. Examples:

- **Continued takeoff with critical engine out'**
- **'landing in crosswind conditions'**
- **'ground roll on water-covered runway'**
- **'coordinated turn at 15° bank'**
- **'stall in takeoff configuration'**
- **'cruise mode at 600 kt and 30000 ft'**



Flight situations of **any** complexity, for **any** aircraft class, **any** phase and **any** operational conditions of flight are easily formalized for M&S using the 'events - processes' scripting language (since 1984).

Design Field of Multifactor Operational Hypotheses – Illustration



In the system dynamics model, **heterogeneous risk factors** (associated with a human pilot, automaton, aircraft and operating environment) are **combined and treated uniformly** - taking into account the desired scope of safety research.

Legend:

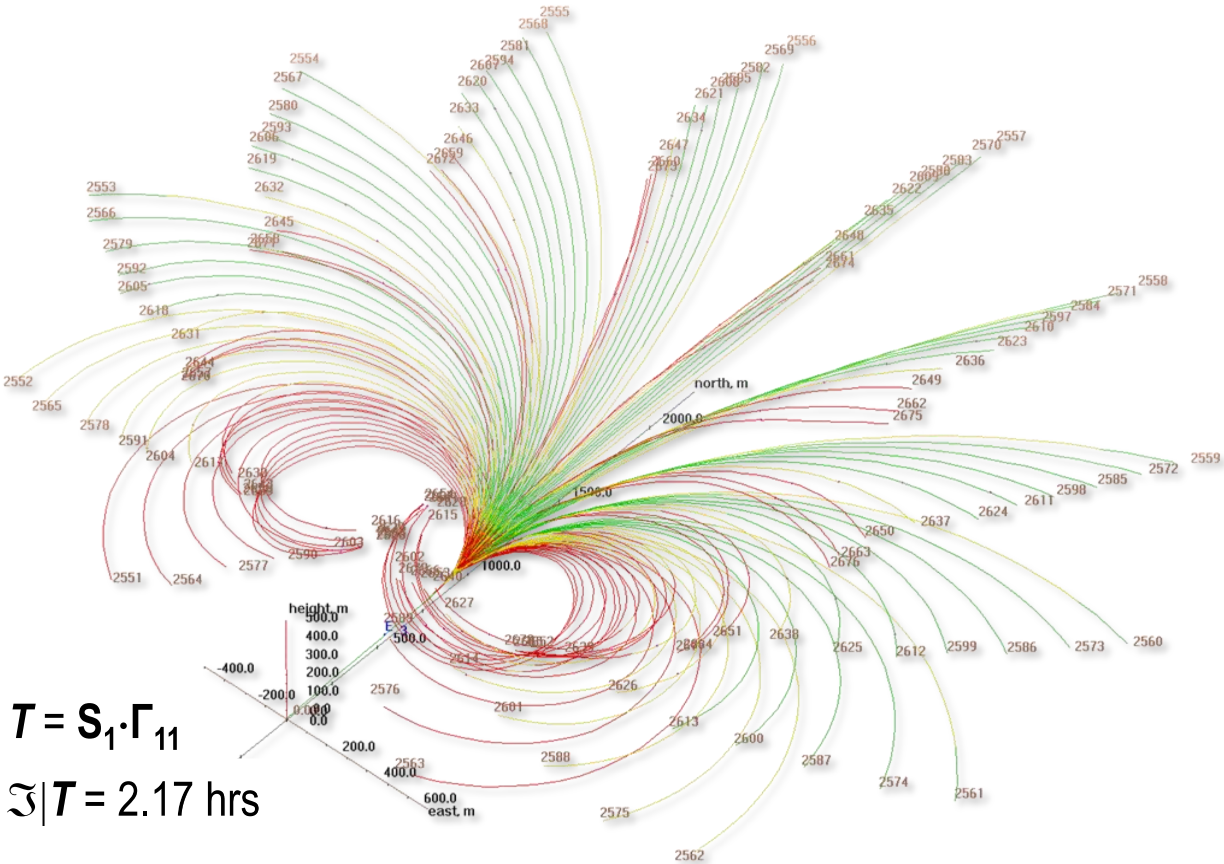
- Γ_2 - operational hypothesis.
- Φ_4 - safety risk factor.
- link between risk factors in Γ: independent and dependent, respectively.

Examples of three- and five-factor operational hypotheses:

$$\Gamma_2 = \Phi_3 \times \Phi_4 \times \Phi_1 \equiv \mu_D \times W_{yg} \times \theta_G$$

$$\Gamma_6 = \Phi_9 \times \Phi_1 \times \Phi_2 \times \Phi_{12} \times \Phi_{10} \equiv \dot{H}_G \times \theta_G \times \gamma_G \times \dot{P} \times V_{EF}$$

Situational Tree of Flight. Virtual Flight Test Experience – Example



$\boldsymbol{T} = \mathbf{S}_1 \cdot \boldsymbol{\Gamma}_{11}$

$\Im | \boldsymbol{T} = 2.17$ hrs

Situational tree $\boldsymbol{T} = \mathbf{S}_1 \cdot \boldsymbol{\Gamma}_{11}$: **'Takeoff. Errors/ variations of selecting commanded flight path angle (θ_G) and commanded bank angle (γ_G) in climb'** (two-factor domain)

Multifactor operational hypothesis for virtual testing (formal definition):

$$\boldsymbol{\Gamma}_{11} = \boldsymbol{\Phi}_1 \times \boldsymbol{\Phi}_2$$

'Virtual flight test time' (virtual test experience) accumulated in tree *T*, hrs:

$$\Im | \boldsymbol{T} = \sum_{i=1}^{N(\boldsymbol{T})} \Delta t(\mathbf{B}_i) \cdot 3600^{-1}$$

<u>Legend</u>: $\boldsymbol{T} = \mathbf{S}_1 \cdot \boldsymbol{\Gamma}_{11}$ – situational tree, $\boldsymbol{T} = \{ \boldsymbol{F}_{2551}, \ldots, \boldsymbol{F}_{2680} \}$, $\boldsymbol{F}_k$ – 'flight', $k = 2551, \ldots, 2680$, $\boldsymbol{F}_k \equiv \mathbf{B}_i$, $\mathbf{B}_i$ – branch in tree $\boldsymbol{T}$, $\Delta t(\boldsymbol{B}_i) = 60$s – branch 'length' [s], $i = 1, \ldots, N(\boldsymbol{T})$, $N(\boldsymbol{T}) = 130$ – total number of branches in tree $\boldsymbol{T}$, $\mathbf{S}_1$ – baseline situation scenario: 'Takeoff and initial climb', $\boldsymbol{\Gamma}_{11} = \boldsymbol{\Phi}_1 \times \boldsymbol{\Phi}_2$ – tree's genotype (tested operational hypothesis), $\boldsymbol{\Phi}_j$ – risk factor, $\boldsymbol{\Phi}_1 \equiv \theta_G$, $\boldsymbol{\Phi}_2 \equiv \gamma_G$, θ_G – commanded flight path angle, $\theta_G \in \{2^o, 4^o, \ldots, 20^o\}$, γ_G – commanded bank angle, $\gamma_G \in \{-45^o, -37.5^o, \ldots, +45^o\}$, (north, east, height) $\equiv (N, E, H)$ – Earth frames, – safety palette.

A multifactor situational tree represents **'what-if neighborhood'** of a baseline flight situation. A 'forest' of such trees constitutes the **output knowledge base** of VFT&C.

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VATES Software Tool Functionality: Core Layout

INPUT

- Library of flight situation scenarios for given types of aircraft
- Library of operational/ design risk factors and multifactor operational hypotheses
- Database of ‘parametric definitions’ for given types of aircraft

PROCESSOR

- ‘Generalized system dynamics model – aircraft type’ tune-up
- Flight situation scenario planning
- Risk factors and operational/ design hypotheses planning
- ‘System dynamics model - flight situation’ tune-up
- Flight simulation experiment planning & management
- Safety analysis, evaluation & knowledge ‘mining’
- Flight M&S output data and safety knowledge mapping
- ‘Parametric definition’ preparation/ editing

OUTPUT

- Database of M&S output (‘flights’) for given aircraft and operational domain
- Library of knowledge maps - single (1) situation’s safety performance analysis
- Library of knowledge maps - many (N) situations’ safety performance analysis
- Case studies (selected examples of studying specific flight safety problems)
- Technical documentation, scientific papers and presentations

A real research pilot/ engineer is not required in autonomous VATES-based fast-time flight M&S cycle. A **‘silicon pilot’ model and AI techniques** control the process of branching and growth of a situational tree.

Realistically complex operational conditions (meaningful combinations of up to 15 risk factors) are **automatically added to a current flight situation** scenario - taking into account flight physics and logic.

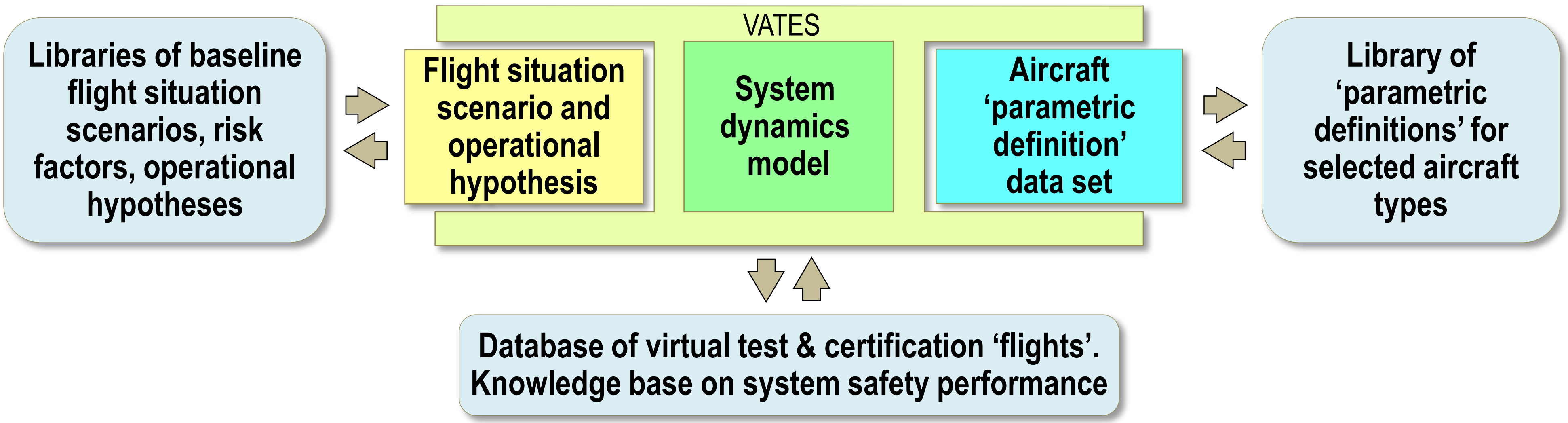
'Pilot – Automaton – Aircraft – Operating Environment' System: Modeled Physical and Logical Properties

3. Software Implementation

- **Aerodynamics**, including unsteady and stall regimes, based on user-defined/ generic 'parametric definition' of an aircraft
- **Power plant**, including direct and reversed thrust, TVC, asymmetric cases, etc. (if present)
- **Atmospheric conditions** (air density, pressure, temperature, etc.)
- **3-D wind** profile (head/ tail, cross, up/down), microburst, wind shear, rotor, wake, 'lee wave', other)
- **Aerostatic** forces and moments if present
- **C.G. travel** along three body axes
- **Undercarriage**/ reaction links (kinematics, dynamics)
- **Runway** surface conditions – dry, wet, water-/ mud-/ snow-/ ice-covered, geometry, dynamics (if present)
- **Virtual** (added) **mass** and virtual inertias if present
- Control **actuators**
- User-defined processes (real flight **data records**, etc.)
- Flight **events**
- **Piloting tasks** and system **state 'observers'**
- Flight **control procedures**
- Onboard **mechanical failures** (propulsion, controls, actuators, landing gear, etc.)
- Air **turbulence**
- Surface **icing** effects on aircraft aerodynamics
- **Gyroscopic** effects of rotating parts
- Generic **instruments** and sensors
- Internal **fuel slosh** if present
- Variations of a/c **mass and moments of inertia**
- Aircraft **guidance and control**
- **Human operator's flaws** (errors/ inattention, unusual tactics - inaction, terrorist/ sick person actions, etc.)
- **Automatic flight control** flaws (data/ logic errors)
- Low and high **Reynolds** numbers
- Sensor **failures**
- Changes of **aerodynamic configuration** (flaps, etc.)
- Kinetic **obstacles**
- Variations/ errors in **flight scenario**, Pilot's **Manual**

Key physical and logical properties of complex flight domains represented in the 'human pilot – automaton – aircraft – operating environment' system dynamics model, as well as the system model fidelity (VATES validity), **match or exceed the requirements** stipulated in EASA Certification Specifications for Aeroplane Flight Simulation Training Devices: **CS-FSTD(A).**

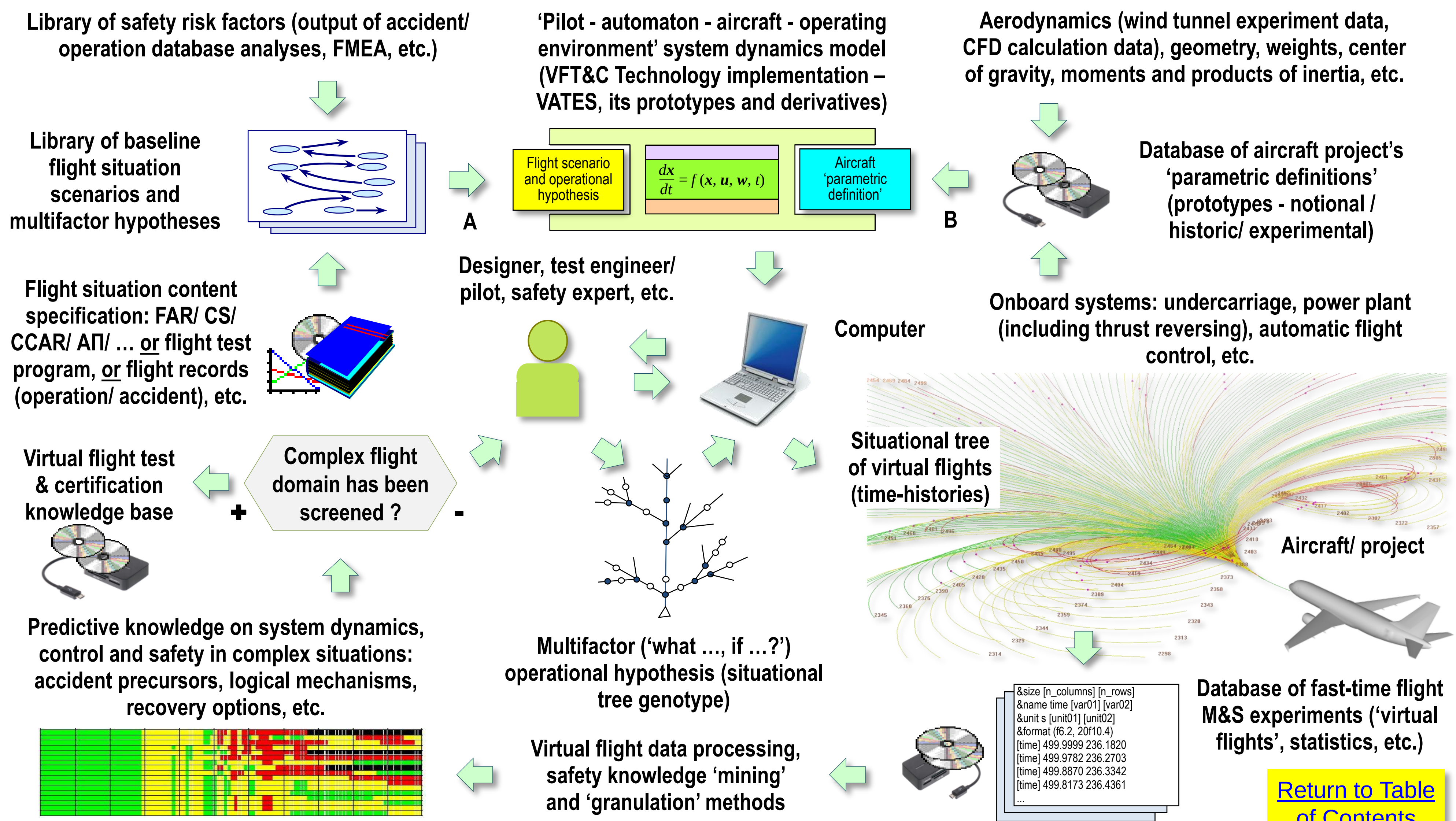
Input-Output Data Flows



Input data requirements:

1. Vehicle/ project/ prototype '**parametric definition**. → **Aerodynamics, mass, moments of inertia, thrust, geometry, landing gear, automatic control, etc.**
2. General description of a **flight domain** of interest. → **Flight phases, modes, scenarios, manoeuvres, other flight content requirements.**
3. **Risk factors** and 'what-if' hypotheses to be tested. → **Human pilot errors, mechanical malfunctions, software flaws, demanding weather conditions.**
4. General formulation of the **research task**. → **Customer category, problem class, vehicle class, research goals, etc.**

Autonomous Fast-Time Flight M&S Environment – Virtual Flight Test ‘Article’



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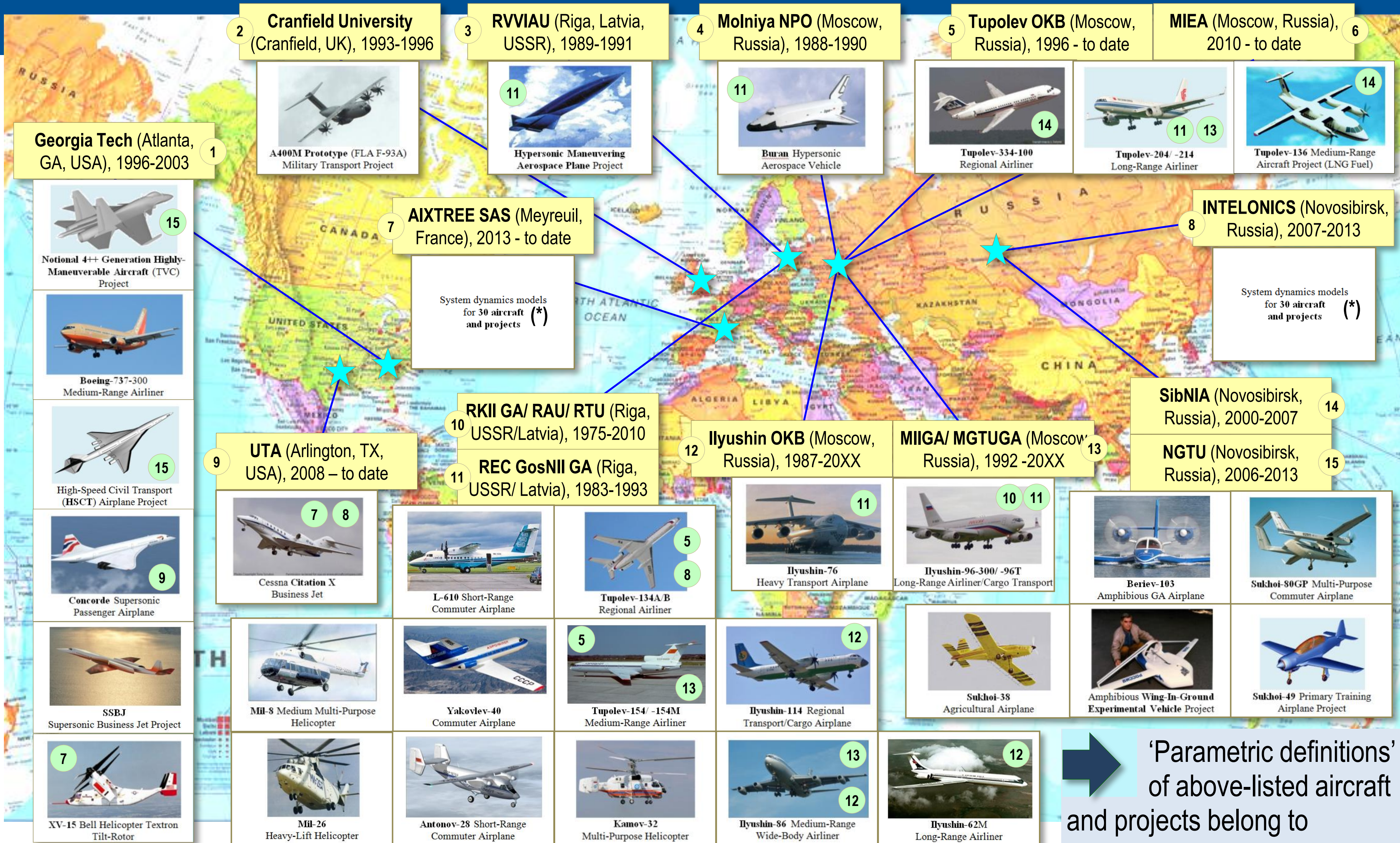
VATES* Development and Applications Geography: 1975 - 2016

4. Applications Statistics



'Parametric definitions' of above-listed aircraft and projects belong to corresponding design centers.

Legend: XX - another institution involved in a given VFT&C project. * - VATES (v.5-7), its prototype (FSSP) and derivative tools.

VFT&C Technology: 'Aircraft Project – Lifecycle Phase Application' Matrix & Statistics

Aircraft type/ project	CD/ PD	DD	FT &C	PT	IO/ FO	AA	SM	SR
1. A400M Prototype (FLA) Transport (*)	■							■
2. Hypersonic Aerospace Plane (*)	■							■
3. Notional 4++ Gen Fighter with TVC (*)								■
4. Experimental WIG Vehicle (*)			■		■			
5. Antonov-28 Commuter Airplane					■			
6. Beriev-103 Amphibious GA Airplane			■		■			
7. Boeing-737-300 Medium-Range Airliner						■		
8. Buran Hypersonic Aerospace Vehicle			■	■				
9. Cessna Citation X Business Jet (*)	■							■
10. Concorde Supersonic Airplane						■		■
11. High-Speed Civil Transport (HSCT) (*)	■							■
12. L-610 Short-Range Airplane			■		■			
13. Ilyushin-114 Regional Airplane		■	■	■	■			
14. Ilyushin-62M Long-Range Airliner						■	■	■
15. Ilyushin-76 Large Cargo Transport				■	■	■		■
16. Ilyushin-86 Wide-Body Airliner			■	■	■	■		■

Aircraft type/ project	CD/ PD	DD	FT &C	PT	IO/ FO	AA	SM	SR
17. Ilyushin-96T Cargo Airplane			■	■	■			■
18. Ilyushin-96-300 Long-Range Airliner			■	■	■			■
19. Kamov-32 Multi-Purpose Helicopter			■		■			
20. Mil-26 Heavy-Lift Helicopter			■		■			
21. Mil-8 Multi-Purpose Helicopter						■		
22. Sukhoi-38 Agricultural Airplane		■						
23. Sukhoi-49 Primary Trainer (*)		■						
24. Sukhoi-80GP Commuter Airplane		■	■					■
25. SSBJ Supersonic Business Jet (*)	■							■
26. Tupolev-134A/B Regional Airliner						■	■	■
27. Tupolev-154/-154M Medium-Range Jet			■			■		■
28. Tupolev-136 Aircraft (LNG fuel) (*)	■							
29. Tupolev-204/-214 Medium-Range Jet			■	■	■			■
30. Tupolev-334-100 Regional Airliner			■	■	■			■
31. XV-15 Bell Textron Tilt-Rotor Craft	■					■		■
32. Yakovlev-40 Regional Airliner					■	■		

Subsonic						Supersonic		Hypersonic	
Fixed-wing		Rotary-wing		Tilt-rotor					
Types	Projects	Types	Projects	Types	Projects	Types	Projects	Types	Projects
18	4	3	-	1	0	1	3	1	1

Major aircraft classes and **lifecycle phases** are covered.

Legend: **CD/ PD/ DD** - conceptual/ preliminary/ detailed design. **FT&C** - flight test & certification. **PT** - pilot training (including test pilot training). **IO/ FO** - introduction into service/ flight operations. **AA** - accident analysis. **SM** - safety management. **SR** – MSc / PhD/ DSc level research projects. **TVC** - thrust vectoring control. **FLA** - Future Large Aircraft. **LNG** - Liquid Natural Gas. **(*)** – design project.

