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UAV "Built-in" Safety Protection: A Knowledge-Centered Approach

Presentation Slides
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Presentation Plan

Problem: UAV flight safety performance prediction and protection in complex (multifactor) situations

Solution approach: ‘Knowledge is Power’

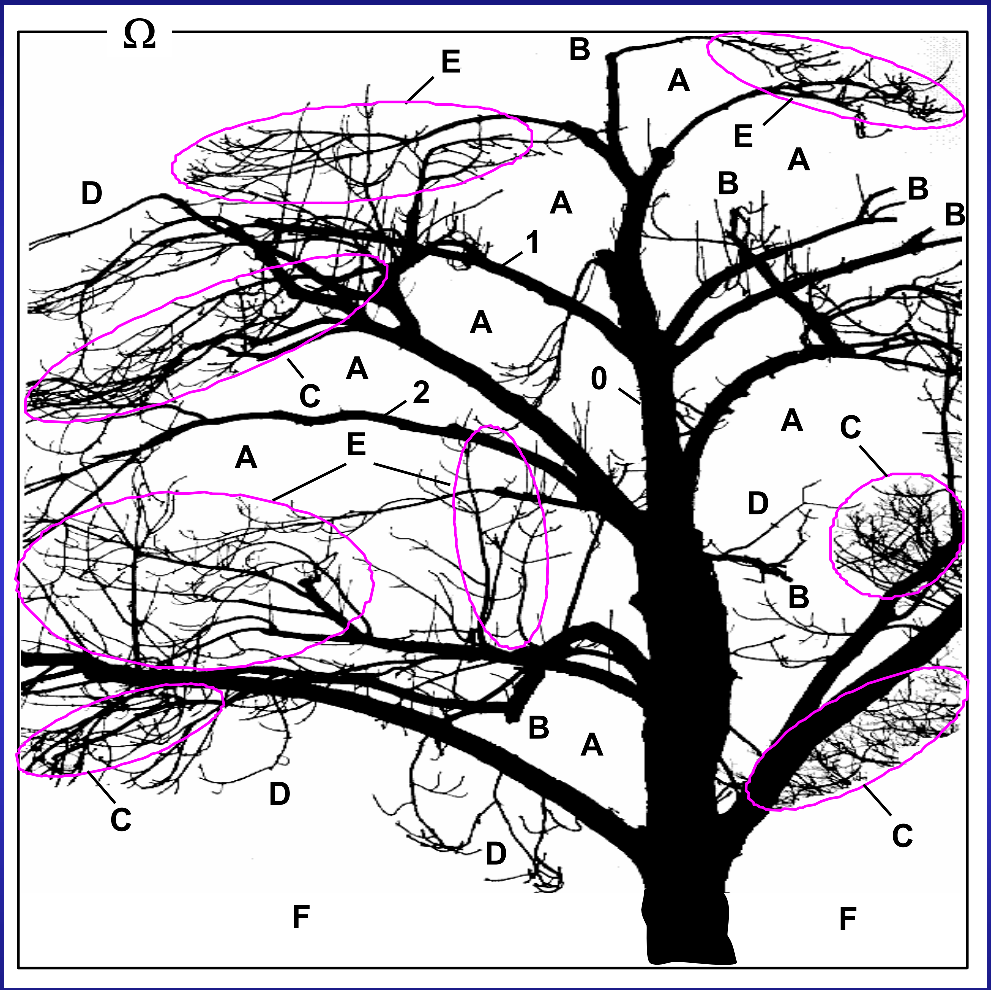
Methodology conceptual framework (introduction):

- micro- and macro-structural knowledge models of flight
- flight situation scenario
- operational factor
- operational hypothesis
- situational tree
- safety spectrum
- flight safety [performance] window
- ‘last chance for recovery’ point, self-preservation decision making
- safety chances distribution time-history
- dynamic safety window tree

Case study: ‘Notional UAV Low-Altitude Flight in the Presence of Urban Infra-Structure Obstacles’

Conclusions

Natural Tree Analogy of Pilot's Situational 'Knowledge Base'



A, **B**,**C**, **D** – main defect types of a human pilot's situational knowledge.

Legend:

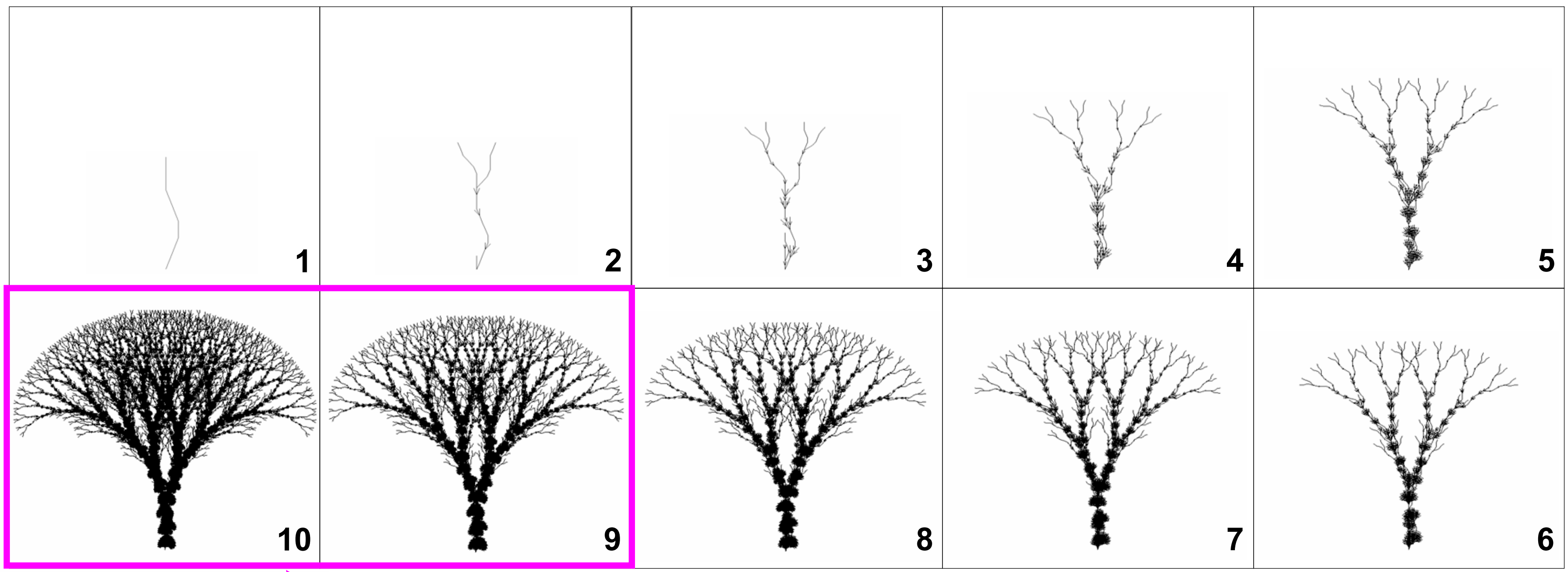
	Characteristic zone of a pilot's situational knowledge base	Natural tree analogy
Ω	Space of possible complex flight situation scenarios	Space available for tree growth
0	Basic (standard/non-standard) flight situation scenario	Tree's trunk
1	One-factor non-standard flight situation scenario	First-order derivative branch
2	Two-factor non-standard flight situation scenario	Second-order derivative branch
A	**Missing knowledge**	**Absent but possible branching**
B	**Forgotten or shadowed knowledge**	**Dry or broken branches**
C	**Non-systematic , occasionally developed knowledge**	**Excessive, chaotic branching**
D	**Fragmentary, incomplete knowledge**	**Insufficient, sparse branching**
E	**Systematic, yet economically developed and stored, knowledge**	Optimally dense branching
F	Physically unattainable flight situation scenarios	A sub-domain where branching is impossible

Strengths to model by means of AI in UAVs

Defects to back up by means of AI in UAVs

➔ Lack of theoretical and practical training (design and testing) – especially under complex (multifactor) conditions – may result in structural disparity of a human pilot's (automaton's) internal 'situational tree' of flight.

Fractal Tree Model Of Pilot's Situational Expertise Growth In Long-Term Memory



desirable maturity levels of AI knowledge for flight safety protection in UAVs

Legend: Characteristic levels of piloting expertise: $k \in \{1, 2, 3\}$ – experience of a student pilot, $k \in \{8, 9, 10\}$ – experience of a professional pilot, ace, or test pilot, $k \in \{4, \ldots, 7\}$ – interim (immature) states of experience.

➔ The most valuable asset of an expert pilot (a perfect automaton) is the reliability and comprehensiveness of his/her (its) knowledge of the system behavior under complex (multifactor, non-standard) operational conditions. This expertise is of critical importance for reliable prediction, timely avoidance or/ and safe resolution of 'chain reaction' type emergencies in UAV flight.

Micro- and Macro- Structural Models Of Complex Flight Situation Domain

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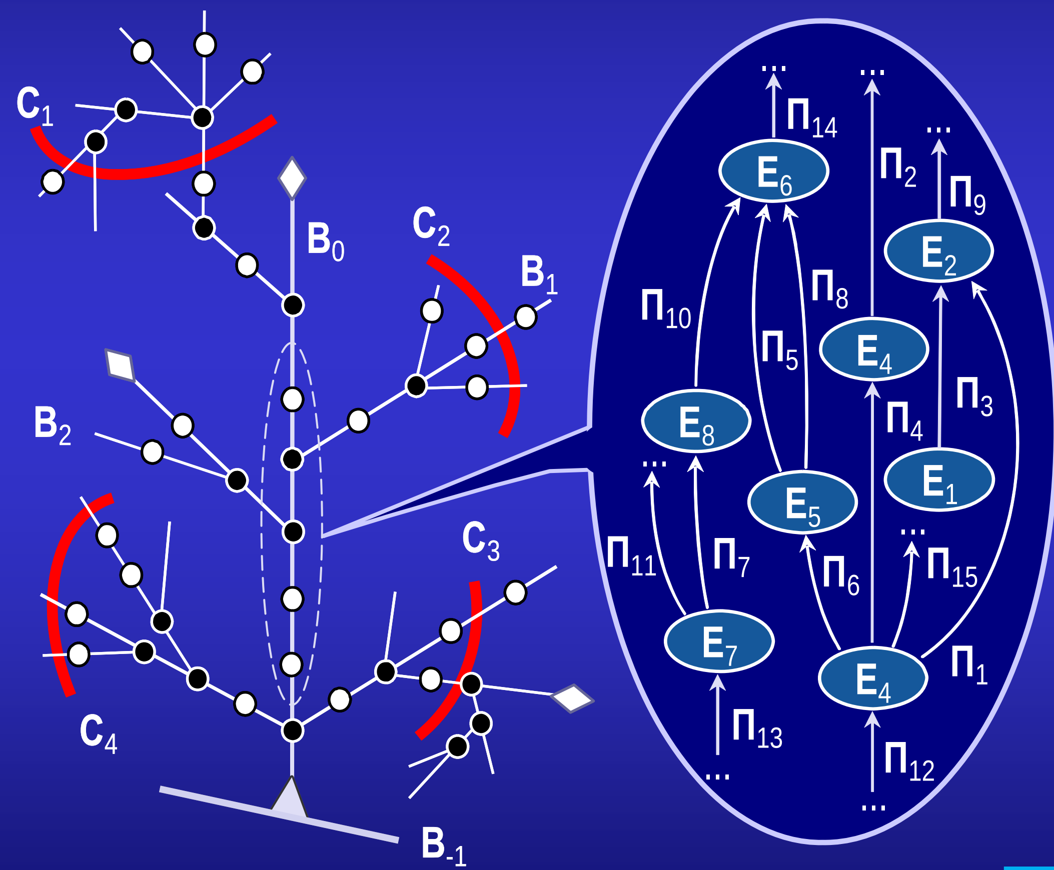
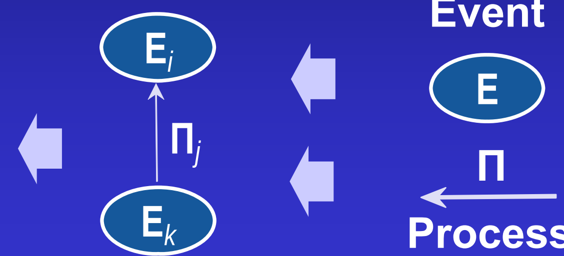
Situational tree-network of flight | **Flight situation scenario** | **Elementary situation (E_i, Π_j, E_k)**





Legend:

E_i - flight event; Π_j - flight process; C_m – fuzzy constraint of flight; ○ - reference state; ● - "bud" type state; ◇ - target state ("leaf"); △ - source state ("root"); B_{-1} – parent branch; B_0 - main branch ("trunk") – basic flight scenario; B_n – n-th order derivative branch (non-standard scenario with n factors, n = 1, 2, …)

Macro-structure of flight | **Micro-structure of flight**

➔ Micro- and macro- structures of flight are two interconnected components of the developed generalized knowledge model of a complex flight situation domain.

Basic Flight Situation Scenario (Examples)

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S_i	Content Description
S_1	Normal takeoff, maintaining commanded flight path and bank angles during initial climb
S_2	Normal takeoff under crosswind and given runway's surface conditions, maintaining commanded flight path and bank angles during initial climb
S_3	Continued takeoff (left-hand engine out at given V_{EF}), maintaining commanded flight path and bank angles during initial climb
S_4	Normal takeoff under wind shear conditions, maintaining commanded flight path and bank angles during initial climb
S_5	Continued takeoff (left-hand engine out at V_{EF}), under crosswind conditions, maintaining commanded flight path and bank angles during initial climb
S_6	Low-altitude level flight

Scenario #6 will be used in the notional case study

➔ Basic (Baseline) Scenario S_i is a plan of some 'central' or reference flight situation – be it standard or non-standard one. It represents the situational tree's trunk. Variations of the basic scenario – derivative cases – constitute the situational tree's crown. The vehicle's flight safety knowledge base is in fact a collection (a 'forest') of the situational trees, which are constructed for various basic scenarios and exemplify a complex (multi-factor) flight situation domain.

Joint Graph of Basic Scenarios (Example)

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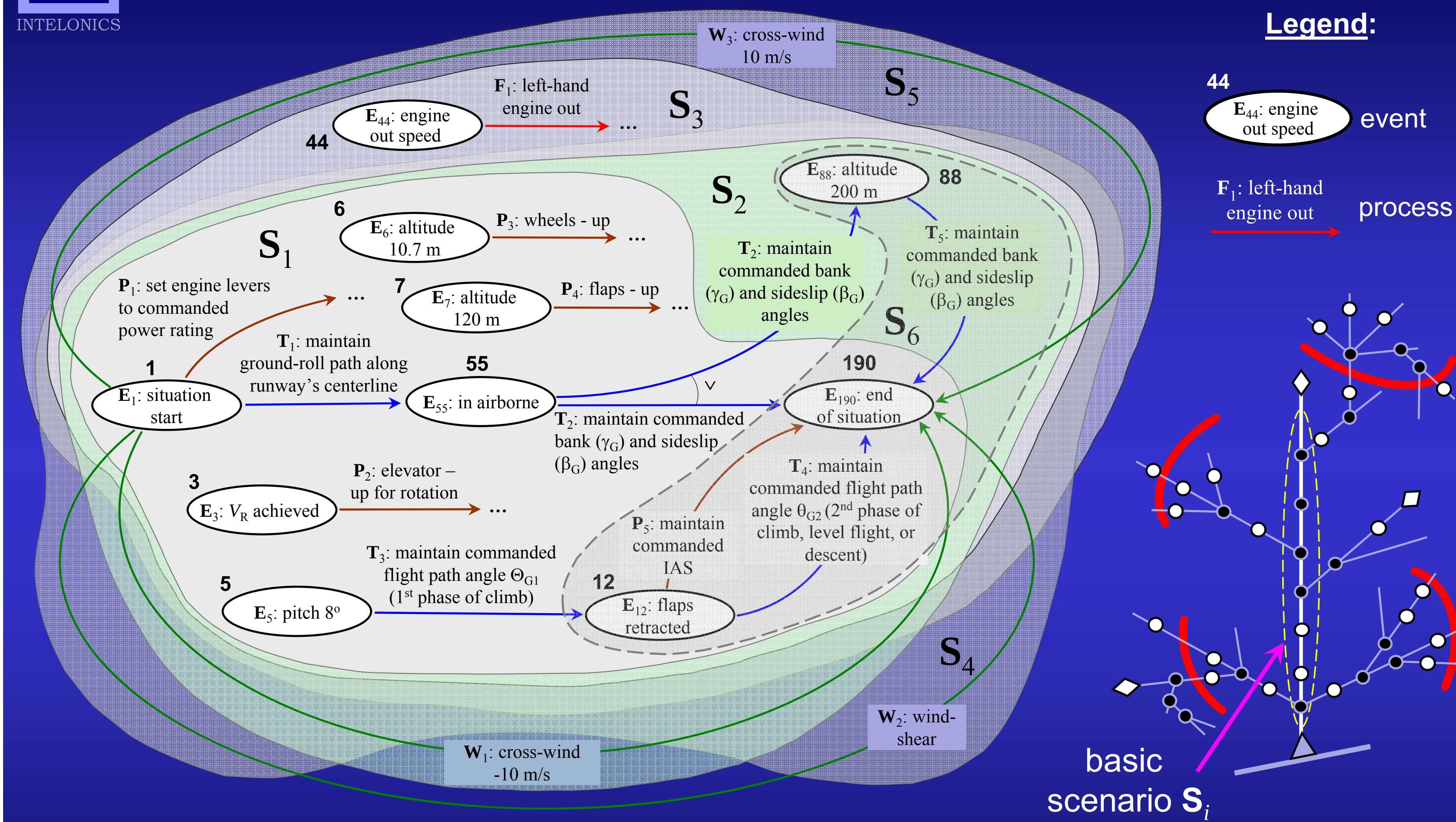

➔ A flight situation scenario is depicted as a directed graph. It defines logic and content of flight. Scenario graph is clear and concise formal description of a flight situation. Basic scenario examples S_1, …, S_6 are structurally close. They can be modified by adding new events/processes or by modifying existing ones.

Design Field of Operational Hypotheses

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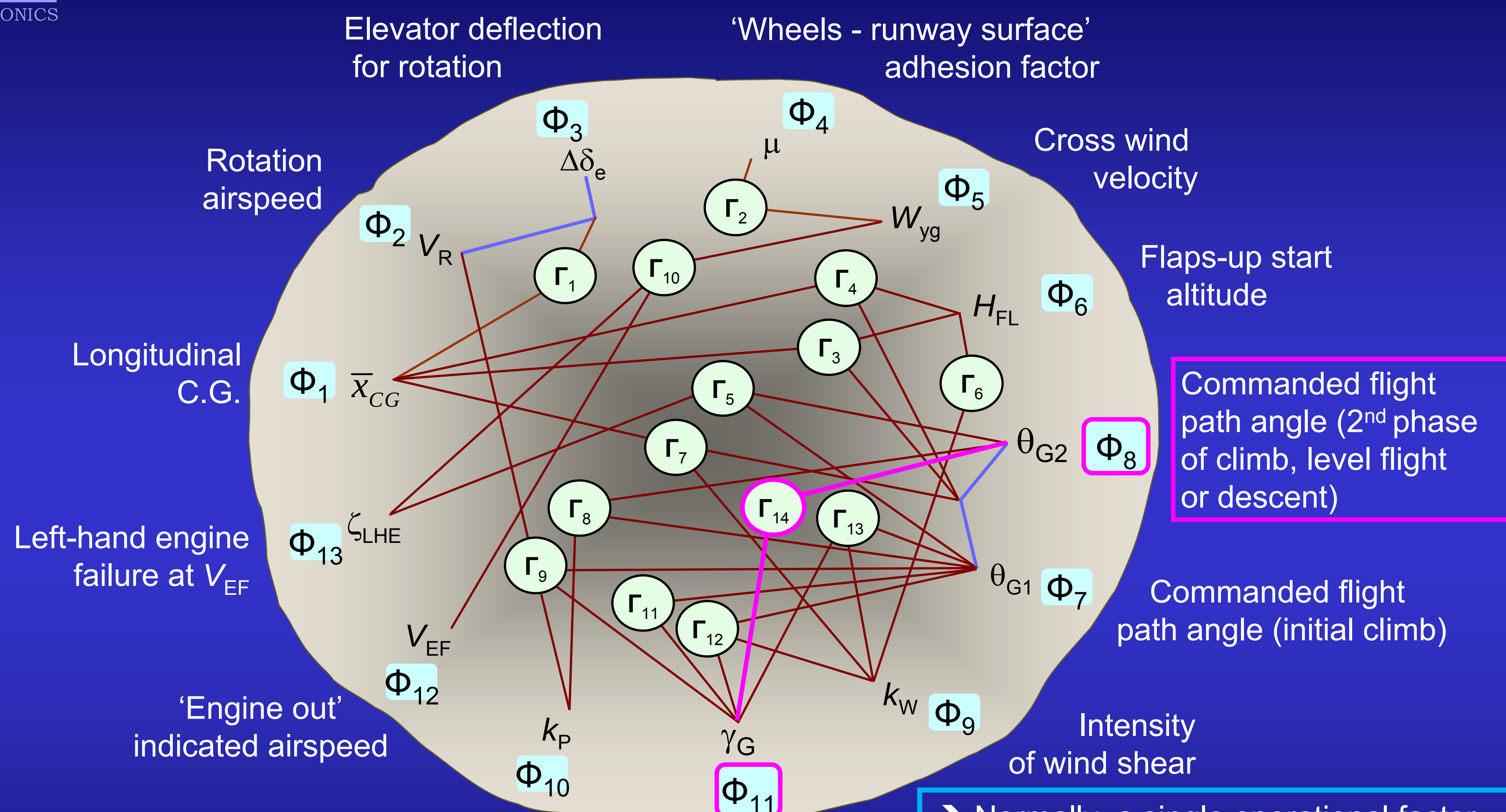


Engines power rating at takeoff

Commanded bank angle

Legend:

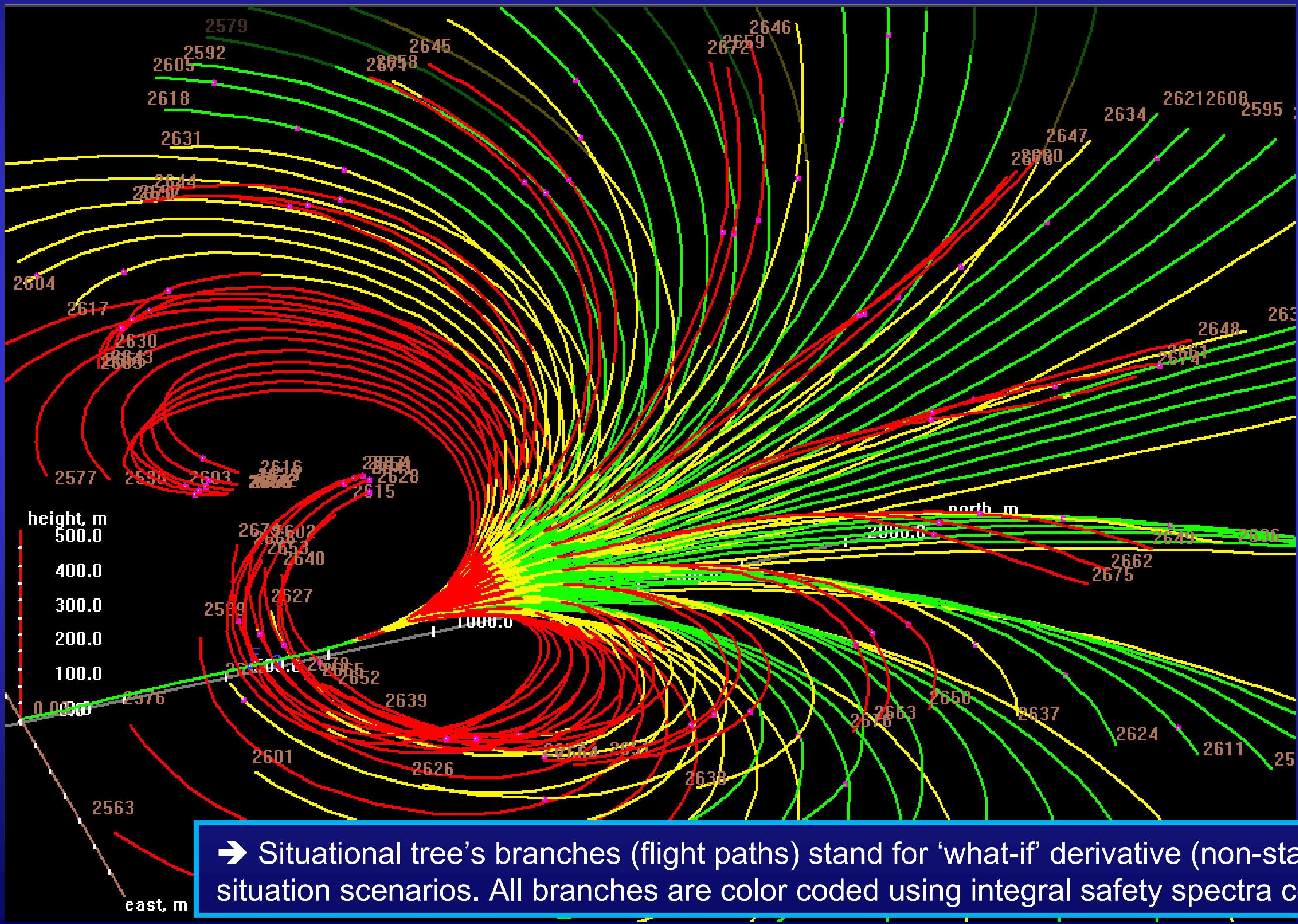
Γ_{13} - operational hypothesis

W_{yg} Φ_5 Cross wind velocity - operational factor

independent / dependent - link between factors in Γ

➔ Normally, a single operational factor is not critically dangerous. More important and much more difficult to learn the effects of multi-factor combinations on flight safety. These multi-factor combinations are called operational hypotheses.

Composition of Situation Scenario (S) and Operational Hypothesis (Γ) is A Situational Tree (S·Γ)



➔ Situational tree's branches (flight paths) stand for 'what-if' derivative (non-standard) situation scenarios. All branches are color coded using integral safety spectra colors.

Safety Palette. Fuzzy Constraint

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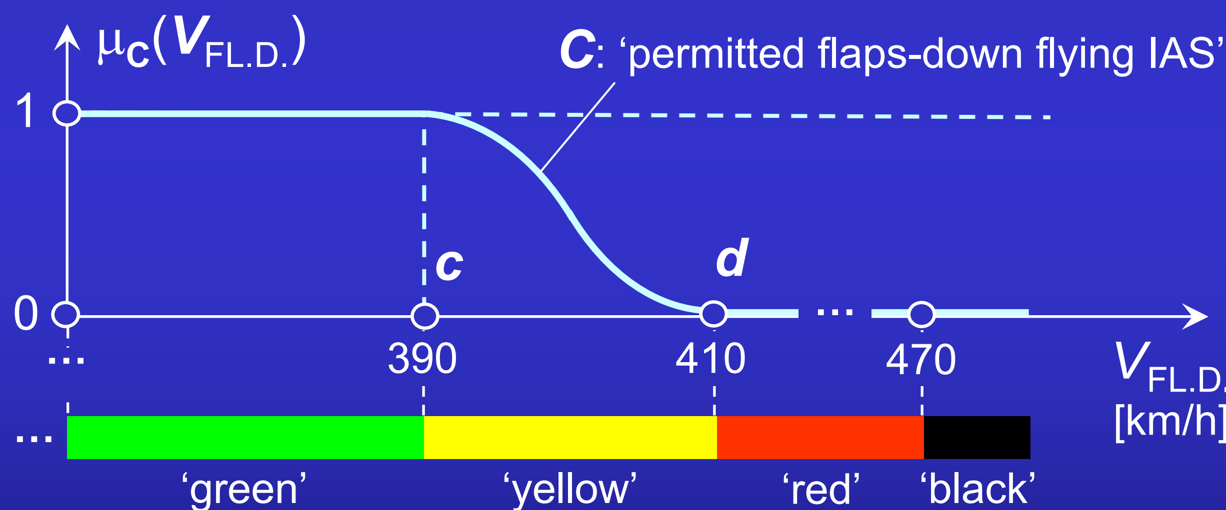
Safety Palette

- green (‘norm’), ξ_G
- yellow/ amber (‘attention’), ξ_Y
- red (‘danger’), ξ_R
- black (‘catastrophe’), ξ_B
- grey/white (‘uncertainty’), ξ_W

➔ Color is natural and, perhaps, the most effective and economic medium for communicating safety-related information to/ from an operator (a pilot or automaton).

