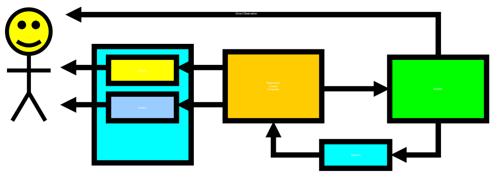
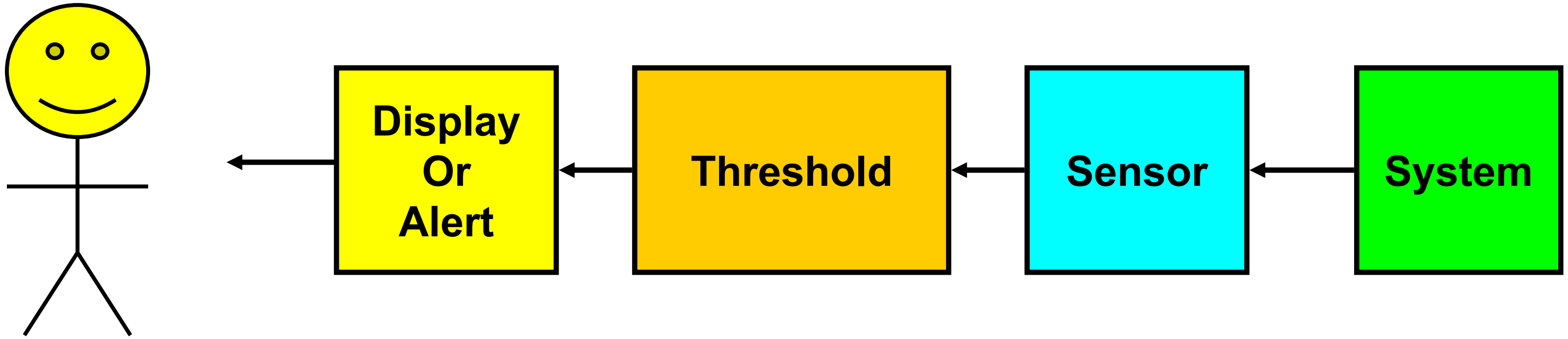
16.422 Alerting Systems