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Reconstruction of Flight Test and Accident Cases for System Dynamics Model Validation – Examples (1 of 2)

Case		Test/ Accident Case Scenario	N (Φ)
#	Code		
1	02.01/06.02.14	**Landing**, cross wind (right → left), dry runway, ground-roll, thrust reversing	1
2	02.01/11.17.14	**Continued landing** (left-hand engine out), wet runway, ground-roll, thrust reversing	2
3	02.02/11.17.14	**Landing**, cross wind (left → right), wet runway, ground-roll, thrust reversing	2
4	02.01/04.13.14	**Normal takeoff,** no wind, dry runway	0 (*)
5	02.01/11.19.15	**Normal takeoff**, cross wind (right → left), dry runway	1
6	02.01/08.07.14	**Continued takeoff**, right-hand engine out, head-cross wind (left → right), high-elevation dry runway	3
7	01.01/04.20.10	**Landing**, dry runway, ground-roll, thrust reversing	0
8	01.01/11.02.10	**Landing**, low temperature, wet runway, ground-roll, thrust reversing	2
9	01.01/09.29.07	**Landing approach and go-around**, left-hand engine out	1

Legend: **(*)** – standard flight situations, benign operational conditions (no risk factors). → - wind direction.
N(Φ) – the number of risk factors in a baseline flight test/ accident scenario.

Reconstruction of Flight Test and Accident Cases for System Dynamics Model Validation – Examples (2 of 2)

Case #	Case Code	Test/ Accident Case Scenario	N (Φ)
10	03.01/05.15.00	**Level flight**, 'saw' type inputs by ailerons and rudder	0 (*)
11	04.01/09.03.89	**Takeoff**, 'microburst', heavy rain, low visibility, pilot errors, ambiguities in Flight Manual	5
12	02.01/02.20.13	**Level flight**, impulses by elevator, clean configuration	0
13	02.01/02.05.13	**Level flight**, ramp pitch-up input by column, landing configuration	0
14	02.02/02.05.13	**Level flight**, ramp pitch-down input by column, takeoff configuration	0
15	02.01/04.16.13	**Descent**, LH-engine out, landing configuration	1
16	02.01/10.04.13	**Climb**, ramp inputs by ailerons, clean configuration	0
17	02.01/10.23.13	**Level flight**, one-side impulses by rudder	0
18	02.02/10.23.13	**Level flight**, two-sides impulses by rudder	0

<u>Legend</u>: **LH** - left-hand. **N(Φ)** – the number of risk factors in a baseline flight test/ accident scenario. (*) – standard flight situations in benign operational conditions (no safety risk).

Some cases from this list are exemplified below. There are **many other real flight situations** (tests, operations, accidents, incidents) that have been reconstructed using the system dynamics model since late 1970s for a number of aircraft types.

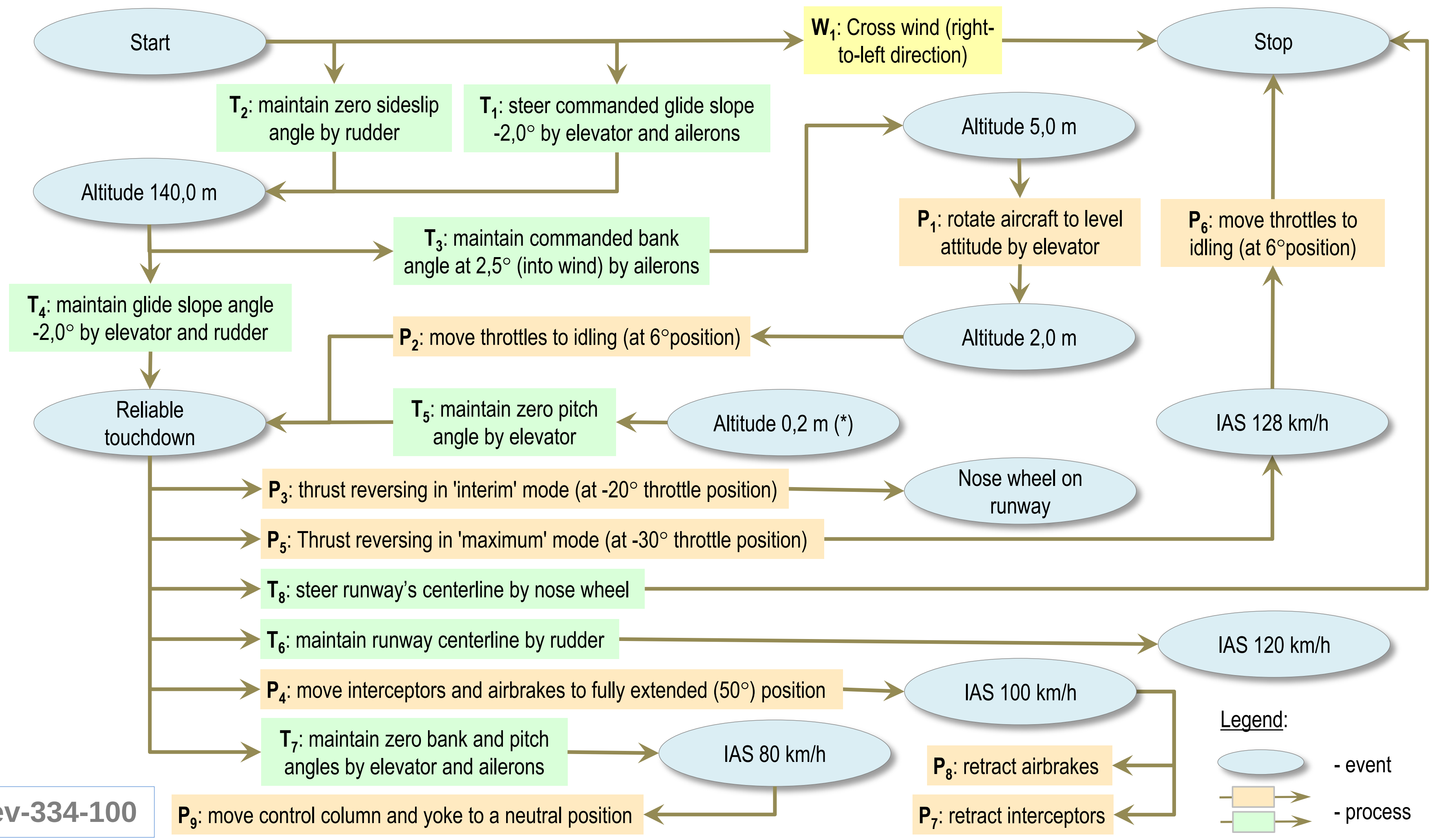
1. Landing, Cross Wind (Right → Left), Dry Runway, Ground-Roll, Thrust Reversing

Initial Conditions of Flight (Case 02.01/06.02.14)

System variable	Value	Unit	Comments
Altitude	320	m	
Aerodrome elevation	0	m	At mean sea level
Aircraft mass	35 300	kg	
C.G. location w.r.t. MAC	36,8	%	C.G. – center of gravity; w.r.t. - with respect to
IAS	280	km/h	Indicated airspeed
Glide path angle	-2,0	°	
Cross wind	9,8	m/s	Direction: right-to-left (R→L)
Flaps	17,0	°	Interim configuration
Slats	22,5	°	Interim configuration
Wheels-runway traction coefficient	0,6	-	Runway surface condition: dry
Atmospheric conditions	ISA	-	Air density, pressure, temperature
Aircraft type	Tupolev-334-100	-	Courtesy of Tupolev Design Bureau

1. Landing, Cross Wind (Right → Left), Dry Runway, Ground-Roll, Thrust Reversing

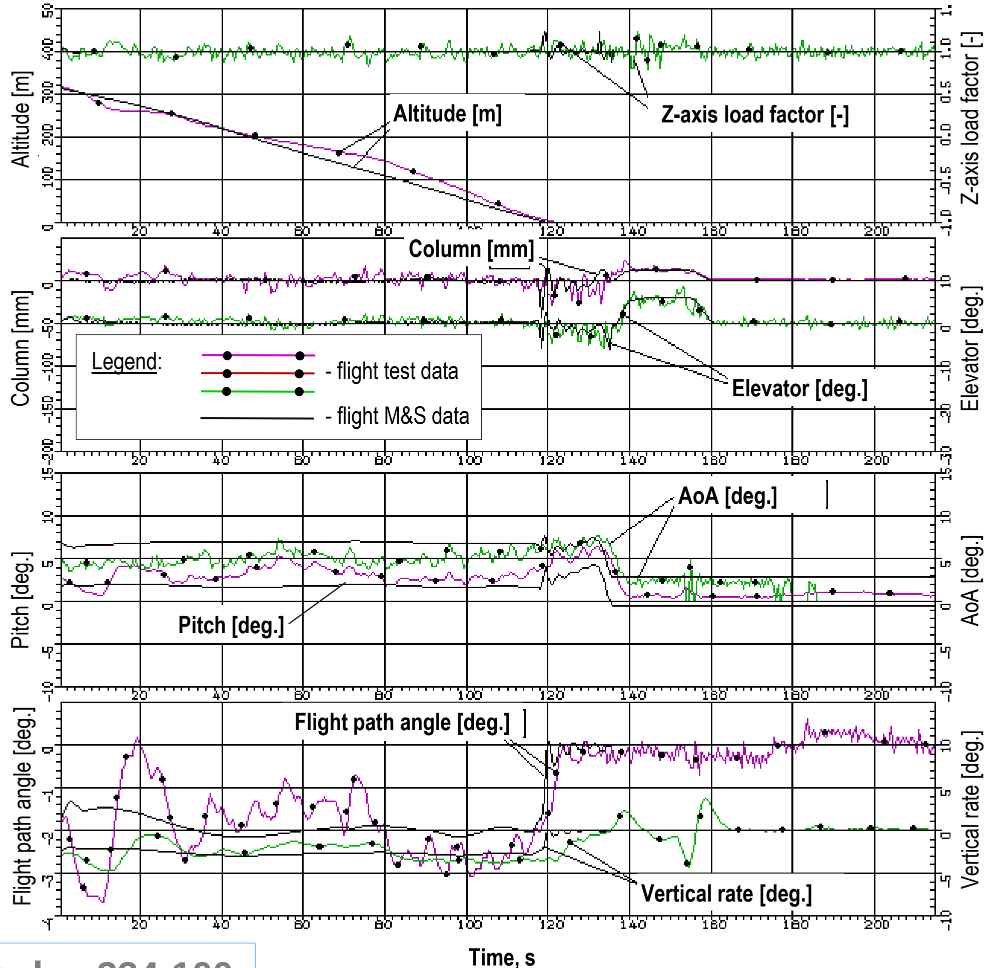
Flight Situation Scenario - Directed Graph Format (Case 02.01/06.02.14)

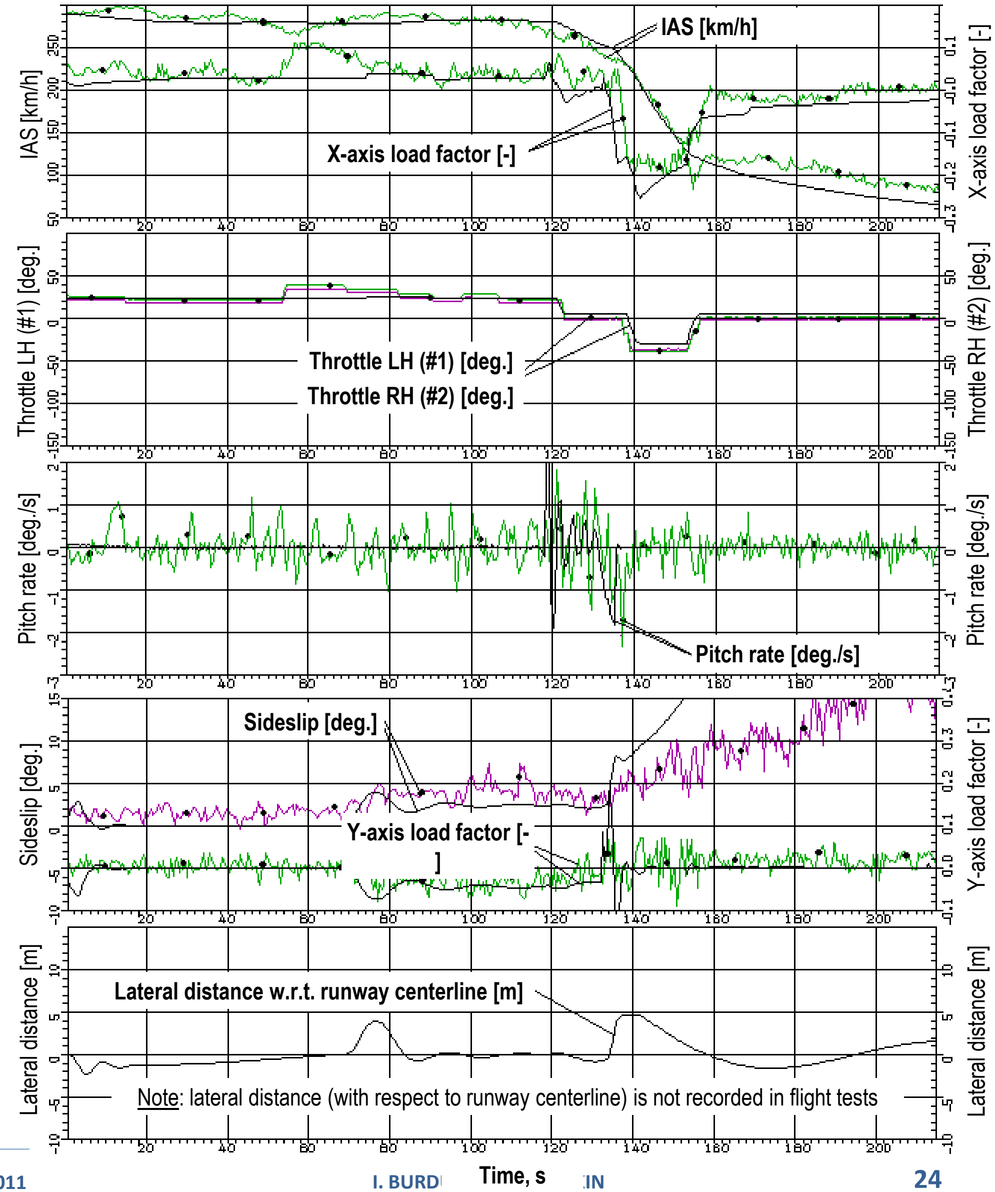


Tupolev-334-100

1. Landing, Cross Wind (Right → Left), Dry Runway, Ground-Roll, Thrust Reversing

Comparison of Simulated and Real Flight Data (Case 02.01/06.02.14) – 1 of 2

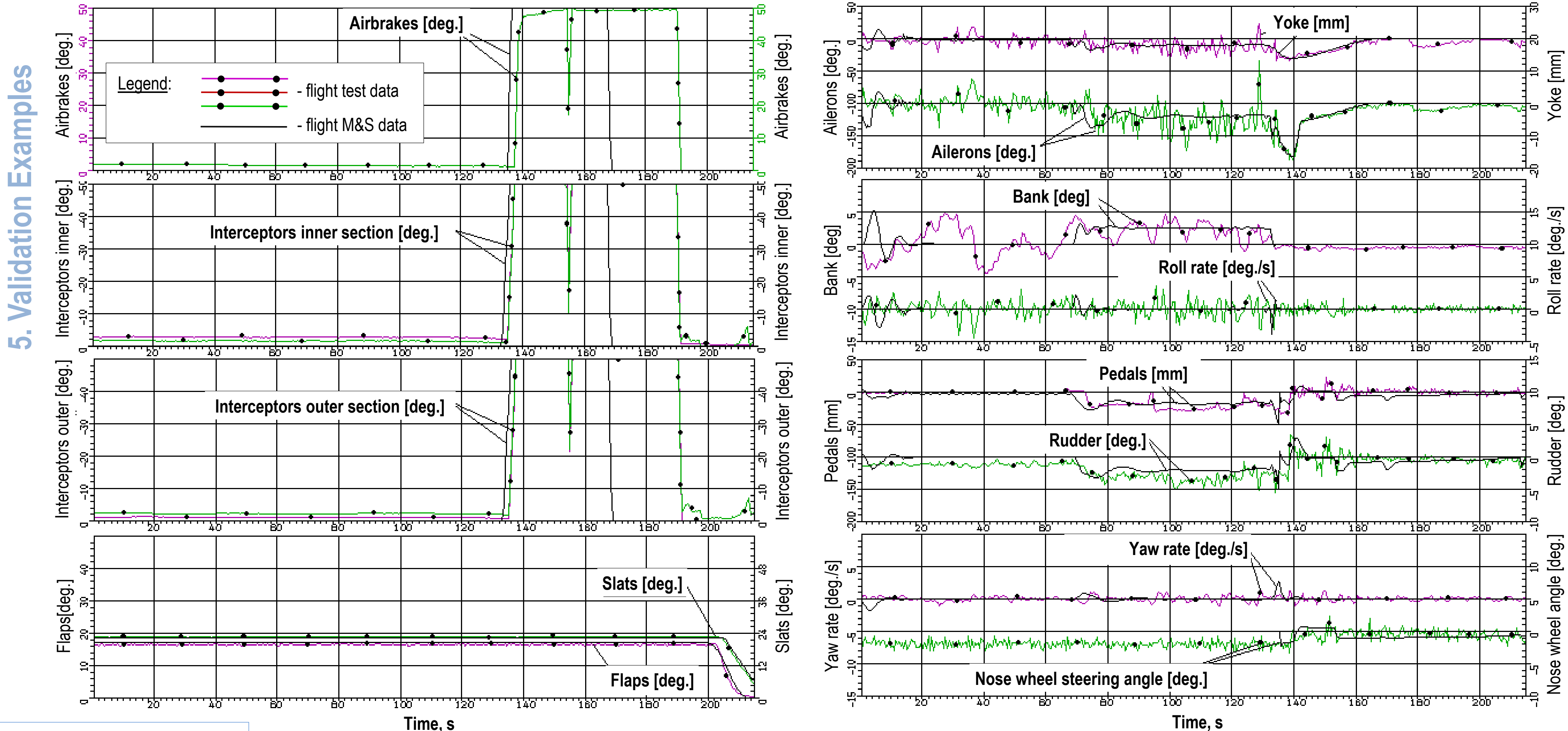




Tupolev-334-100

1. Landing, Cross Wind (Right → Left), Dry Runway, Ground-Roll, Thrust Reversing

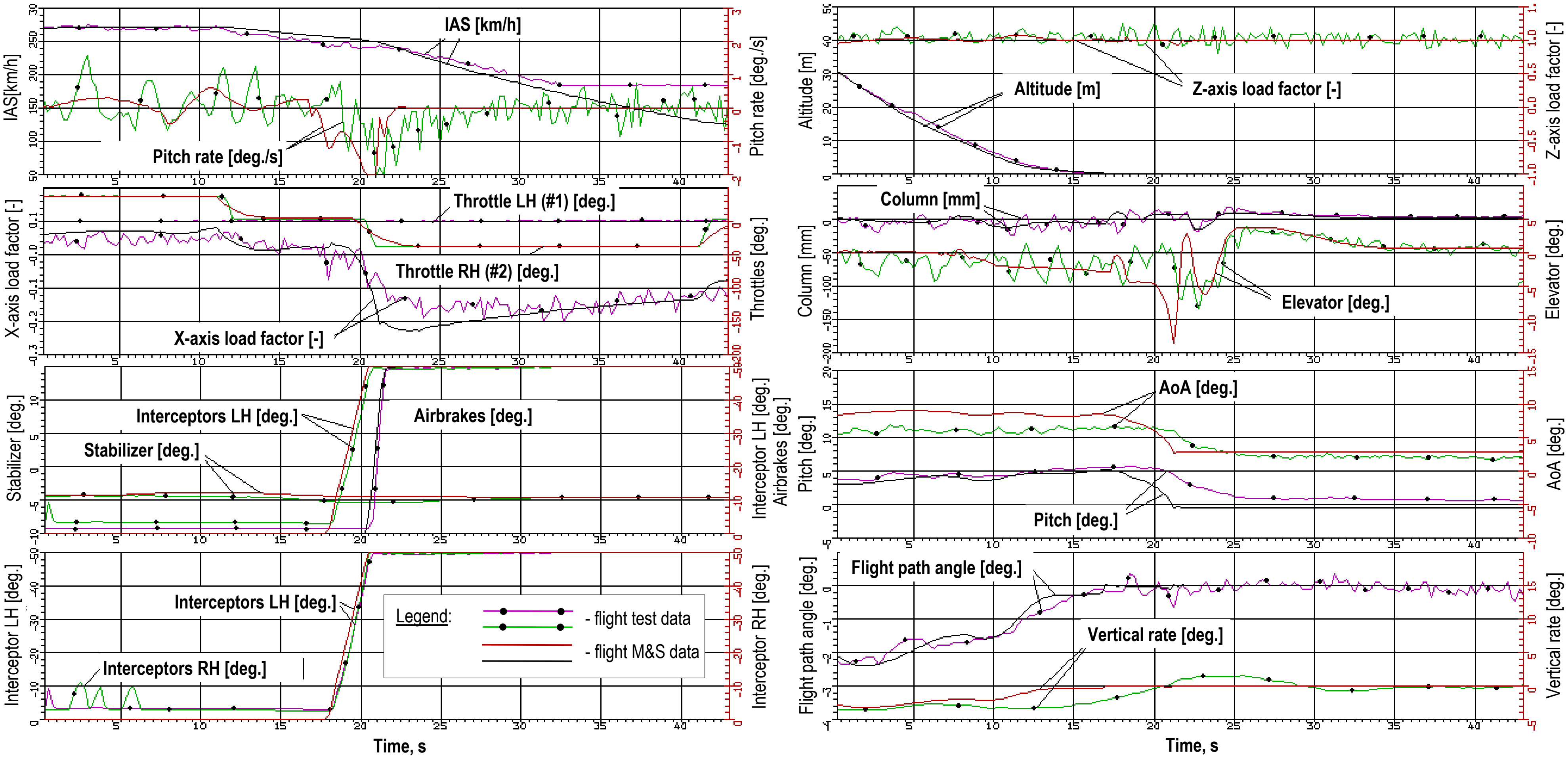
Comparison of Simulated and Real Flight Data (Case 02.01/06.02.14) – 2 of 2



Tupolev-334-100

2. Continued Landing (Left-Hand Engine Out), Wet Runway, Ground-Roll, Thrust Reversing

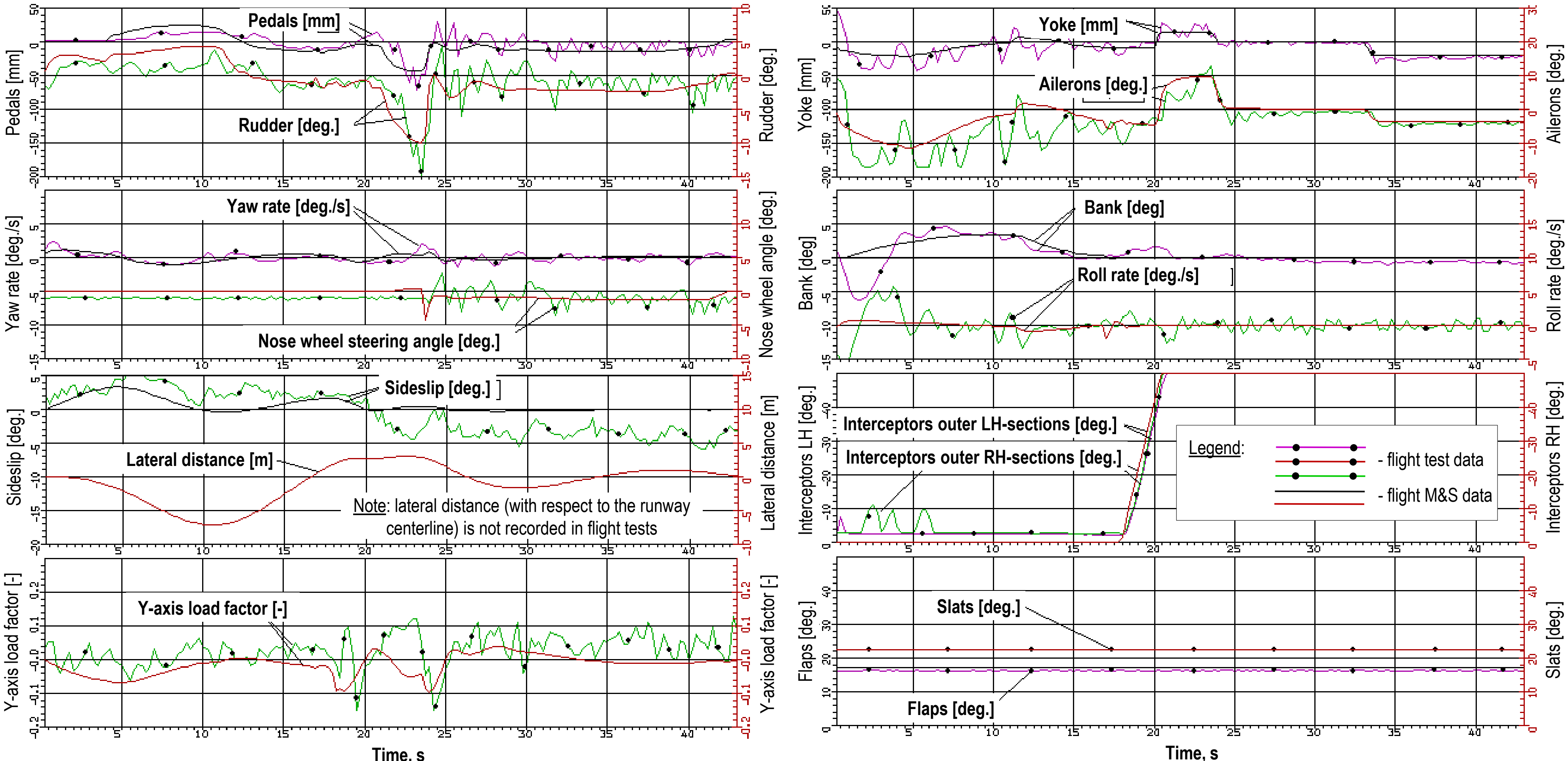
Comparison of Simulated and Real Flight Data (Case 02.01/11.17.14) – 1 of 2