Fuzzy Constraint (Example)



Legend: *c*, *d* – characteristic points of the carrier of fuzzy set-constraint *C*, $\mu_C(x)$ – L.A. Zadeh membership function

➔ Operational constraints under multi-factor flight conditions are not known precisely. They are inherently ‘fuzzy’. The notion of fuzzy constraint (by L.A. Zadeh) and the notion of safety palette are employed for approximate measurement of the compatibility of current (i.e. measured at time instants *t*) system states with operational constraints for key system variables (monitored flight parameters).

Partial and Integral Safety Spectra

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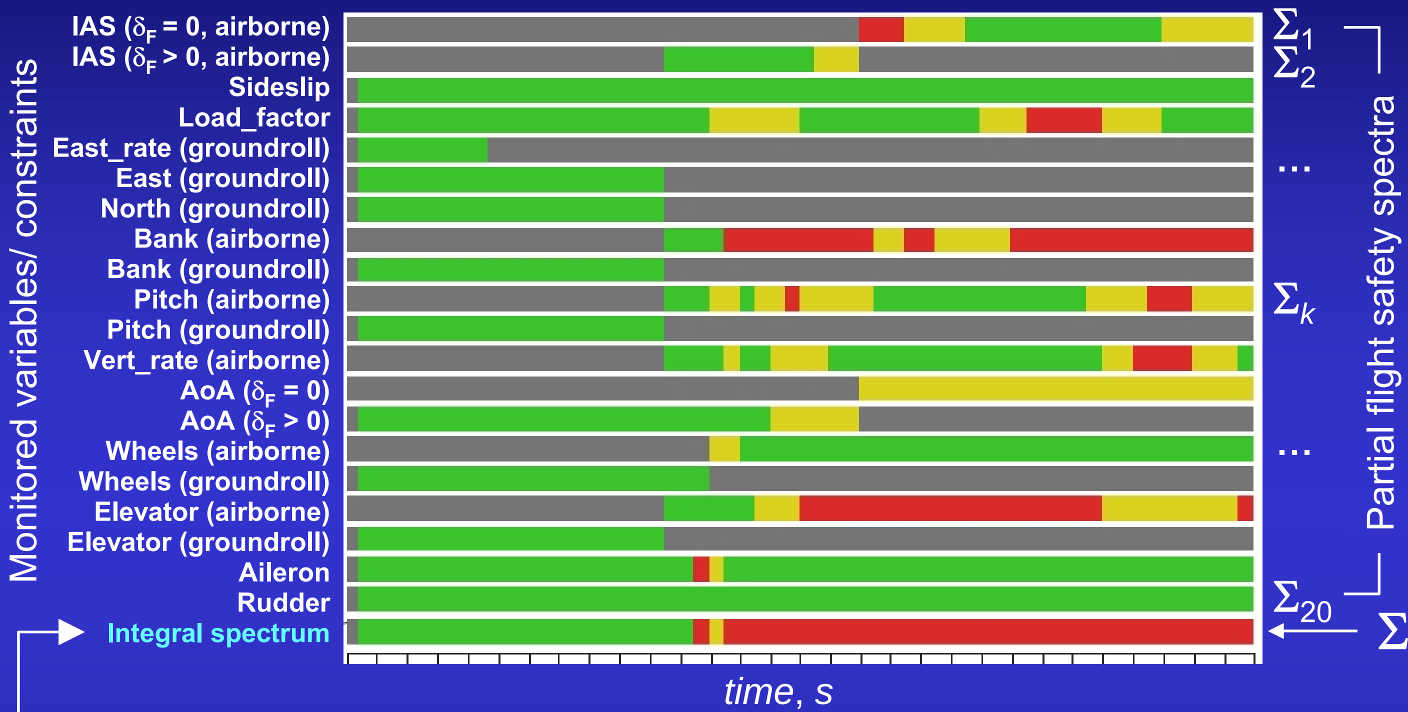

Legend: Σ_k – partial safety spectrum for variable x_k, $k = 1, \ldots, p$; p – total number of monitored constraints/ variables, $p = 20$. Σ – integral safety spectrum; t – flight time; ξ_i – color from safety palette, $i \in$ {B (black), R (red), Y (yellow), G (green),…}; < – 'colder than' operation for comparing two safety colors; *max* – operation of selecting the 'hottest' color at time instant t; || - operation of safety colors concatenation in Σ; $[t_*; t^*]$ – examined flight time interval; Δ – spectrum construction time step.

- green ('norm'), ξ_G
- yellow ('attention'), ξ_Y
- red ('danger'), ξ_R
- black ('catastrophe'), ξ_B
- gray/white ('uncertainty'), ξ_W

Integral Safety Spectrum Calculation Algorithm:

$$(\forall t)\ (t \in [t_*; t^*])\ (\exists \xi(x_k(t))\ (\xi(x_k(t)) \in \{\xi_W, \xi_G, \xi_Y, \xi_R, \xi_B, \ldots\} \wedge (\xi_W < \xi_G < \xi_Y < \xi_R < \xi_B))$$

$$(\xi(t) = max\ \xi(x_k(t)),\ k = 1, \ldots, p) \Rightarrow (\xi(t) \in \Sigma \wedge \Sigma = \xi(t_*)\ ||\ \xi(t_*+\Delta)\ ||\ \xi(t_*+2\Delta)\ ||\ \ldots\ ||\ \xi(t^*))$$

➔ For each flight situation from the situational tree, safety levels are measured for all monitored variables x_k at all recorded time instants. As a result, for each situation from the tree, a family of Partial Safety Spectra Σ_k, $k = 1, \ldots, p$, and an Integral Safety Spectrum Σ are obtained. The integral safety spectrum is a color-coded time-history of violation and restoration of monitored fuzzy constrains during a flight situation.

Safety Classification Categories

Flight Safety Category			Situation Classification Criterion
Color	**Code**	**Name**	
Green	**I**	**Safe**	The system state resides mainly inside the 'green' zone. As a maximum, the system state may stay, for a *short time*, in close proximity to operational constraints, i.e. inside the 'yellow' zone, but must leave it by the end of the flight situation
Light green	**II-a**	**Conditionally Safe – a**	As a maximum, the system state may stay for a *medium time* in close proximity to operational constraints, i.e. inside the 'yellow' zone
Yellow	**II-b**	**Conditionally Safe – b**	As a maximum, the system state may stay for a *long time* in close proximity to operational constraints, i.e. inside the 'yellow' zone
Orange	**III**	**Potentially Unsafe**	As a maximum, the system state may violate operational constraints, i.e. enter the 'red' zone, for a *short or medium time*, but must leave it by the end of the situation
Red	**IV**	**Dangerous (Prohibited)**	As a maximum, the system state may stay beyond operational constraints, i.e. inside the 'red' zone, for a *long time* or till the end of the flight situation
Black	**V**	**Catastrophic ('Chain Reaction')**	There is at least one (for a *short time*) occurrence of a 'black' violation of any operational constraint

➔ One more level of flight safety knowledge generalization is introduced. The goal is to measure the vehicle's safety performance in a flight situation as a whole. With this aim, a generalized 'safety ruler' consisting of five Safety Classification Categories **I**, …, **V** is employed. Why five? – It is because experts cannot reliably recognize and use more than 5-10 gradations of a complex, difficult-to-formalize system-level property (e.g.: Cooper-Harper scale). New 'light green' ('salad green') and 'orange' colors have been added to the existing Safety Palette in order to denote interim Categories **II-a** and **III**, respectively.

Safety Window for Situational Tree $S_1 \cdot \Gamma_{11}$: Takeoff. Errors of Selecting Commanded Flight Path and Bank Angles in Climb

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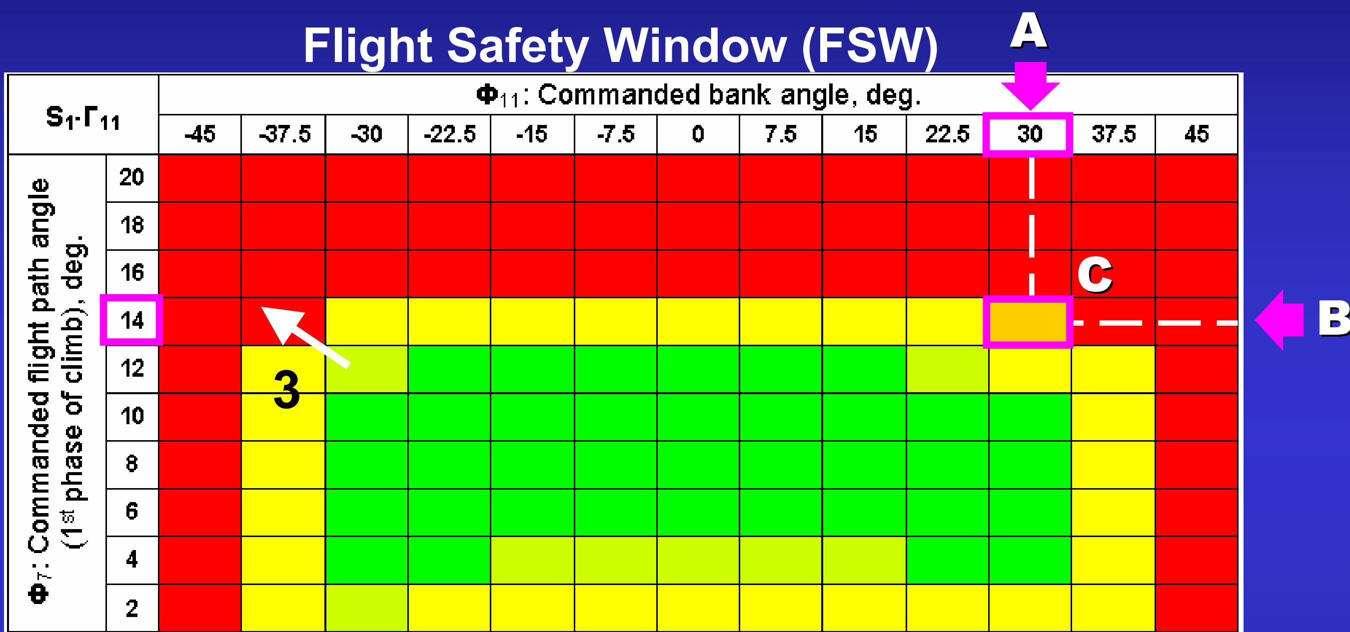
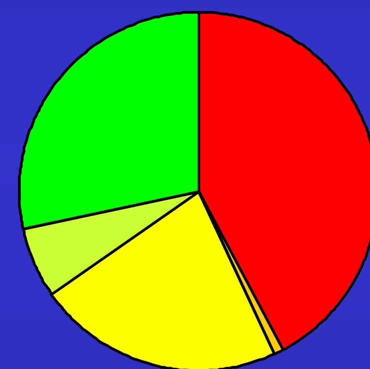
Flight Safety Window (FSW)



Safety Chances Distribution Pie Chart



Category	ξ^j	n^j	χ^j, %
I		37	28
II-a		8	6
II-b		29	22
III		1	1
IV		55	43
V		0	0
Σn^j, $\Sigma \chi^j$ | $S_1 \cdot \Gamma_{11}$		130	100

➔ Let us map safety classification levels (categories) obtained for all situations for tree $S_1 \cdot \Gamma_{11}$ onto a two-factor plane. This gives a Flight Safety [Performance] Window (FSW). In FSW above, cell **C** is located at 'column **A** - row **B**' crossing. This cell depicts safety status of one flight path-branch from the tree. It is a non-standard situation with values of 30° and 14° of factors Φ_7 and Φ_{11} in S_1. This cell is painted using the situation's Flight Safety Category color ('orange'). The FSW has a dangerous 'corner' (upper-left). Rapid transition (**3**) from safe ('salad green') to dangerous ('red') zone is possible (Cat. **II-a** → **IV**), bypassing interim zones (**II-b**, **III**). Control at such 'corners' therefore requires enhanced attention.

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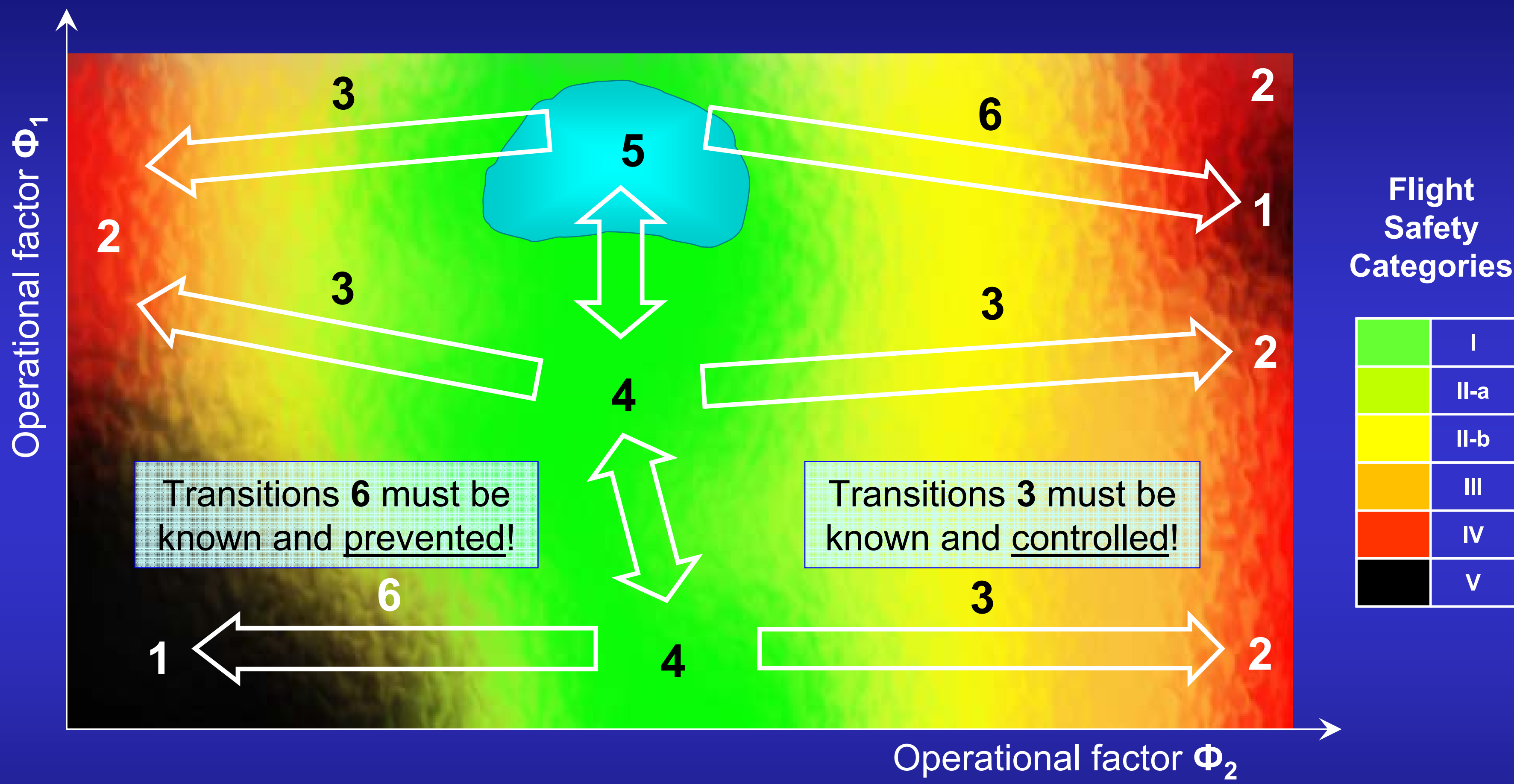
Flight Safety ‘Topology’ Map

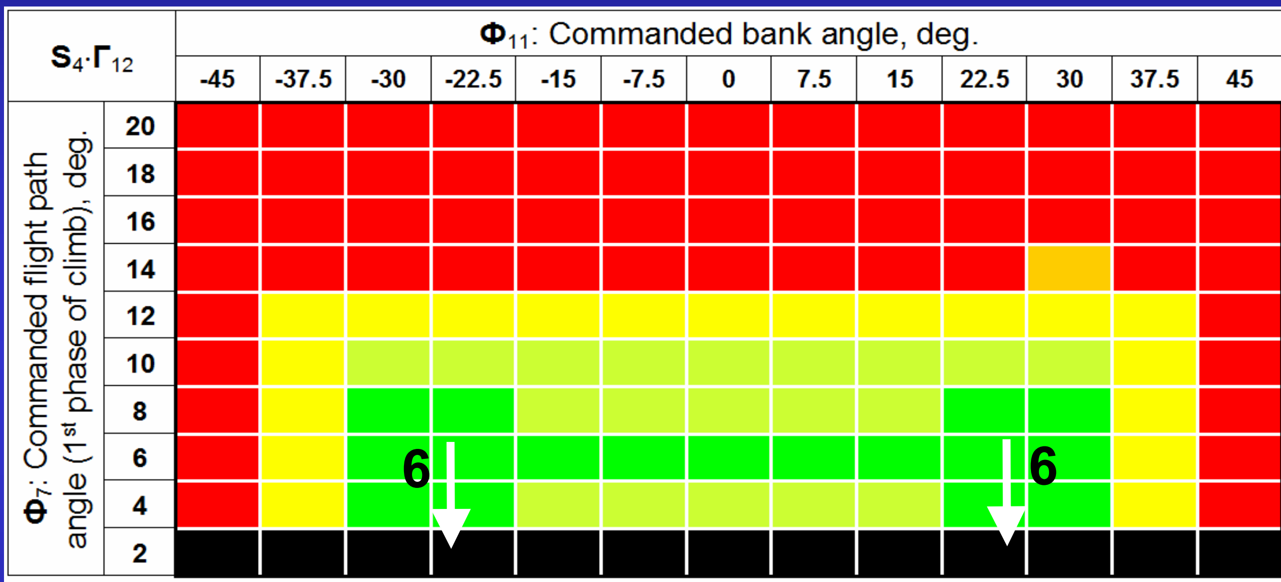


➔ In general, the following characteristic objects can be defined within Flight Safety ‘Topology’ Map:

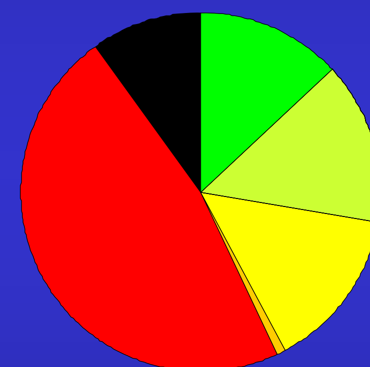
1 ‘**Abyss**’ (catastrophe)
2 ‘**Hill**’ (danger)
3 ‘**Slope**’ (reversible state transitions)
4 ‘**Valley**’ (standard safety, norm)
5 ‘**Lake**’ (maximum safety, optimum)
6 ‘**Precipice**’ (abrupt, irreversible state transitions, ‘chain reaction’)

$S_4 \cdot \Gamma_{12}$: Normal Takeoff. ‘Strong’ Wind Shear. Errors of Selecting Commanded Flight Path and Bank Angles in Climb

Flight Safety Window



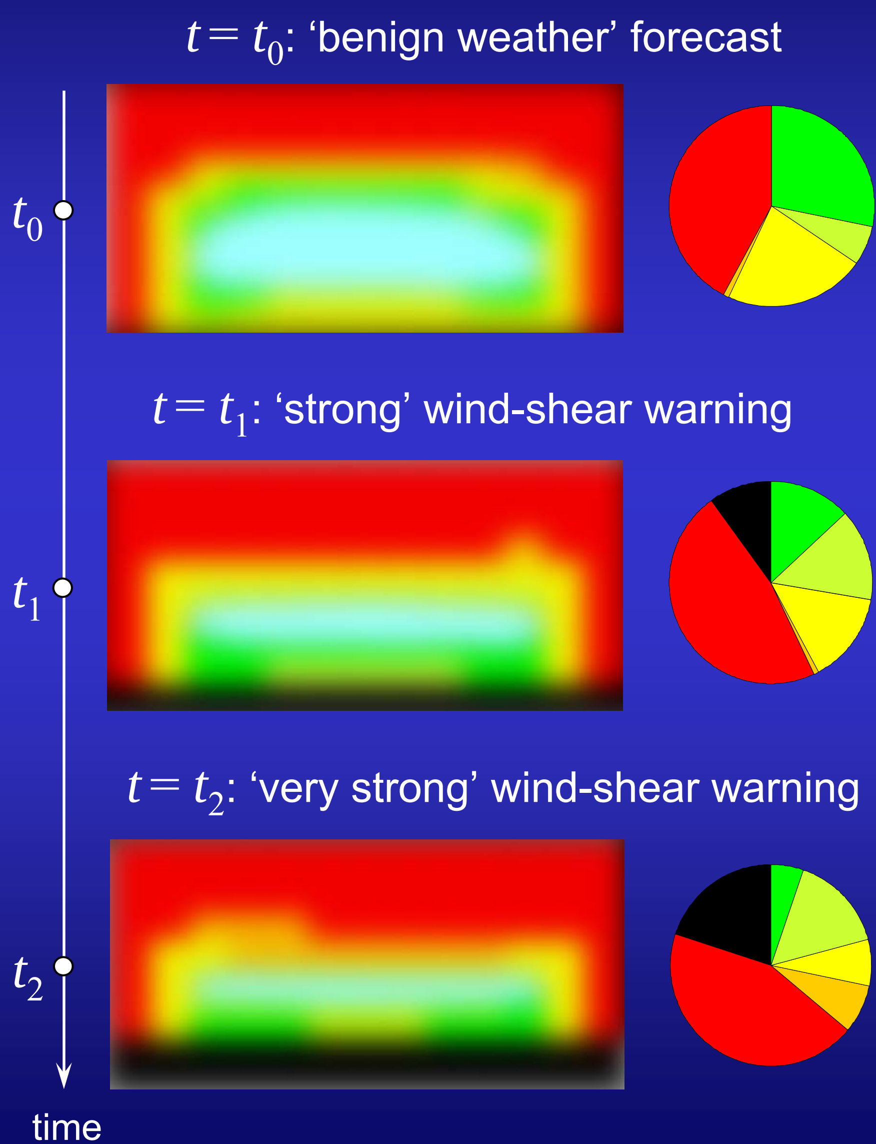
Safety Chances Distribution Pie Chart



Category	ξ^j	n^j	χ^j, %
I		17	13
II-a		19	15
II-b		19	15
III		1	1
IV		61	46
V		13	10
Σn^j, $\Sigma \chi^j$ | $S_4 \cdot \Gamma_{12}$		130	100

➔ This safety ‘topology’ corresponds to the tree $S_4 \cdot \Gamma_{12}$ obtained under ‘strong’ wind shear conditions. At small flight path angles θ_{G1} and any bank angles γ_G it reveals a stable catastrophic ‘abyss’ (a black strip in the bottom) and ‘precipice’ type transitions (**6**). It means that attempts of climbing at small commanded flight path angles (1° … 2°) will inevitably lead the vehicle to a fatal outcome.

Real-Time Safety Knowledge Map (Dynamic Safety Window)



Presented is a time-history of safety windows and safety chances distribution pie charts that correspond to a hypothetical complex flight situation domain - a union of three compositions $\mathbf{S}_4 \cdot (\mathbf{\Gamma}_{\mathbf{11}} + \mathbf{\Gamma}_{12} + \mathbf{\Gamma}_{13})$: "Normal takeoff. Possible variations of wind-shear intensity, errors/ variations in maintaining commanded flight path and bank angles during initial climb".

➔The concept of dynamic safety window is based on use of a 'forest' of situational trees. Provided that key operational factors are measurable on board the vehicle in real time, a dynamic safety window can be used as a medium for coherent monitoring of tactical goals and constraints of flight under uncertainty.

➔ Safety chances distribution pie charts are expedient to use in UAV safety indicators to monitor current state and predict the system safety chances dynamics under anticipated operational conditions during flight.

➔ Note that in this particular example, the share of 'red' and 'black' scenario options increases at the expense of reducing the share of safer outcomes.

Situational Trees for Short-Term Prediction of Flight Safety

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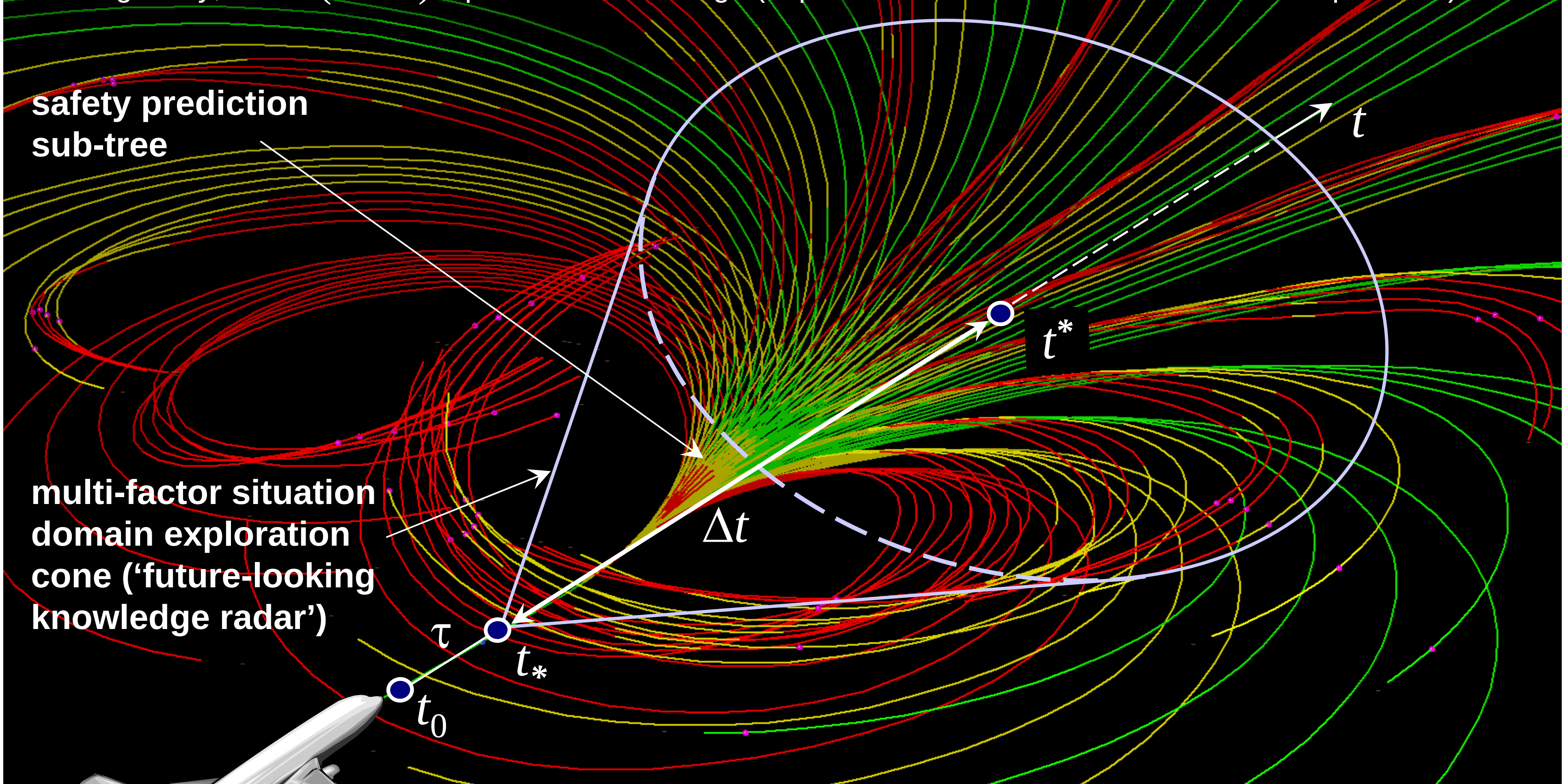
<u>Legend</u>: t_o – current flight time, t_* – prediction start time, t^* – prediction stop time, $\tau = (t_* - t_o)$ – decision-making delay, $\Delta t = (t^* - t_*)$ – prediction time range (depth of tree-based multi-factor domain exploration)



➔ Situational tree construction and tree-based safety prediction (a 'what-if' analysis) methodology accounts for both physics and logic of multi-factor flight situation domain.