Prof. R. John Hansman

Acknowledgements to Jim Kuchar

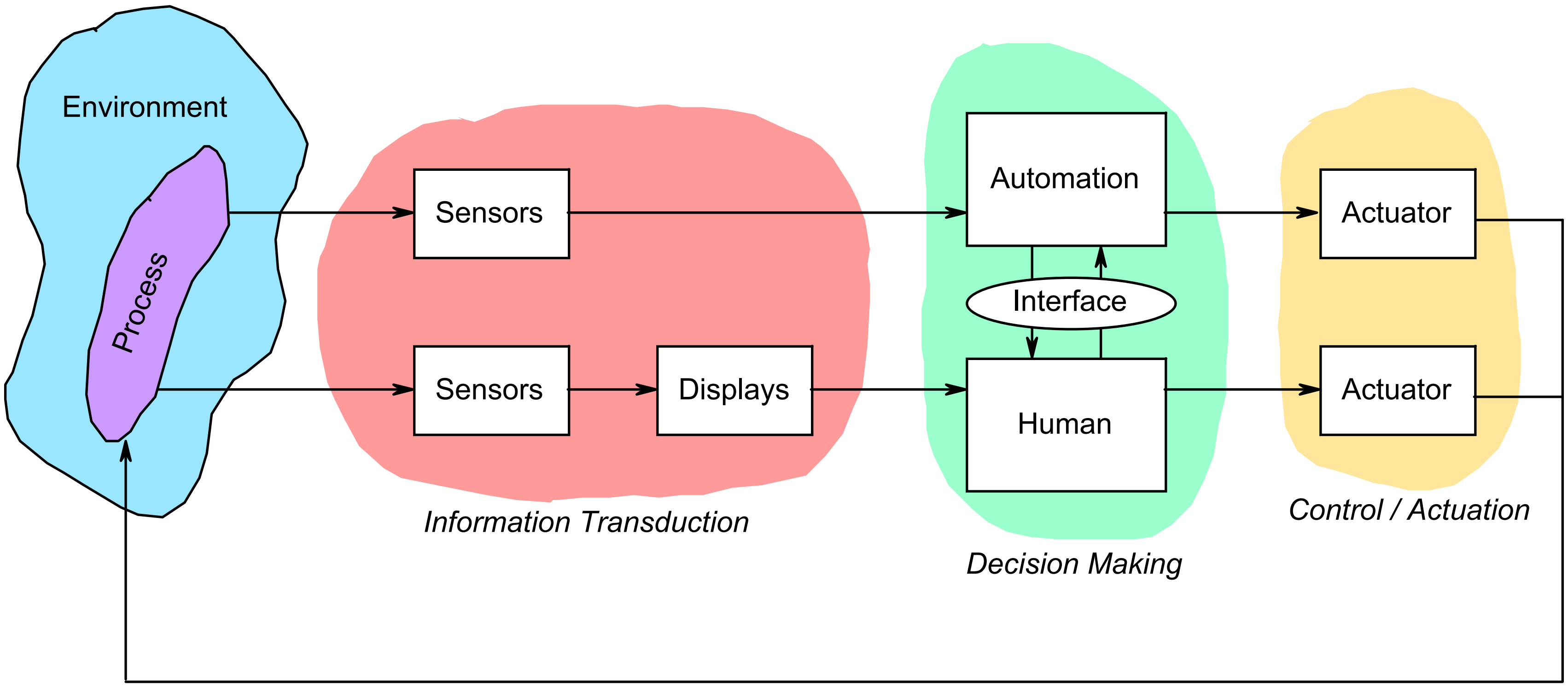


Consider Sensor System



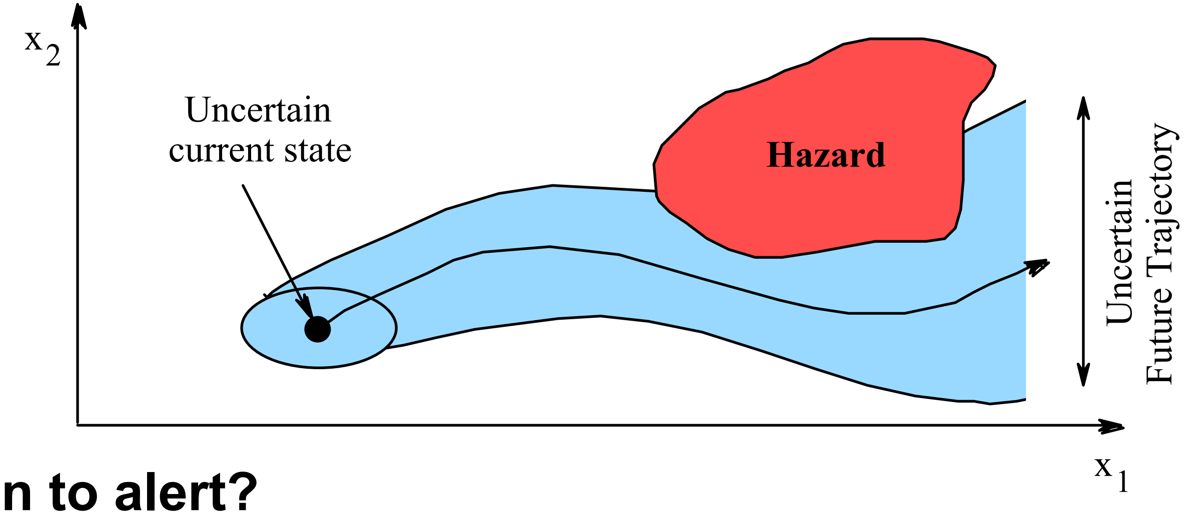
- Radar
- Engine Fire Detection
- Other

Decision-Aiding / Alerting System Architecture



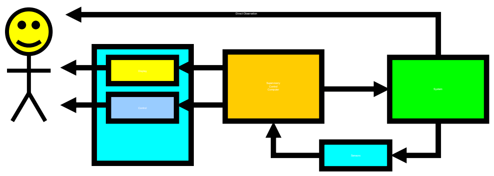
Courtesy: Jim Kuchar

Fundamental Tradeoff in Alerting Decisions



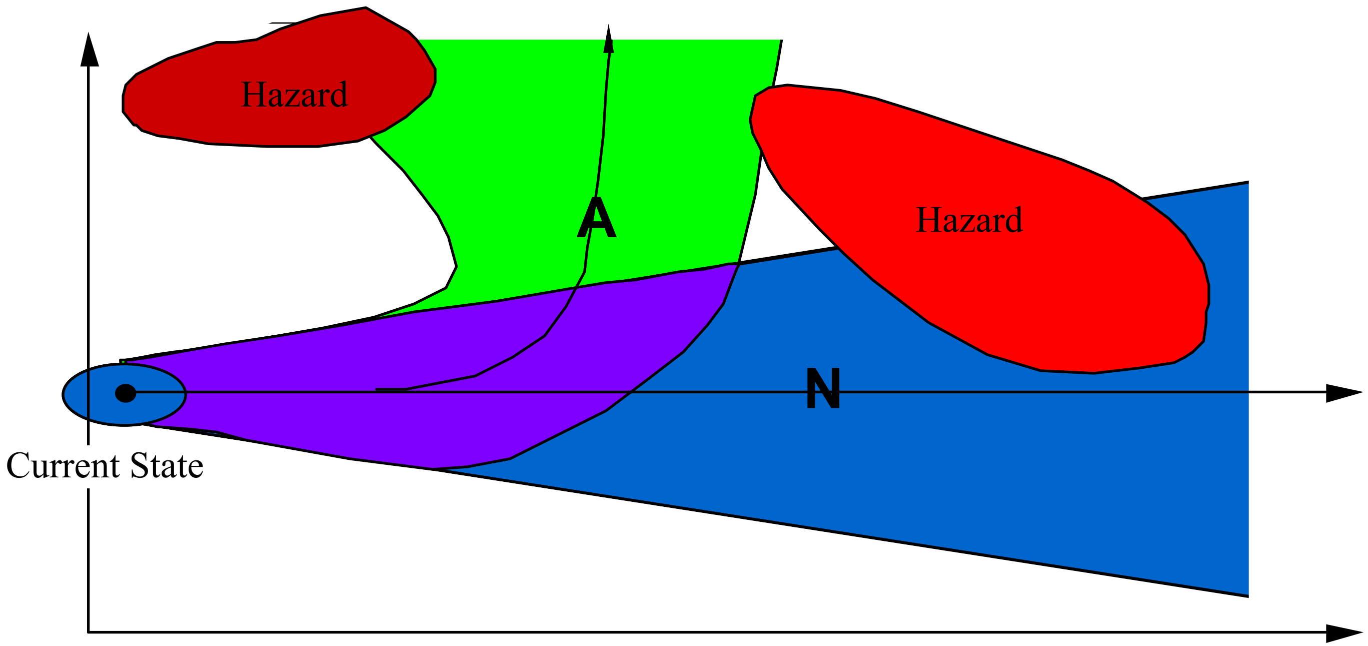
- **When to alert?**
  - ☐ Too early → Unnecessary Alert
    - ◆ Operator would have avoided hazard without alert
    - ◆ Leads to distrust of system, delayed response
  - ☐ Too late → Missed Detection
    - ◆ Incident occurs even with the alerting system
- **Must balance Unnecessary Alerts and Missed Detections**

Courtesy: Jim Kuchar



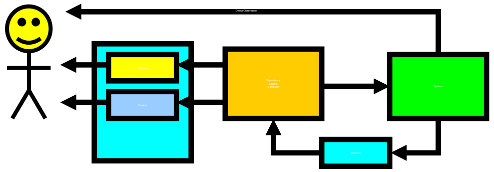
The Alerting Decision

- **Examine consequences of alerting / not alerting**
  - ☐ Alert is not issued: Nominal Trajectory (N)
  - ☐ Alert is issued: Avoidance Trajectory (A)