Tupolev-334-100

2. Continued Landing (Left-Hand Engine Out), Wet Runway, Ground-Roll, Thrust Reversing

Comparison of Simulated and Real Flight Data (Case 02.01/11.17.14) – 2 of 2

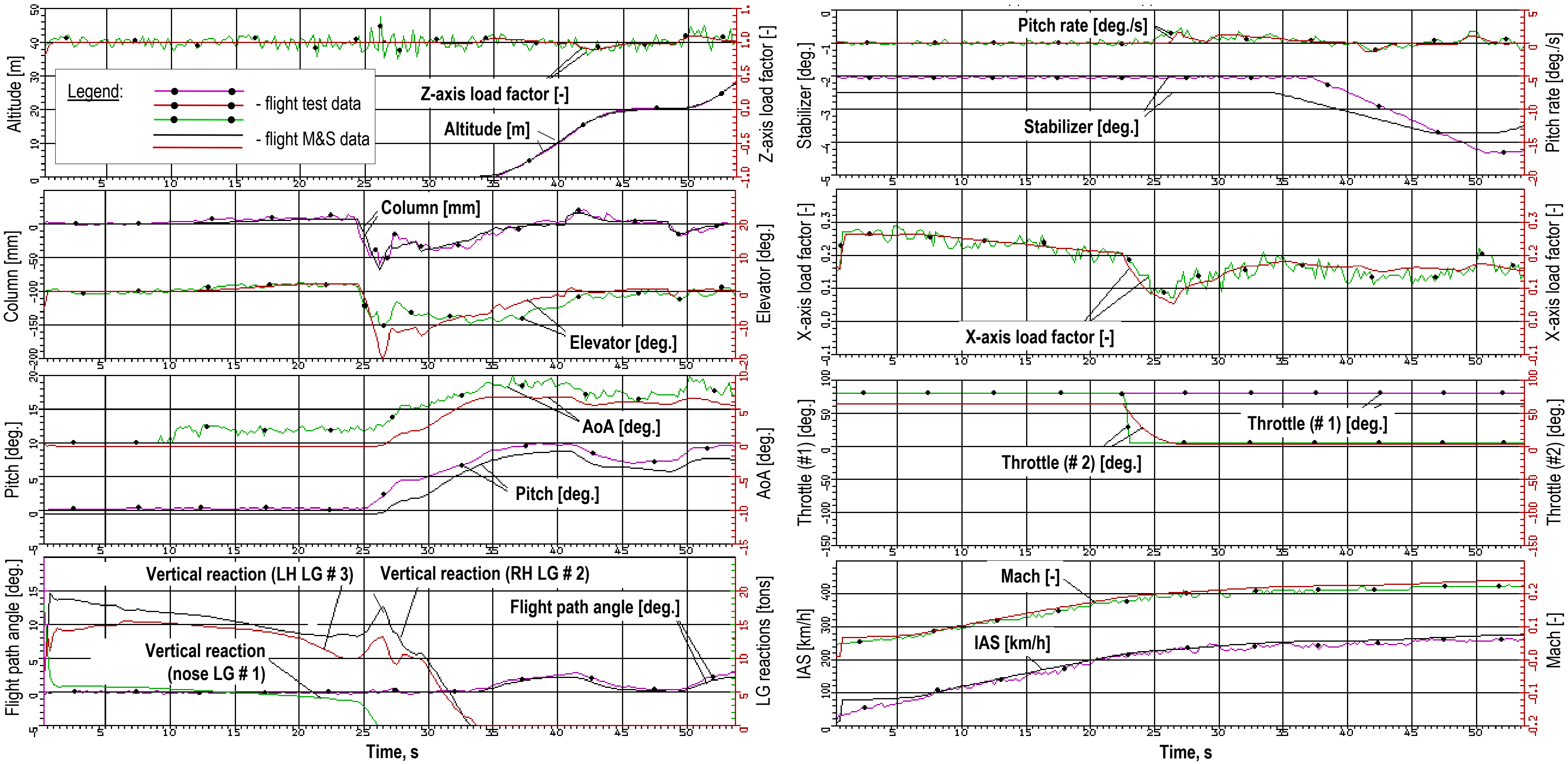


Tupolev-334-100

6. Continued Takeoff, Right-Hand Engine Out, Head-Cross Wind (Left → Right), High-Elevation Dry Runway

5. Validation Examples

Comparison of Simulated and Real Flight Data (Case 02.01/08.07.14) – 1 of 2

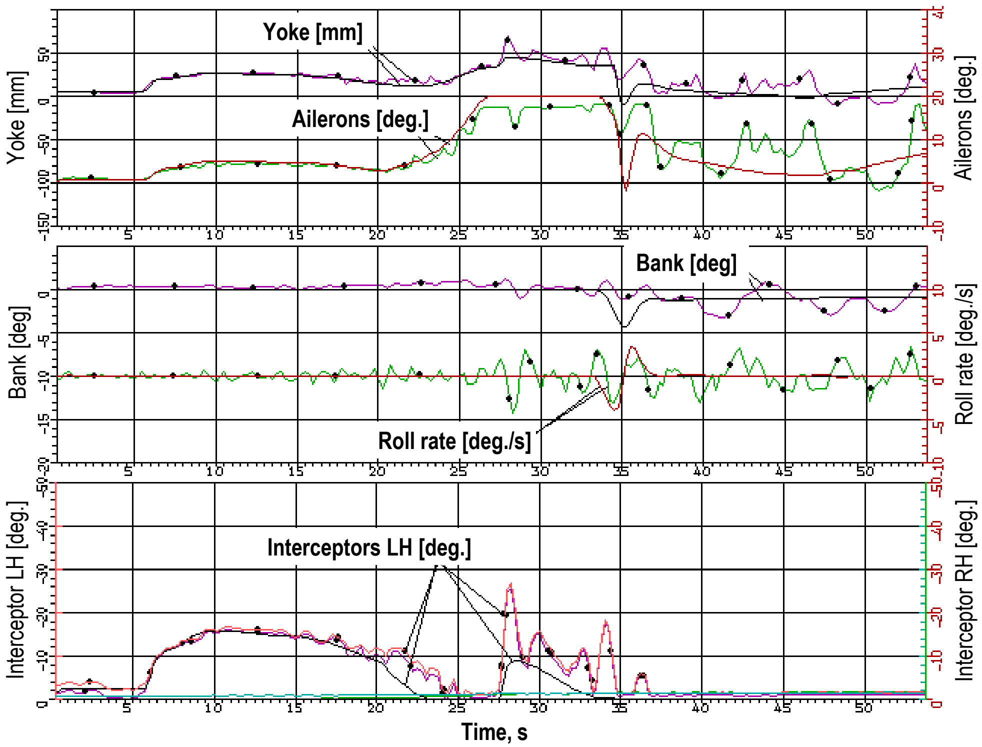


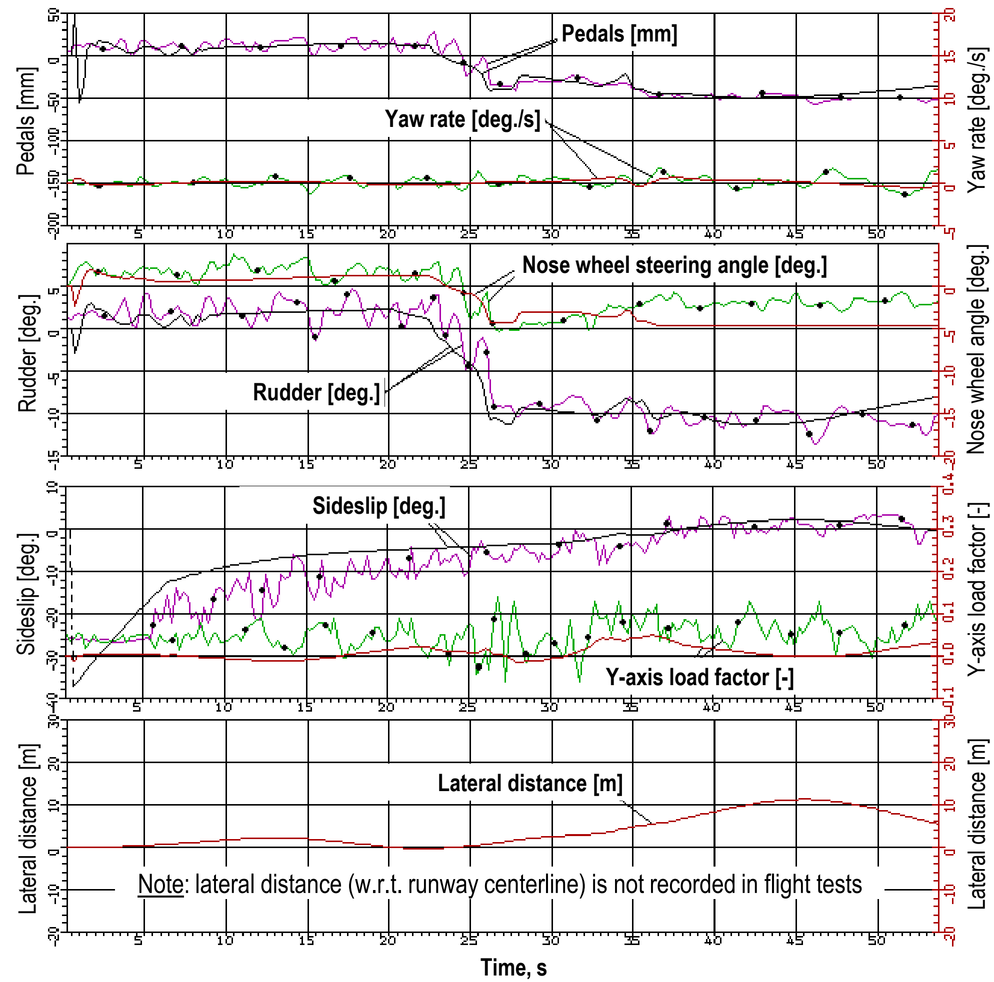
Tupolev-334-100

Note: landing gear vertical reactions are not recorded in flight tests

6. Continued Takeoff, Right-Hand Engine Out, Head-Cross Wind (Left → Right), High-Elevation Dry Runway

Comparison of Simulated and Real Flight Data (Case 02.01/08.07.14) – 2 of 2





Legend:
- flight test data
- flight M&S data

Tupolev-334-100

7. Landing, Dry Runway, Ground-roll, Thrust Reversing

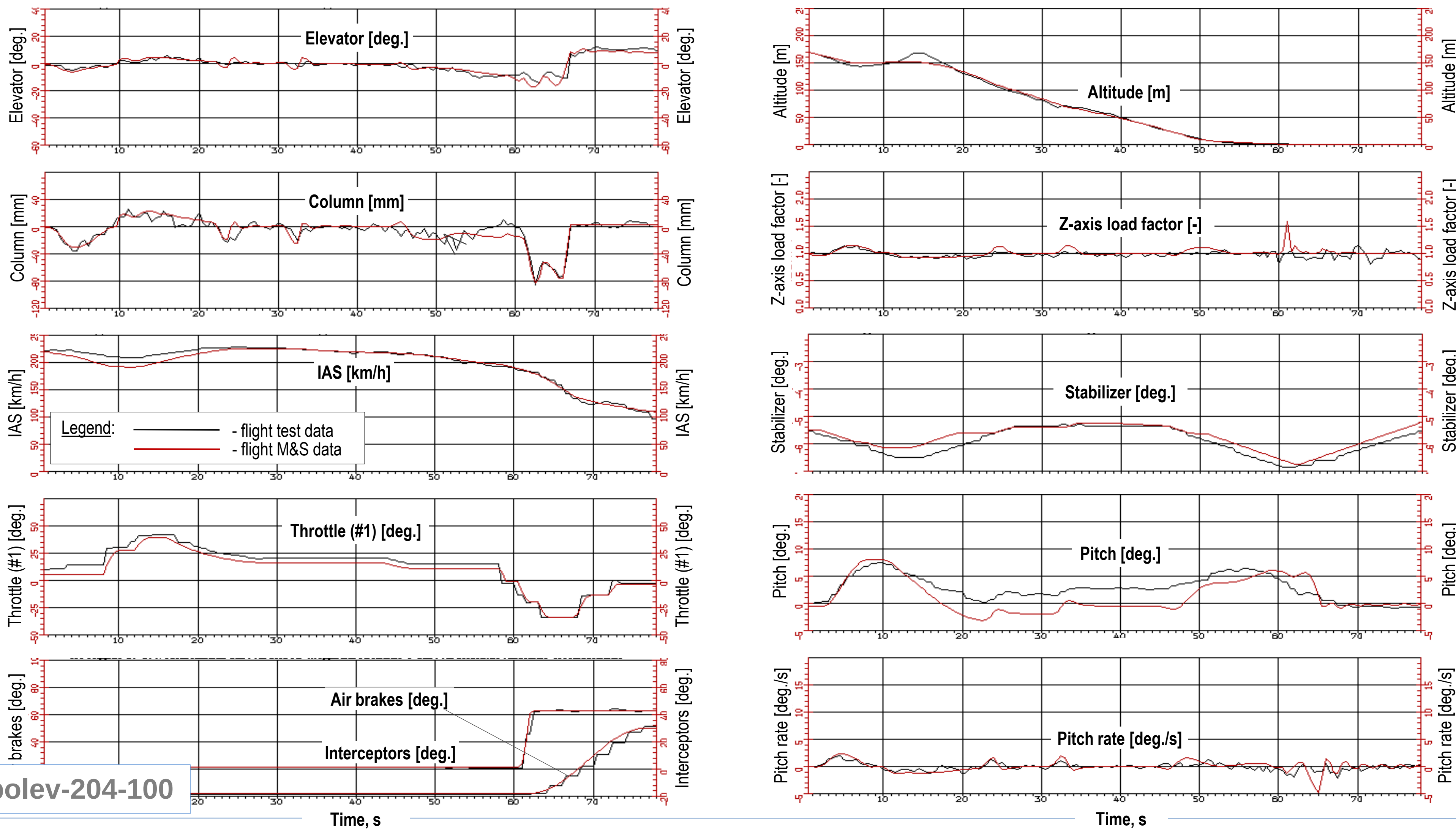
Initial Conditions of Flight (Case 01.01/04.20.10)

System variable	Value	Unit	Comments
Altitude	175	m	
Aerodrome elevation	0	m	At mean sea level
Aircraft mass	64 280	kg	
C.G. location w.r.t. MAC	28,8	%	C.G. – center of gravity; w.r.t. - with respect to
IAS	280	km/h	Indicated airspeed
Glide path angle	-2,6	°	
Cross wind	0	m/s	Benign weather conditions: no wind
Flaps	37	°	Landing configuration
Slats	23	°	Landing configuration
Wheels-runway traction coefficient	0,6	-	Runway surface condition: dry
Atmospheric conditions	ISA	-	Air density, pressure, temperature
Aircraft type	Tupolev-204-100	-	Courtesy of Tupolev Aircraft Design Bureau

7. Landing, Dry Runway, Ground-roll, Thrust Reversing

5. Validation Examples

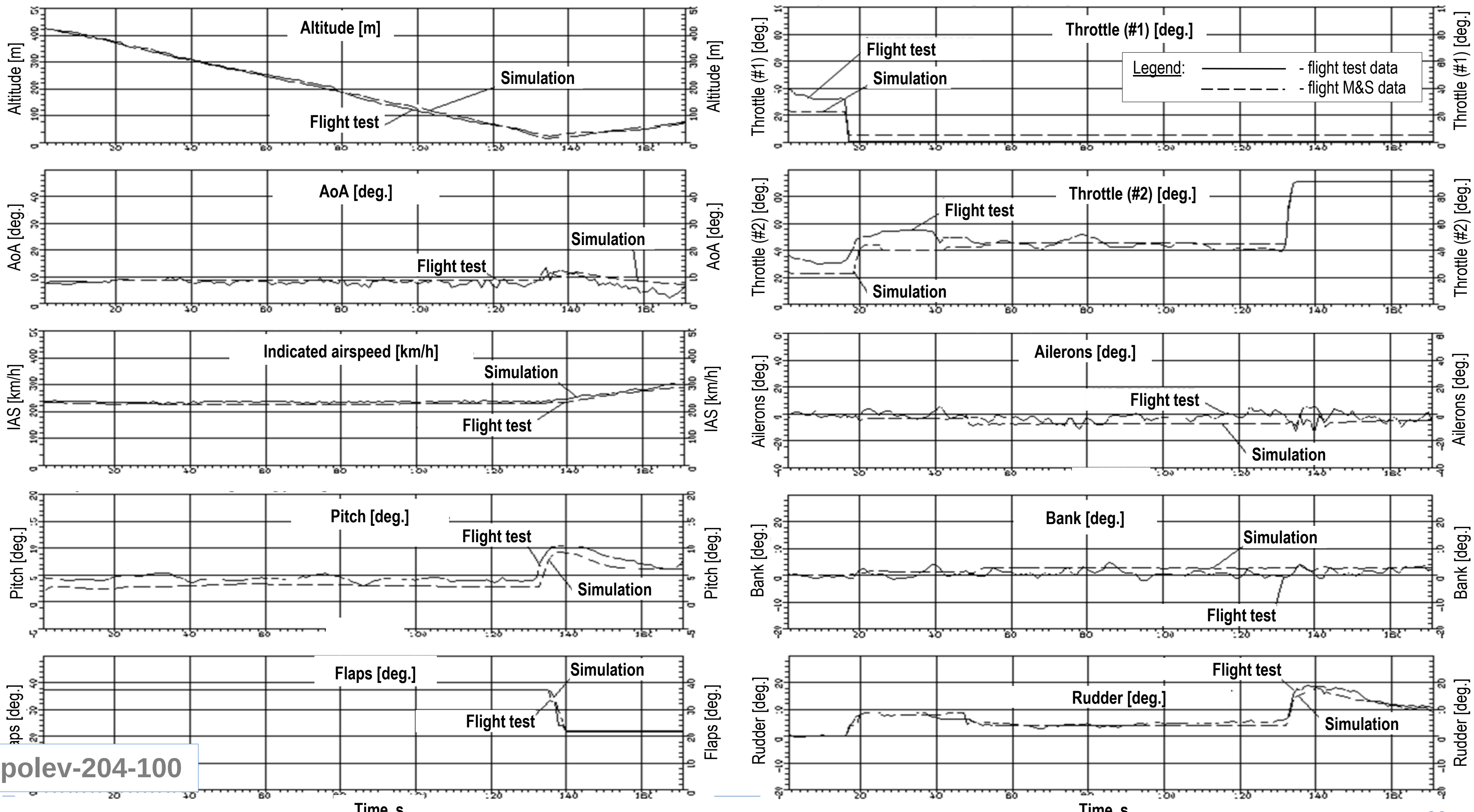
Comparison of Simulated and Real Flight Data (Case 01.01/04.20.10)



Tupolev-204-100

9. Landing Approach and Go-Around, Left-Hand Engine Out

Comparison of Simulated and Real Flight Data (Case 01.01/09.29.07)



Tupolev-204-100

10. Level Flight, ‘Saw’ Type Inputs by Ailerons and Rudder

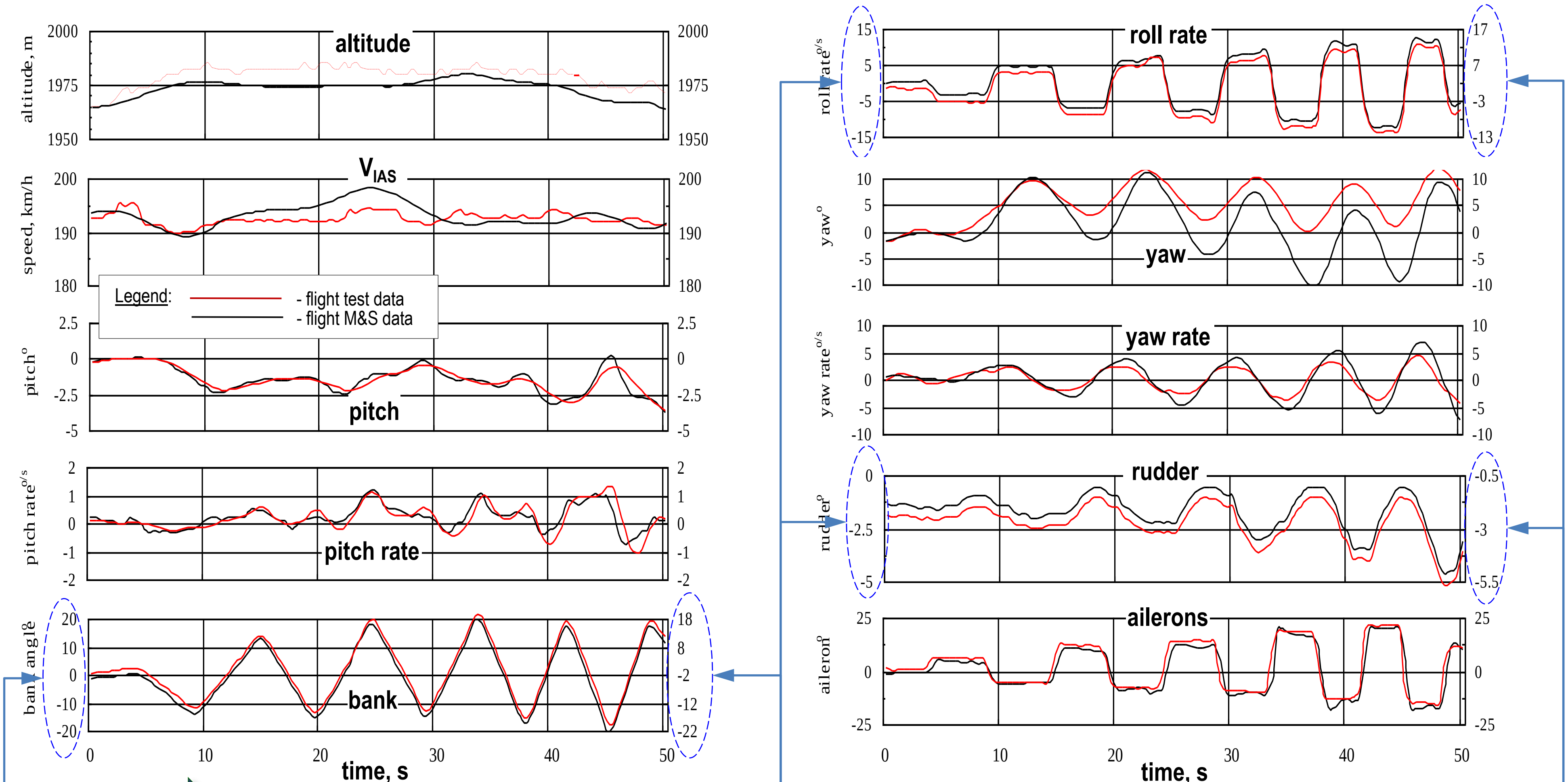
Initial Conditions of Flight (Case 03.01/05.15.00)

System variable	Value	Unit	Comments
Altitude	1965	m	
Aerodrome elevation	0	m	At mean sea level
Aircraft mass	20 000	kg	
C.G. location w.r.t. MAC	22,1	%	C.G. – center of gravity; w.r.t. - with respect to
IAS	197	km/h	Indicated airspeed
Flight path angle	0	°	
Cross wind	0	m/s	Benign weather conditions: no wind
Flaps	0	°	Clean configuration
Slats	0	°	Clean configuration
Landing gear	retracted	-	
Atmospheric conditions	ISA	-	Air density, pressure, temperature
Aircraft type	Ilyushin-114	-	Courtesy of Ilyushin Aircraft Design Bureau

Ilyushin-114

10. Level Flight, ‘Saw’ Type Inputs by Ailerons and Rudder

Comparison of Simulated and Real Flight Data (Case 03.01/05.15.00)



Ilyushin-114

LH- and RH-scales are shifted for clarity: there is **no difference** between modeled and real flight data.