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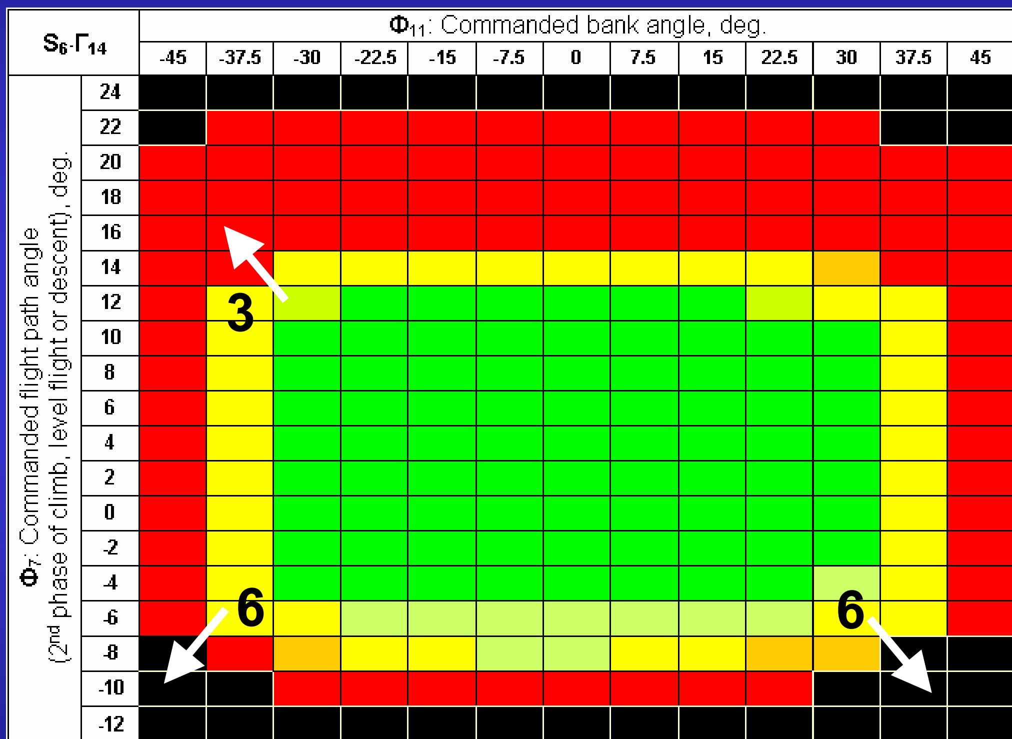
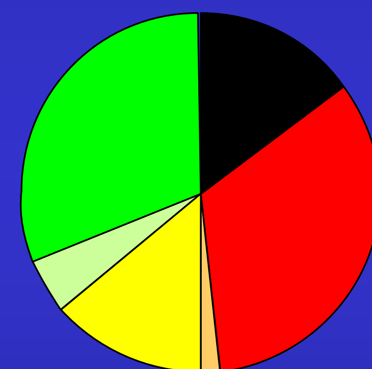
$S_6 \cdot \Gamma_{14}$: Low-Altitude Level Flight. Errors Of Selecting Commanded Flight Path And Bank Angles

Flight Safety Window



Safety Chances Distribution Pie Chart



Category	ξ^j	n^j	χ^j, %
I		77	33
II-a		12	5
II-b		35	14
III		4	2
IV		82	33
V		37	15
Σn^j, $\Sigma \chi^j$ | **$S_6 \cdot \Gamma_{14}$**		247	100

➔ This Safety Window has two catastrophically dangerous ‘corners’ (6) corresponding to (θ_{G1}, γ_G) ≅ (-10º…-12º, |37.5º…45º|). Sharp transition (**3**) of states from safe (‘salad green’) to dangerous (‘red’) zone is also possible in the left upper corner (Cat. **II-a**→**IV**), bypassing interim zones (Cat. **II-b**, **III**).

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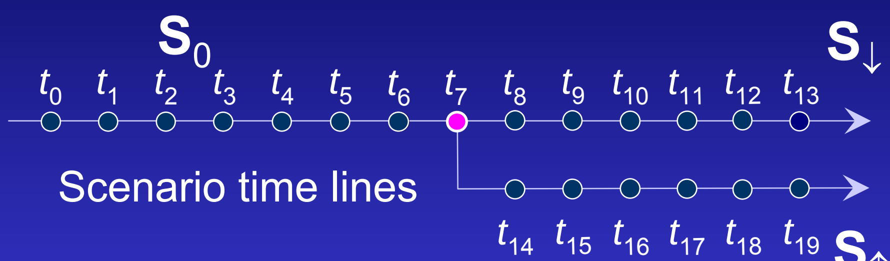
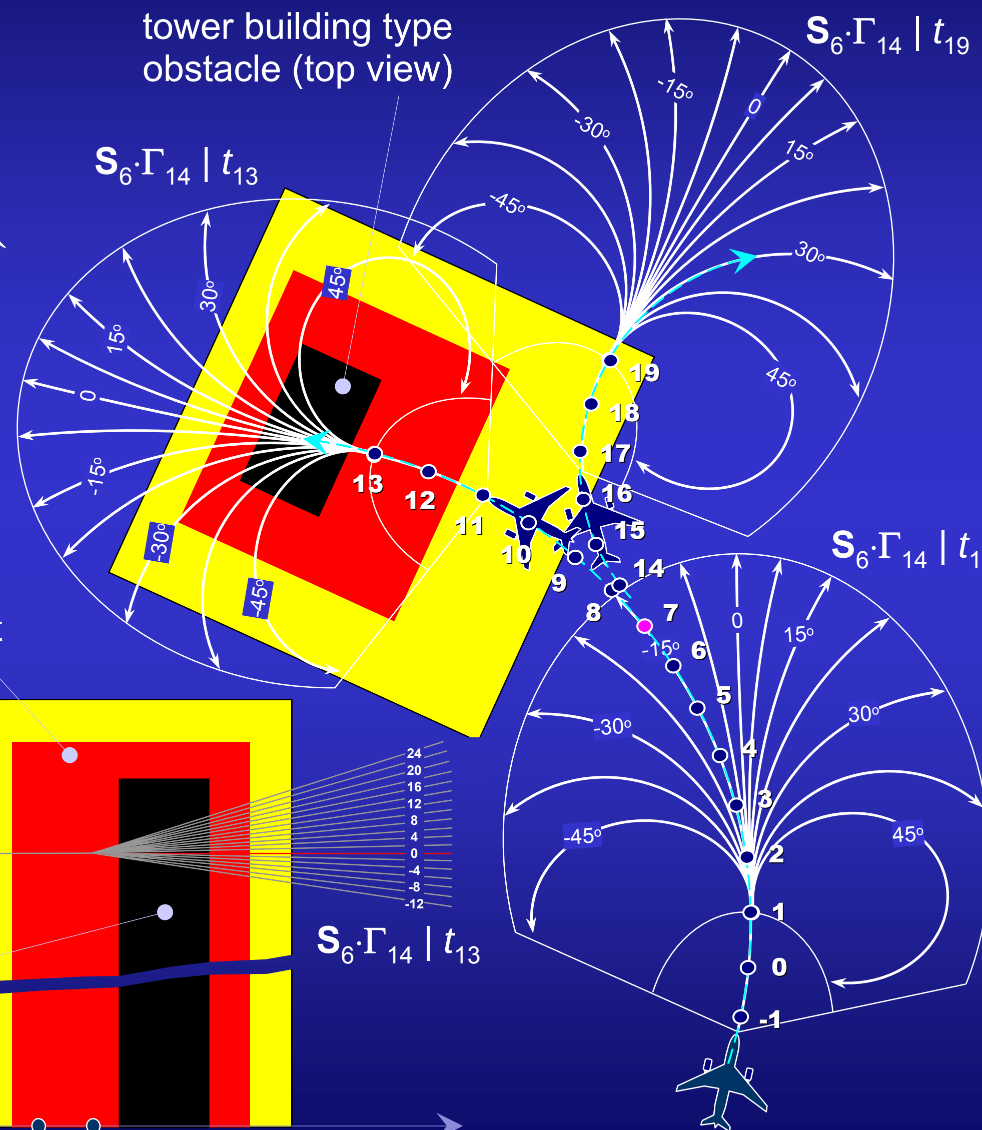
$S_6 \cdot \Gamma_{14}$: Low-Altitude Level Flight In the Presence of Urban Obstacles

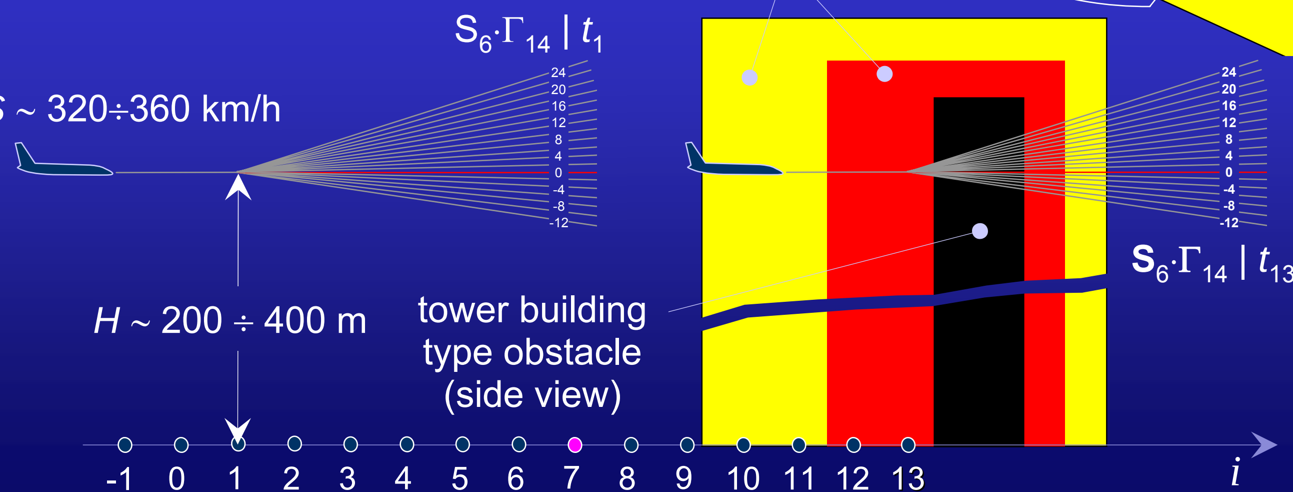


Legend: S_0, $S_\downarrow$, $S_\uparrow$ - scenario segments, S_0 - obstacle approach, $S_\downarrow$ - imminent collision, $S_\uparrow$ - collision avoidance, $S_6 \cdot \Gamma_{14} \mid t_i$ - tree location at t_i

➔ $S_0 \cup S_\downarrow$ - terrorist-/ fool-type control, $S_0 \cup S_\uparrow$ - AI-based self-preservation control.

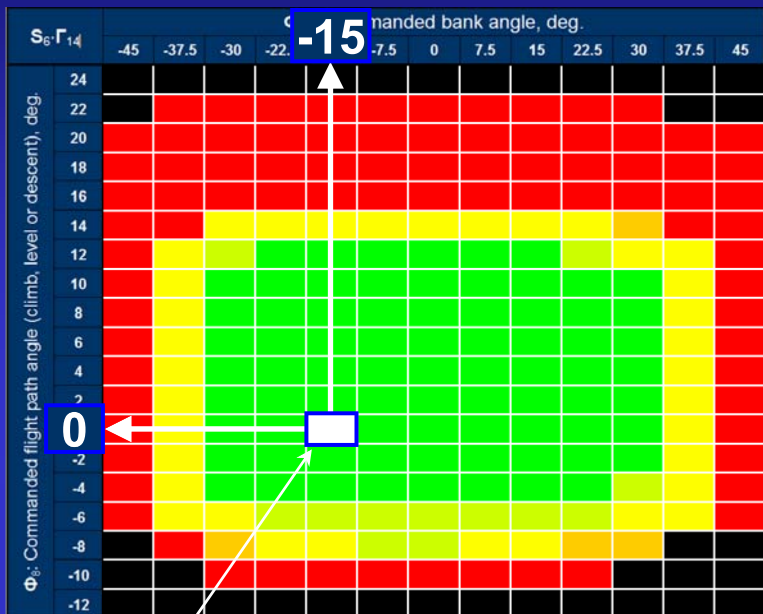
'yellow' and 'red' zones of obstacle's fuzzy constraint





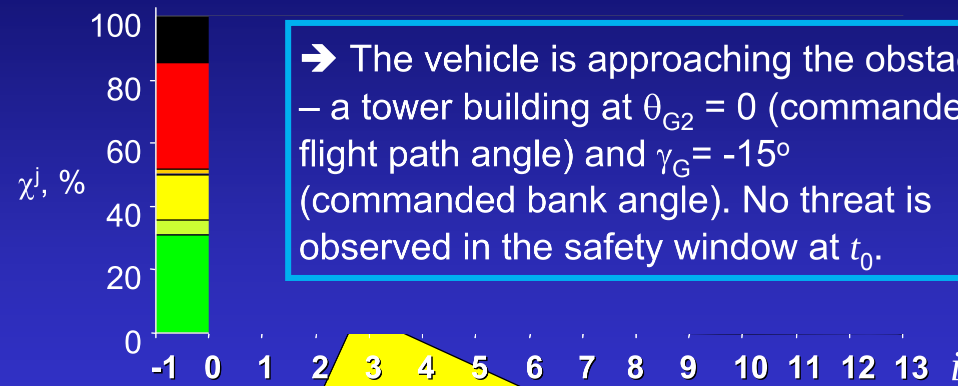
S_0: Obstacle Approach (t_0)

Safety Window

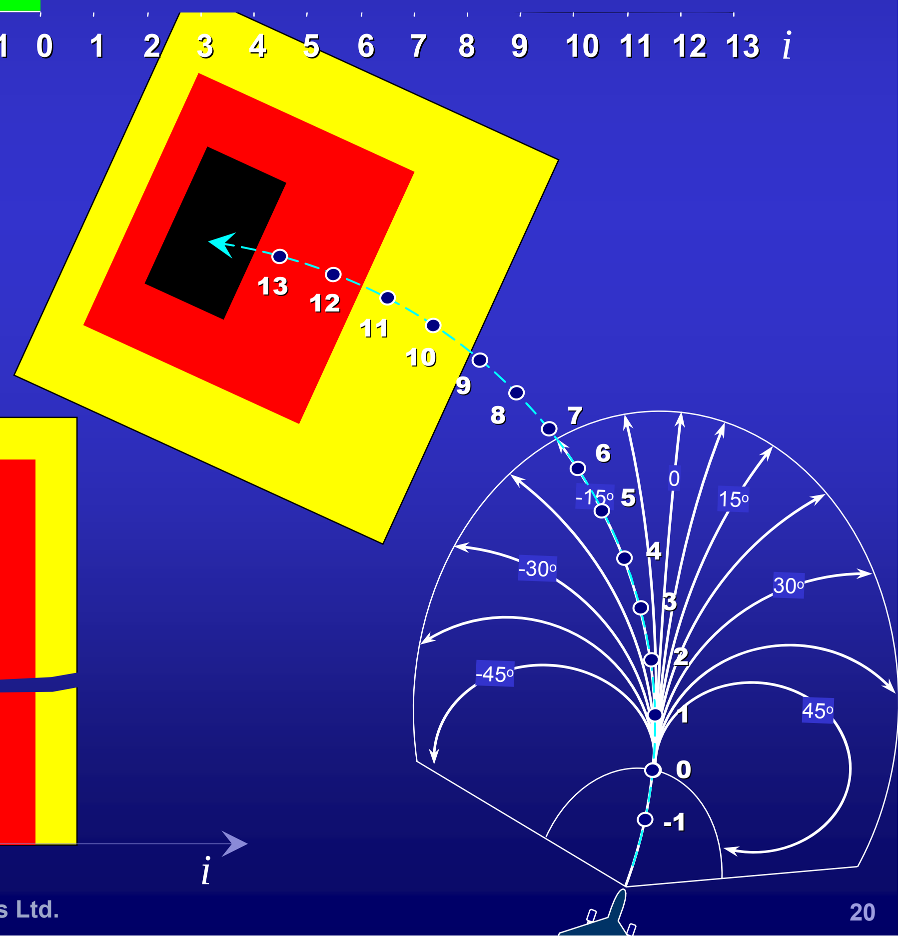


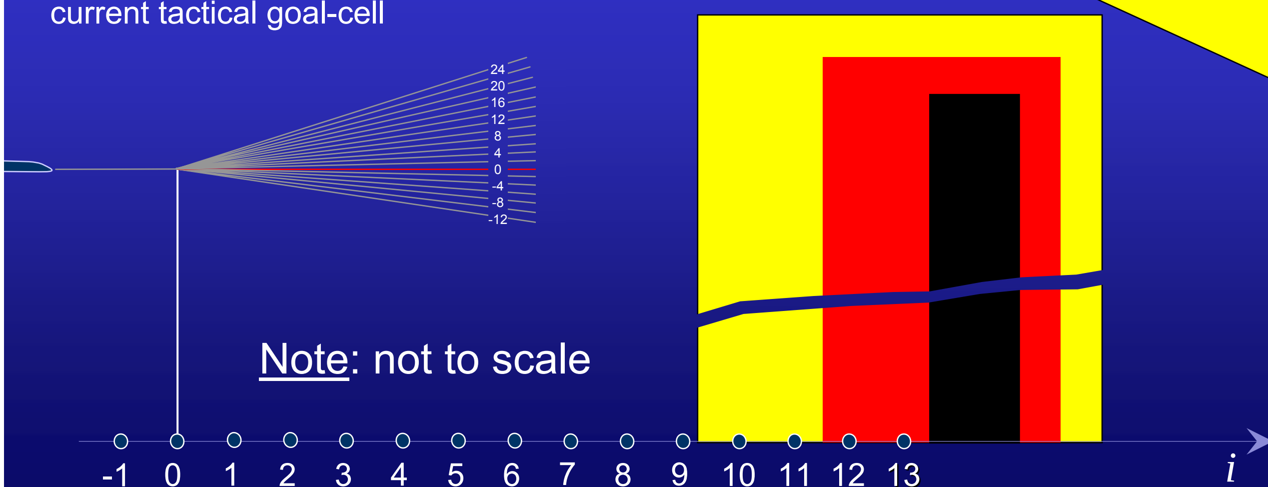
current tactical goal-cell

Safety Chances Distribution



➔ The vehicle is approaching the obstacle – a tower building at θ_{G2} = 0 (commanded flight path angle) and γ_G = -15º (commanded bank angle). No threat is observed in the safety window at t_0.





Note: not to scale

S_0: Obstacle Approach (t_1)

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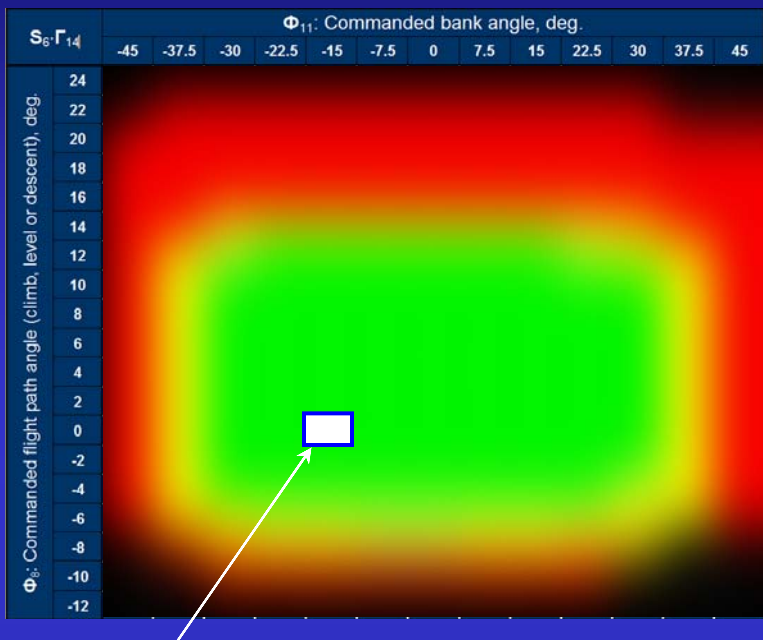
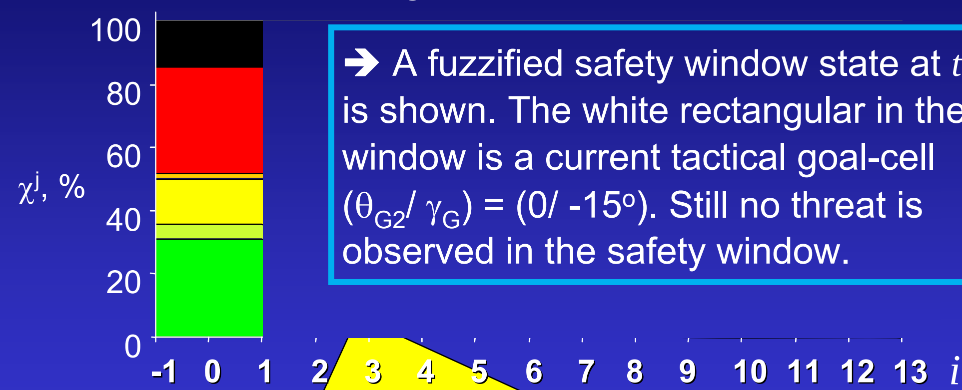
Safety Window

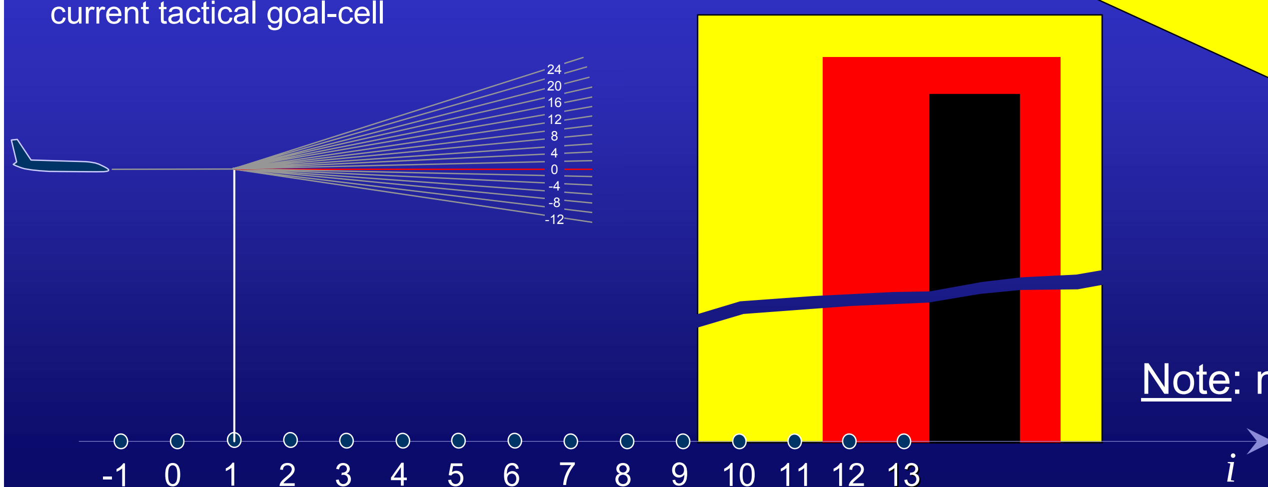


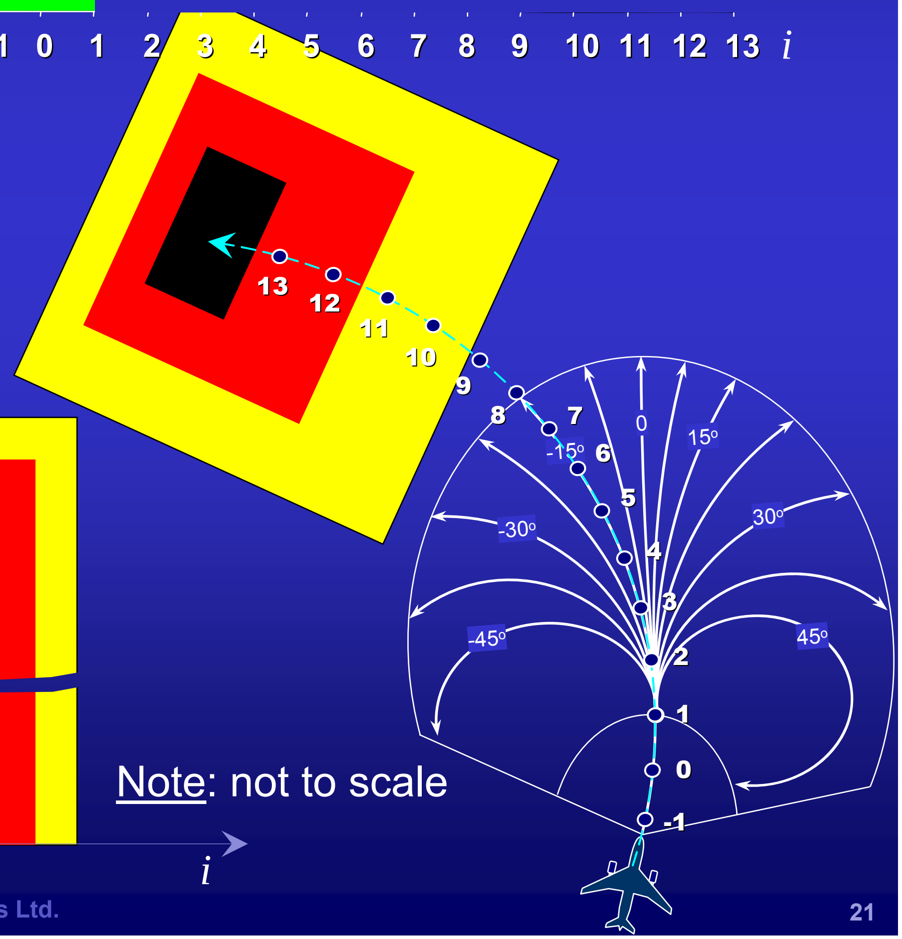
current tactical goal-cell

Safety Chances Distribution



➔ A fuzzified safety window state at t_1 is shown. The white rectangular in the window is a current tactical goal-cell $(\theta_{G2}/\ \gamma_G) = (0/\ -15^o)$. Still no threat is observed in the safety window.