11. Takeoff, Strong Wind-Shear (‘Microburst’), Heavy Rain, Low Visibility, Pilot Errors, Ambiguities in Flight Manual

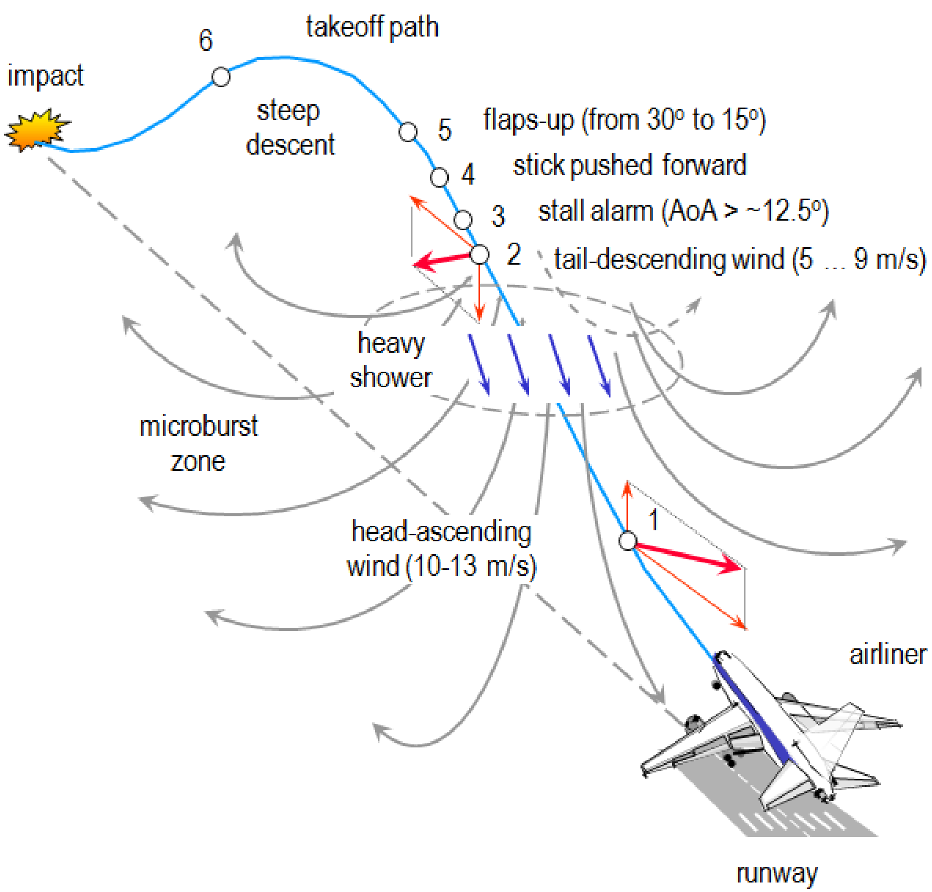
Initial Conditions of Flight (Accident Case 04.01/09.03.89)

System variable	Value	Unit	Comments
Aerodrome elevation	0	m	At mean sea level
Aircraft mass	164 625	kg	
C.G. location w.r.t. MAC	25	%	C.G. – center of gravity; w.r.t. - with respect to
IAS	223	km/h	Indicated airspeed
Flight path angle	0	°	
Wind conditions	‘microburst’	m/s	‘Very strong’ wind shear - see flight scenario
Rain Intensity	225	mm/h	Visibility 500 m
Flaps	30	°	Takeoff configuration
Landing gear	extended	-	
Atmospheric conditions	ISA	-	Air density, pressure, temperature
Aircraft type	Ilyushin-62M	-	Courtesy of Ilyushin Design Bureau

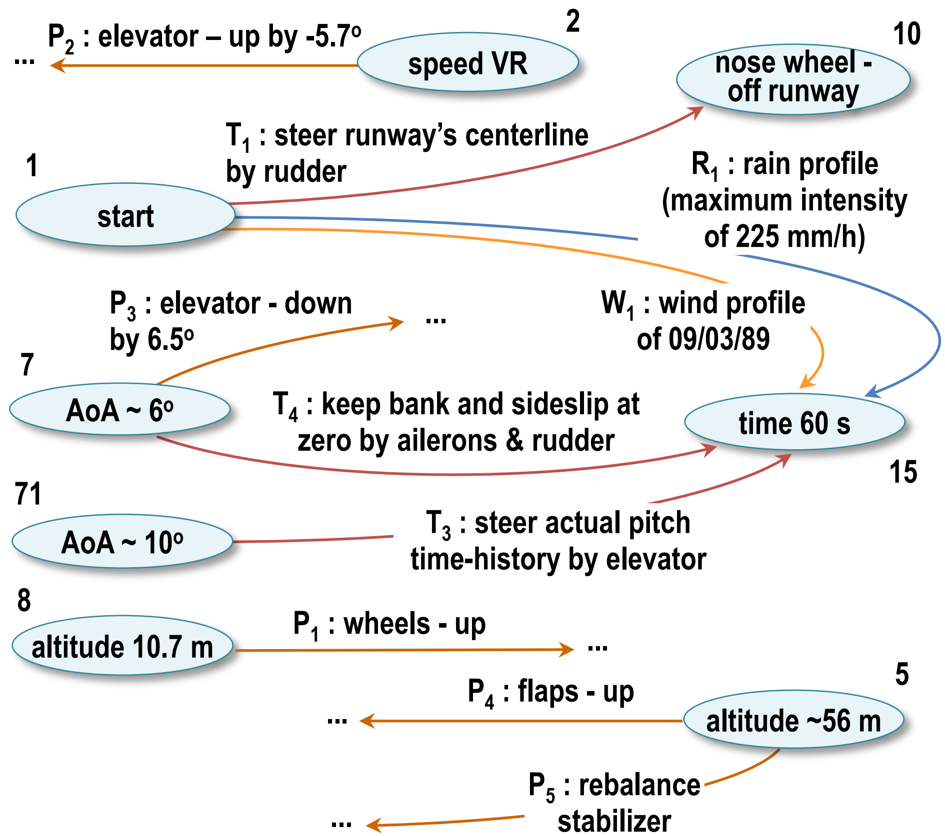
Ilyushin-62M

11. Takeoff, Strong Wind-Shear ('Microburst'), Heavy Rain, Low Visibility, Pilot Errors, Ambiguities in Flight Manual

Flight Profile (Accident Case 04.01/09.03.89 – HAV, Cuba)



Flight Situation Scenario (Accident Case 04.01/09.03.89)

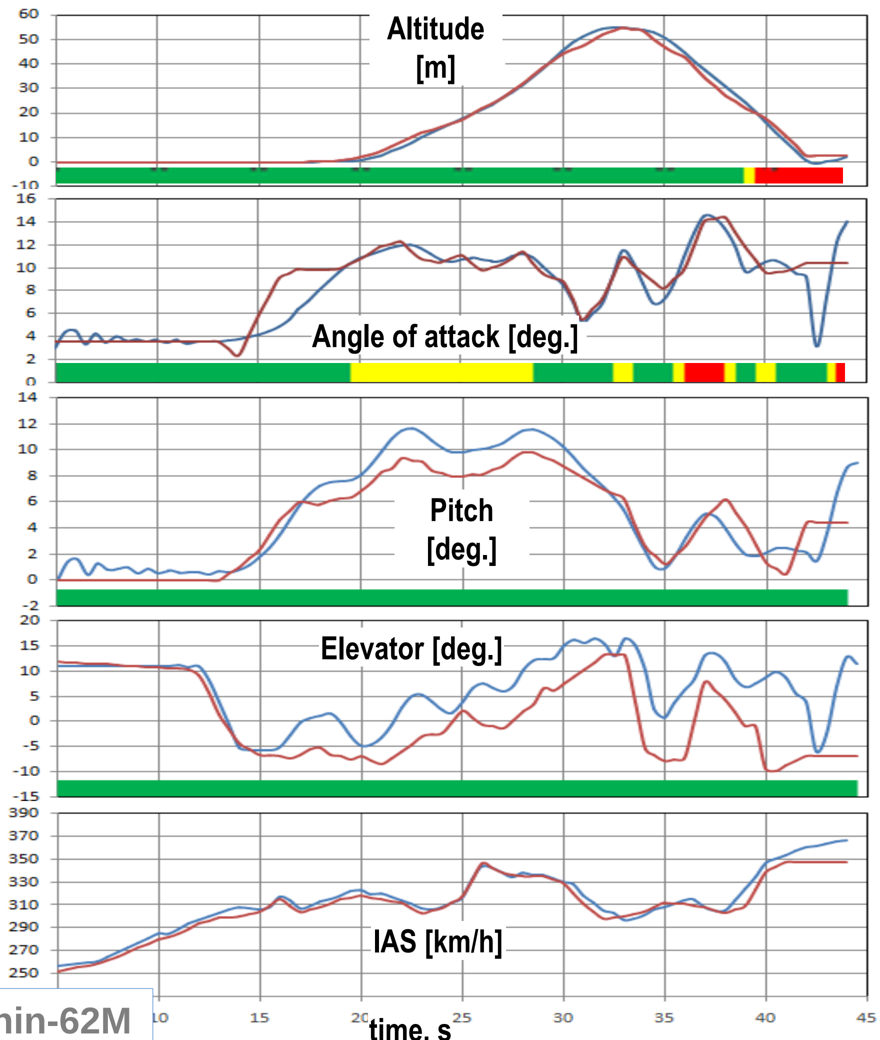


Ilyushin-62M

11. Takeoff, Strong Wind-Shear (‘Microburst’), Heavy Rain, Low Visibility, Pilot Errors, Ambiguities in Flight Manual

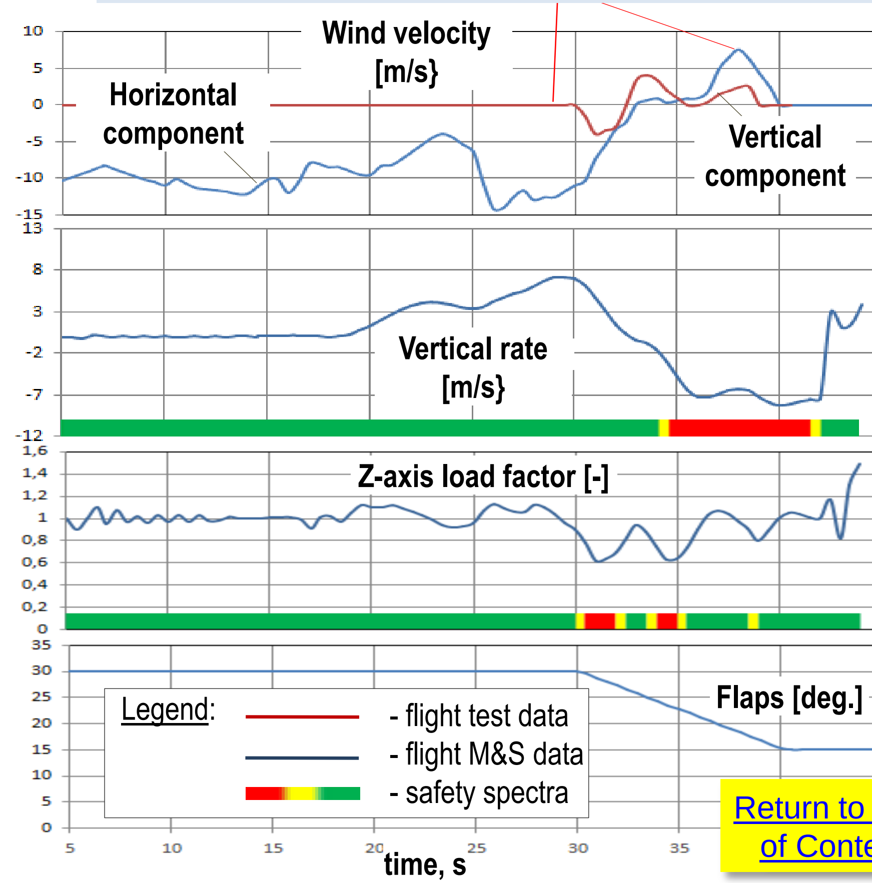
5. Validation Examples

Comparison of Simulated and Real Flight Data (Accident Case 04.01/09.03.89)



Ilyushin-62M

‘Very strong’ wind shear profile (vertical and horizontal velocity components) have been identified using flight recorder data and M&S.



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Multifactor Operational Domains Examined in VFT&C Experiments - Examples (1 of 3)

#	Flight phase	Examined combination of risk factors	N (Φ)
1	**Level flight**	Hydraulic systems ## 1&3 failure (ref. FME matrix), pitch-up/down impulses by column, altitude, C.G., mass, flaps/ slats, V_{EF}	**8**
2	**Landing approach, landing, ground roll**	Hydraulic systems ## 1&2 failure (ref. FME matrix), cross wind, V_{LA}, slats/ flaps, C.G., mass, runway condition, aerodrome elevation	**9**
3	**Go-around**	Hydraulic systems ## 1&2 failure (ref. FME matrix), cross wind, V_{LA}, slats/ flaps, C.G., mass, H_{DM}	**8**
4	**Continued takeoff, initial climb**	Critical LH-engine out, cross wind (L→R), mass, C.G., V_{EF}, slats/flaps, runway condition, aerodrome elevation	**8**
5	**Continued takeoff, initial climb**	Critical LH-engine out, cross wind (L→R), mass, C.G., V_{EF} , lateral control, ABC-flap failure	**7**
6	**Aborted takeoff**	Critical LH-engine out, cross wind (L→R), mass, C.G., V_{EF}, slats/flaps, runway condition, aerodrome elevation	**8**
7	**Continued landing, ground roll**	Critical LH-engine out, cross wind (L→R), V_{LA}, slats/flaps, C.G., mass, runway condition, aerodrome elevation	**8**
8	**Level flight**	Hydraulic systems ## 1&2 failure (ref. FME matrix), ailerons impulses LH-RH bank), interceptors, H_{LF}, V_{LF}, C.G., mass	**8**
9	**Continued landing, ground roll**	Critical engine out, H_{EF}, cross wind, C.G., mass, runway condition, aerodrome elevation, pilot errors/ inattention in lateral control during ground roll, differential thrust reversing	**9**
10	**Climb**	Hydraulic systems ## 1&2 failure (ref. FME matrix), cross wind, updrafts, downdrafts, V_{CL}, slats/ flaps, C.G., mass	**9**

Legend: **N(Φ)** - number of risk factors constituting a complex operational domain. **DM** - decision making. **EF** - engine failure. **FME** - failure modes & effects. **CL** - climb. **LA** - landing approach. **LF** - level flight. **L→R** - left-to-right. **ABC** - automatic bank compensation.

Each combination of N(Φ) risk factors is used to generate a situational tree. The goal is to screen a complex operational domain of flight for **hidden safety flaws** and possible **recovery options**.

Multifactor Operational Domains Examined in VFT&C Experiments - Examples (2 of 3)

#	Flight phase	Examined combination of risk factors	N (Φ)
11	**Descent**	Hydraulic systems ## 1&2 failure (ref. FME matrix), cross wind, updrafts, downdrafts, V_{DES}, slats/ flaps, C.G., mass	**9**
12	**Level flight**	Hydraulic systems ## 1&2 failure (ref. FME matrix), cross wind, up-/down-drafts, V_{DES}, H_{LF}, slats/ flaps, C.G., mass	**10**
13	**Level flight, descent, climb, turns**	Deceleration, cross wind, up-/down-drafts, V_{LF}, slats/flaps, C.G., mass, H_{LF}, commanded flight path and bank angles, impulses by ailerons and rudder, ramps by rudder	**14**
14	**Go-around**	Cross wind, wind shear, downdrafts, V_{LA}, slats/ flaps, C.G., mass, undercarriage, H_{DM}, atmospheric conditions (high temperature)	**10**
15	**Go-around**	Critical engine out, H_{EF} or V_{EF}, cross wind, V_{LA}, slats/ flaps, C.G., mass, H_{DM}, high temperature, pilot delay in responding to engine failure	**11**
16	**Landing approach, landing, ground roll**	Hydraulic systems ## 1&3 failure (ref. FME matrix), cross wind, V_{LA}, slats/flaps, C.G., mass, runway condition, aerodrome elevation	**12**
17	**Go-around**	Hydraulic systems ## 1&3 failure (ref. FME matrix), cross wind, V_{LA}, slats/ flaps, C.G., mass, H_{DM}, atmospheric conditions (high temperature)	**13**
18	**Continued takeoff, initial climb**	Critical engine out, H_{EF} or V_{EF}, slats/ flaps, C.G., mass, undercarriage, runway condition, aerodrome elevation, atmospheric conditions (low temperature), aircraft icing	**10**
19	**Climb**	Critical engine out, H_{EF} or V_{EF}, slats/flaps, C.G., mass, undercarriage, atmospheric conditions (low temperature), aircraft icing.	**8**
20	**Descent**	Critical engine out, H_{EF} or V_{EF}, updrafts, downdrafts, C.G., mass, undercarriage, interceptors, aircraft icing.	**9**
Legend: N(**Φ**) - number of risk factors constituting a complex operational domain. **DM** - decision making. **EF** - engine failure. **FME** - failure modes and effects. **CR** - cruise. **DES** – descent. **LA** - landing approach. **LF** - level flight.			

Multifactor Operational Domains Examined in VFT&C Experiments - Examples (3 of 3)

#	Flight phase	Examined combination of risk factors	N (Φ)
21	**Landing, ground roll**	Critical engine out, V_{EF}, cross wind, C.G., mass, runway condition, aerodrome elevation, atmospheric high temperature, lateral piloting, pilot delay in responding to engine failure	**10**
22	**Cruise flight**	Critical engine out, H_{CR}, V_{EF}, updrafts, downdrafts, indicated airspeed, C.G., mass, impulses by ailerons, impulses by rudder, ramps by rudder	**11**
23	**Cruise flight**	H_{CR}, V_{CR}, updrafts, downdrafts, C.G., mass, impulses by elevator, impulses by ailerons, impulses by rudder, aircraft icing	**10**
24	**Continued takeoff, initial climb**	Critical engine out, H_{EF} or V_{EF}, wind shear, slats/flaps, C.G., mass, undercarriage, runway condition, aerodrome elevation, atmospheric conditions (high temperature), heavy rain	**11**
25	**Landing, ground roll**	Thrust reversers failure (symmetric and asymmetric cases), cross wind, C.G., mass, runway condition, aerodrome elevation, atmospheric conditions (high temperature), lateral piloting	**9**
26	**Landing, ground roll**	Cross wind, C.G., mass, runway condition, aerodrome elevation, atmospheric conditions (high temperature), lateral piloting, nose wheel steering inoperative (nose wheel castoring)	**8**
27	**Landing, ground roll**	Cross wind, C.G., mass, runway condition, aerodrome elevation, main wheel brakes – jammed/ inoperative/ differential control, thrust - differential/ emergency control	**9**
28	**Takeoff (ground roll)**	Cross wind, C.G., mass, runway condition, aerodrome elevation, nose wheel steering (1/2 power)	**6**
29	**Go-around**	Critical engine out, H_{EF} or V_{EF}, wind shear, V_{LA}, slats/ flaps, C.G., mass, H_{DM}, piloting techniques variations (pitch, bank, sideslip)	**11**

Legend: **N(Φ)** - number of risk factors constituting a complex operational domain. **DM** - decision making. **EF** - engine failure. **FME** - failure modes and effects. **CR** - cruise. **LA** - landing approach. **LF** - level flight.

The above-listed multifactor composites (tree 'genotypes') **map the content of flight test cases stipulated in airworthiness certification regulations** Part 23/ 25/ … : FAR, JAR, CCAR, АП, etc.

Onboard Hardware Failure Modes & Effects Matrix Used in VFT&C Process - Fragment

FME Group #	Energy sources					Energy consumers																									
	Hydraulic system #			Engine		Elevator		Ailerons		Rudder		Interceptors				Flaps actuators			Slats actuators			Undercarriage			Wheels brakes		Thrust reversers ('backet' doors)		Interceptors, air brakes		Nose whe-el
	1	2	3	LH	RH	LH	RH	LH	RH	LS	US	OLH	ILH	IRH	ORH	Main	Track.	Back-up	Main	Track.	Back up	Main	Back-up	Emer-gency	Main	Back-up	LH	RH	Air-borne	Gro-und	Cast-ering
1																															
2	M.	M.				M., F		M., F			M., F		M, S	M		M	M	1/2	M	M	M	M			M	M	M		P		
3	M		M				M, F		M, F	M, F						M	M	M	M	M	1/2		M	M			M	M	P		M
4		M	M									M (A, G)			M (A, G)	1/2	1/2	1/2	1/2	1/2	1/2	M	M		M			M	P	M, W	
5	M				M											1/2	1/2	1/2	1/2	1/2	1/2						M	M			
6			M	M												1/2	1/2	1/2	1/2	1/2	1/2						M	M			
7		M		M												1/2	1/2	1/2	1/2	1/2	1/2	M			M						
8		M			M											1/2	1/2	1/2	1/2	1/2	1/2	M			M						
9	M			M												1/2	1/2	1/2	1/2	1/2	1/2										
10			M		M											1/2	1/2	1/2	1/2	1/2	1/2										

Legend:

FME Group #	–	Failure modes and effects scenario group number.	**Emergency**	–	'Emergency' operational mode, emergency system.
M	–	Malfunction (inoperative).	**Backup**	–	Back-up system.
F	–	Feathering of an aerodynamic surface.	**LH**	–	Left-hand.
A	–	Airborne phase of flight.	**RH**	–	Right-hand.
G	–	Ground phase of flight.	**IRH**	–	Inner right-hand.
P	–	The effect is possible depending on the physical conditions of a specific aerodynamic surface in current flight mode.	**ORH**	–	Outer right-hand.
S	–	Suction.	**ILH**	–	Inner left-hand.
W	–	Weak effect (lowered effectiveness).	**OLH**	–	Outer left-hand.
1/2	–	Two times (approximately) reduced rate of operation of high-lift devices.	**LS**	–	Lower section
Main	–	'Main' operational mode of a high-lift device, main onboard system.	**US**	–	Upper section
Track.	–	'Tracking' operational mode of a high-lift device.	**FME**	–	Failure modes and effects.

Similar FMEA matrices are an **essential part of flight T&C programs** for Tupolev-334, Tupolev-204 and other families of aircraft.