Note: not to scale

S_0: Obstacle Approach (t_2)

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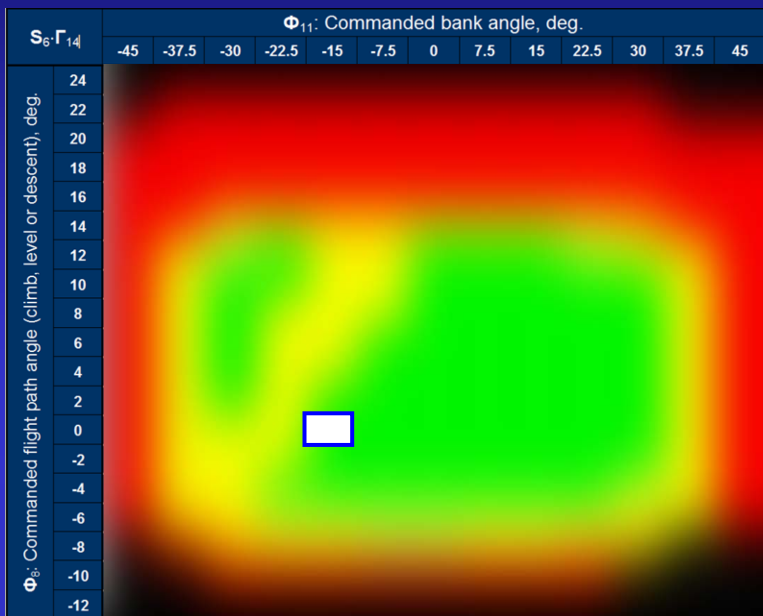
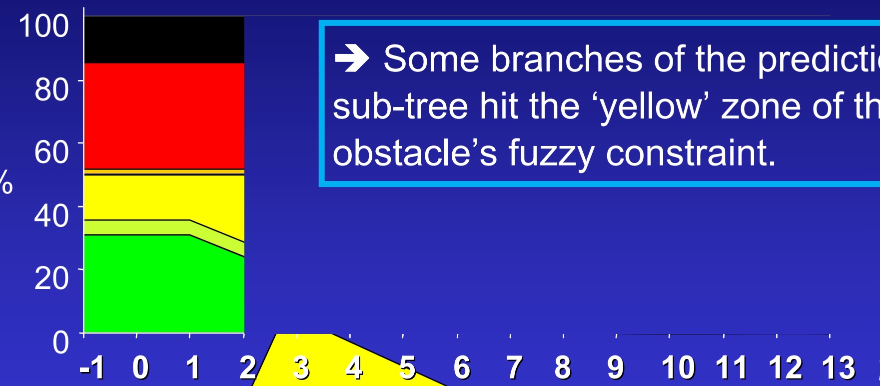
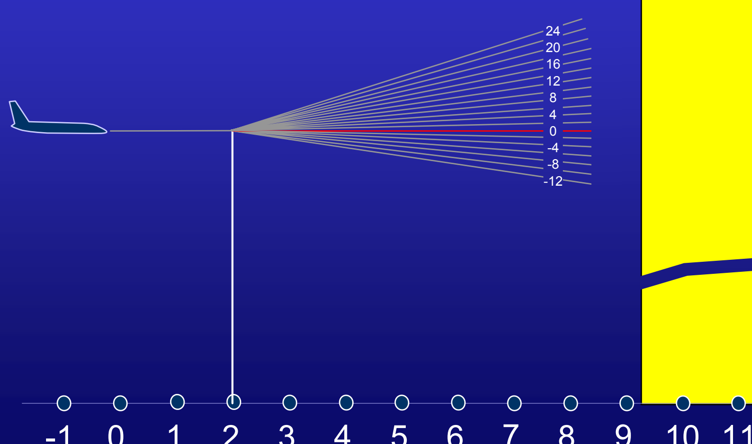
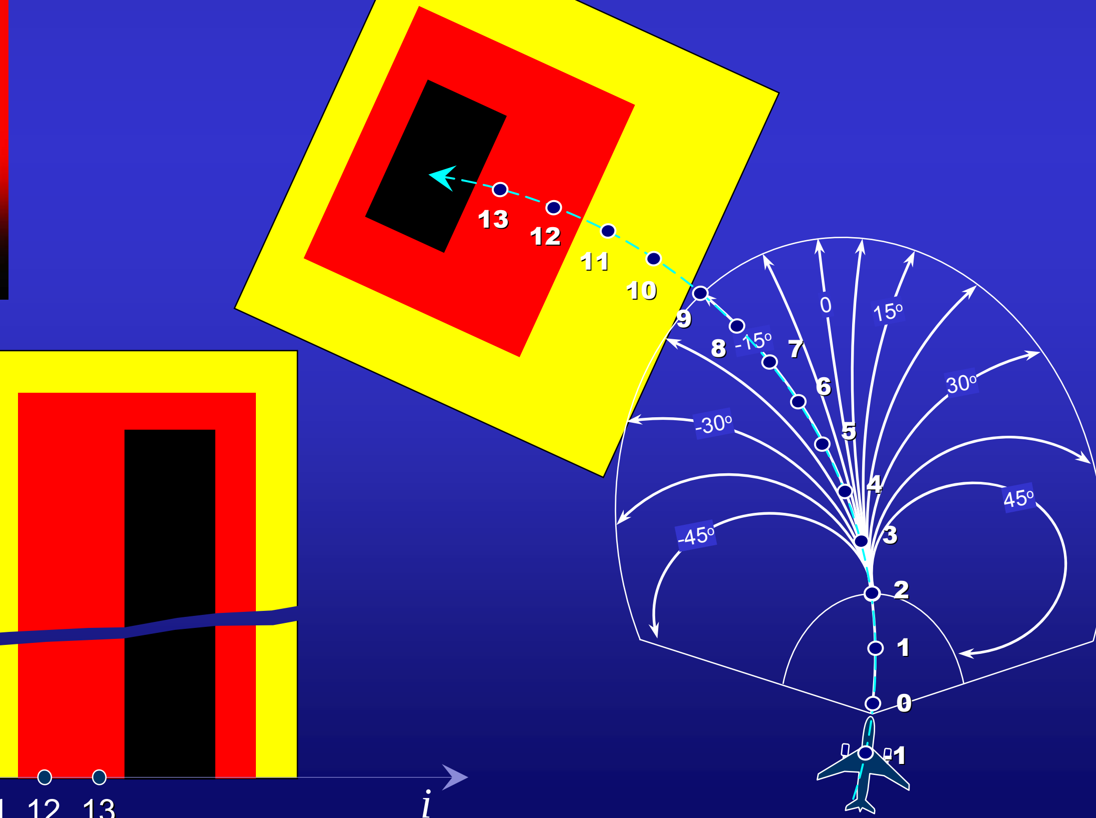
Safety Window



Safety Chances Distribution

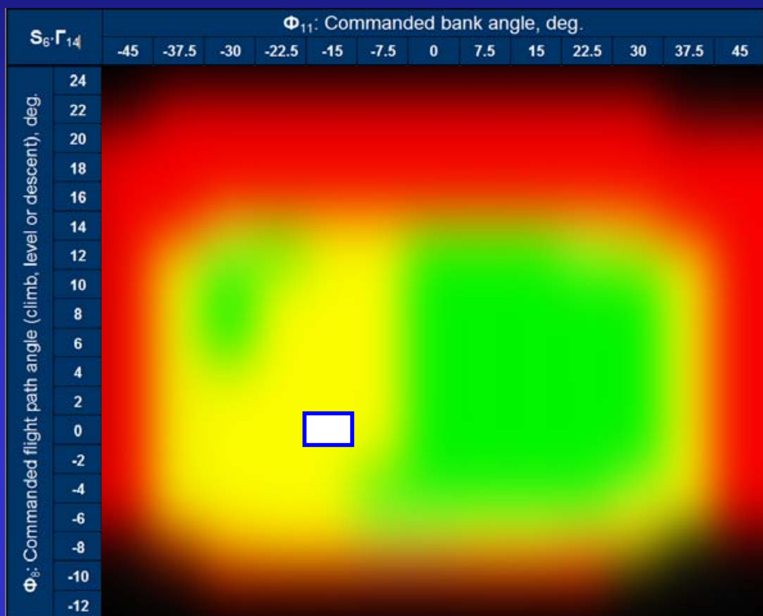


➔ Some branches of the prediction sub-tree hit the 'yellow' zone of the obstacle's fuzzy constraint.

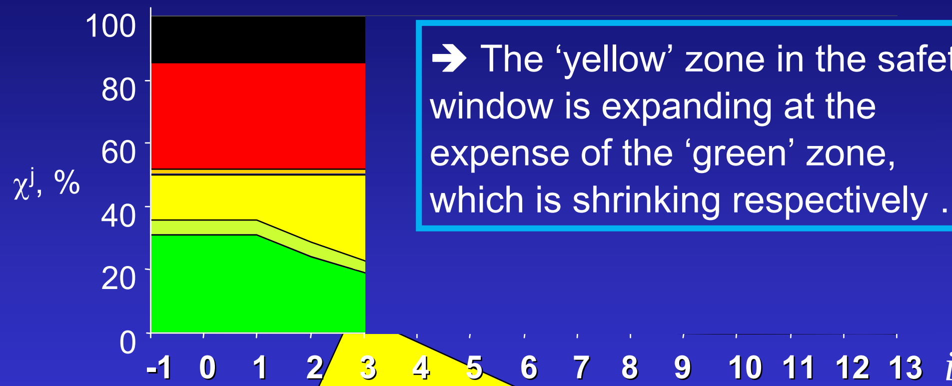



S_0: Obstacle Approach (t_3)

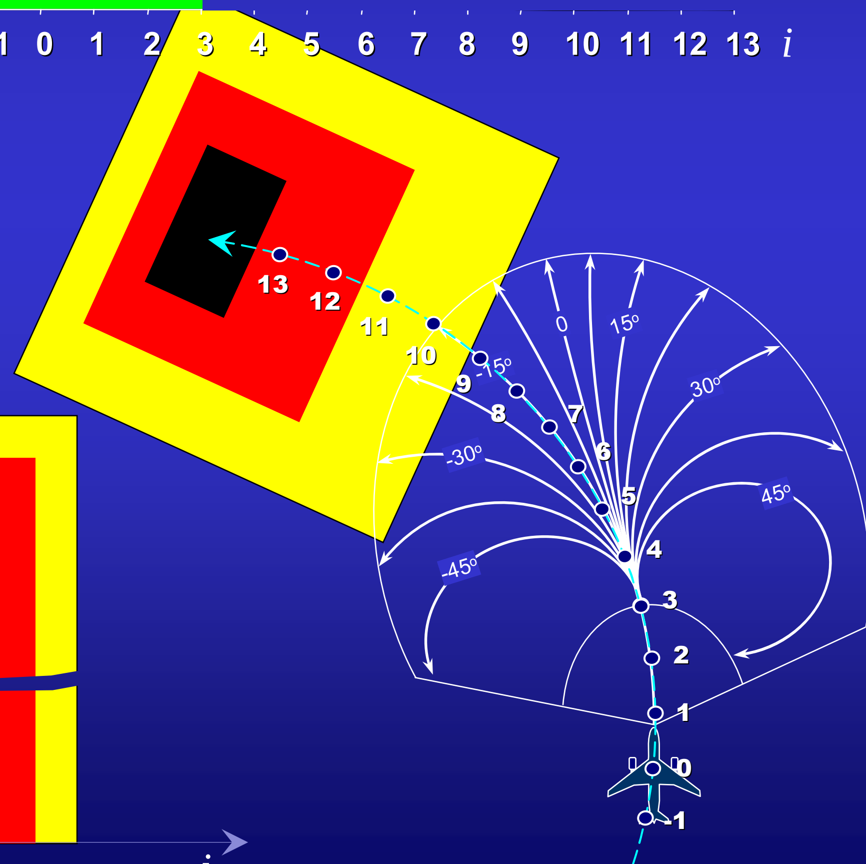
Safety Window

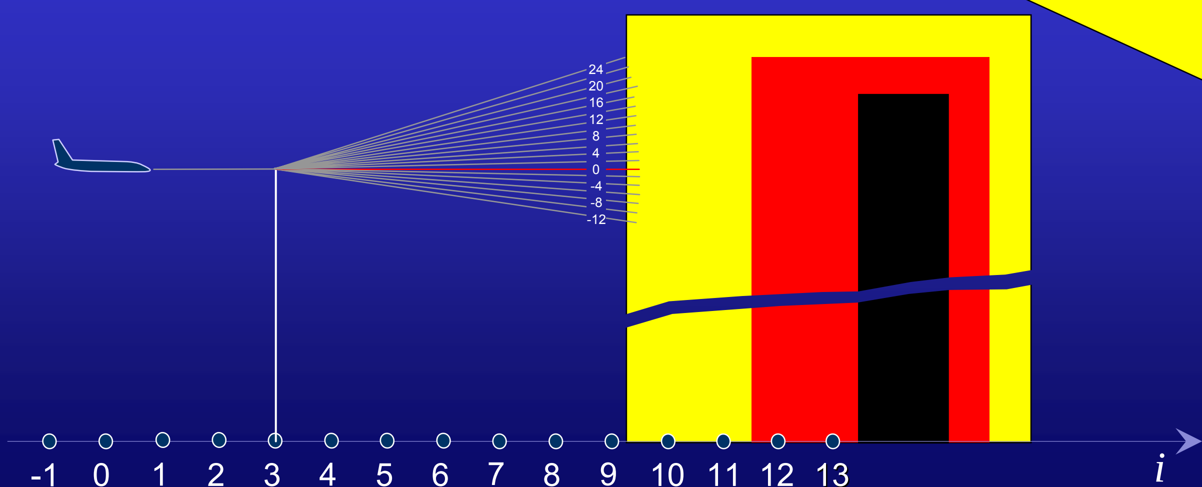


Safety Chances Distribution



➔ The ‘yellow’ zone in the safety window is expanding at the expense of the ‘green’ zone, which is shrinking respectively …

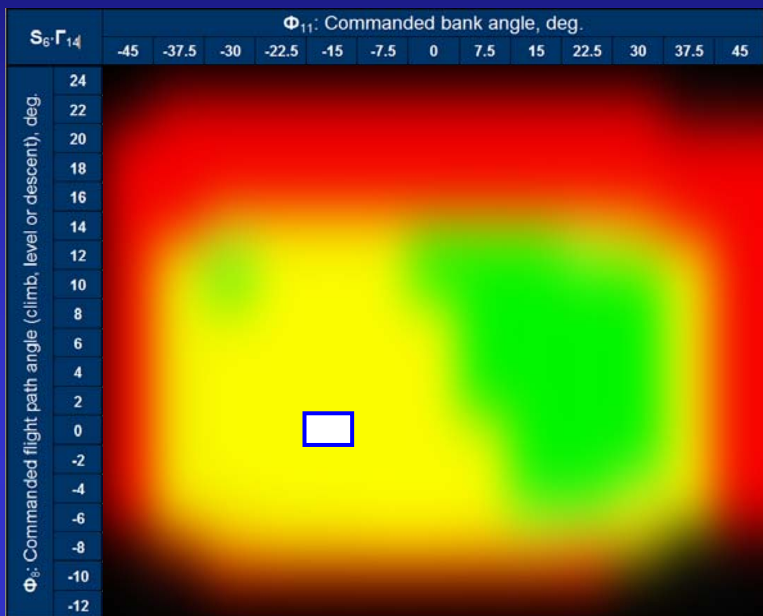




S_0: Obstacle Approach (t_4)

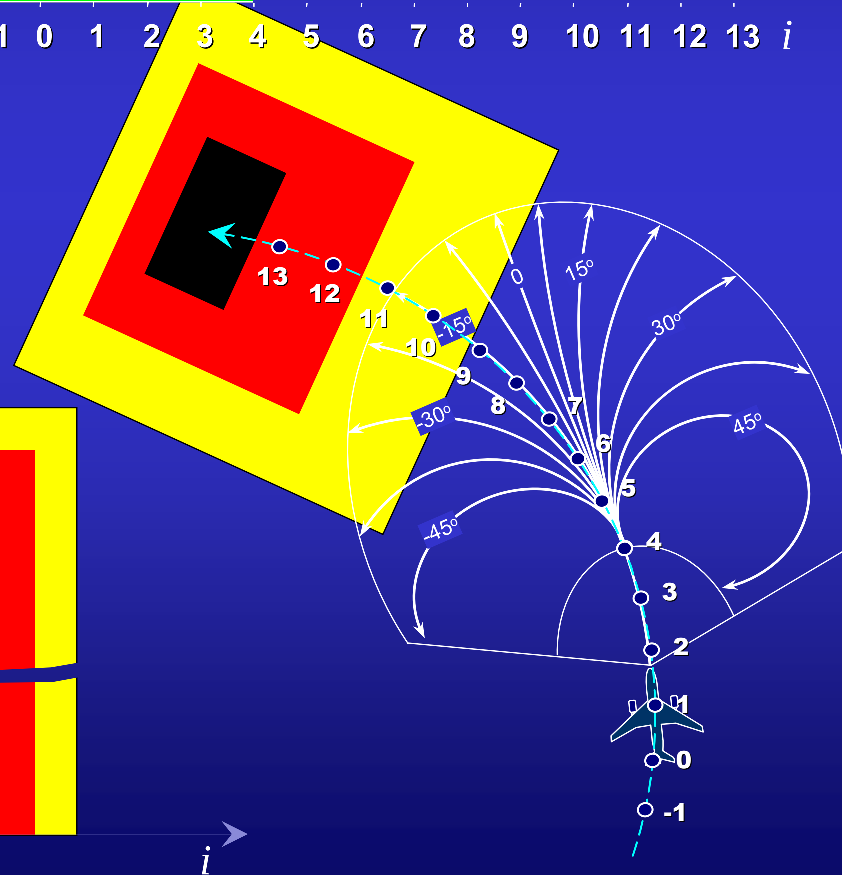
INTELONICS

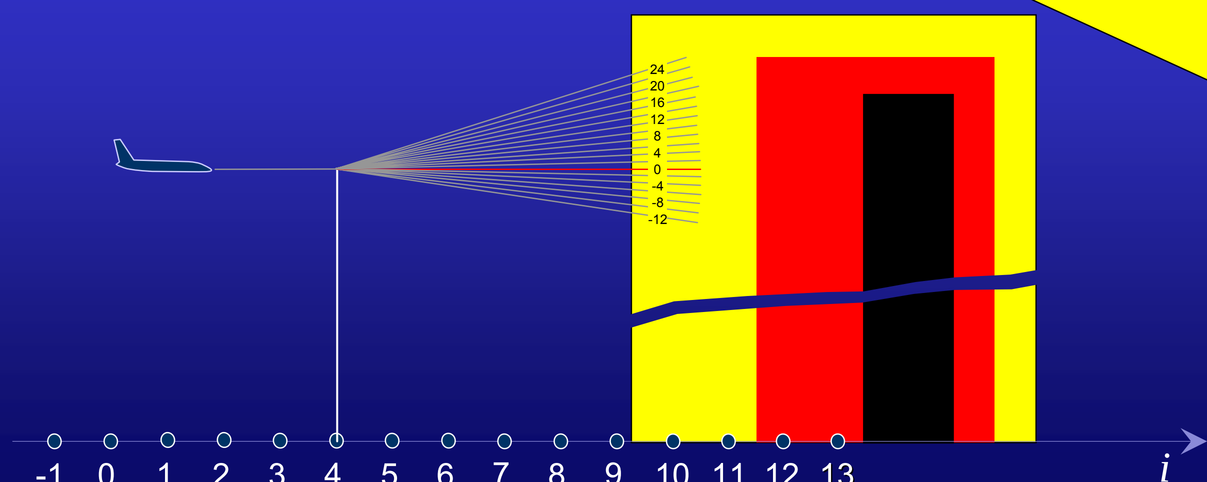
Safety Window



Safety Chances Distribution

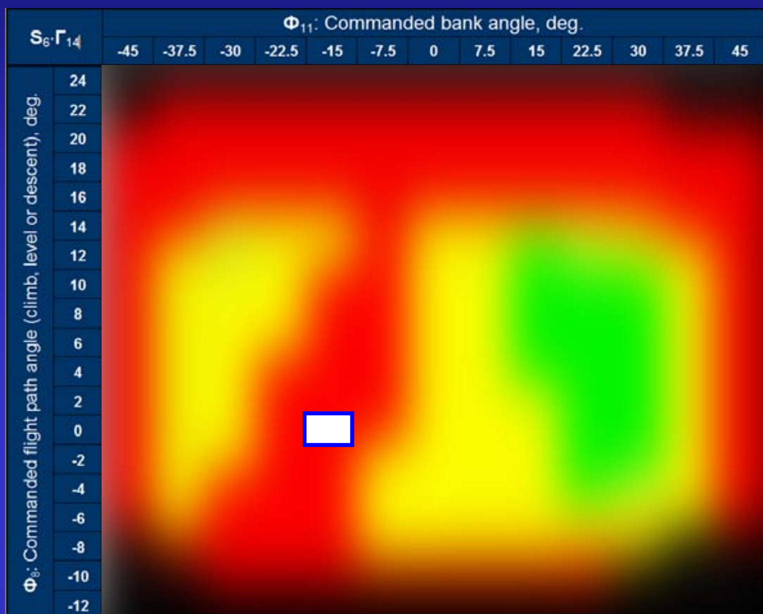
➔ Now the 'yellow' zone occupies almost all the left-hand half of the safety window.



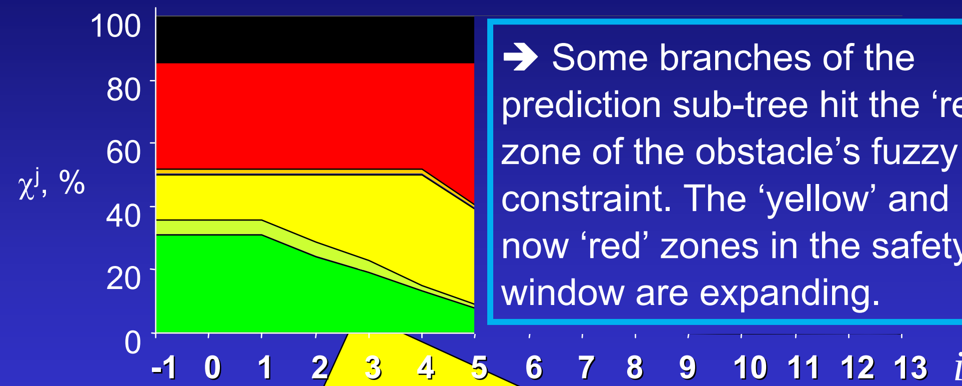


S_0: Obstacle Approach (t_5)

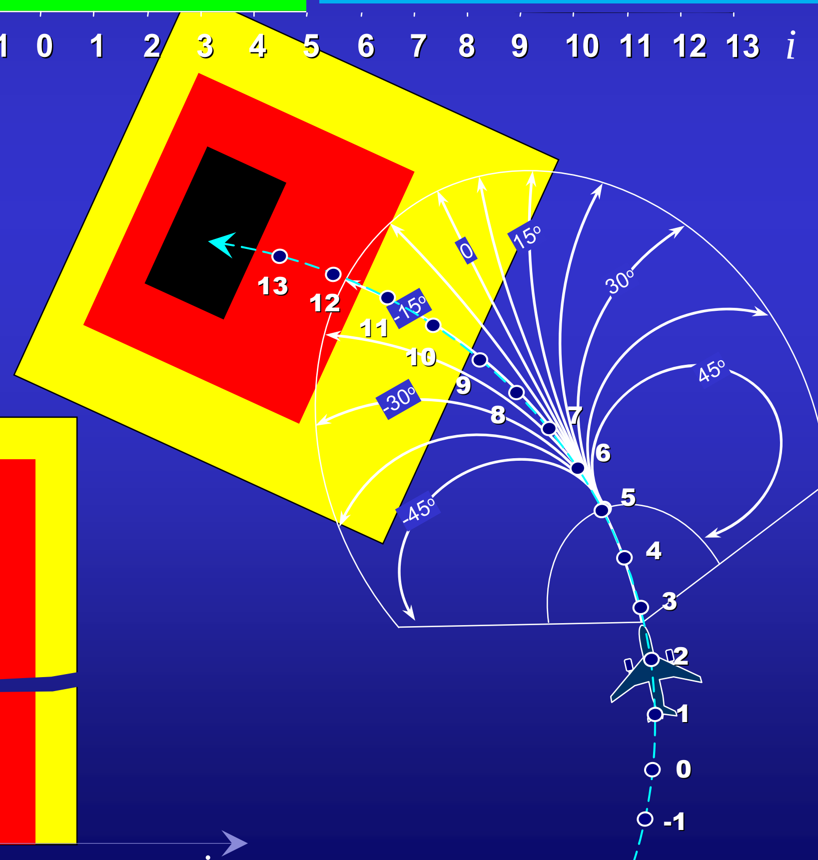
Safety Window

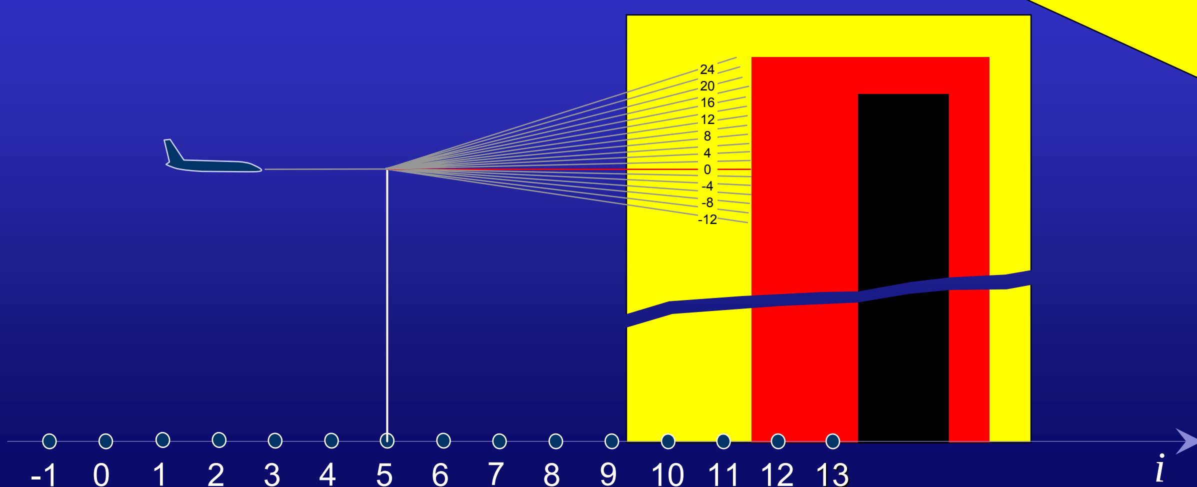


Safety Chances Distribution



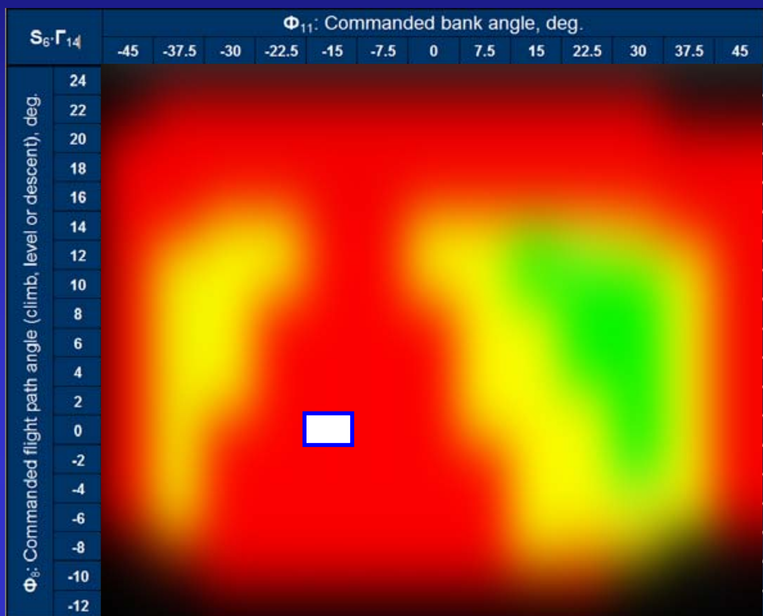
➔ Some branches of the prediction sub-tree hit the 'red' zone of the obstacle's fuzzy constraint. The 'yellow' and now 'red' zones in the safety window are expanding.





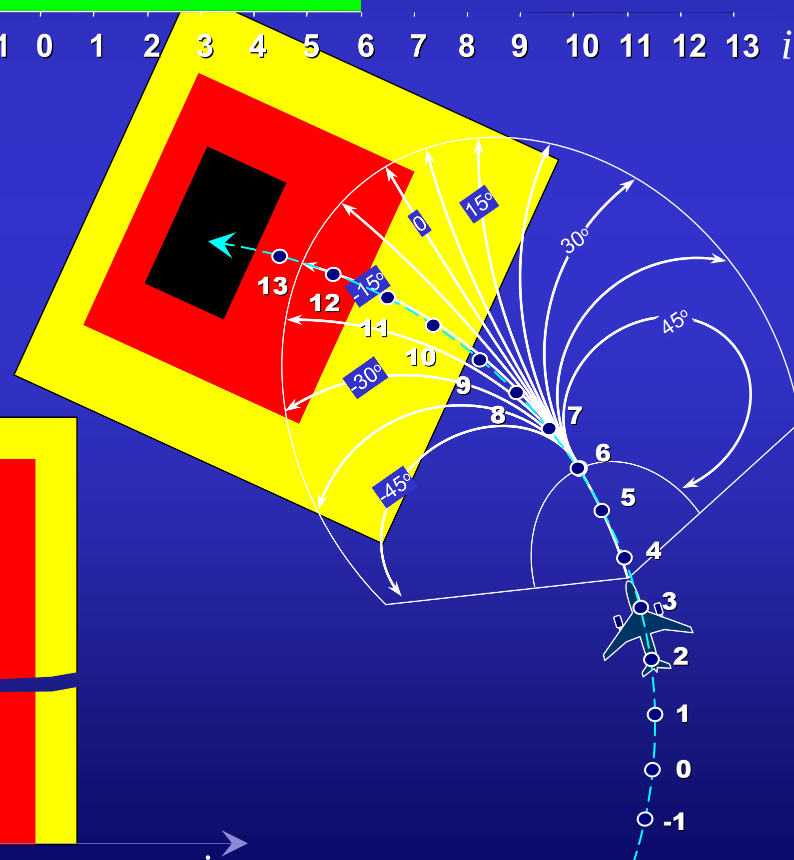
S_0: Obstacle Approach (t_6)

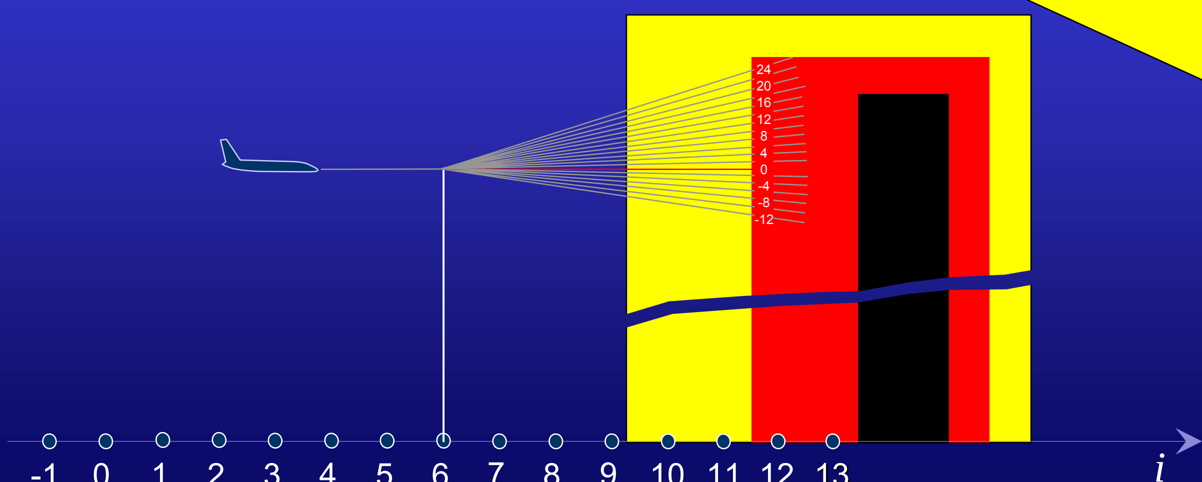
Safety Window



Safety Chances Distribution

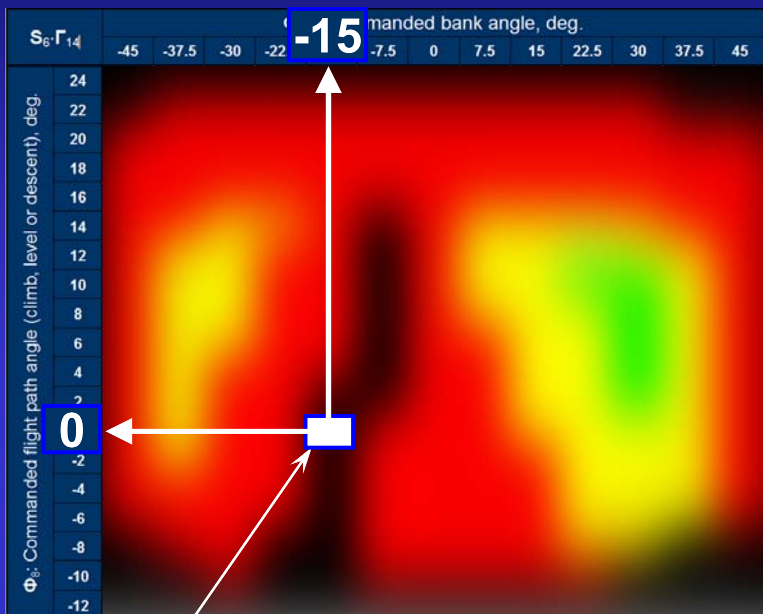
➔ The 'red' zone is spreading through the left-hand part of the safety window.





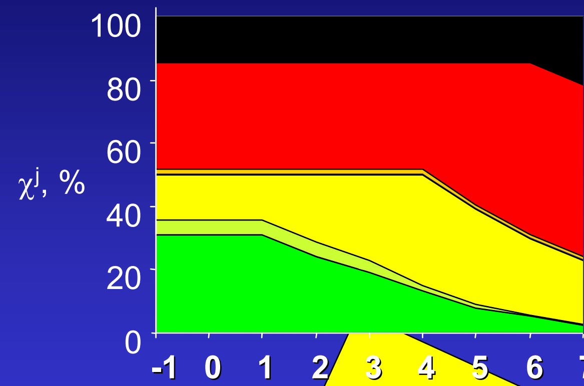
S_0: Obstacle Approach (t_7)

Safety Window

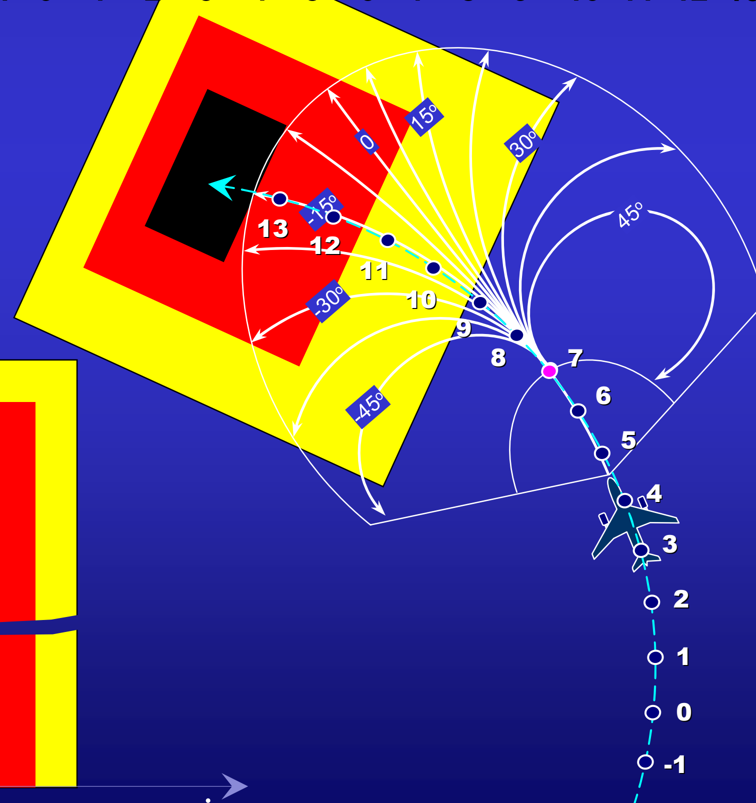


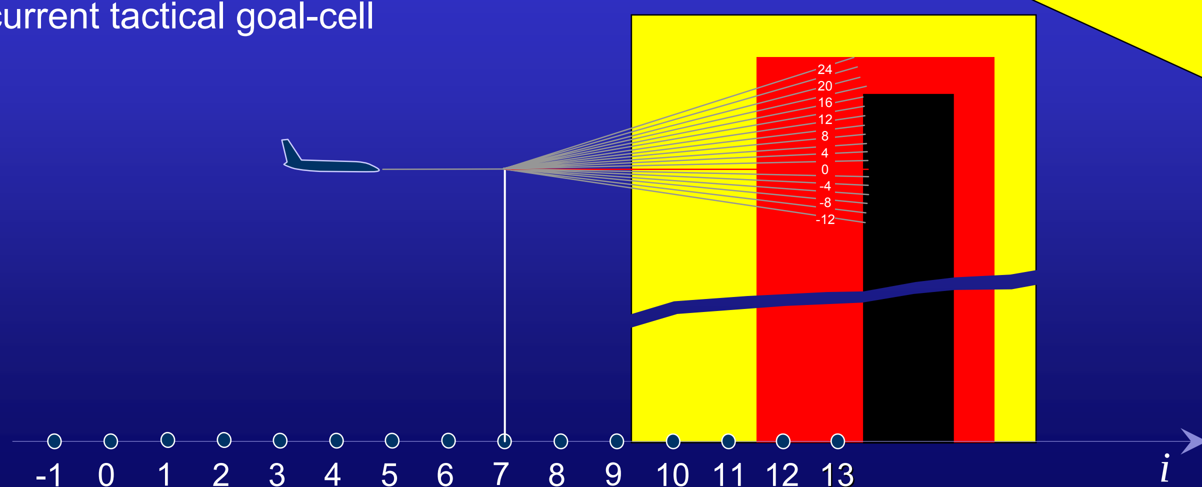
current tactical goal-cell

Safety Chances Distribution



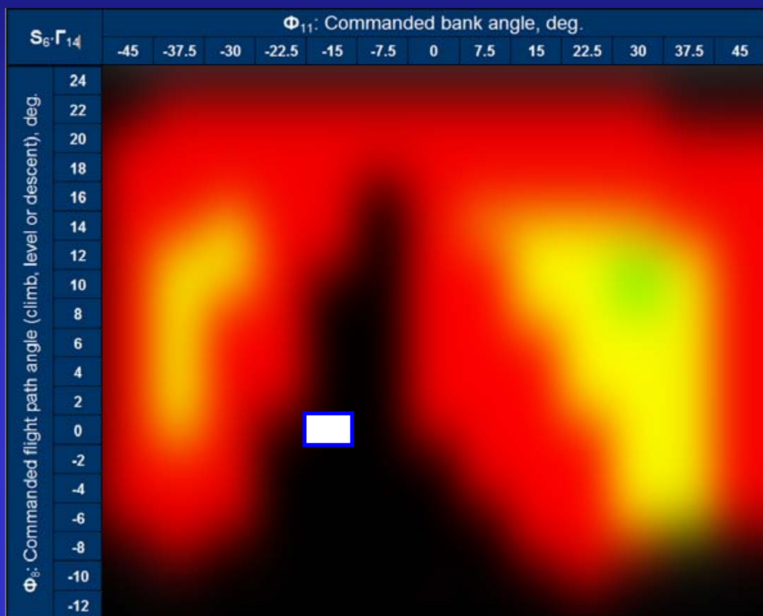
➔ A 'black' ('imminent collision') zone appears in the safety window. NB: It overlaps with the current tactical goal-cell.



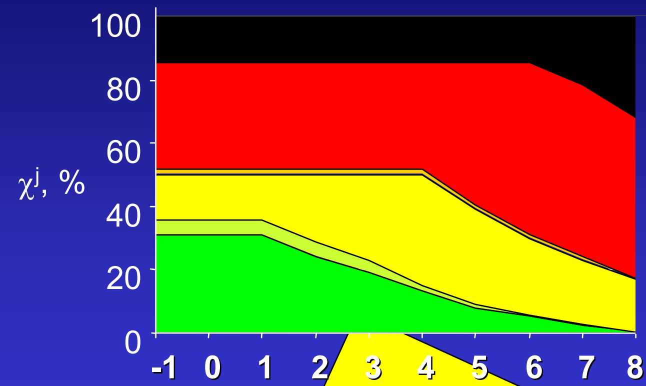


S↓: Imminent Collision (t_8)

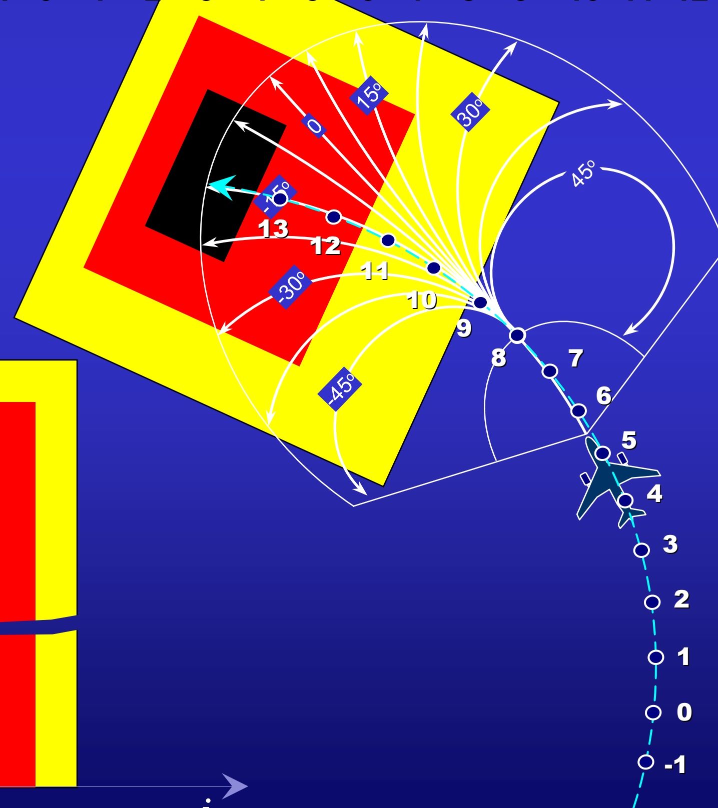
Safety Window



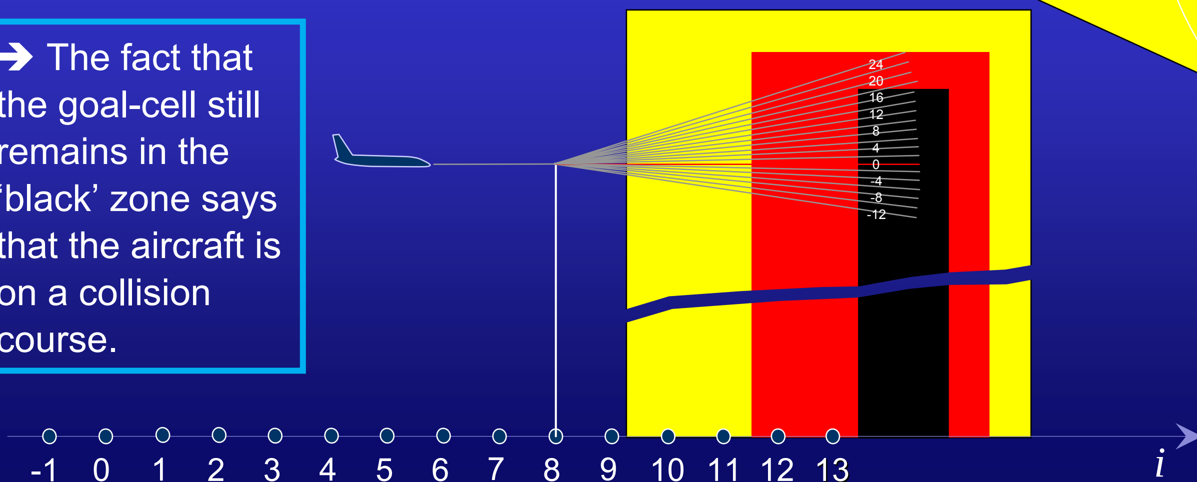
Safety Chances Distribution



➔ The 'black' zone is expanding – now at the expense of shrinking both the 'green' and 'yellow' zones.

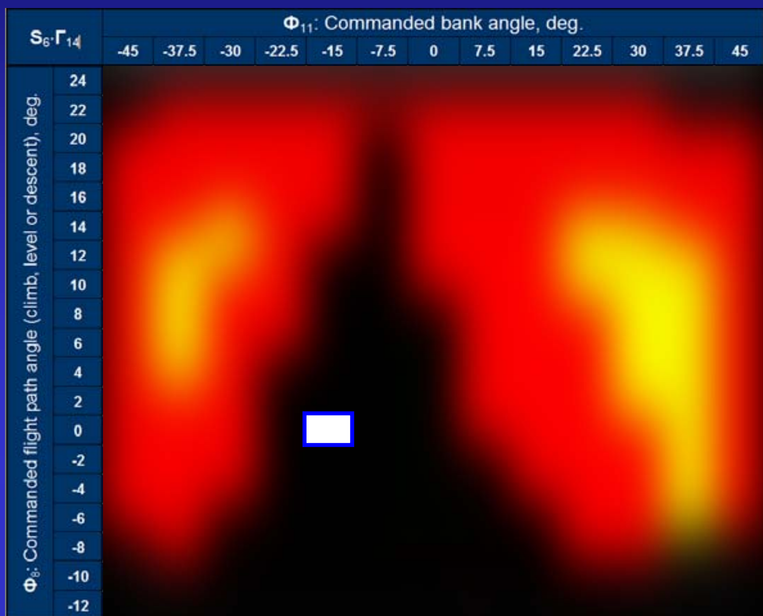


➔ The fact that the goal-cell still remains in the 'black' zone says that the aircraft is on a collision course.

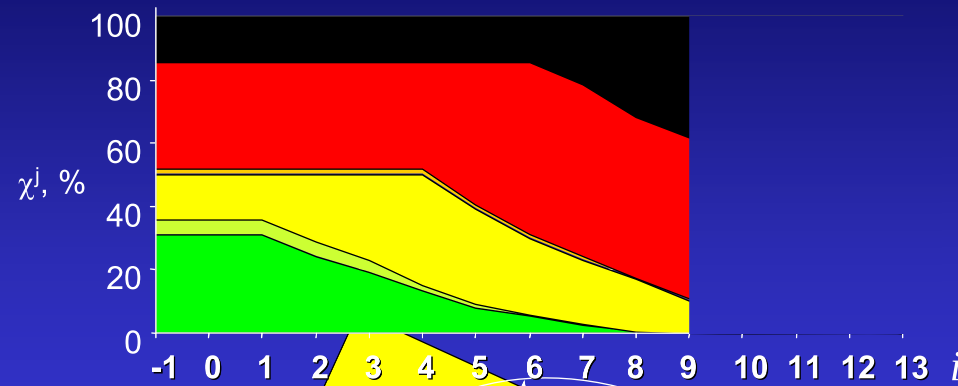


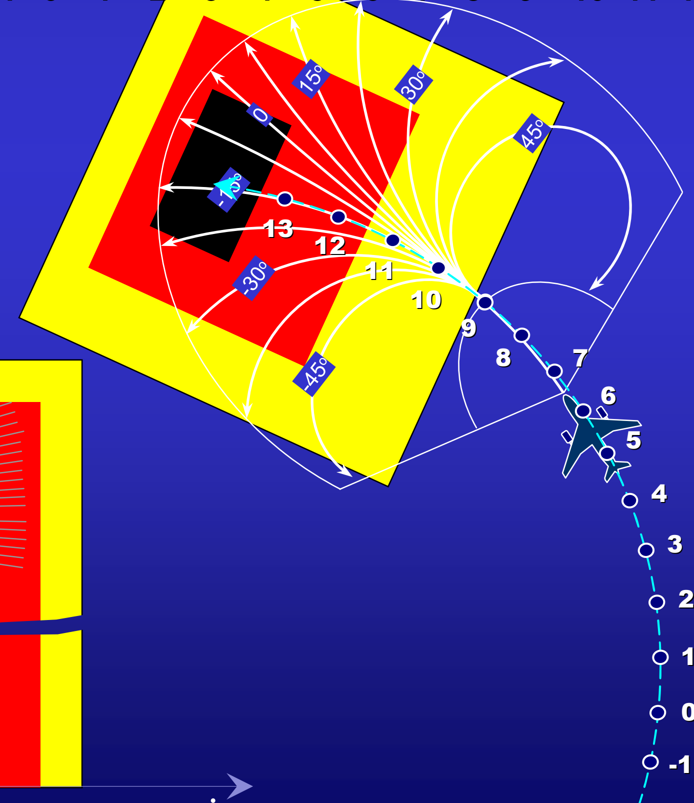
S↓: Imminent Collision (t_9)

Safety Window

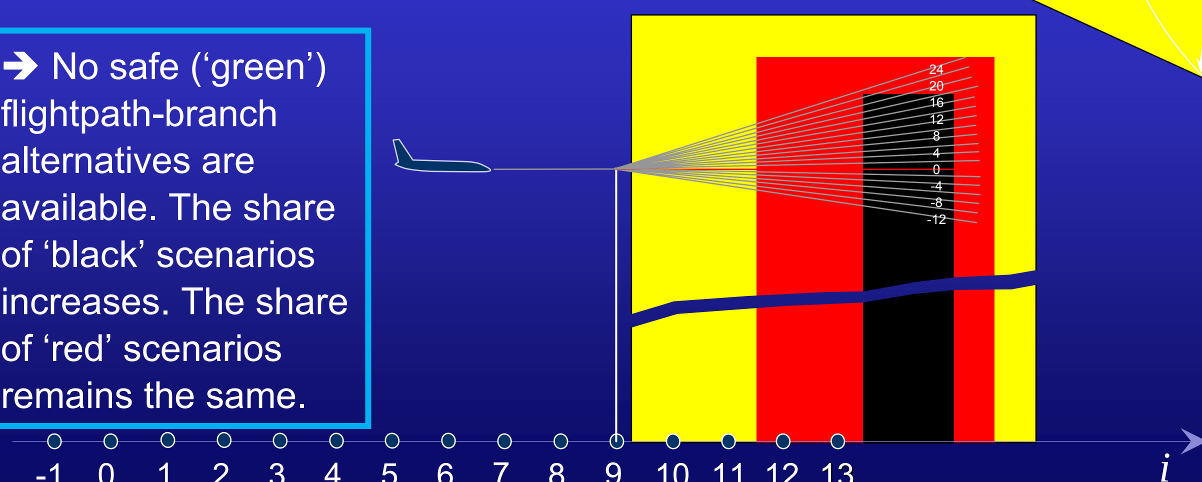


Safety Chances Distribution





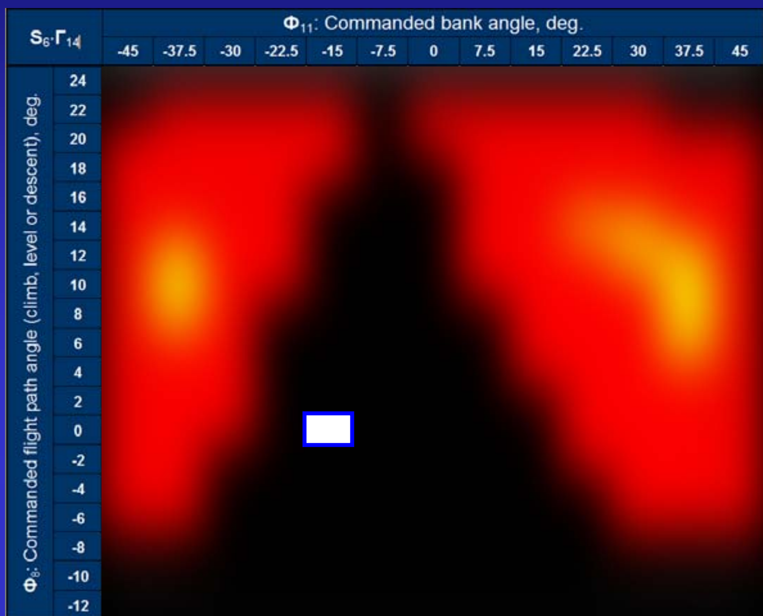
➔ No safe ('green') flightpath-branch alternatives are available. The share of 'black' scenarios increases. The share of 'red' scenarios remains the same.