Knowledge Statistics of Virtual Flight Test Experiments for Selected Multifactor Domains

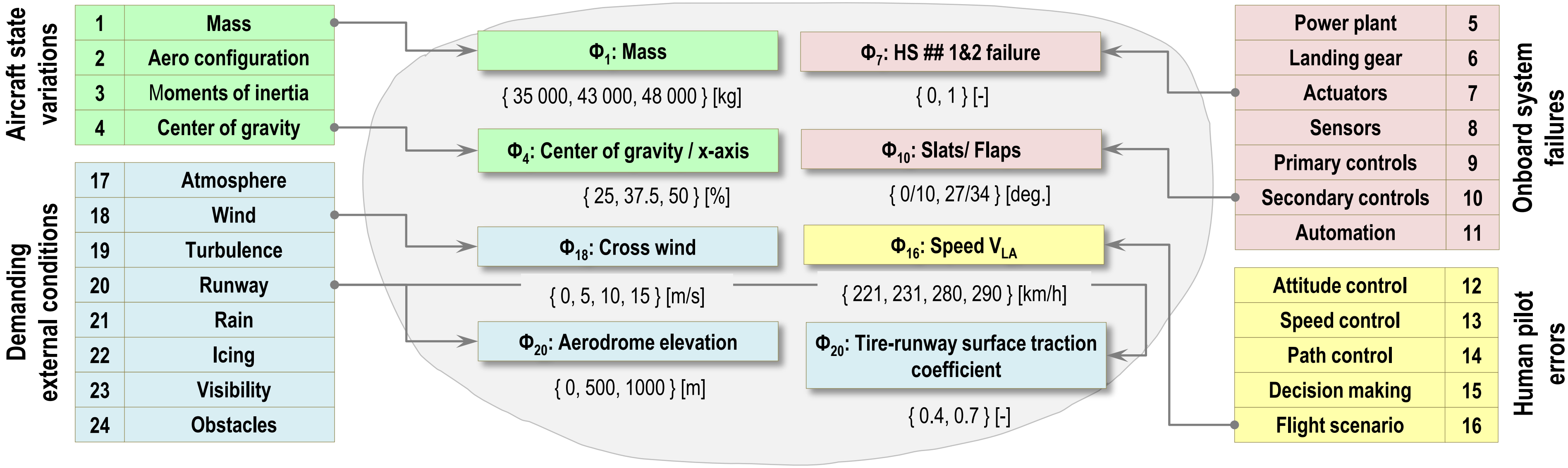
#	Flight phase	Examined combination of risk factors	N (Φ)	N_{max} (T)	$\mathfrak{I}_{max} \mid T$, hrs
1	**Level flight**	HS ## 1&3 failure, pitch-up/down impulses by column, H_{LF}, C.G., mass, flaps/ slats, V_{EF}	8	436	1.8
2	**Landing approach, landing, ground roll**	HS ## 1&2 failure, cross wind, V_{LA}, slats/ flaps, C.G., mass, runway condition, aerodrome elevation	9	3 456	69.0
3	**Go-around**	HS ## 1&2 failure, cross wind, V_{LA}, slats/ flaps, C.G., mass, H_{DM}	8	2 160	51.0
4	**Continued takeoff, initial climb**	Critical LH-engine out, cross wind (L→R), mass, C.G., V_{EF}, slats/ flaps, runway condition, aerodrome elevation	8	4 320	276.0
5	**Continued takeoff, initial climb**	Critical LH-engine out, cross wind (L→R), mass, C.G., V_{EF} , lateral control, ABC-flap failure	7	4 320	144.0
6	**Aborted takeoff**	Critical LH-engine out, cross wind (L→R), mass, C.G., V_{EF}, slats/ flaps, runway condition, aerodrome elevation	8	2 160	18.0
7	**Continued landing, ground roll**	Critical LH-engine out, cross wind (L→R), V_{LA}, slats/ flaps, C.G., mass, runway condition, aerodrome elevation, lateral piloting	9	3 456	56.0
8	**Level flight**	HS ## 1&2 failure, ailerons impulses (left-right bank), interceptors, H_{LF}, V_{LF}, C.G., mass	8	1152	6.4

Legend: **N(Φ)** - number of risk factors constituting a complex operational domain. **LH** - left-hand. **DM** - decision making. **EF** - engine failure. **FME** - failure modes & effects. **LA** - landing approach. **LF** - level flight. **L→R** - left-to-right. **ABC** - automatic bank control. **N_{max} (T)** - maximal number of branches in tree T. $\mathfrak{I}_{max} \mid T$ – maximal total virtual flight test time accumulated in tree T. **HS** – hydraulic system.

The actual number of cases (**N (T)**) and the total virtual test time ($\mathfrak{I} \mid T$) of the above-listed complex operational domains **may be smaller than the maximal values** shown here – due to physical and logical constraints imposed on 'what-if' scenarios by AI algorithms controlling the tree growth.

2. Landing, HS ## 1&2 Failure, Cross Wind, V_{LA}, Slats/ Flaps, C.G., Mass, Runway Condition, Aerodrome Elevation (9-Factor Domain)

Situational tree's genotype



Number of 'flights': $N_{\max}(\boldsymbol{T}) = 3456$

Total virtual flight test time: $\Im_{\max} \mid \boldsymbol{T} = 69\,hrs$

Virtual flight test program (fragment)

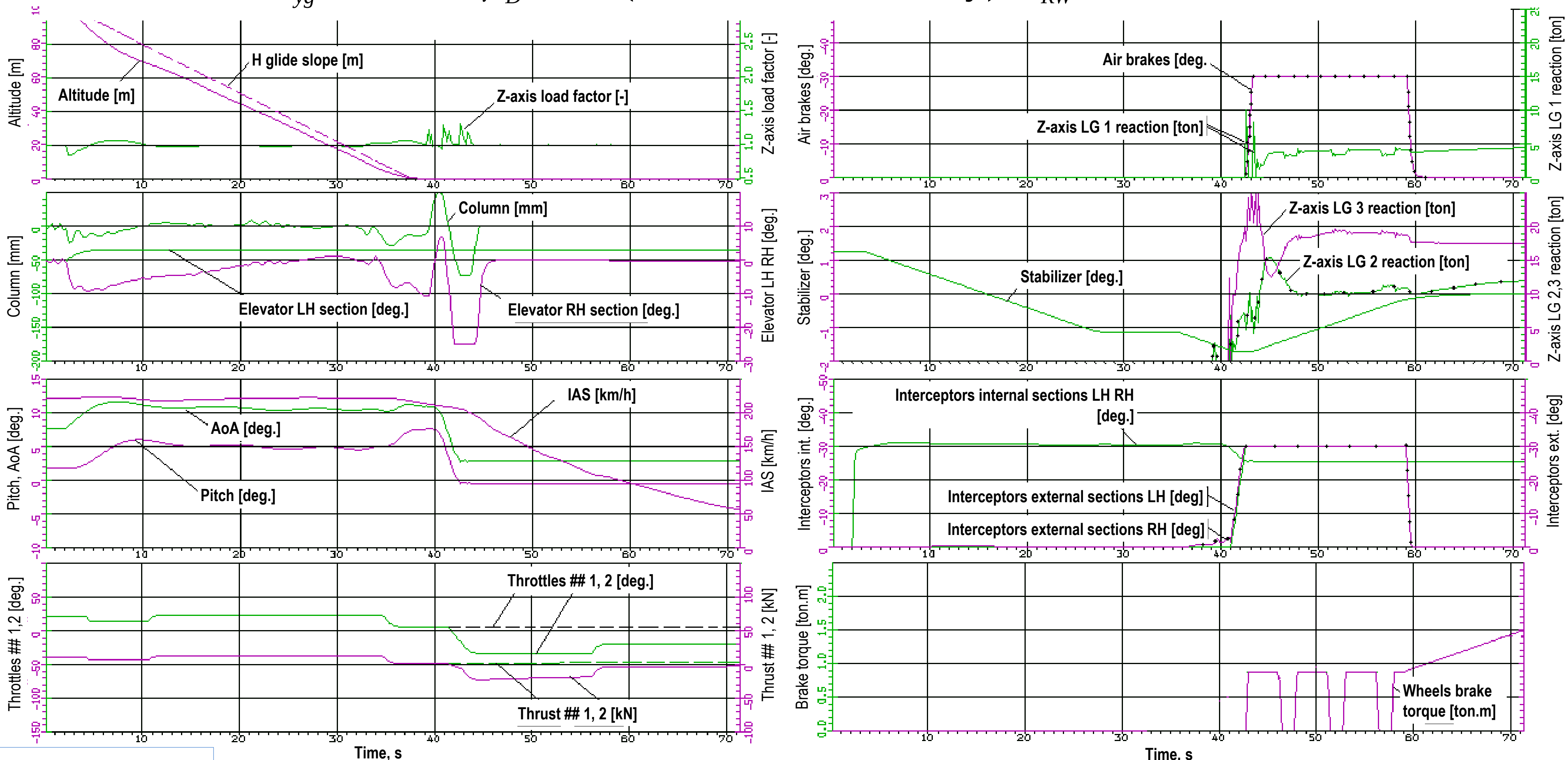
Branch #	Φ_7: HS ## 1&2 failure	Φ_{18}: Cross wind	Φ_1: Mass	Φ_4: Center of gravity	Φ_{10}: Slats/Flaps	Φ_{20}: Aerodrome elevation	Φ_{20}: Tire-runway traction coefficient	Φ_{16}: Speed V_{LA}
0001	0	0	35 000 kg	25 %	0/10 deg.	0	0.4	290 km/h
0002	0	0	35 000 kg	25 %	0/10 deg.	0	0.4	290 km/h
…	…	…	…	…	…	…	…	…
3456	1	15 m/s	48 000 kg	50 %	27/34 deg.	1000 m	0.7	221 km/h

Tupolev-334-100

Legend: Φ_i – risk factor. **HS** – hydraulic system. **LA** – landing approach. $\boldsymbol{N}_{\max}$ ($\boldsymbol{T}$) - maximal number of 'flights' (branches) in $\boldsymbol{T}$. $\Im_{\max} \mid \boldsymbol{T}$ – total virtual flight test time in $\boldsymbol{T}$. Ref. 'Failure Modes and Effects Propagation Matrix'.

2. Landing, HS ## 1&2 Failure, Cross Wind, V_{LA}, Slats/ Flaps, C.G., Mass, Runway Condition, Aerodrome Elevation (9-Factor Domain)

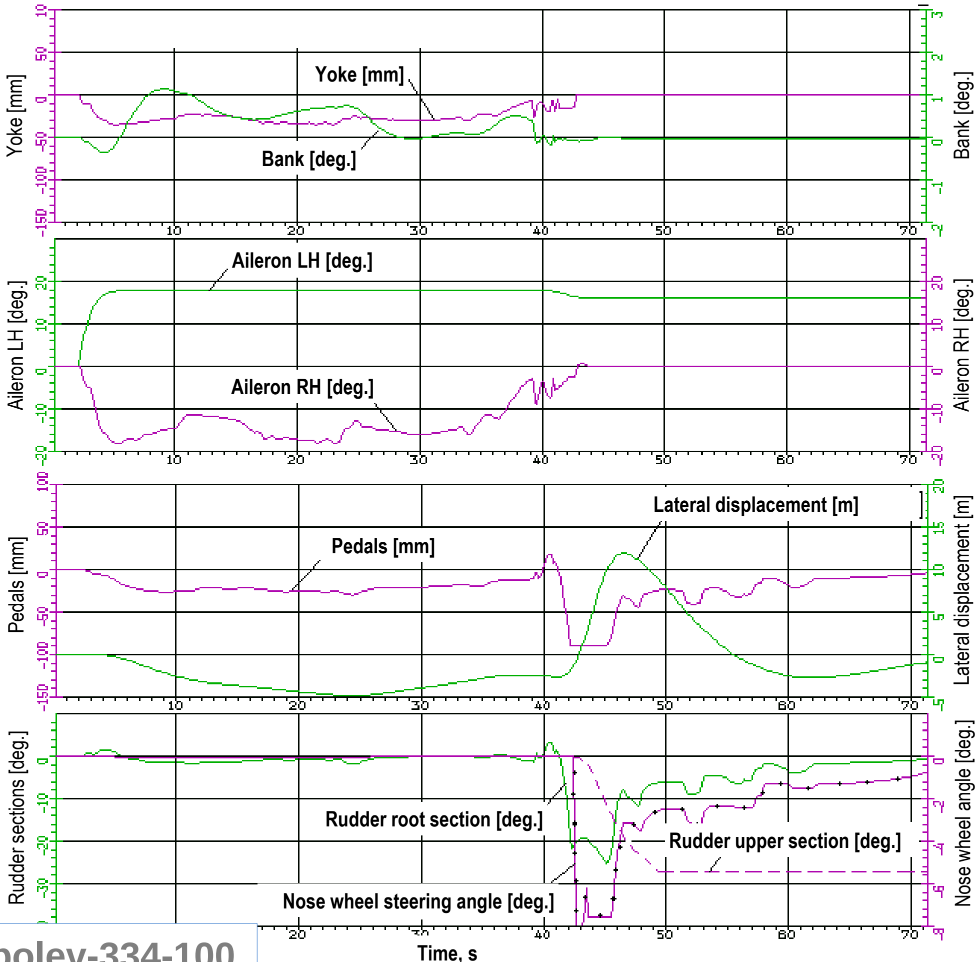
Flight # xxxx: $\text{HS \#\#1,2 failure} = 1, V_{LA} = 221\ km/h, \bar{x}_{CG} = 50\%, m = 35000\ kg, \delta_S / \delta_F = 24^o / 37^o,$
$W_{yg} = 15\ m/s, \mu_D = 0.4\ (\text{water covered runway}), H_{RW} = 0$

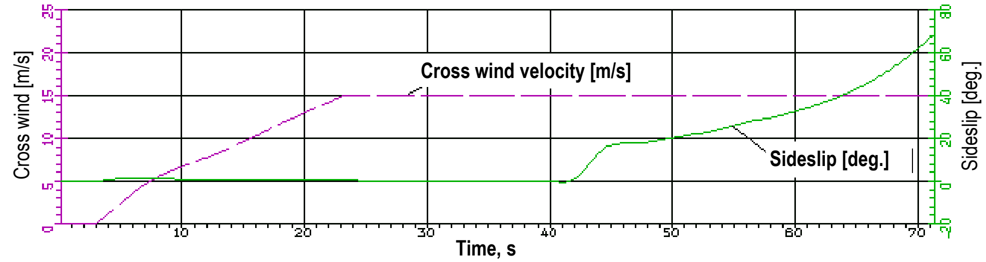


Tupolev-334-100

2. Landing, HS ## 1&2 Failure, Cross Wind, V_{LA}, Slats/ Flaps, C.G., Mass, Runway Condition, Aerodrome Elevation (9-Factor Domain)

Flight # xxxx: $\text{HS \#\#1,2 failure} = 1, V_{LA} = 221\ km/h, \bar{x}_{CG} = 50\%, m = 35000\,kg, \delta_S/\delta_F = 24^o/37^o,$
$W_{yg} = 15\ m/s, \mu_D = 0.4\ \text{(water covered runway)}, H_{RW} = 0$

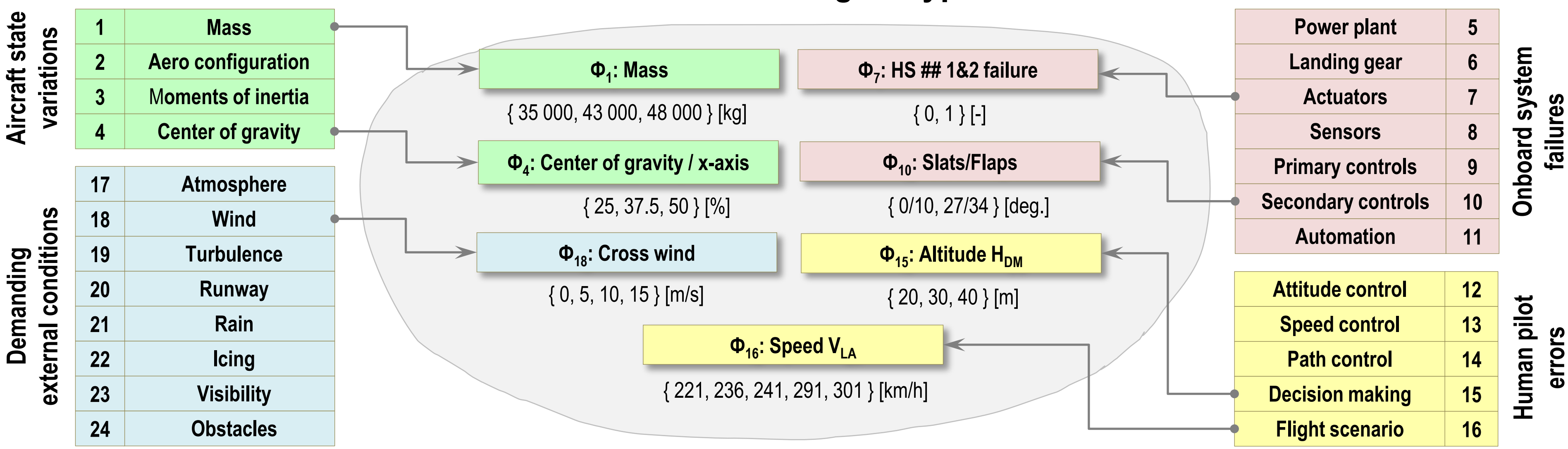




Tupolev-334-100

3. Go-Around, HS ## 1&2 Failure, Cross Wind, V_{LA}, Slats/ Flaps, C.G., Mass, H_{DM} (8-Factor Domain)

Multifactor tree genotype



Number of 'flights': $N_{\max}(\boldsymbol{T}) = 2160$ **Total virtual flight test time:** $\Im_{\max} \,|\, \boldsymbol{T} = 51 hrs$

Virtual flight test program (fragment)

Branch #	Φ_7: HS ## 1&2 failure	Φ_{18}: Cross wind	Φ_1: Mass	Φ_4: Center of gravity	Φ_{10}: Slats/Flaps	Φ_{15}: Altitude H_{DM}	Φ_{16}: Speed V_{LA}
0001	0	0	35 000 kg	25 %	0/10 deg.	20 m	221 km/h
0002	0	0	35 000 kg	25 %	0/10 deg.	20 m	221 km/h
...	...	...	...	...	...	...	...
2160	1	15 m/s	48 000 kg	50 %	27/34 deg.	40 m	301 km/h

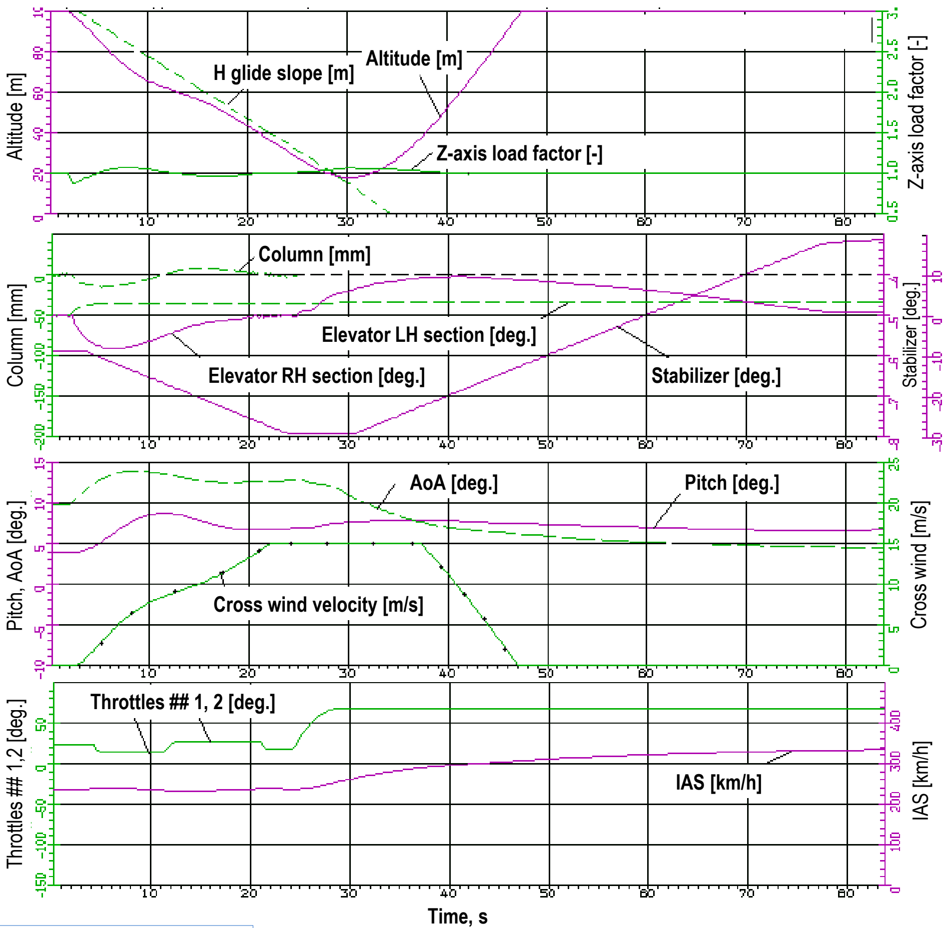
Tupolev-334-100

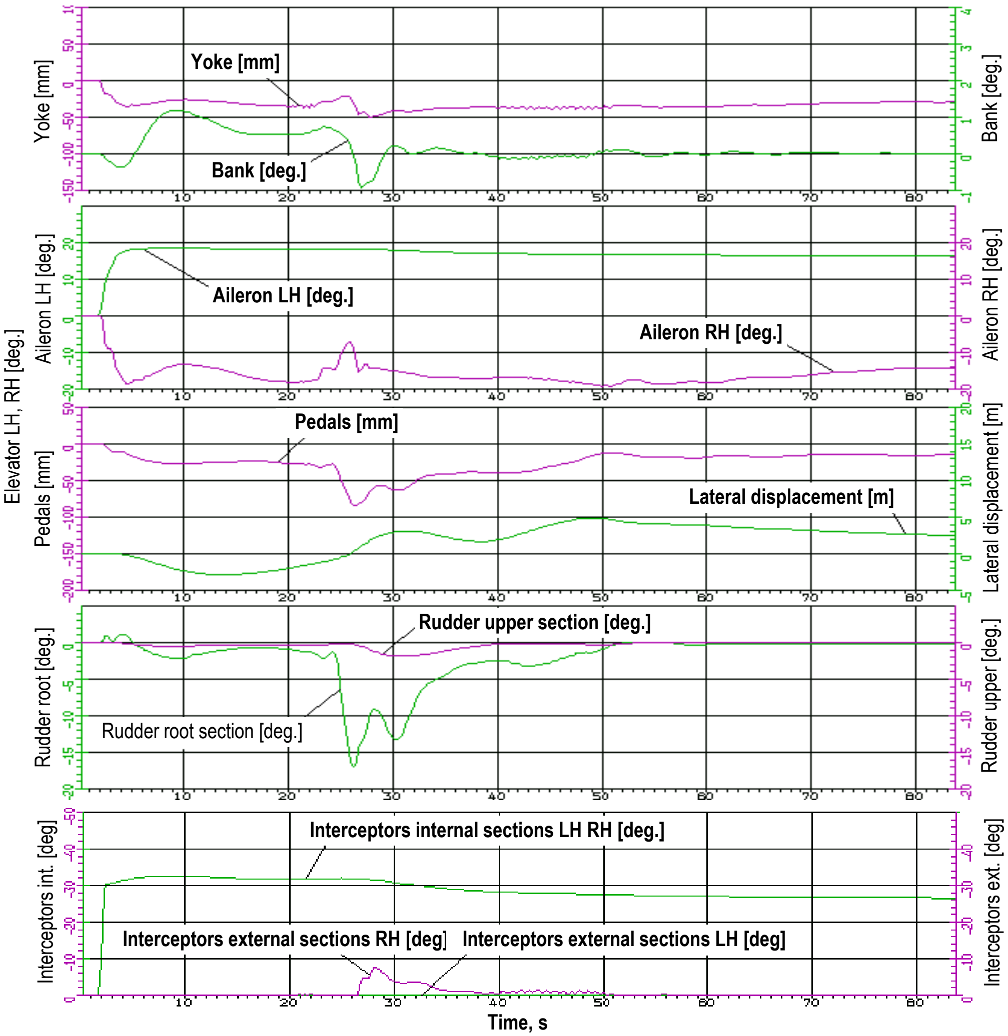
Legend: $\boldsymbol{\Phi}_i$ – risk factor. **HS** – hydraulic system. **LA** – landing approach. **DM** – decision making (to go-around) $N_{\max}(\boldsymbol{T})$ - maximal number of 'flights' in $\boldsymbol{T}$. $\Im_{\max} \,|\, \boldsymbol{T}$ – total virtual flight test time in $\boldsymbol{T}$. Ref. 'FME Propagation Matrix'.