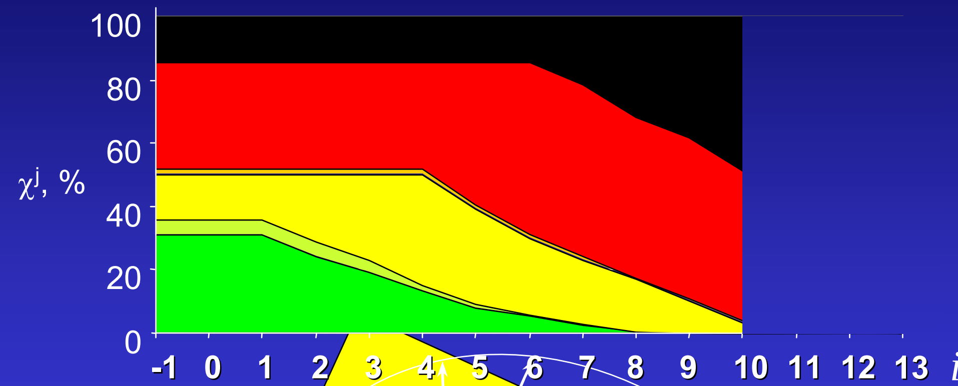
$S_\downarrow$: Imminent Collision (t_{10})

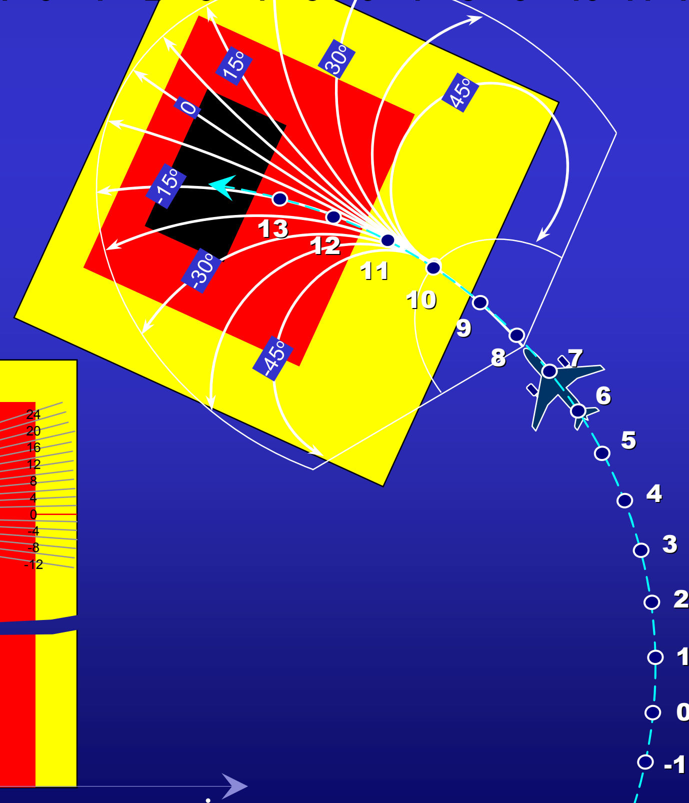
INTELONICS

Safety Window

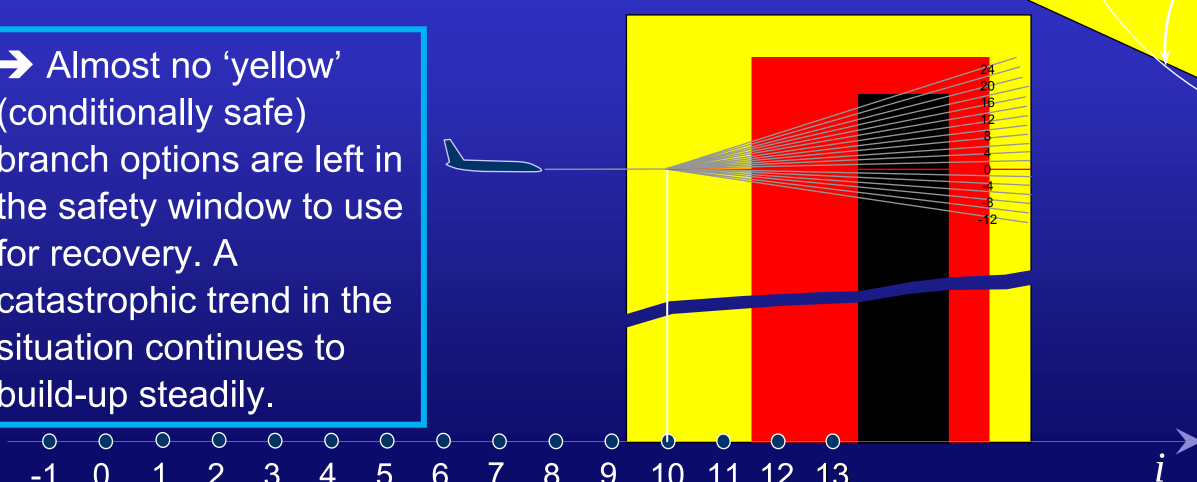


Safety Chances Distribution



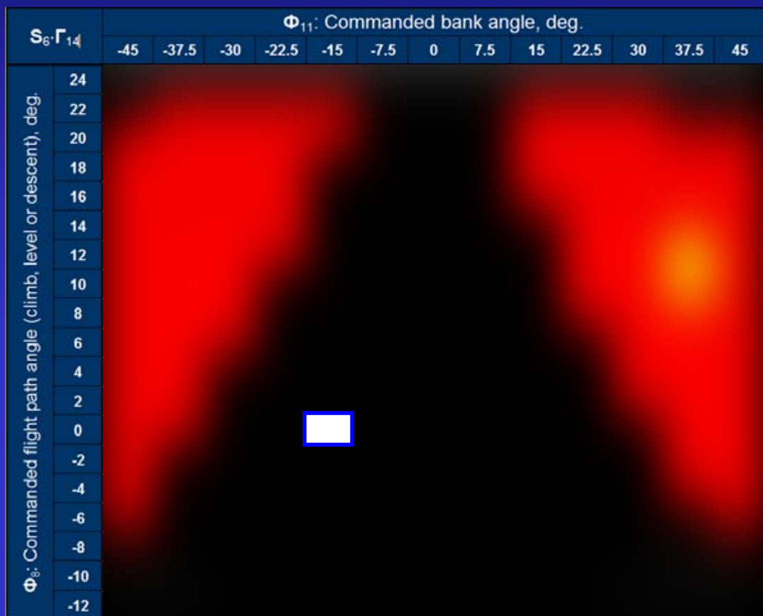


➔ Almost no 'yellow' (conditionally safe) branch options are left in the safety window to use for recovery. A catastrophic trend in the situation continues to build-up steadily.

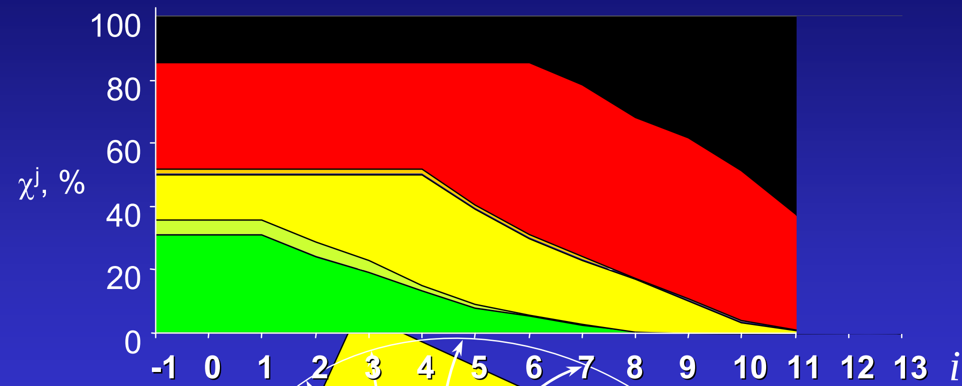


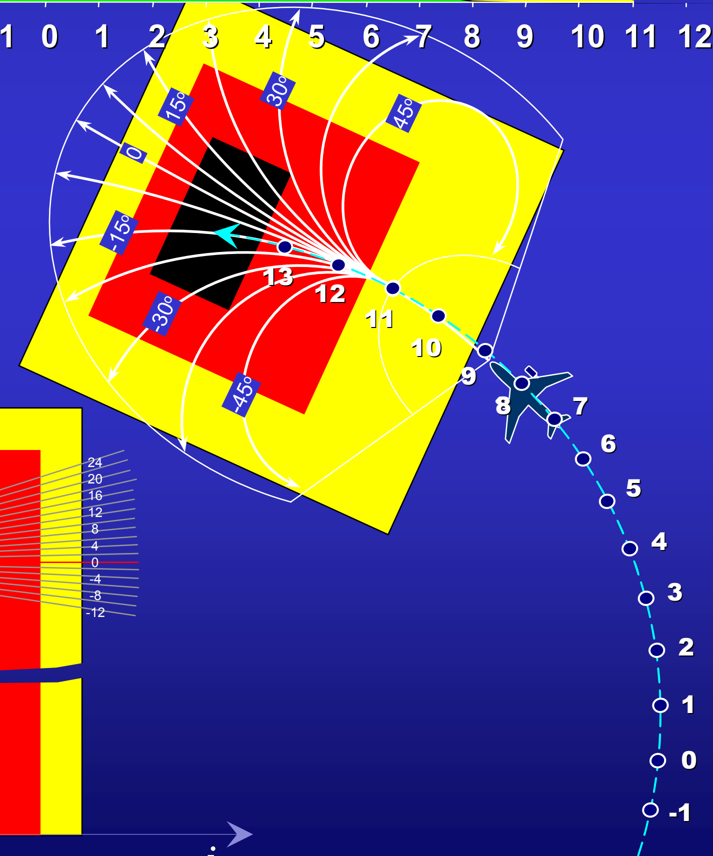
S↓: Imminent Collision (t_{11})

Safety Window

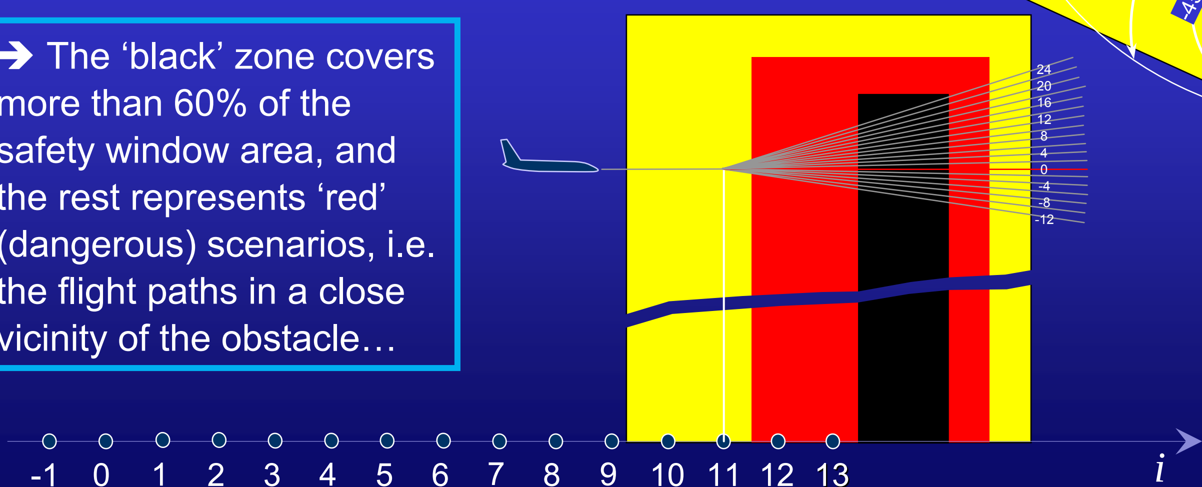


Safety Chances Distribution





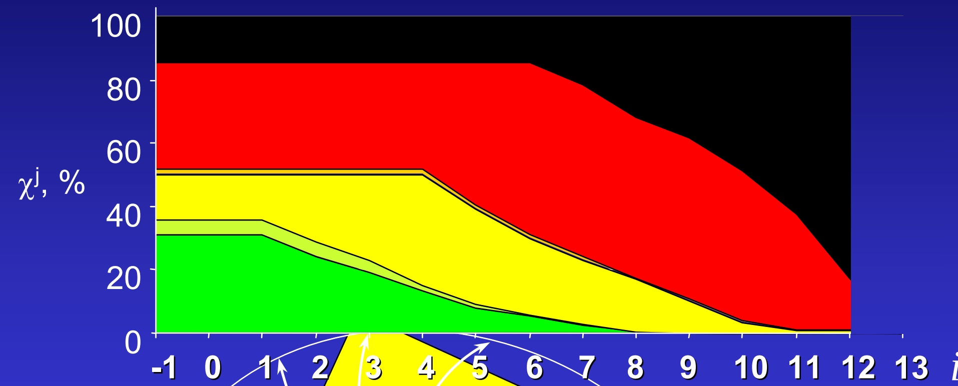
➔ The ‘black’ zone covers more than 60% of the safety window area, and the rest represents ‘red’ (dangerous) scenarios, i.e. the flight paths in a close vicinity of the obstacle…

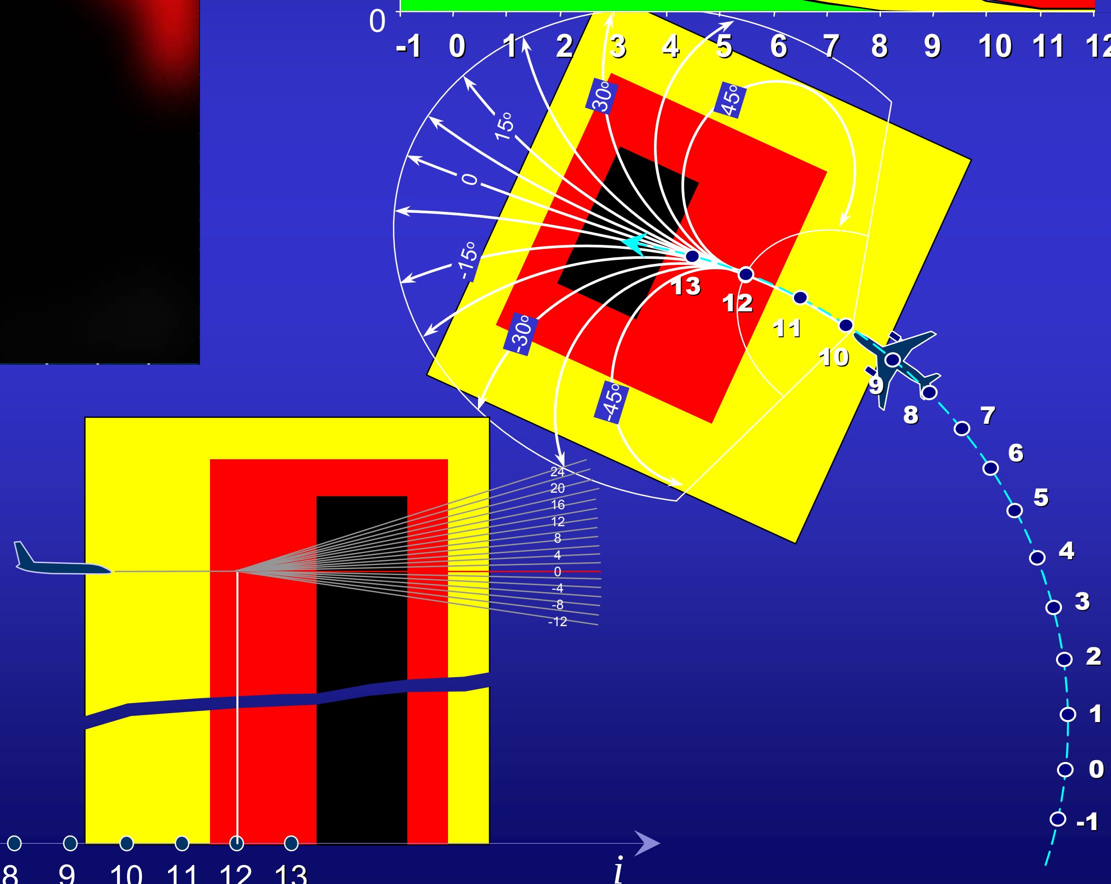


S↓: Imminent Collision (t_{12})

Safety Window

Safety Chances Distribution

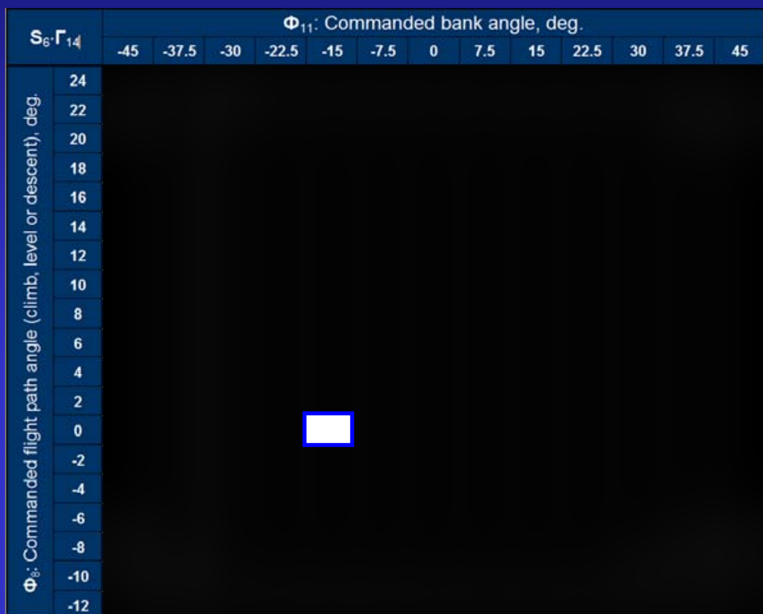




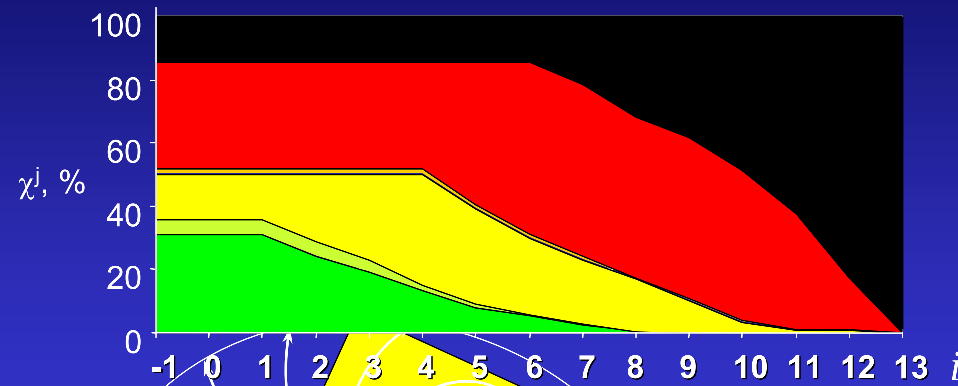
➔ The 'black' zone occupies more than 80% of the safety window area. A catastrophic trend accelerates, and the chances of collision are very high.

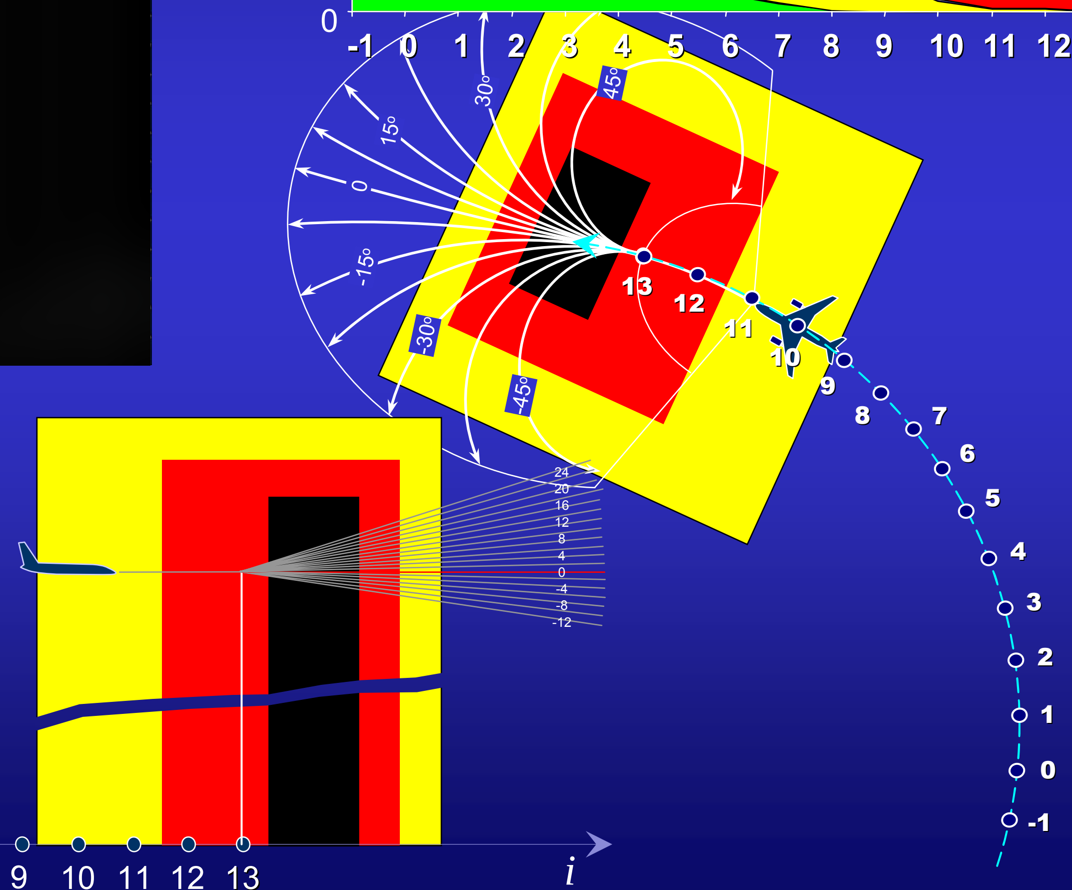
S↓: Imminent Collision (t_{13})

Safety Window



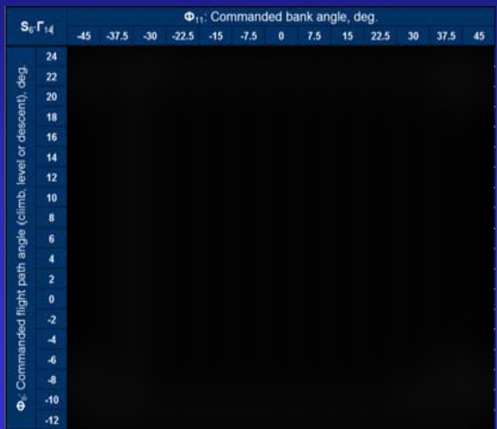
Safety Chances Distribution



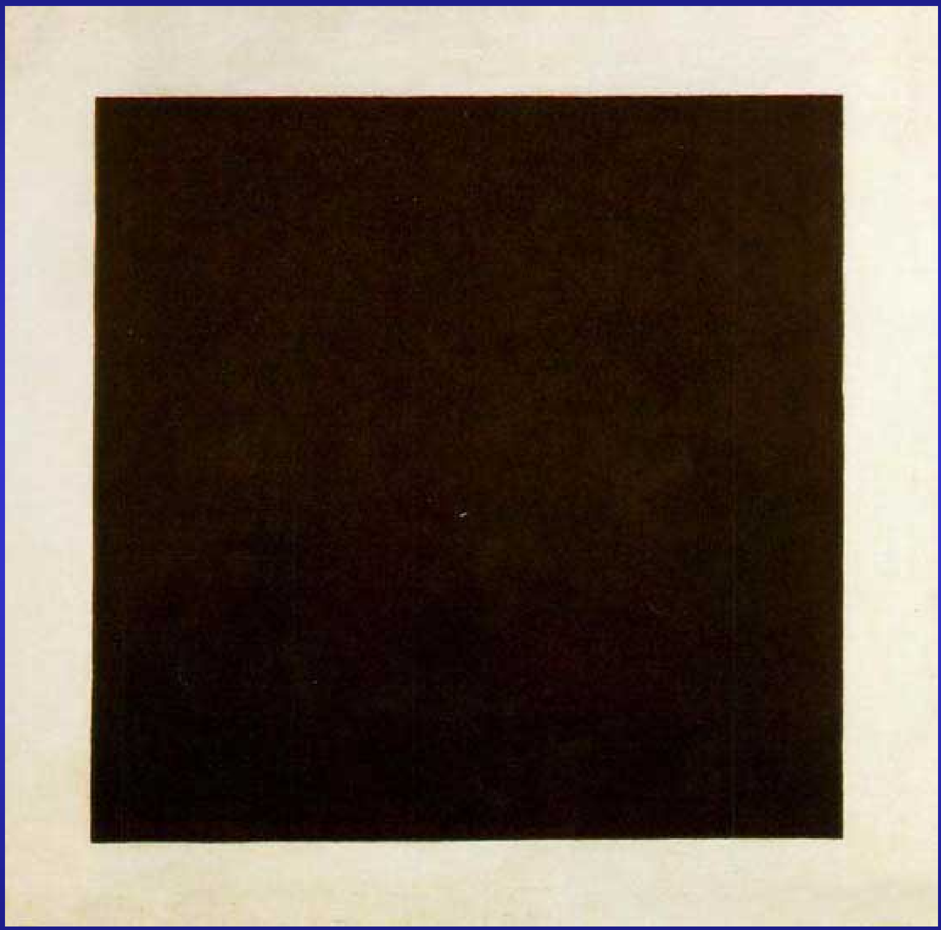


➔ The 'black' zone now occupies the entire safety window's area (100%). This means that the collision is unavoidable…

Kazimir Malevich's 'The Black Square' Painting and '9/11'



➔ The safety window state just before collision point ($\mathbf{S}_{\downarrow} \mid t_{13}$), perhaps, helps better understand the meaning of Kazimir Malevich's painting 'The Black Square' - The fatal end is imminent. And there is no chance left to remedy the situation …

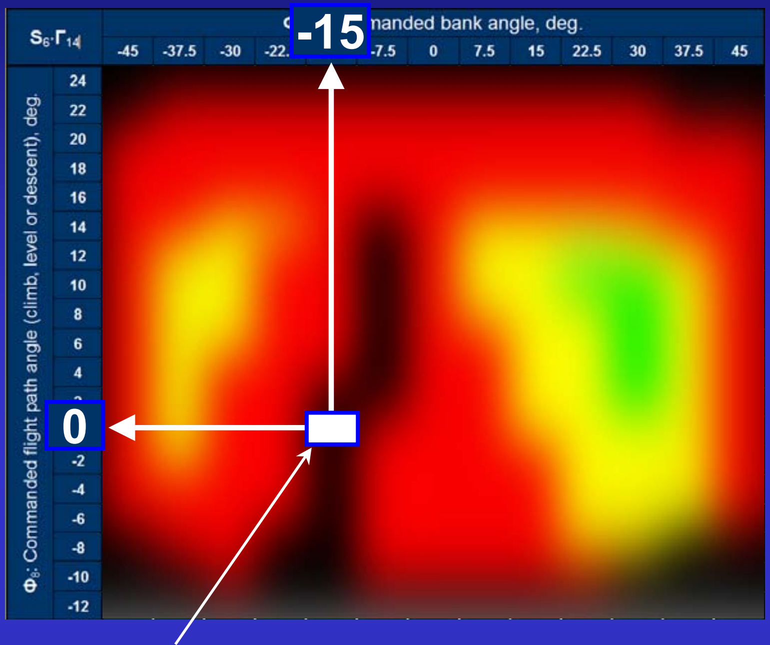


K. Malevich. 'The Black Square' (1913)

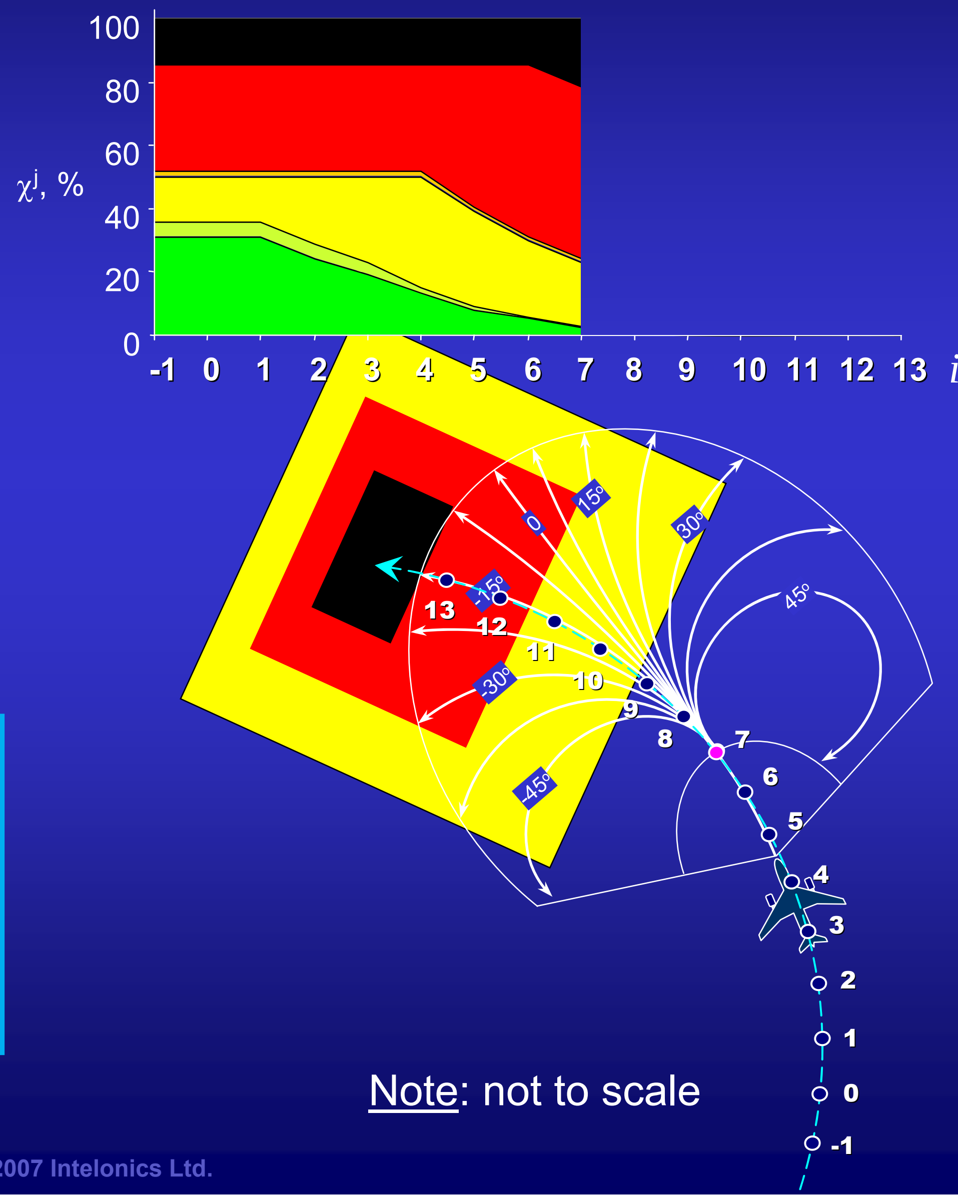
‘Last Chance for Recovery’ Point ($t_{\uparrow} \equiv t_7$)

INTELONICS

Safety Window



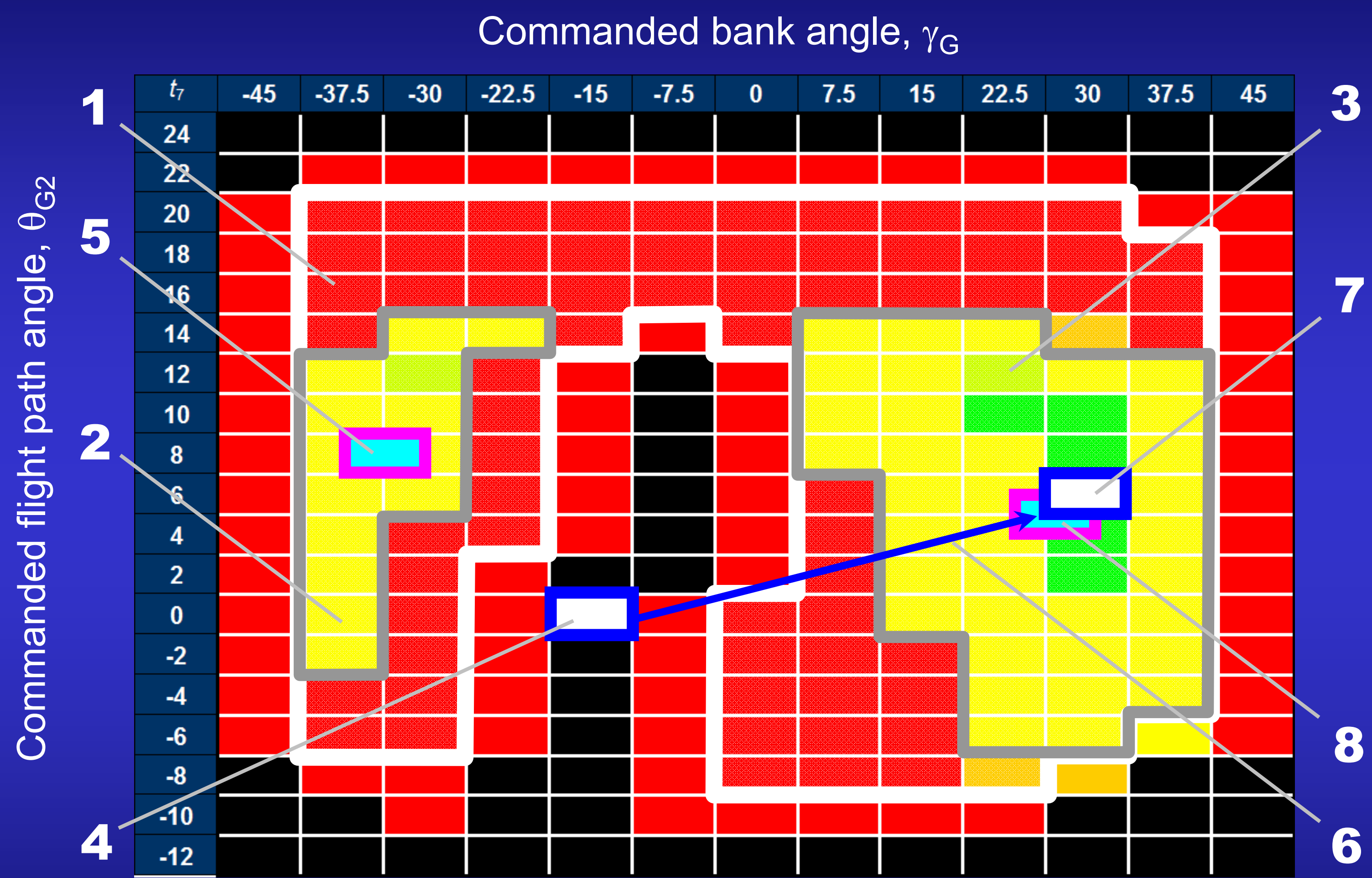
Safety Chances Distribution



➔ However, the ‘last chance for recovery’ point ($t_{\uparrow}$) does exist, and it must be assigned to t_7. This is marked by the system state when the new ‘black’ zone (induced by the obstacle) in the safety window first time overlaps with the current tactical goal-cell of the operator’s flight control.

INTELONICS

Safety Window State at 'Last Chance For Recovery' Point ($t_{\uparrow} \equiv t_7$): $S_0 \rightarrow S_{\uparrow}$

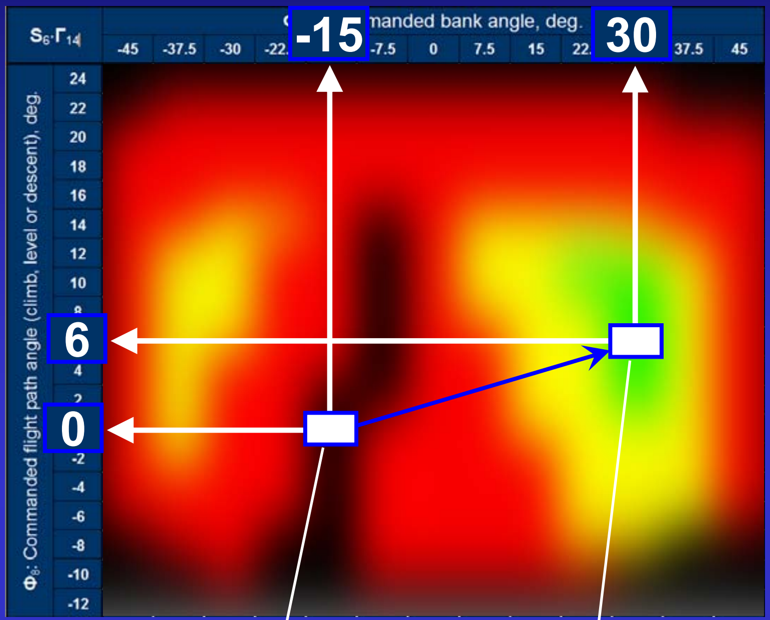


$\Delta\Phi \equiv (\Delta\theta_{G2}, \Delta\gamma_G) = (2^o, 7.5^o)$

Legend: **1** – zone of ΔΦ-secured non-catastrophic scenarios; **2**, **3** – zones ('islands') of remaining safe/conditionally safe scenarios; **5**, **8** – 'C.G.' locations for left- and right-hand 'islands' of remaining safe/conditionally safe scenarios; **4**, **7** – old (catastrophe-prone) and new (safety restoring) cells of the commanded flight path and bank angles, **6** – required shift of the tactical flight goal-cell in the safety window.

$S_0 \rightarrow S_\uparrow$: Self-Preservation Automatic Decision Making at $t_7 \equiv t_\uparrow$

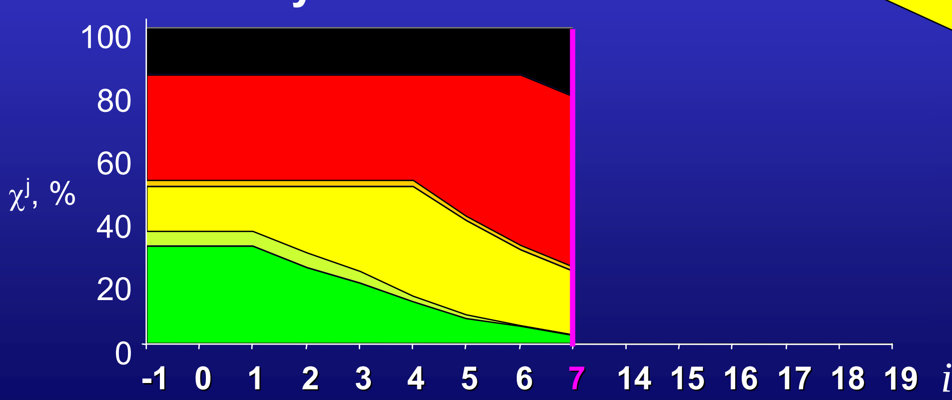
Safety Window

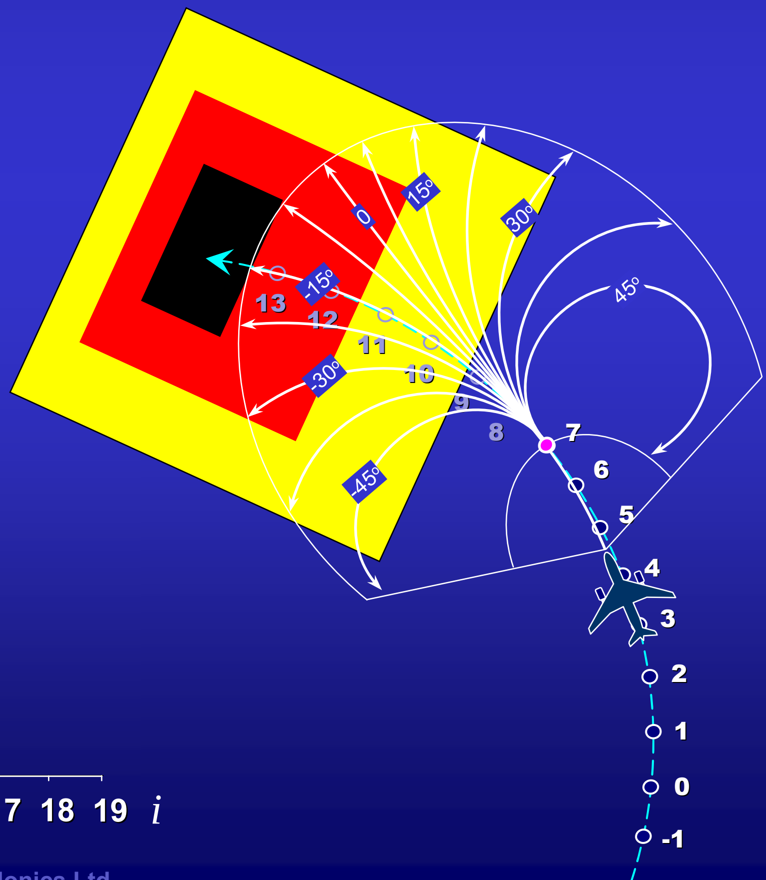


old tactical goal-cell   new tactical goal-cell

→ Based on results of safety 'topology' analysis at t_7, a self-preservation decision must be made - the current tactical control goal is shifted from the old ('black', collision-prone) cell, (θ_{G2}/γ_G) = (0/-15°), to a new ('green', safe) cell, (θ_{G2}/γ_G) = (6°/+30°), located in the right-hand 'safety island' of the window.

Safety Chances Distribution

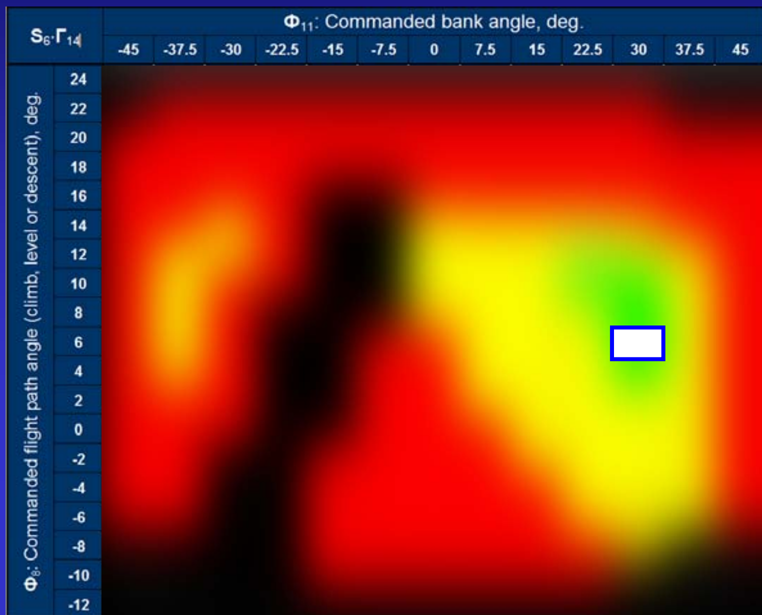




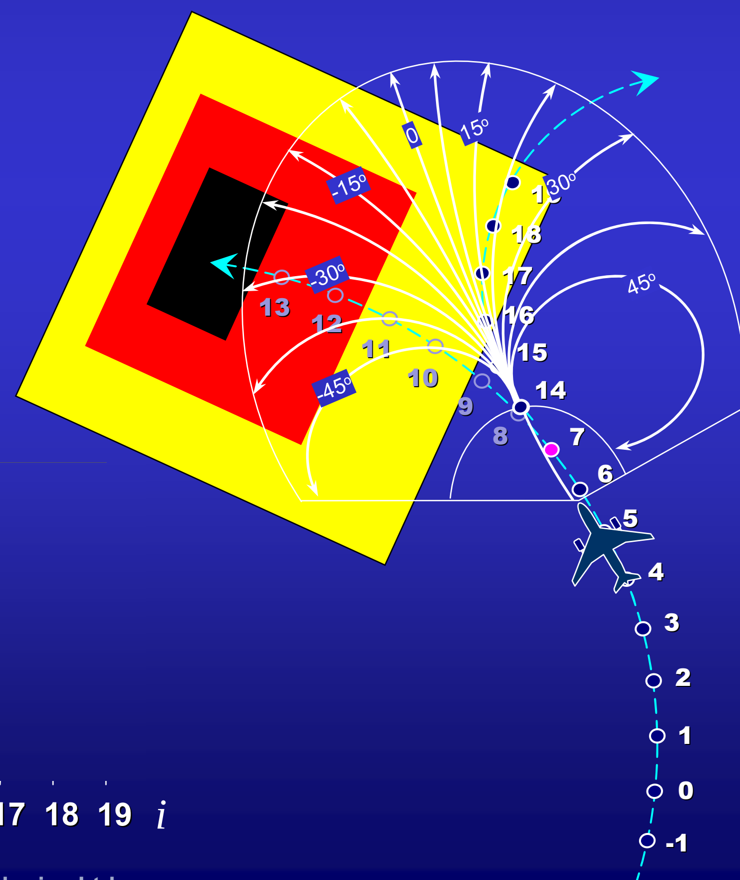
$S_{\uparrow}$: Collision Avoidance (t_{14})

INTELONICS

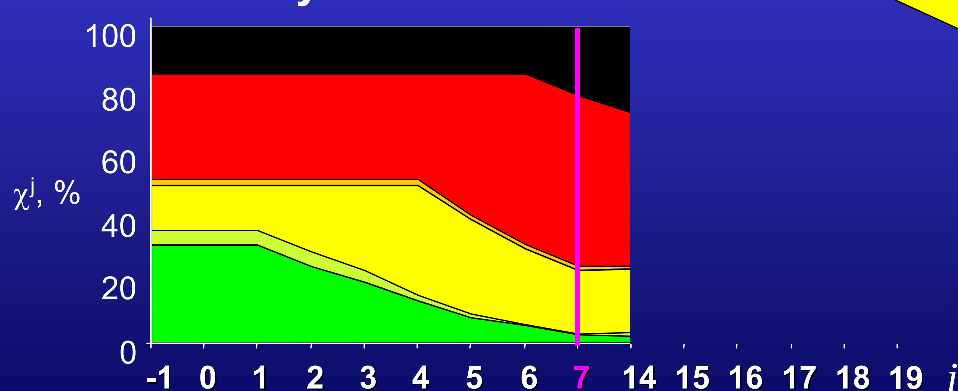
Safety Window



➔ The 'black' zone in the safety window is still expanding (due to vehicle dynamics lag). However, the 'red' zone begins to shrink, and the 'yellow' zone size remains unchanged. The commanded (tactical goal) cell is now located outside the danger and catastrophe-prone zones.



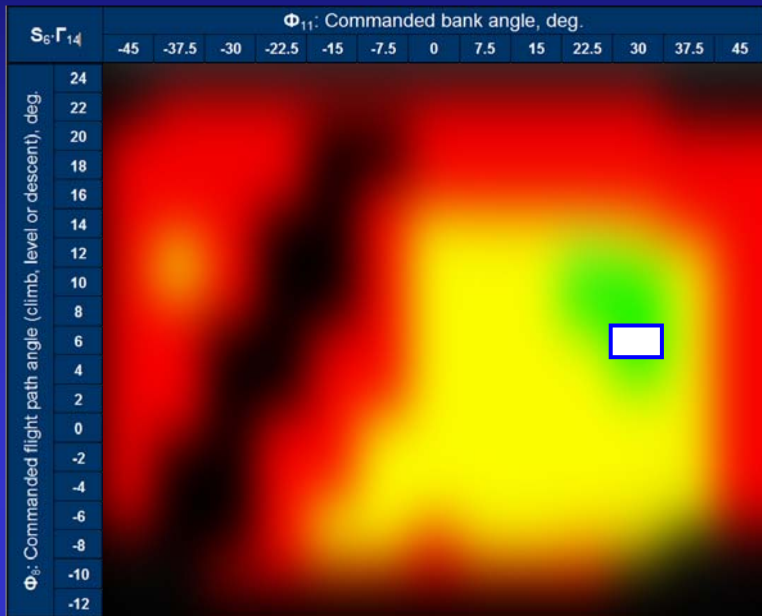
Safety Chances Distribution



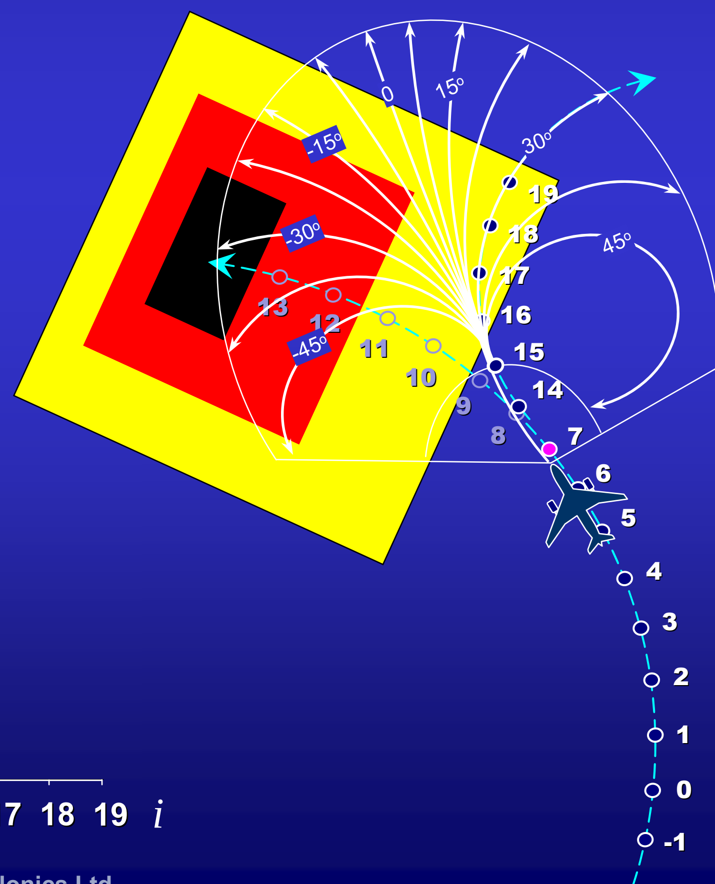
$S_{\uparrow}$: Collision Avoidance (t_{15})

INTELONICS

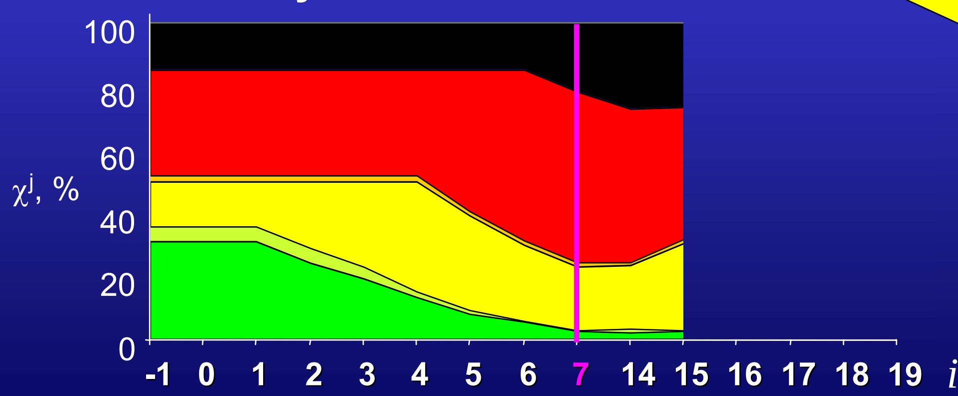
Safety Window



➔ A positive (recovery) safety trend begins to develop. The 'yellow' zone is expanding, and the 'red' zone is shrinking in the safety window.



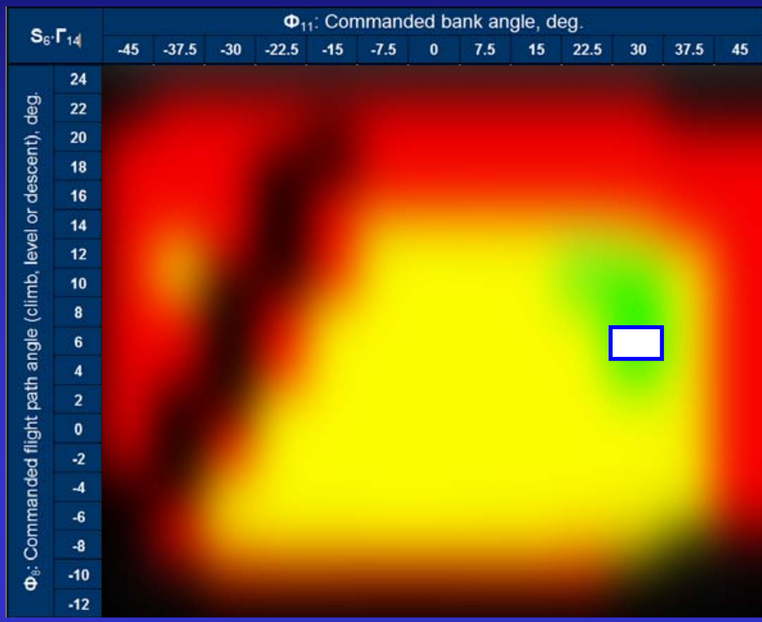
Safety Chances Distribution



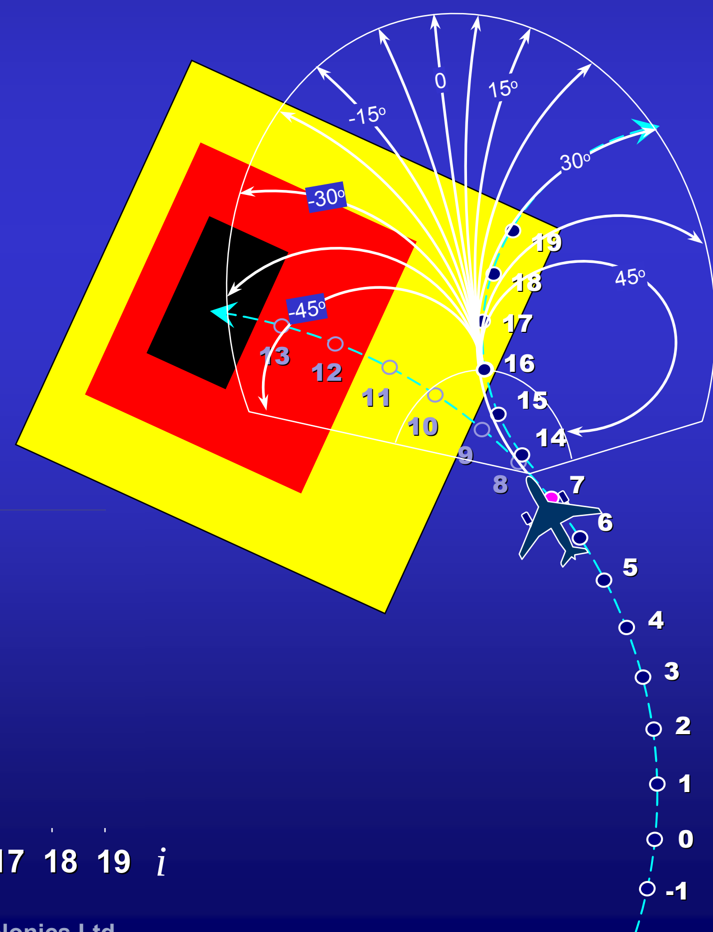
INTELONICS

$S_{\uparrow}$: Collision Avoidance (t_{16})

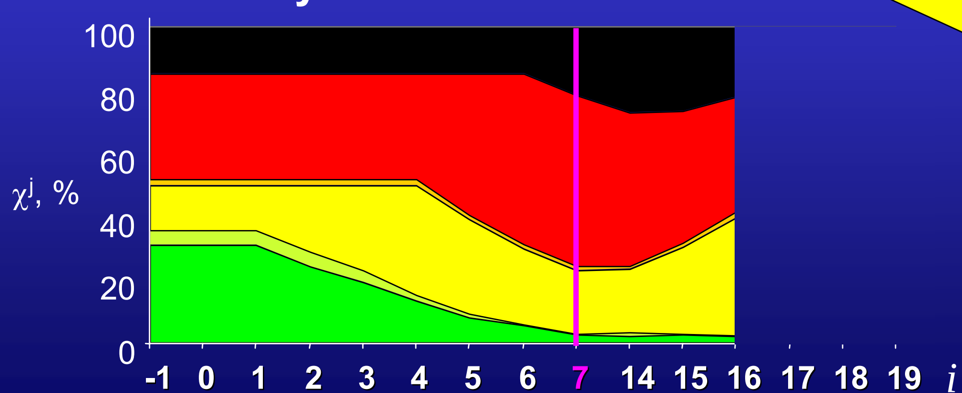
Safety Window



➔ Positive safety trend remains steady. The 'yellow' zone is expanding, and the 'red' zone is shrinking. The 'black' zone begins to shrink as well …