3. Go-Around, HS ## 1&2 Failure, Cross Wind, V_{LA}, Slats/ Flaps, C.G., Mass, H_{DM} (8-Factor Domain)

Flight # xxxx: $\text{HS \#\#1,2 failure} = 1, V_{LA} = 236\ km/h, \bar{x}_{CG} = 25\%, m = 43000\,kg, \delta_S/\delta_F = 27^o/34^o,$

$$W_{yg} = 15\ m/s, H_{DM} = 30\,m$$

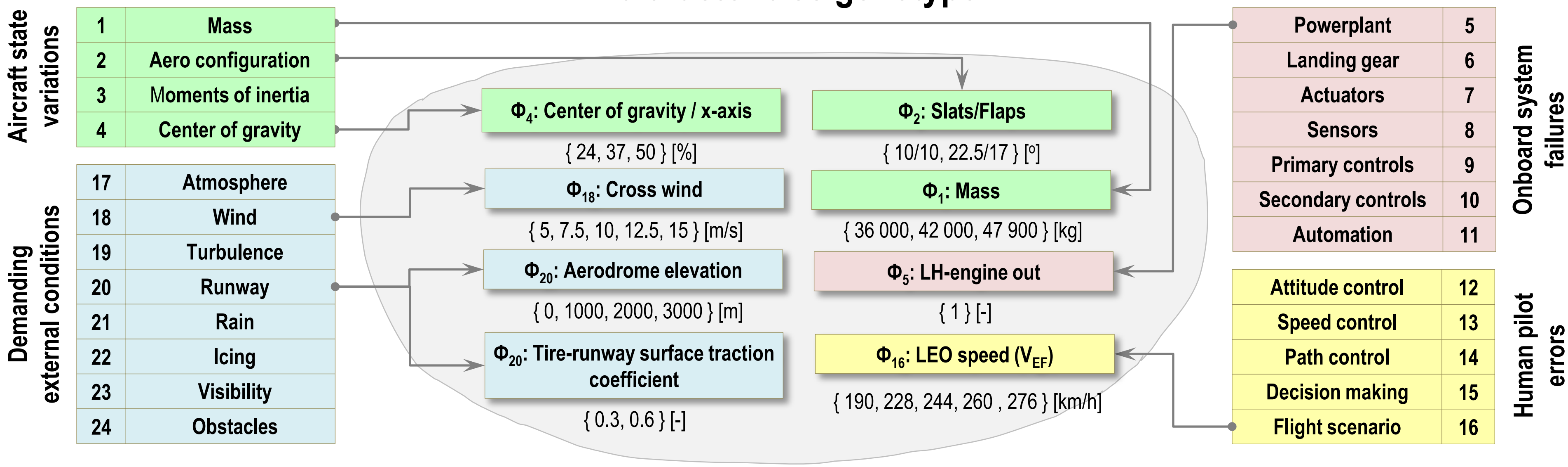




Tupolev-334-100

4. Cont'd Takeoff, LEO, Crosswind (L→R), Mass, C.G., V_{EF}, Slats/ Flaps, Runway Condition, Aerodrome Elevation (8-Factor Domain)

Multifactor tree genotype



Number of 'flights': $N_{\max}(\boldsymbol{T}) = 4320$ **Total virtual flight test time:** $\Im_{\max} \,|\, \boldsymbol{T} = 276\, hrs$

Virtual flight test program (fragment)

Branch #	Φ_5: LH-engine out	Φ_{16}: LEO speed (V_{EF})	Φ_1: Mass	Φ_4: Center of gravity	Φ_{18}: Cross wind	Φ_{20}: Tire-runway traction coefficient	Φ_2: Slats/Flaps	Φ_{20}: Aerodrome elevation
0001	1	190 km/h	36 000 kg	24 %	5 m/s	0.3	10º/10º	0
0002	1	190 km/h	36 000 kg	24 %	5 m/s	0.3	10º/10º	0
...	...	...	...	...	...		...	...
4320	1	276 km/h	47 900 kg	50%	15 m/s	0.6	22.5º/17º	3000 m

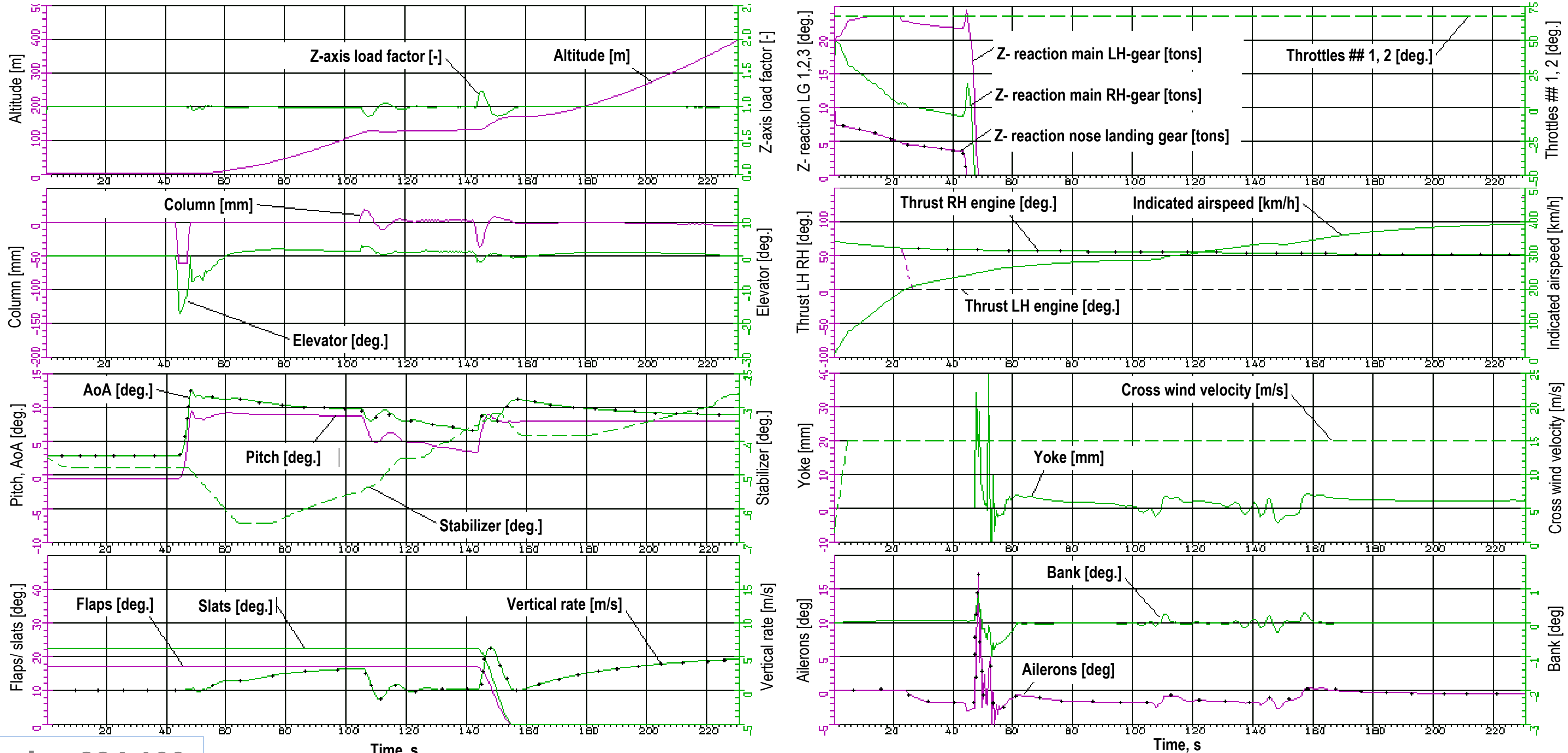
Tupolev-334-100

Legend: Φ_i – risk factor. **LH** – left-hand. **LEO** – left-hand engine out. **L→R** – left-to-right (wind direction). **EF** - engine failure. $N_{\max}(T)$ - maximal number of 'flights' in tree T. $\Im_{\max} | T$ – total virtual flight test time in tree T.

4. Cont'd Takeoff, LEO, Crosswind (L→R), Mass, C.G., V_{EF}, Slats/ Flaps, Runway Condition, Aerodrome Elevation (8-Factor Domain)

Flight # xxxx: $\text{LH} - \text{engine out} = 1,\ V_{EF} = 190\ km/h,\ V_R = 240\ km/h,\ \bar{x}_{CG} = 24\%,\ m = 47\ 900\ kg,$

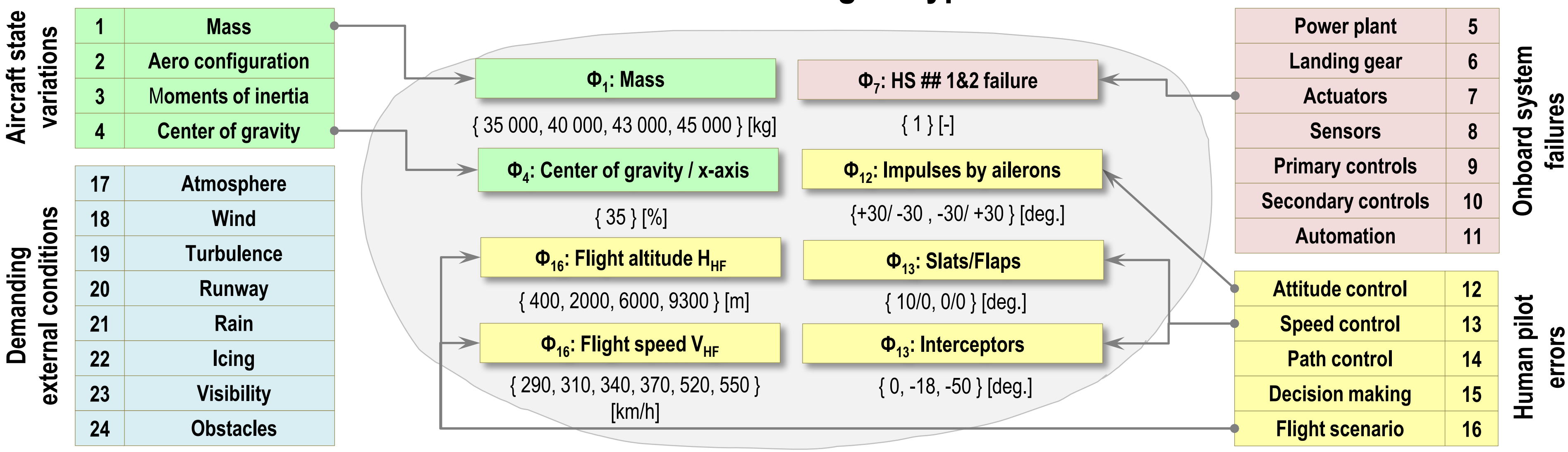
$\delta_S / \delta_F = 22.5^o / 17^o,\ W_{yg} = 15\ m/s,\ \mu_D = 0.6\ \text{(dry runway)}$



Tupolev-334-100

8. Level Flight, HS ## 1&2 Failure, Ailerons Impulses (Left-Right Bank), Interceptors, H_{LF}, V_{LF}, C.G., Mass (8-Factor Domain)

Multifactor tree genotype



Number of 'flights': $N_{\max}(\boldsymbol{T}) = 1152$

Total virtual flight test time: $\Im_{\max} \,|\, \boldsymbol{T} = 6.4\,hrs$

Virtual flight test program (fragment)

Branch #	Φ_7: HS ## 1&2 failure	Φ_{12}: Impulses by ailerons	Φ_1: Mass	Φ_4: Center of gravity	Φ_{13}: Slats/Flaps	Φ_{16}: Flight altitude H_{HF}	Φ_{16}: Flight speed V_{HF}	Φ_{13}: Interceptors
0001	1	+30/-30 deg.	35 000 kg	35 %	0/0	9300 m	550 km/h	0
0002	1	-30/+30 deg.	35 000 kg	35 %	0/0	9300 m	550 km/h	0
...	...	...	...	...	...	...	...	...
1152	1	-30/+30 deg.	45 000 kg	35 %	10/0 deg.	400 m	290 km/h	-50 deg.

Tupolev-334-100

Legend: Φ_i – risk factor. **HS** – hydraulic system. $N_{\max}$ (T) - maximal number of 'flights' in tree T. $\Im_{\max} \,|\, T$ – total virtual flight test time accumulated in tree T. **HF** - horizontal flight. Ref. FME Propagation Matrix'.

8. Level Flight, HS ## 1&2 Failure, Ailerons Impulses (Left-Right Bank), Interceptors, H_{LF}, V_{LF}, C.G., Mass (8-Factor Domain)

6. Application Examples

Longitudinal motion parameters

$\text{HS \#\#1,2 failure} = 1,$

$\gamma_G : (+30^o) \rightarrow (-30^o)$

$\gamma_G : (-30^o) \rightarrow (+30^o)$

$H_{LF} = 9\,300\, m,$

$V_{LF} = 370\; km/h,$

$\bar{x}_{CG} = 35\%,$

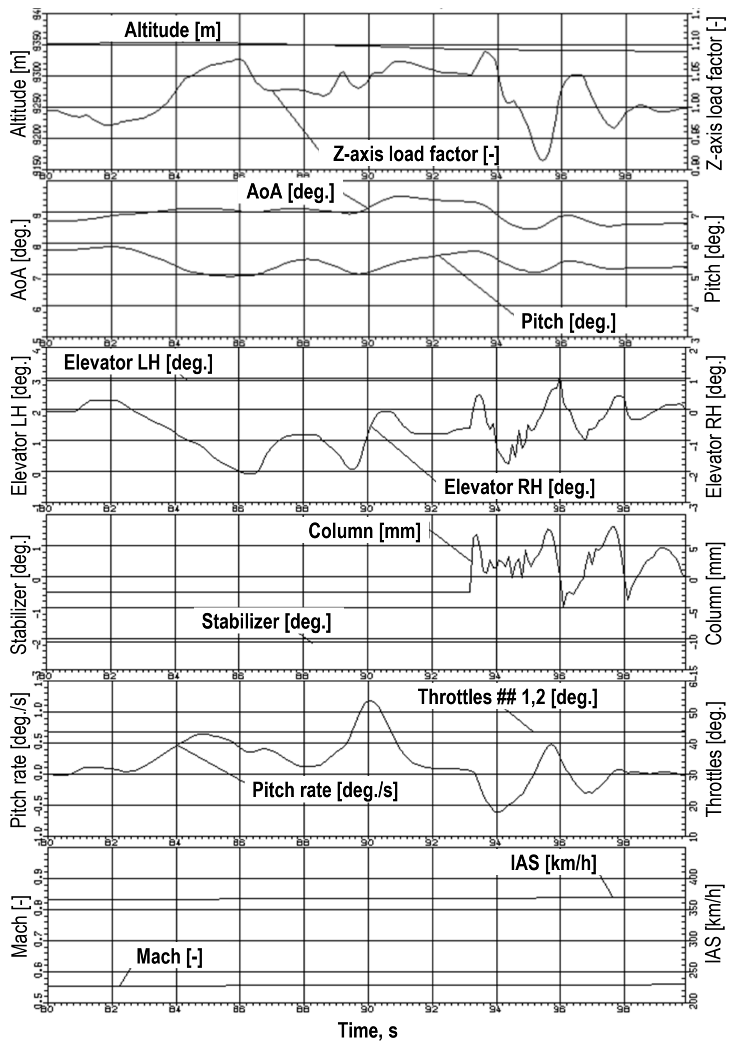
$m = 40\,000\; kg,$

$\delta_S / \delta_F = 0/0,$

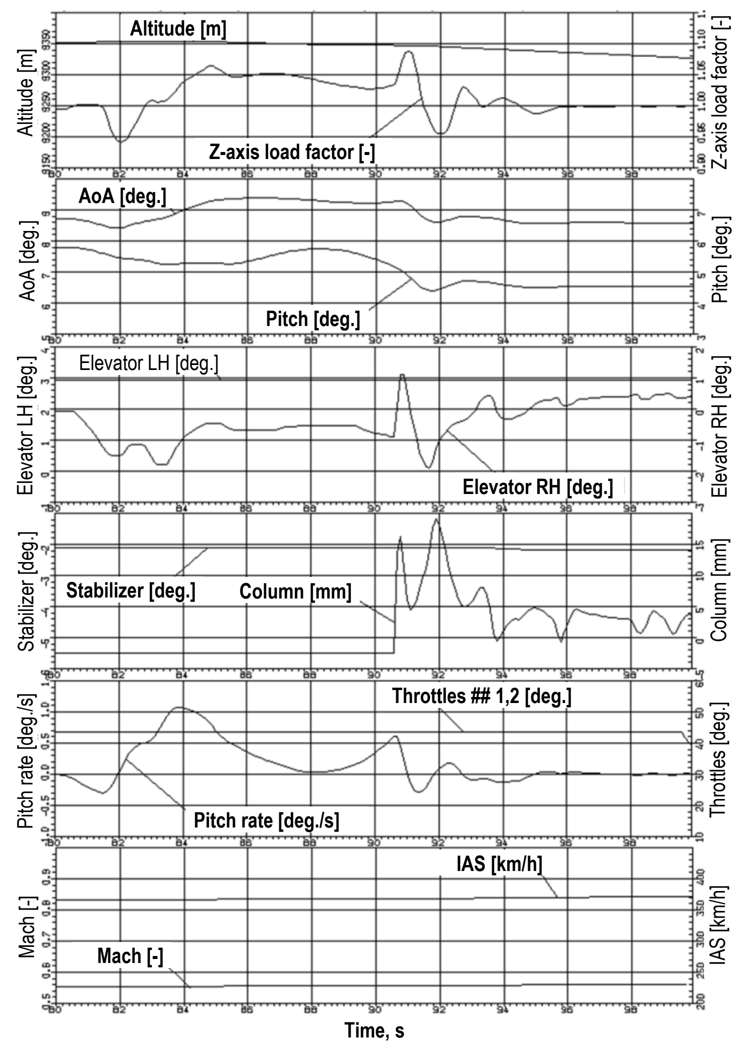
$\delta_{\text{int}} = 0.$

Tupolev-334-100

Flight # xxxx: $\gamma_G : (+30^o) \rightarrow (-30^o)$



Flight # yyyy: $\gamma_G : (-30^o) \rightarrow (+30^o)$



8. Level Flight, HS ## 1&2 Failure, Ailerons Impulses (Left-Right Bank), Interceptors, H_{LF}, V_{LF}, C.G., Mass (8-Factor Domain)

Lateral motion parameters

$$HS\ \#\#1,2\ \text{failure} = 1,$$

$$\gamma_G : (+30^o) \rightarrow (-30^o)$$

$$\gamma_G : (-30^o) \rightarrow (+30^o)$$

$$H_{LF} = 9\,300\,m,$$

$$V_{LF} = 370\ km/h,$$

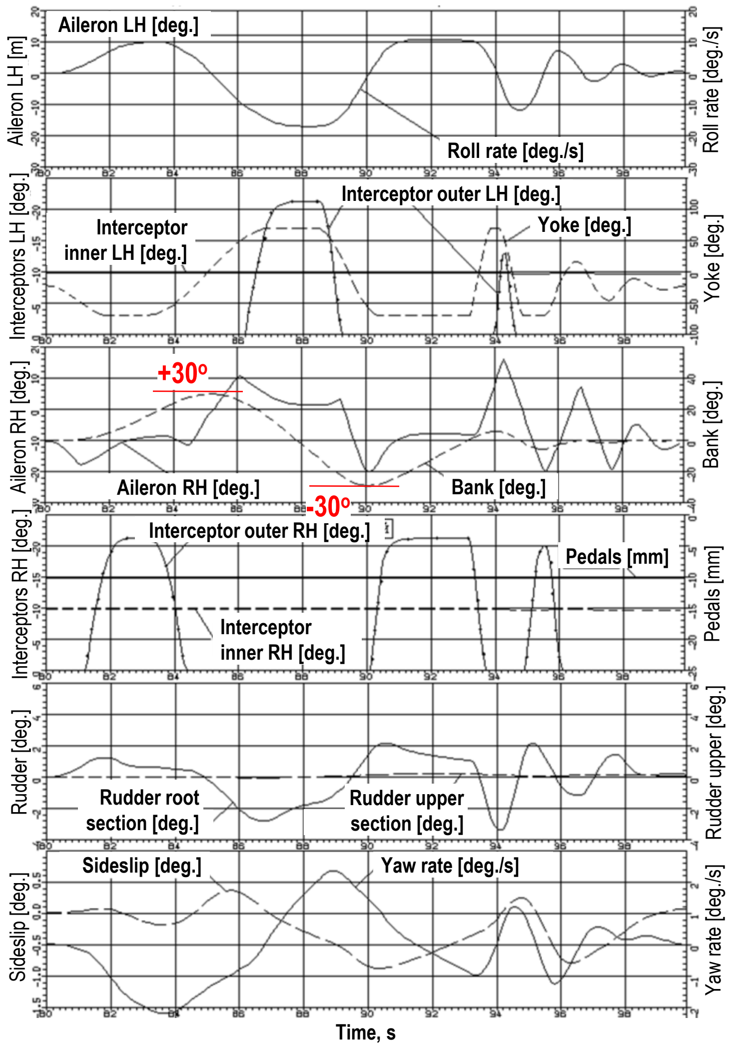
$$\bar{x}_{CG} = 35\%,$$

$$m = 40\,000\ kg,$$

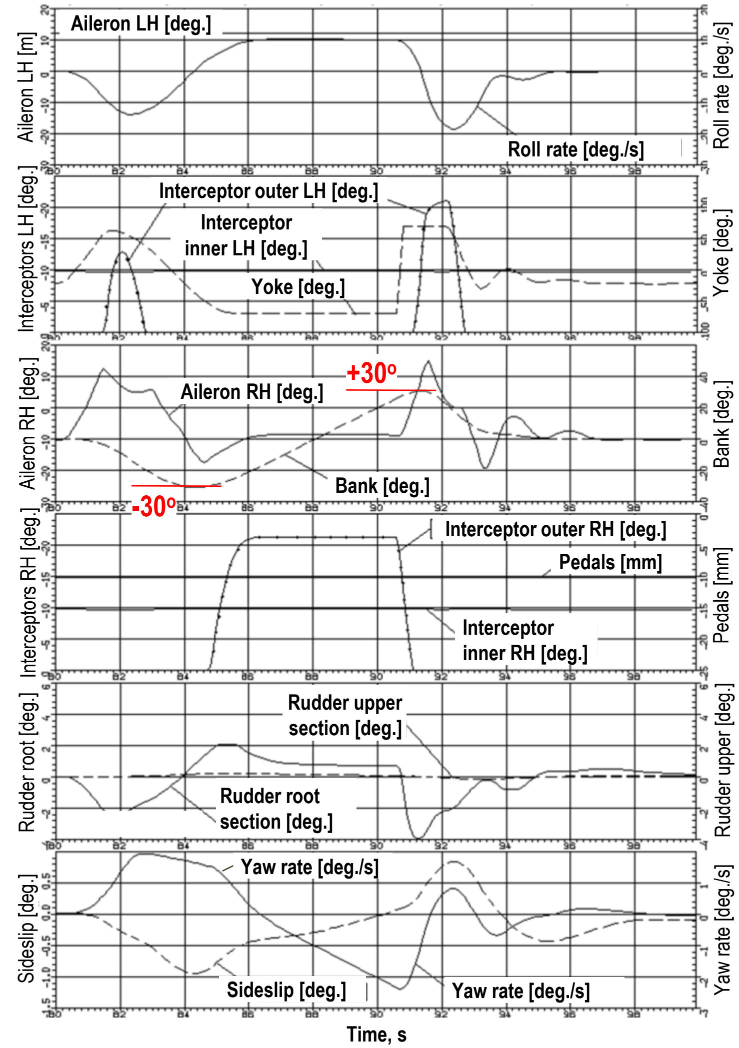
$$\delta_S / \delta_F = 0/0,$$

$$\delta_{\text{int}} = 0.$$

Flight # xxxx: $\gamma_G : (+30^o) \rightarrow (-30^o)$



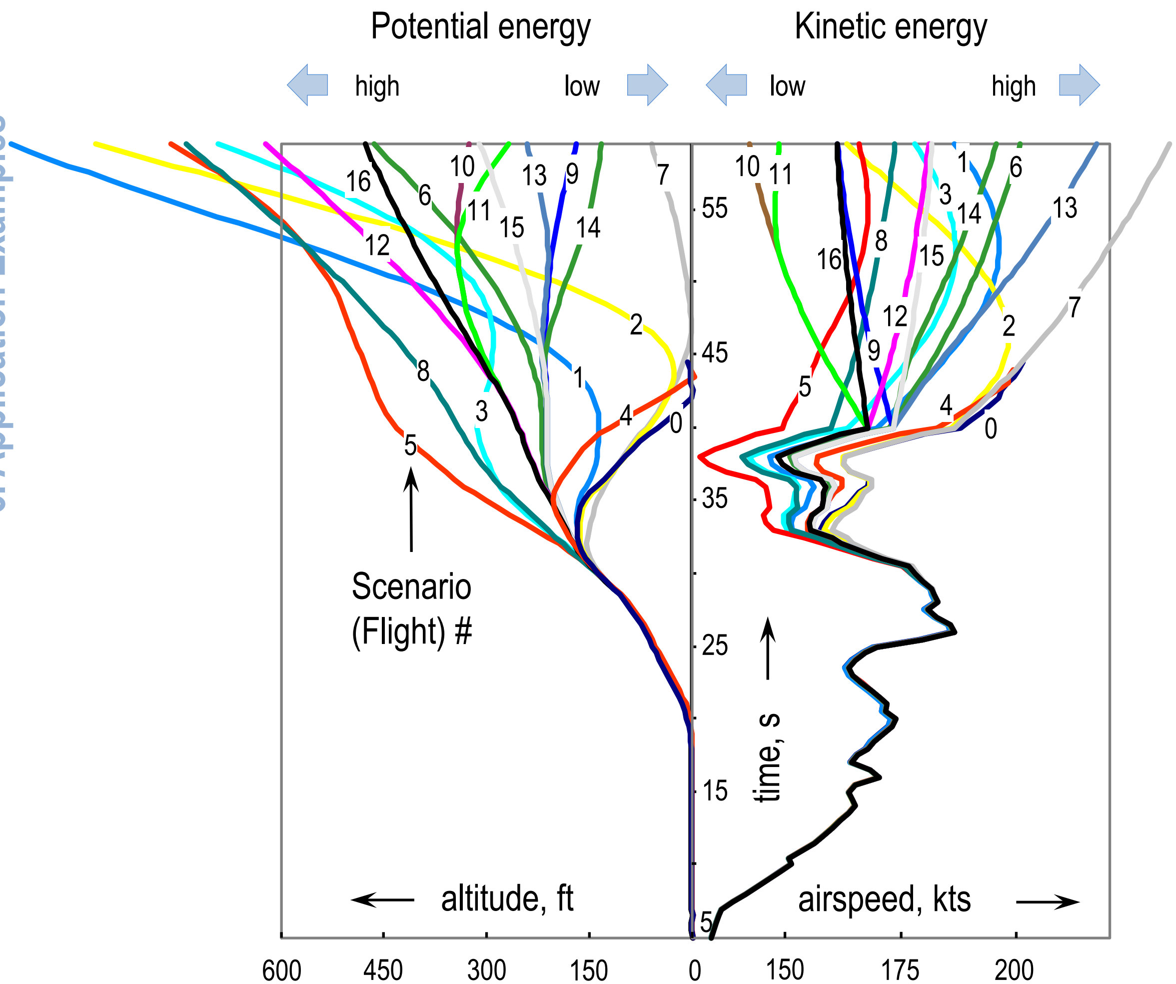
Flight # yyyy: $\gamma_G : (-30^o) \rightarrow (+30^o)$



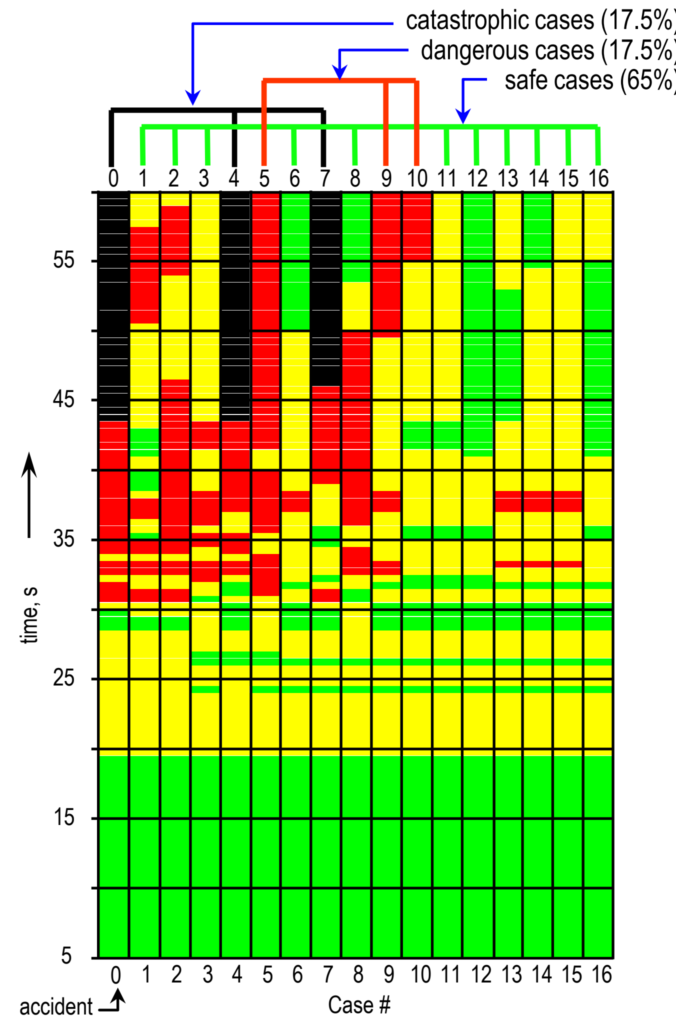
Tupolev-334-100

Takeoff, ‘Microburst’, Heavy Rain, Low Visibility, Pilot Errors, Ambiguities in Flight Manual (6-Factor Domain)

Flight accident situation and its ‘what-if neighborhood’ tree



Integral safety spectra



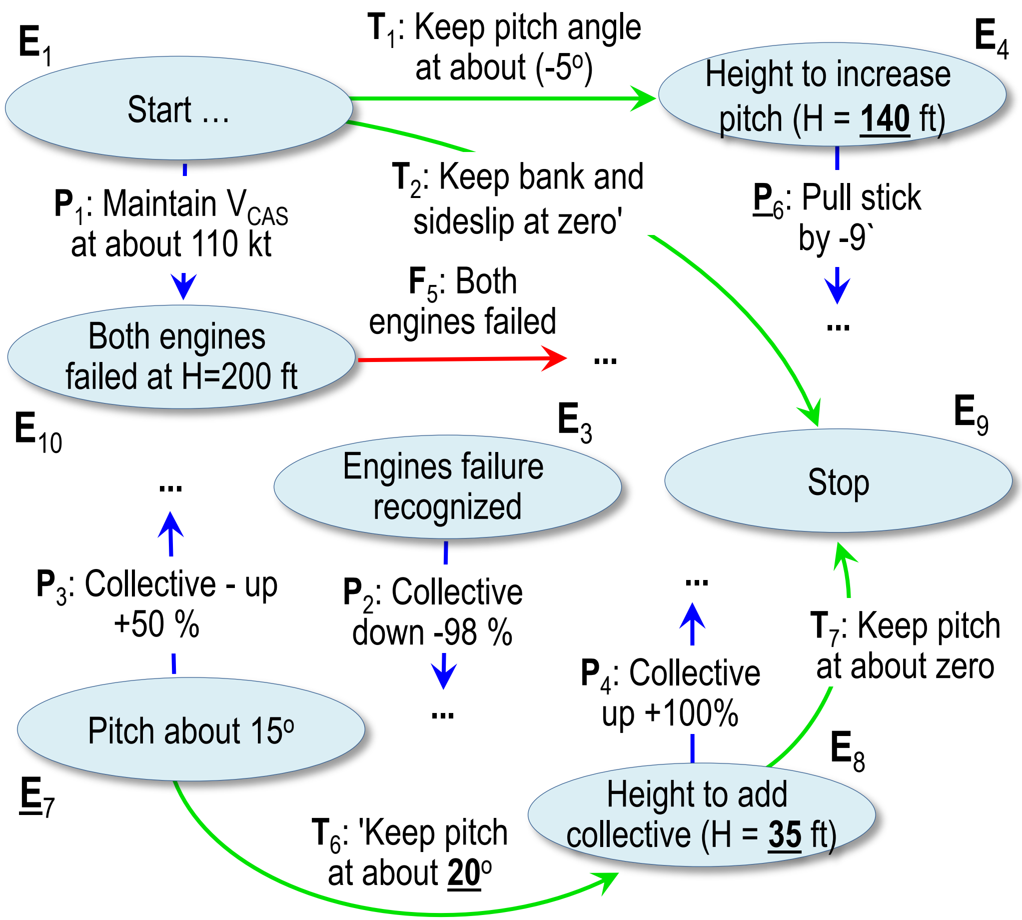
Ilyushin-62M

Legend: Case # 0 – accident. { 1, 2, …, 16 } - alternative scenarios. ■■■■ – safety palette (for integral safety spectra).

Tilt-Rotor Auto-Rotation Landing with Two Engines Out and Piloting Tactics Variations (6-Factor Accident Domain)

6. Application Examples

Flight Situation Scenario



'What-if' Risk Factors for Virtual Testing

Φ_1. Variation of event **E_8**: 'Height to add collective': { 30, **<u>35</u>**, 40, 45, 50 } ft.

Φ_2. Variation of event **E_4**: 'Height to increase pitch': { 120, 125, 130, **135**, **<u>140</u>**, 145, 150 } ft.

Φ_3. First increase of pitch angle at event **E_4**: 'Height to increase pitch (procedure **P_6**)': { **<u>yes</u>**, no }.

Φ_4. Variation of commanded pitch angle in piloting task **T_6**: 'Keep pitch at about [commanded/ goal level]': { 15°, **<u>20</u>**°, 25°, 30°, 35° }.

Φ_5. Second collective pull-up input at event **E_7**: { **<u>yes</u>**, no }.

Φ_6. Variation in flaps/ flaperon position: { **<u>0/0</u>**, 20°/12.5°, 40°/25°, 75°/47° }.

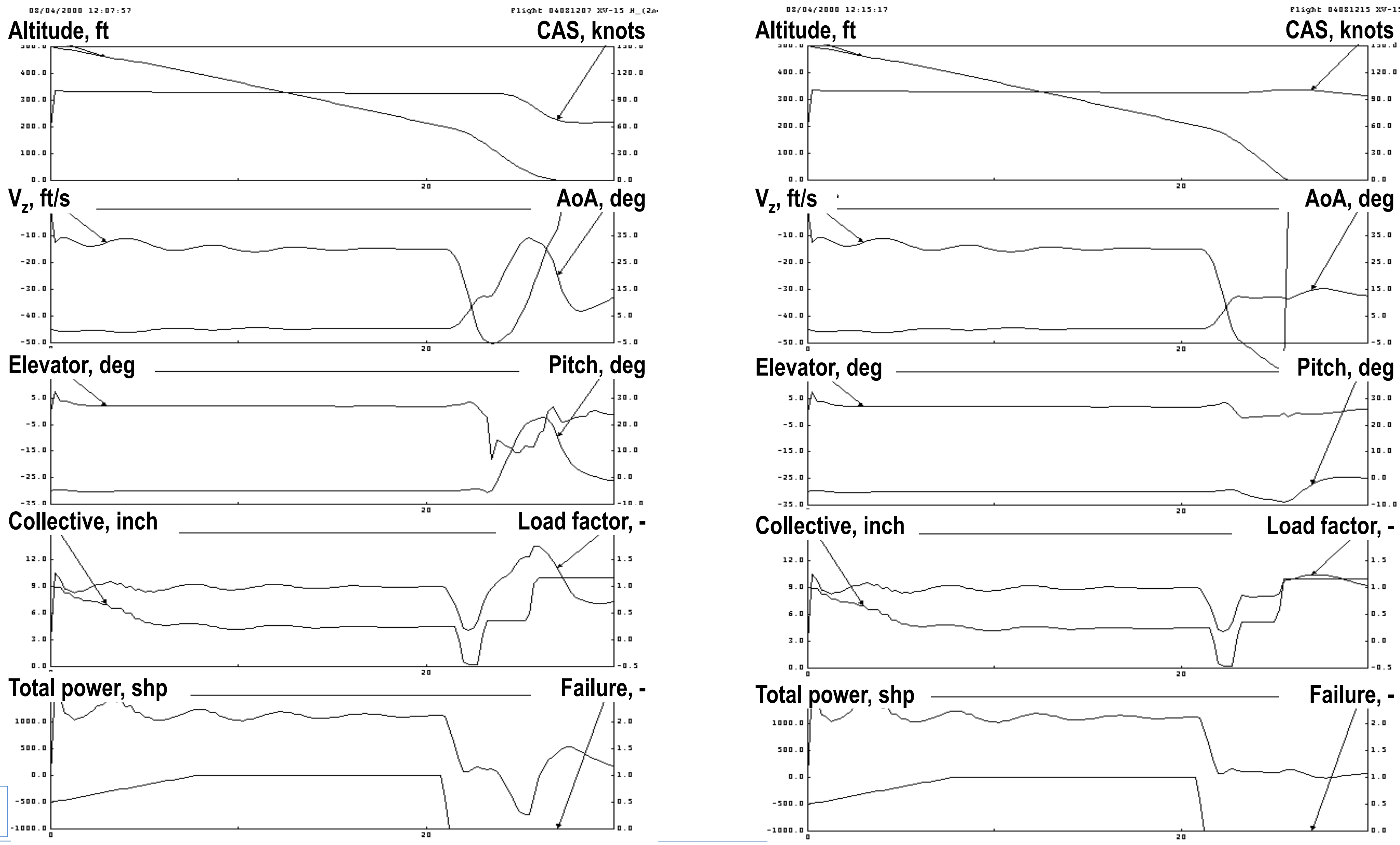
XV-15

<u>Note</u>: In this scenario graph, nominal values of parameters are shown in **bold** and **<u>underlined</u>**.

Tilt-Rotor Auto-Rotation Landing with Two Engines Out and Piloting Tactics Variations (6-Factor Accident Domain)

Flight #1209: **Nominal Recovery Case** (safe)

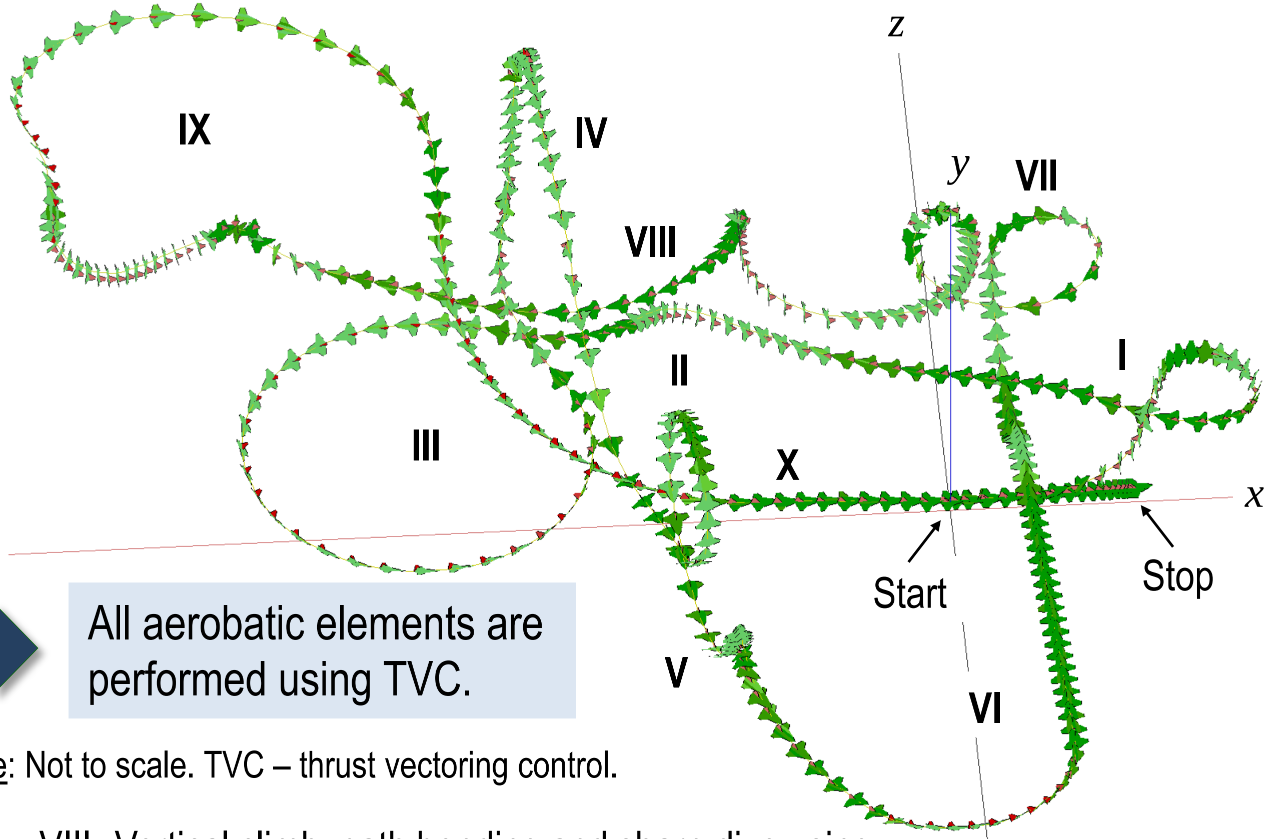
Flight #1215: **No Pitch Increase at E_4** (unsafe)



XV-15

Acrobatic Maneuvers of Notional 4++ Generation Highly Maneuverable Aircraft with TVC

Complete aerobatic sequence - 4D profile



All aerobatic elements are performed using TVC.

Note: Not to scale. TVC – thrust vectoring control.

Legend: **I, II, …, X** – flight phases:

I. Ground roll, takeoff, vertical climb, 180° right roll, and ¾ loop.

II. First Pougachev Cobra.

III. Left 65° bank turn, 270° heading change, ¼ loop.

IV. Vertical climb with double (720°) left roll, path bending vertical descent with single right roll.

V. Loop, vertical climb; fixed 90° pitch vertical position and path bending (Bell), descent.

VI. Left turn at 55° roll for heading reversal; second Cobra maneuver.

VII. Loop with 90° roll, followed by a loop with 1½ Somersault and descent at medium pitch (side view).

VIII. Vertical climb, path bending and sharp dive using TVC (augmented Bell), double Somersault, tail-down slide (pitch 80°).

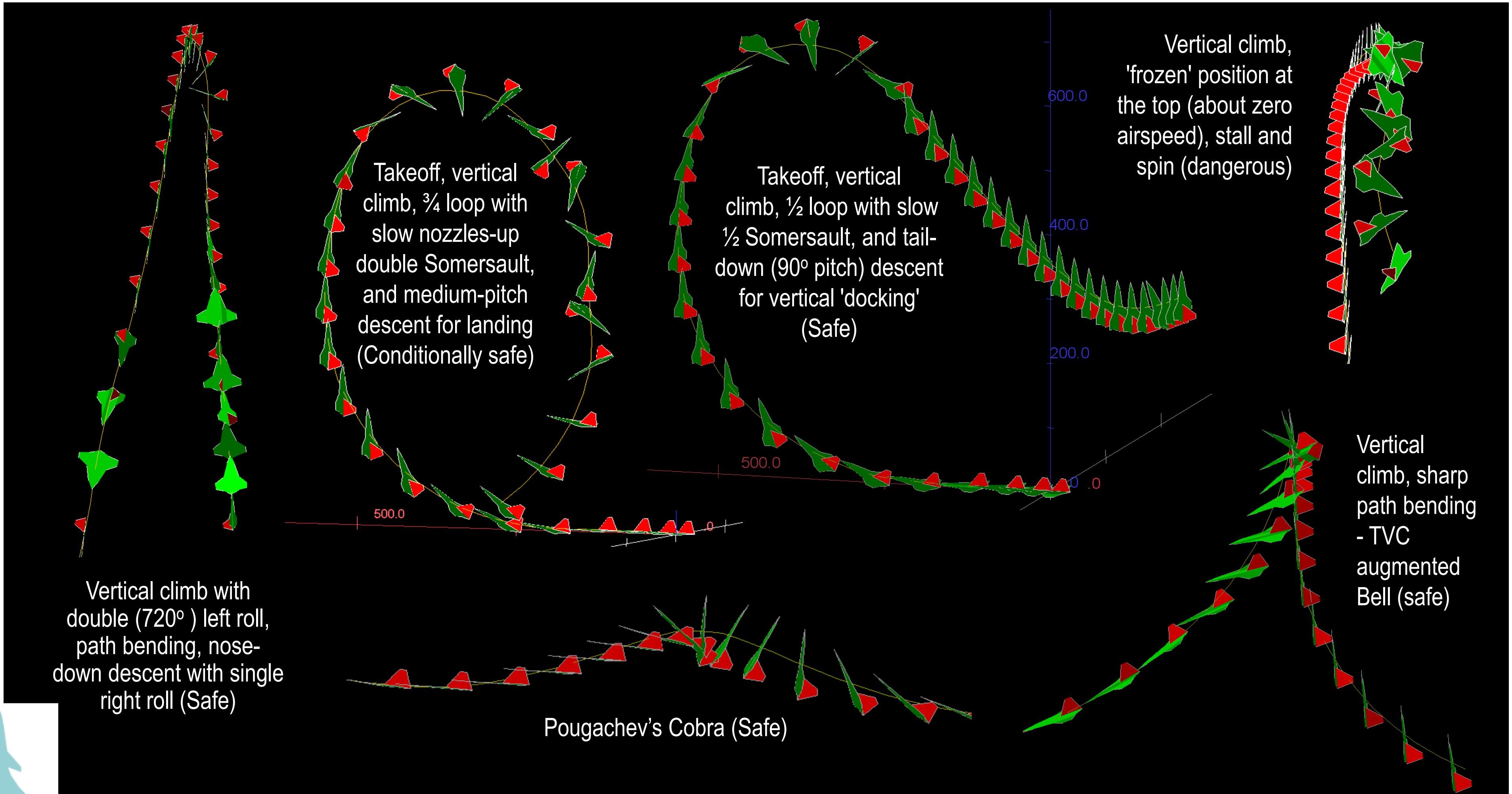
IX. 'Tail walk', evasive pitch, S-turn at 70° bank to acquire runway heading 0°.

X. Landing approach, landing, touchdown, and ground roll.

Acrobatic Maneuvers of Notional 4++ Generation Highly Maneuverable Aircraft with TVC

6. Application Examples

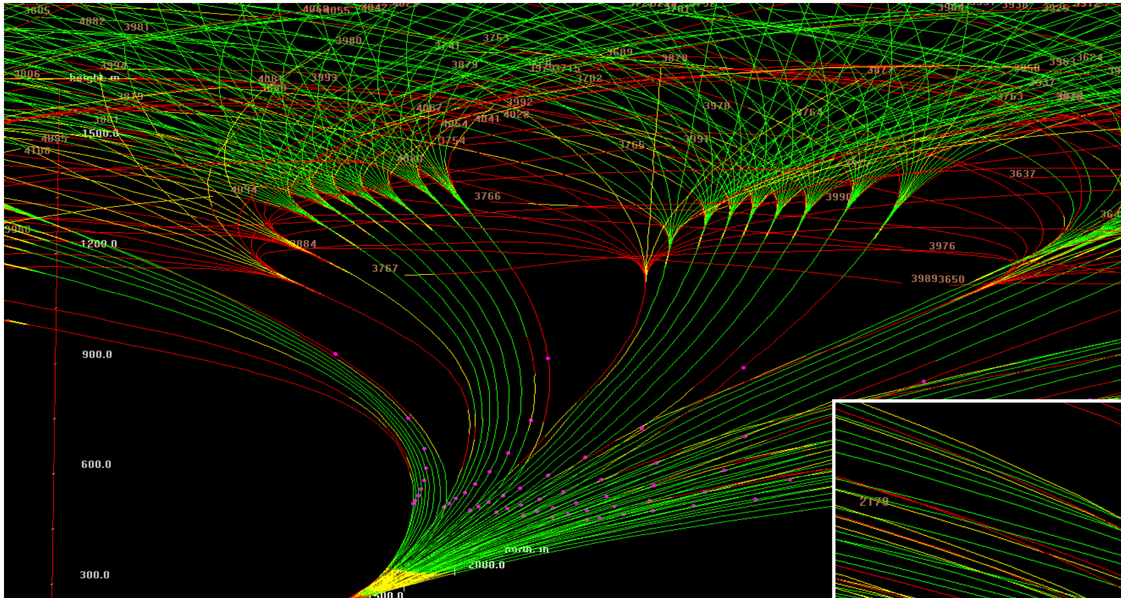
Analysis of flight safety for selected maneuvers



All maneuvers are performed under TVC.