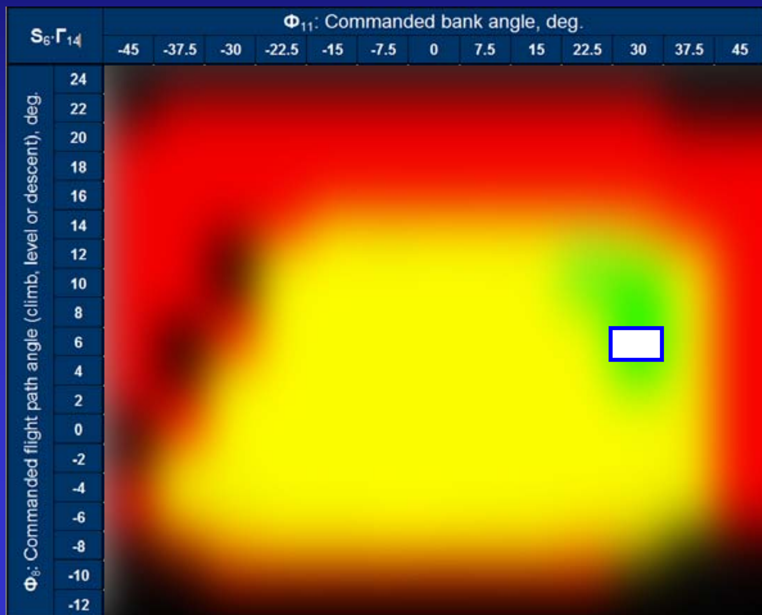


Safety Chances Distribution

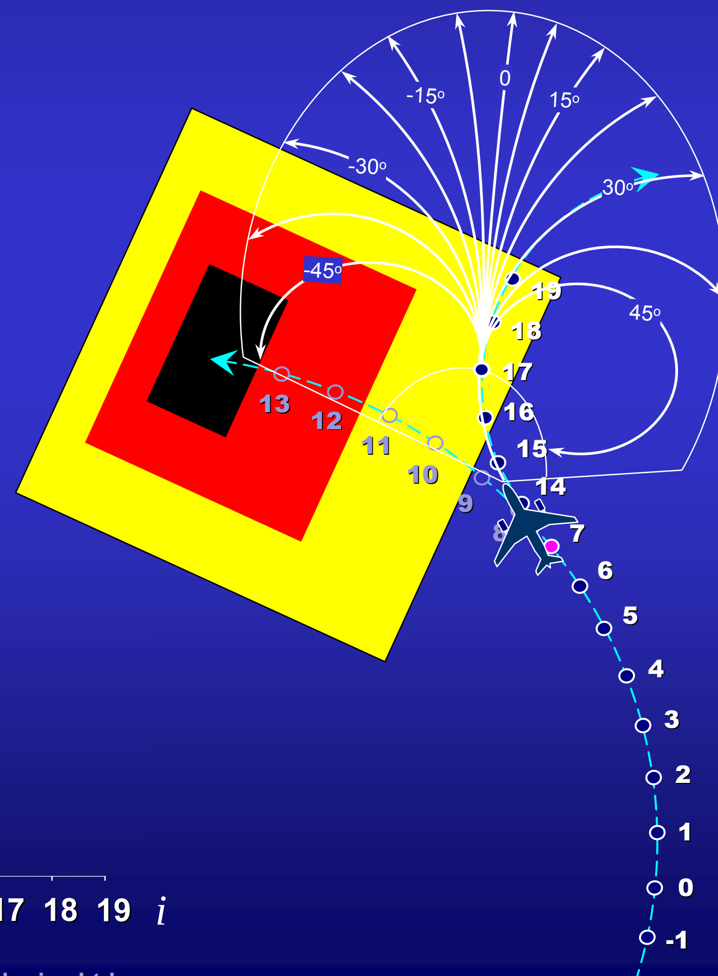


$S_{\uparrow}$: Collision Avoidance (t_{17})

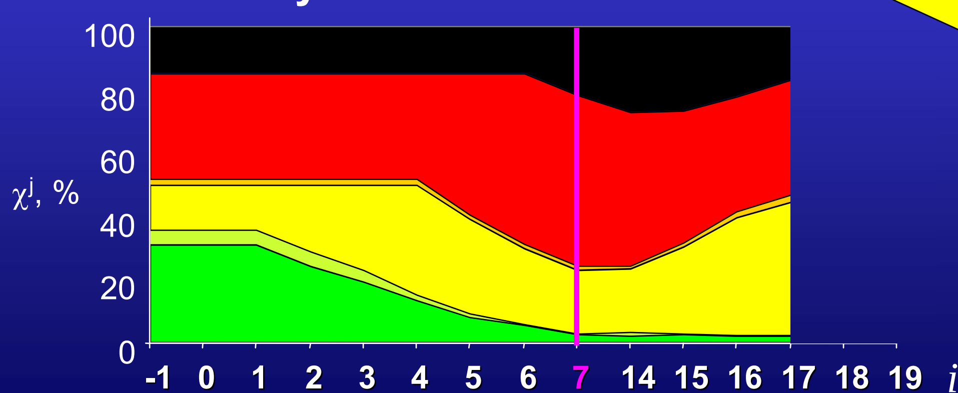
Safety Window



➔ 'Black' zone induced by the obstacle is about to disappear. Positive safety trend is now irreversible. The 'yellow' zone continues to expand.

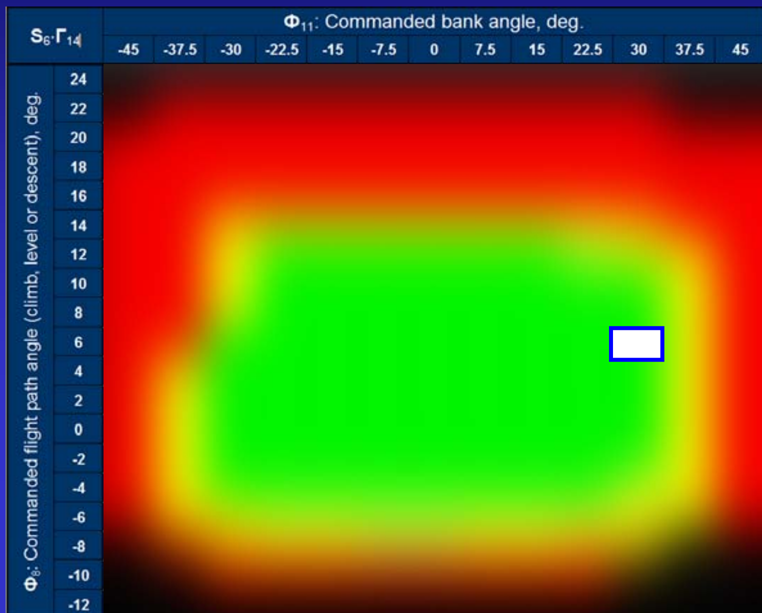


Safety Chances Distribution

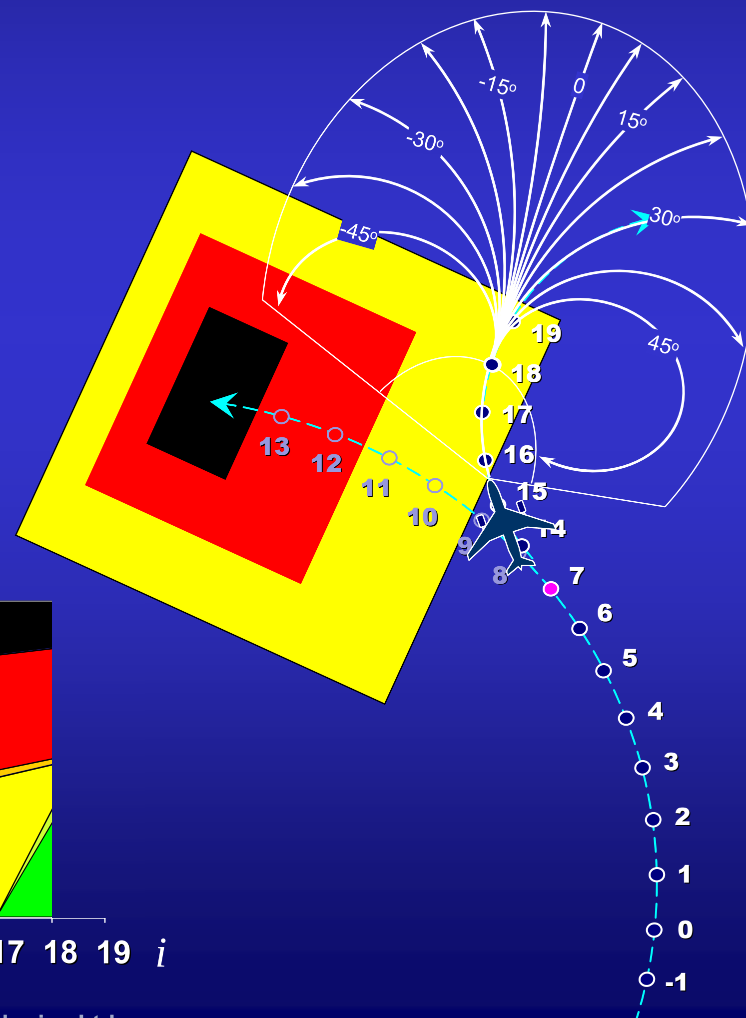


$S_{\uparrow}$: Collision Avoidance (t_{18})

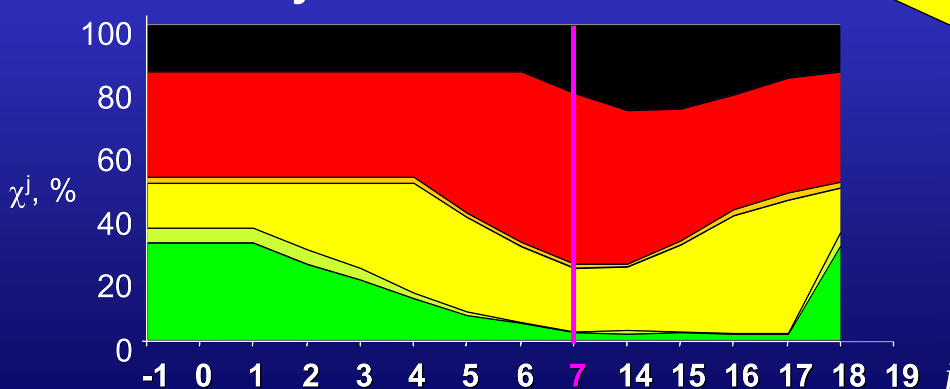
Safety Window



➔ The safety window is about to resume its initial state (vehicle's performance only) as the obstacle (a tower type building) has been safely avoided.



Safety Chances Distribution



$S_{\uparrow}$: Collision Avoidance (t_{19})

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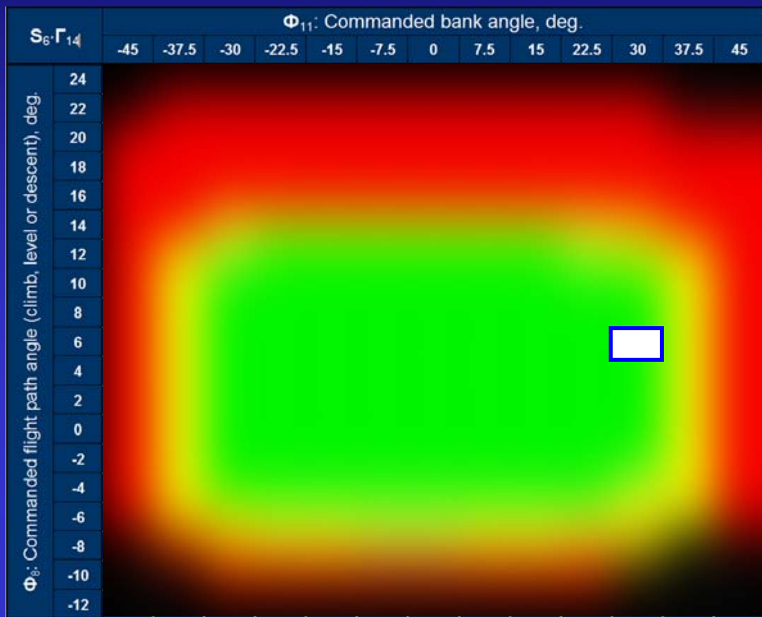
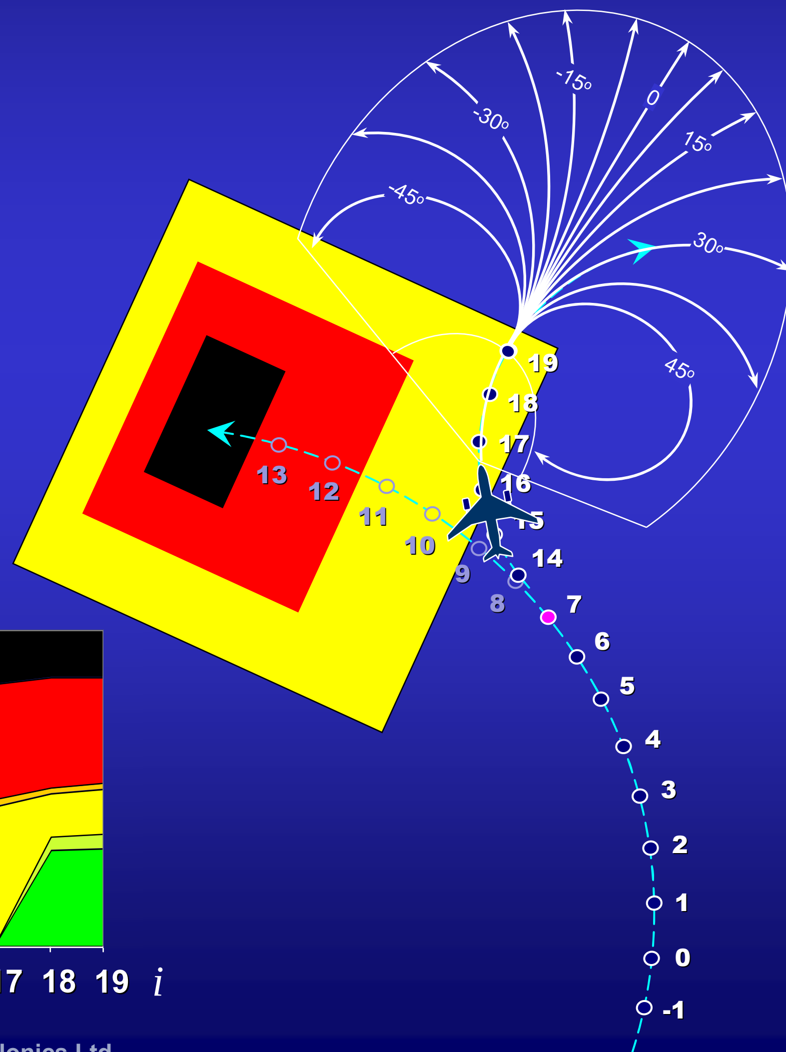
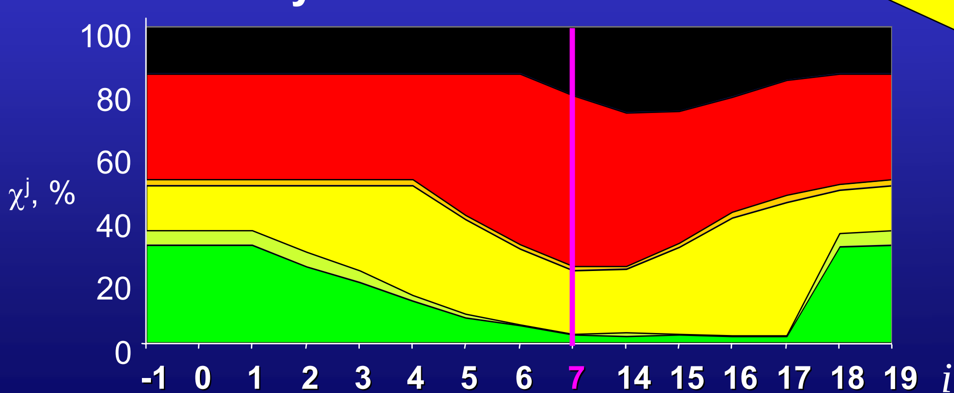
Safety Window



➔ The knowledge-centered process of flight safety restoration is complete by now.



Safety Chances Distribution



‘Bird’s Eye’ View Of Dynamic Safety Window Tree: Catastrophic and Recovery Scenarios

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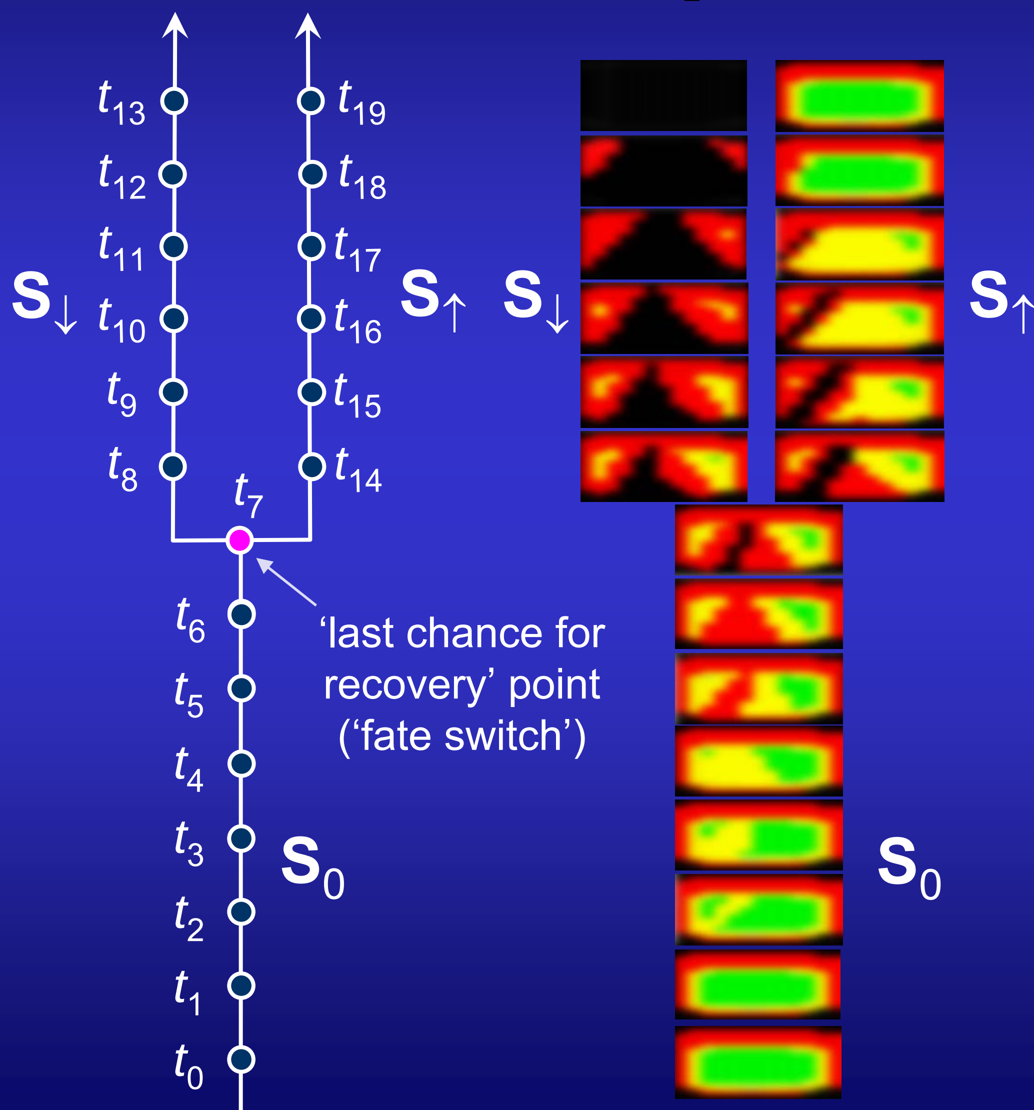

➔ This is a safety window time-history tree. It provides a systematic – ‘bird’s eye’ view level – picture of two alternative scenarios of aircraft flight control in the presence of an urban type obstacle. Such obstacles can be a part of a multi-factor flight situation domain-‘neighborhood’ of the current situation.

Legend:

Scenario segments:

- S_0 – obstacle approach
- $S_\downarrow$ – imminent collision
- $S_\uparrow$ – AI based collision avoidance

Scenario time lines:

- $\{t_0, t_1, \ldots, t_7\}$ – S_0
- $\{t_8, \ldots, t_{13}\}$ – $S_\downarrow$
- $\{t_{14}, \ldots, t_{19}\}$ – $S_\uparrow$

Key time instants:

- t_7 – ‘last chance for recovery’
- t_{13} – ‘just before impact’
- t_{19} – ‘safety restoration complete’

Safety Chances Distribution Time-History for Two Control Tactics

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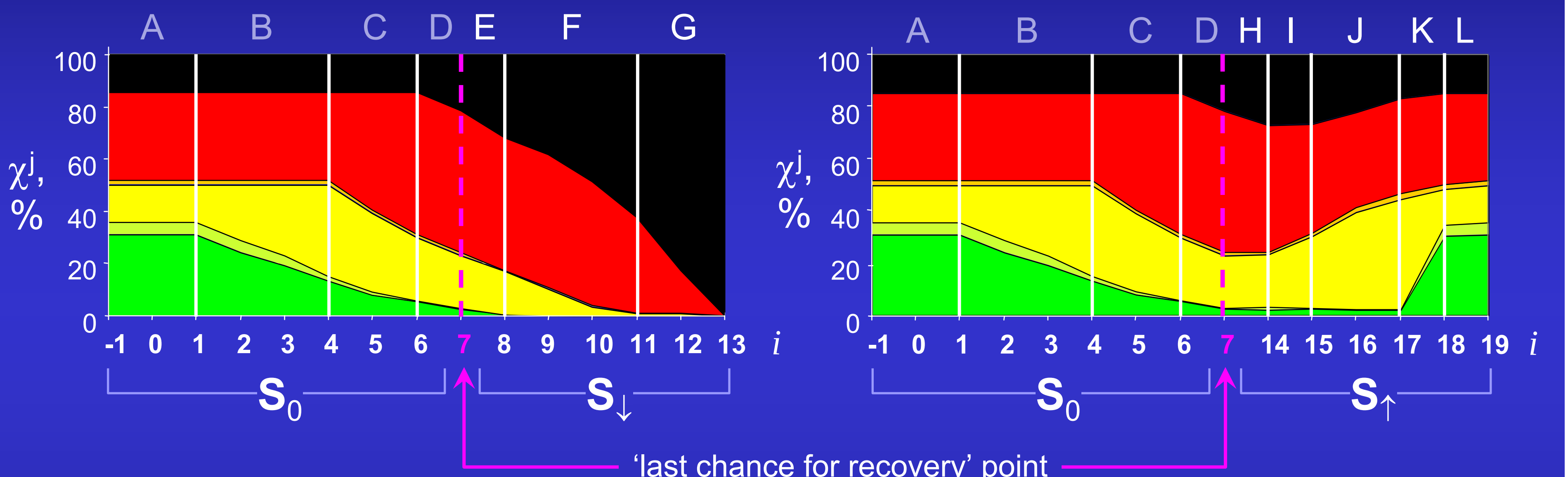
(1) terrorist-/ fool-type control **(2) AI based self-preservation control**



<u>Legend</u>: A, B, …, L - characteristic states of the aircraft safety dynamics; χ^j – flight safety chances at ξ^j level, j∈{**I**, **II-a**, **II-b**, **III**, **IV**, **V**}; t_i – time instants, $i \in$ {-1, 0, 1, …, 13} ∨ $i \in$ {-1, 0, 1, …, 7, 14, 15, .., 19}.

I | **II-a** | **II-b** | **III** | **IV** | **V** – safety classification categories and colors

➔ Characteristic states {A, B, C, …, L} of the vehicle's safety dynamics and their recognition criteria are expedient to use in the automatic or manual recovery decision-making process in emergency situations under uncertainty. In accordance with the self-preservation imperative for a civil aircraft, flight control authority in a life-threatening situation must be dynamically assigned/transferred to a most competent agent.

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Conclusions

1. Generalized knowledge-centered methodology has been developed for UAV flight safety prediction and protection in multifactor situations near operational constraints.

2. Method's advantages are: use of integrated conceptual framework, simple real-time calculations, open memory-based knowledge system, situation-independent decision-making algorithm, exploration of situation 'what-if neighborhood' tree for short-term flight path probing, use of 'bird's eye' view 'topology maps' for flight safety status monitoring and automatic recovery in emergencies.

3. However, prerequisites for successful implementation of developed methodology are:
   - ➔ availability of vehicle's validated 'parametric definition' database, and
   - ➔ onboard integrated sensor suit capable of detecting potentially dangerous physical/ virtual obstacles inside vehicle's 'safety ellipsoid/cone'.

4. Potential application areas are as follows:
   - ➔ design of affordable, yet expert pilot level AI safety protection systems based on self-preservation imperative for unmanned/ manned air vehicles to prevent key accident/ incident scenarios such as LOC, CFIT, 'pilot error', hardware failure, mid-air collision, and '9/11'
   - ➔ design of adaptive mission control and autonomous collision avoidance systems (integrated with C.Reynolds swarming model, ethology principles, etc.) for heterogeneous multivehicle clusters and free-flight operations.

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Thank You

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Questions, please …

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2. Burdun, I.Y., "Studying Physics and Logics of Complex Flight Situation Domains by Means of VATES Modeling and Simulation Tool", *Proc. of 2nd Science and Technology Conference "Flight Simulation Technologies and Pilot Training: New Approaches and Goals", TsAGI, 24 – 25 April 2003, Zhoukovsky, Moscow Region,* TsAGI, 2003, 11 pp. (in Russian).
3. Burdun, I.Y., Parfentyev, O.M., "Fuzzy Situational Tree-Networks for Intelligent Flight Support", *Int. Journal of Engineering Applications of Artificial Intelligence (EAAI)*, 12 (1999), pp. 523 – 541.
4. Schrage, D.P., Calise, A.J., Burdun, I.Y., Pritchett, A., and Rysdyk, R.T., "An Integrated Knowledge-Based Approach to Improving Aircraft Safety", *White Paper*, School of Aerospace Engineering, Georgia Tech, USA, Oct. 1998, 20 pp.
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8. Burdun, I.Y., and Burdun, E.I., 'VATES – Virtual Autonomous Test and Evaluation Simulator' (Version 7 – Professional), User's Manual, 2000, 155 pp.
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11. Burdun, I.Y., "C.Reynolds Model of Motion Self-Organization and Some Issues of Application of Highly-Maneuverable Highly-Autonomous Unmanned Air Vehicles", *Proc.of XVI TsAGI Workshop "Aerodynamics of Aircraft", 3 – 4 March 2005, Volodarsky, Moscow Region*, TsAGI, 2005, pp. 28 – 29 (in Russian).