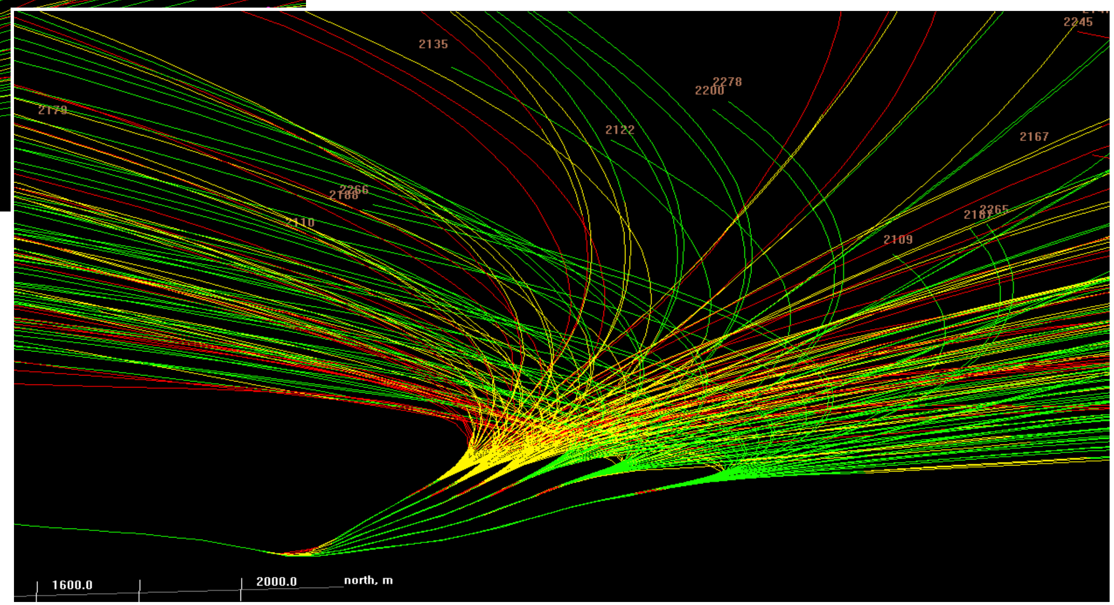
Note: Not to scale. TVC – thrust vectoring control.

Screening and Mapping of Complex Operational Domains Using Situational Trees



Takeoff in wind-shear conditions. Errors in selecting (variations of) commanded flight path and bank angles in initial climb (3-factor operational domain)

Legend: – safety palette.

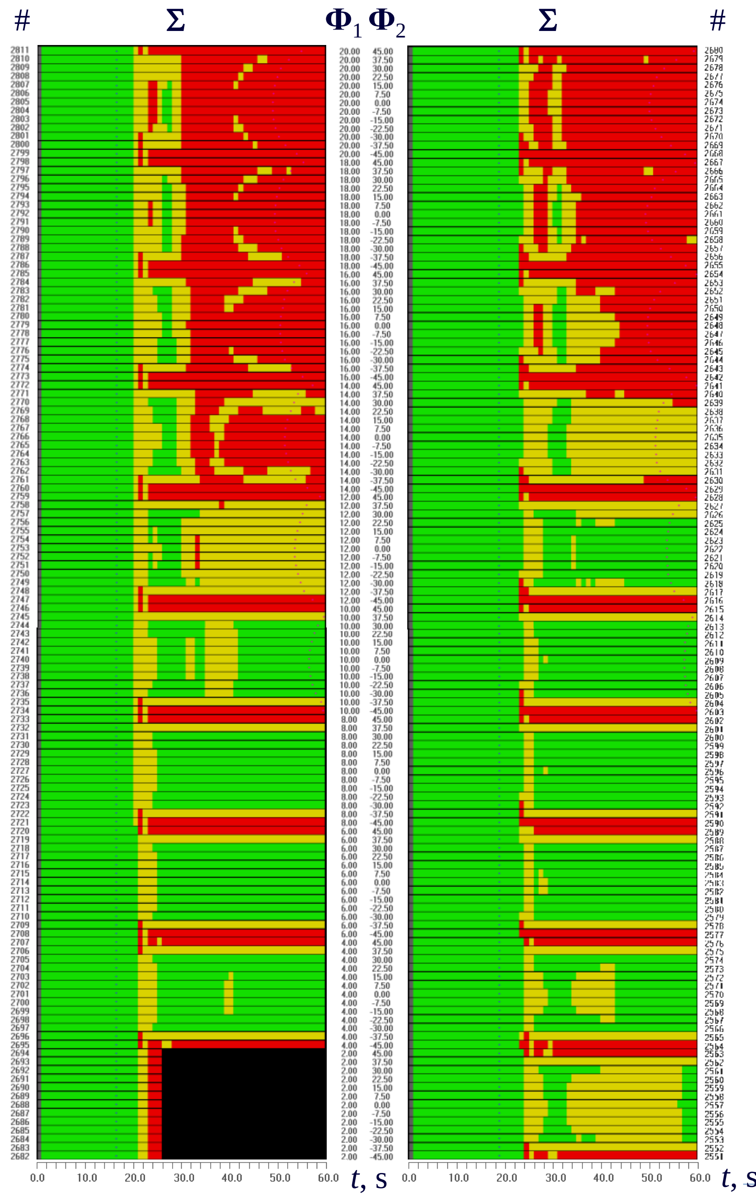


Landing approach and go-around in strong wind-shear conditions. Errors/ variations of selecting go-around thrust setting, commanded flight path and bank angles (4-factor operational domain)

Shown are 3D-views of two situational trees (in earth frames, safety color-coded), which **thread hypothetical off-normal operational domains** of flight for a commuter airplane.

Comparative Qualitative & Quantitative Sensitivity Analysis of Off-Normal Operational Domains Using Integral Safety Spectra

Normal takeoff and initial climb at commanded flight path angle θ_G and commanded bank angle γ_G errors/ variations <u>and 'very strong' wind shear</u> (3-factor operational domain)

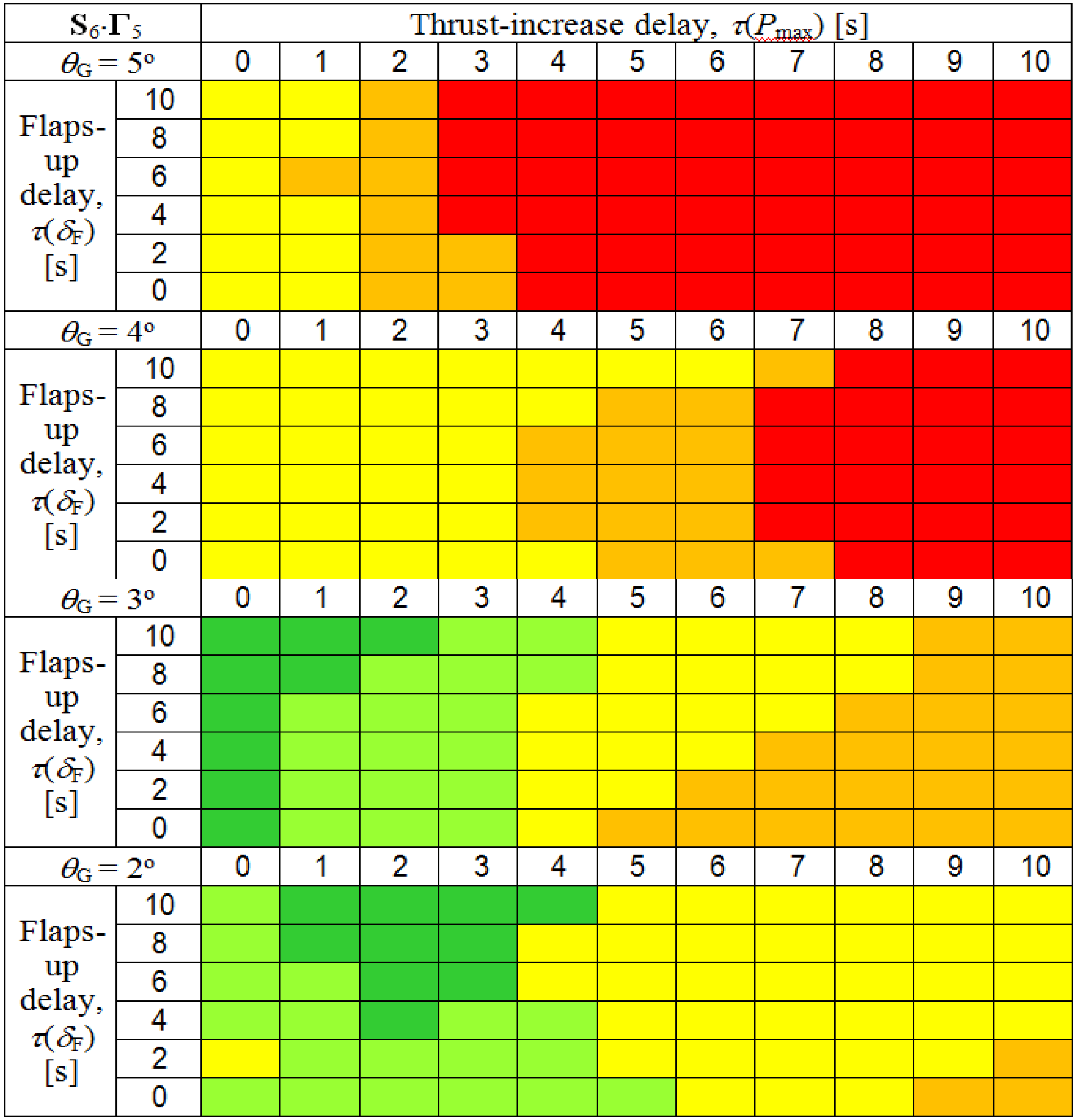


Normal takeoff and initial climb at commanded flight path angle θ_G and commanded bank angle γ_G errors/ variations (2-factor operational domain)

The only difference between these two domains is the **presence** and **absence** of a 'very strong' wind shear: left-hand chart and right-hand chart, respectively.

<u>Legend</u>:
\# - virtual flight code. $\mathbf{\Phi}_1 \equiv \theta_G$ (commanded flight path angle). $\mathbf{\Phi}_2 \equiv \gamma_G$ (commanded bank angle). $\mathbf{\Phi}_3 \equiv (W_{xg}, W_{zg} = f(t)$ – 'very strong' wind shear profile taken from Accident Case 04.01/ 09.03.89 – HAV, Cuba). **Σ -** integral safety spectra. – safety colors.

‘Bird’s Eye View’ Visual Analytics of Flight Safety Topology using Safety Windows (5-Factor Domain)



Situational tree $\mathbf{T_7 \equiv S_6 \cdot \Gamma_5}$: ‘**Landing approach and go-around in wind shear conditions with left-hand engine out. Variations of go-around thrust increase delay, flaps-up decision delay, and commanded flight path angle**’ (5-factor domain).

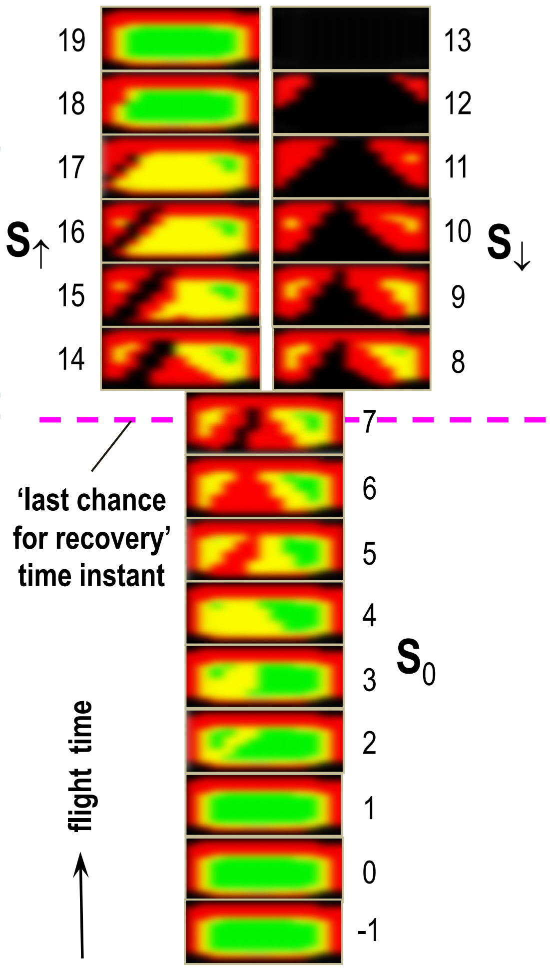
This ‘3D safety window’ knowledge map depicts a cross-coupling effect of 5-factor operational composites on airplane safety performance at go-around. It is useful to **quantify flight goals and constraints**, determine optimal states and accident precursors, structuralize and memorize complex ‘topology’ of a realistic N-dimensional safety risk factor space.

Legend: – safety categories.

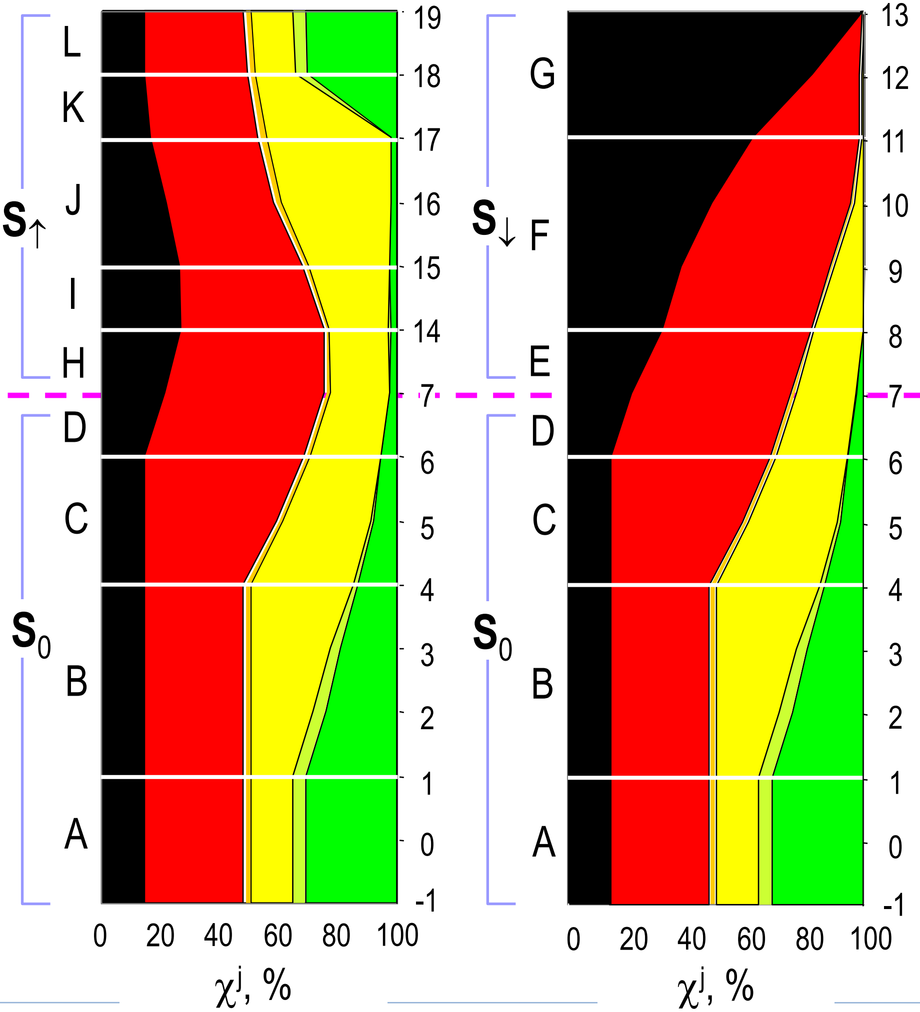
Knowledge Mapping of Fatal and Recovery Control Tactics for ‘11.09.2001’ and ‘24.03.2015’ Class Accidents (Notional Scenarios)

6. Application Examples

Safety Windows Tree

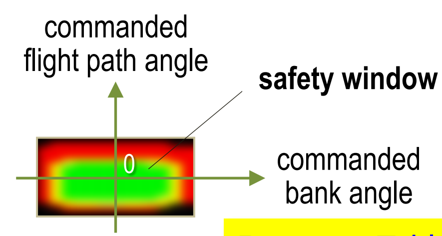


Safety Chances Distribution Time-Histories



Such knowledge maps support **AI-based and manual predictive recovery decision-making** in emergency under uncertainty.

Legend: – safety colors. Scenario segments: $\mathbf{S}_0$ – obstacle approach (time line: -1, 0, …, 7). $\mathbf{S}_\downarrow$ – obstacle collision (time line: 8, …, 13). $\mathbf{S}_\uparrow$ – obstacle avoidance (time line: 14, …, 19). $\mathbf{S}_0 \cup \mathbf{S}_\uparrow$ – AI recovery tactics. $\mathbf{S}_0 \cup \mathbf{S}_\downarrow$ – suicide pilot’s fatal tactics. χ^j – safety chances at j-level, j ∈ { , , , , , }. A, B, … L – characteristic states of system safety dynamics.



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VFT&C Technology: Distinguishing Features

ISAFE Methodology

Generalized verified & validated system dynamics model.

Generalized model of a complex flight situation domain.

Universal events-processes language for flight scenario scripting.

Built-in fatigue-free ‘silicon pilot’ model.

Efficient data structures and computational algorithms.

Use of any situation as a tree’s trunk.

Automated design of multifactor operational hypotheses.

Automated generation of branching flight domains.

Automatic ‘mining’ of safety knowledge from raw ‘flight’ data.

Automatic ‘bird’s eye view’ mapping of aircraft ‘safety topology’.

VATES Tool

(1:100 … 1:200) times increase in flight simulation speed compared to real time.

(10^4 … 10^5) times increase in the volume and diversity of system-level knowledge (not data) on flight performance and safety in off-normal conditions.

Relaxation of the ‘curse of dimensionality’ when screening complex flight T&C scenario sets.

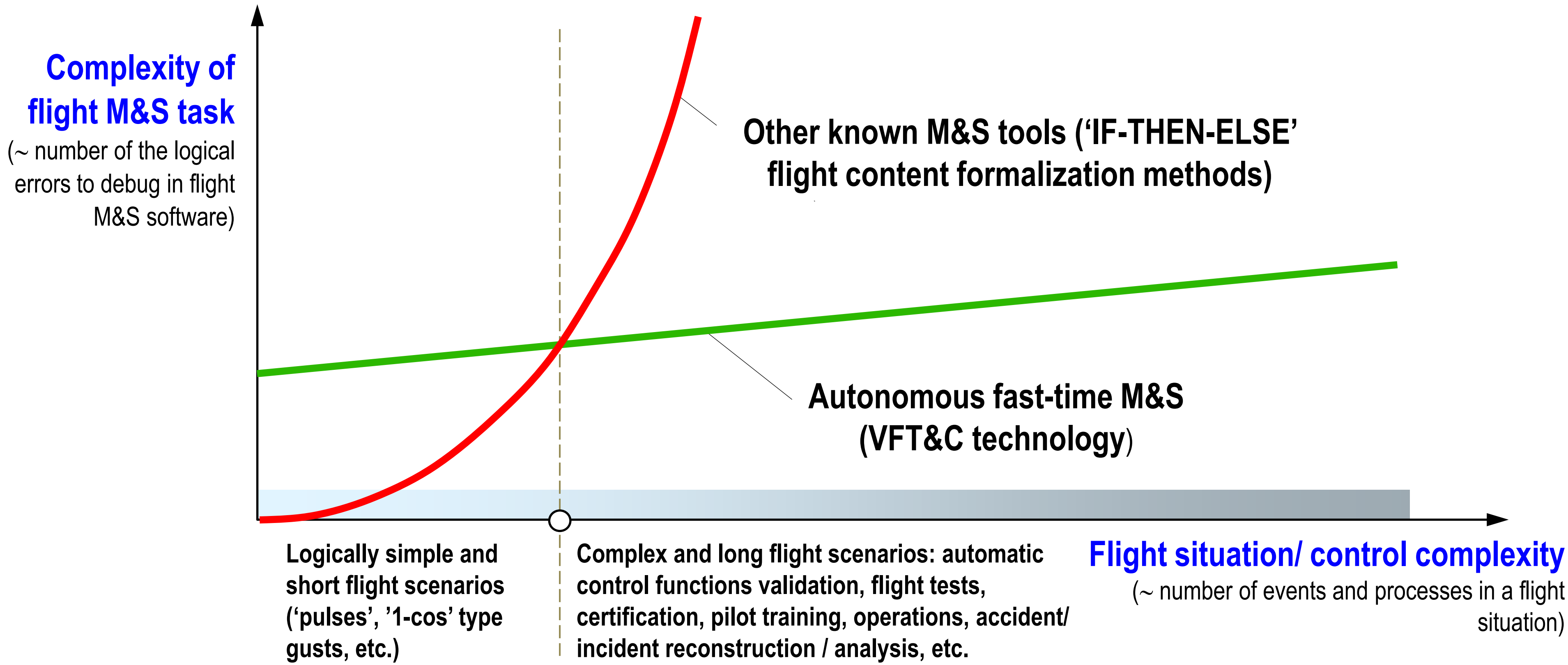
Accident/ incident reconstruction and ‘what-if neighbourhood’ analysis under uncertainty.

Accumulation of a library of flight test scenarios and multifactor risk hypotheses for future reuse.

Proactive, affordable and fast safety research into multifactor flight test/ operation domains.

Acquiring professional flight test pilot knowledge and skills by non-pilots.

VFT&C Technology: Main Advantage and Main Limitation



Main advantage: The complexity of a flight scenario planning and simulation task **does not depend** on the complexity of a operational domain under screening.

Main limitation: In order to obtain valid results from VFT&C cycle, it is required to have:

(1) aircraft '**parametric definition**' for all flight regimes and conditions of interest, and

(2) flight test/ simulation/ operation data records for a prototype aircraft.

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Conclusions

VFT&C Technology: Input Requirements

Aircraft/ project **'parametric definition'** for the entire range of flight modes and conditions of interest.

Automatic control (stability & controllability augmentation) system algorithms for a project / prototype – as a 'black box' or in open format.

Failure modes and effects analysis data for a project/ prototype.

Flight data time-histories (**flight test/ simulation/ operation data records**) **for a prototype**.

Short-term training of users in fast-time flight modeling & simulation (ISAFE-VATES) technique.

VFT&C Technology: Market Advantages

NB **Lower cost and shorter schedule** of design, flight test, certification and pilot training.

NB **Earlier formation of predictive knowledge base** on flight performance and safety (steeper 'learning curve').

Less re-design work (due to earlier and better awareness of the project's flight safety flaws).

Better **'built-in' safety protection** in multifactor conditions.

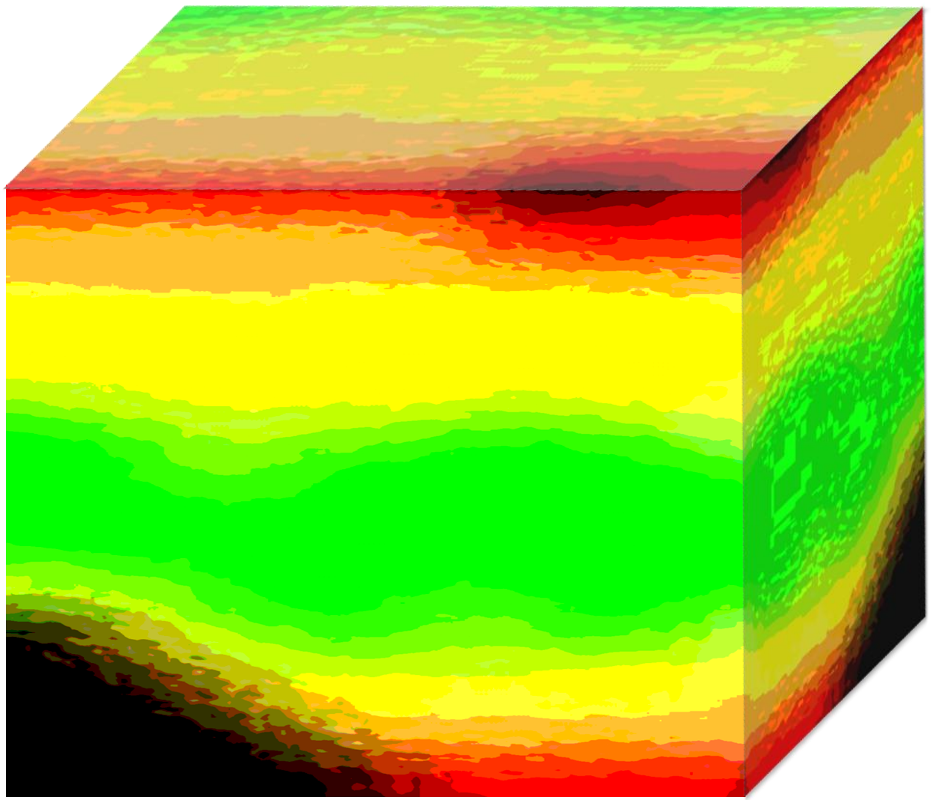
Expanded and better protected **flight envelope**.

Suitability for **theoretical training of pilots** and engineers.

Earlier **prototyping of AI flight control/ safety** systems.

Key benefits include: **stronger competitiveness and increased market share**. A pre-requisite is the user's **corporate policy open to innovations.**

Thank You Very Much for Your Attention!
Questions, Please…



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