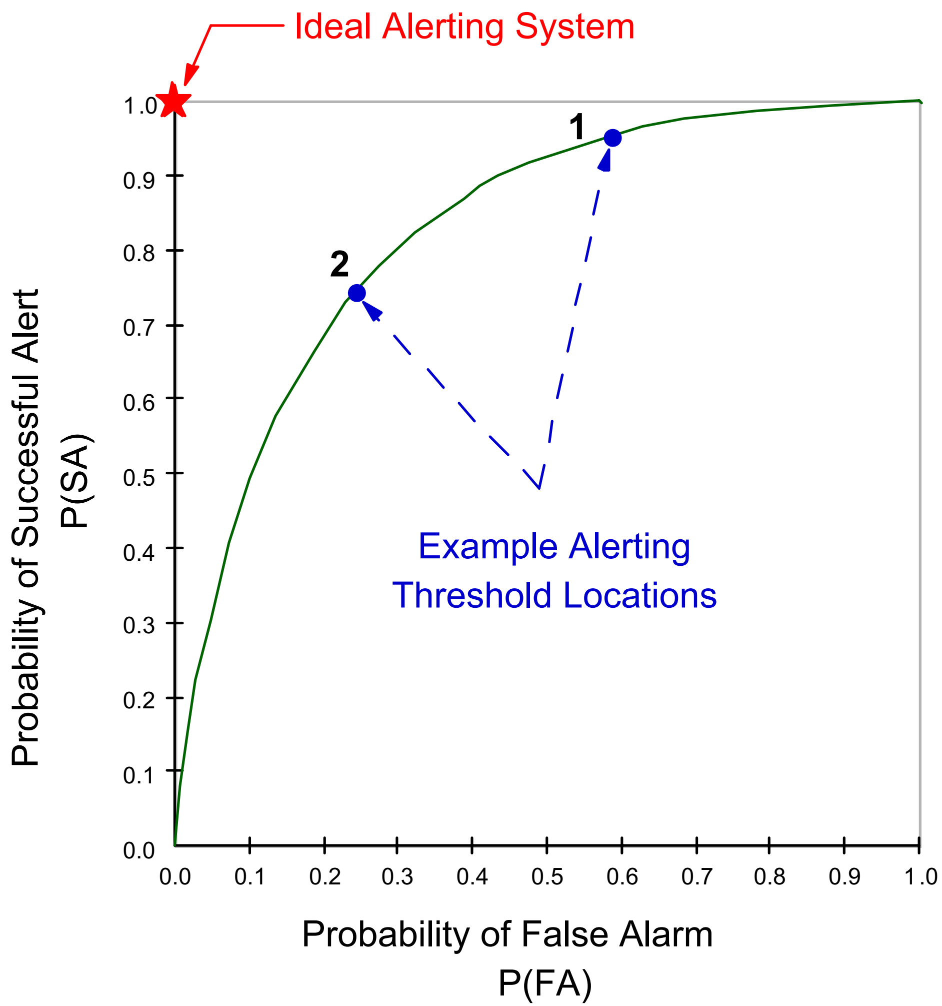


Compute probability of Incident along each trajectory

Courtesy: Jim Kuchar



Threshold Placement



Courtesy: Jim Kuchar

Threshold Placement

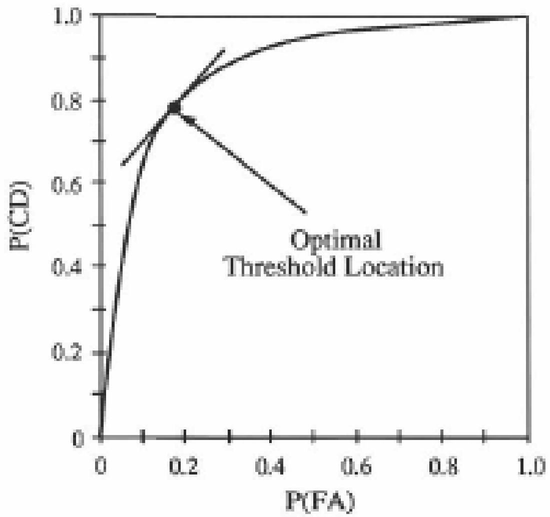
- **Use specified P(FA) or P(MD)**
- **Alerting Cost Function: Define C_{FA}, C_{MD} as alert decision costs**

$$\begin{aligned} J &= P(FA)\, C_{FA} + P(MD)\, C_{MD} \\ &= P(FA)\, C_{FA} + (1 - P(CD))\, C_{MD} \end{aligned}$$

Minimize Cost:

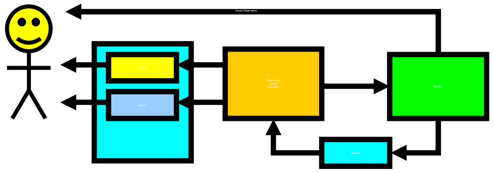
$$dJ = dP(FA)\, C_{FA} - dP(CD)\, C_{MD} = 0$$

$$\frac{dP(CD)}{dP(FA)} = \frac{C_{FA}}{C_{MD}}$$



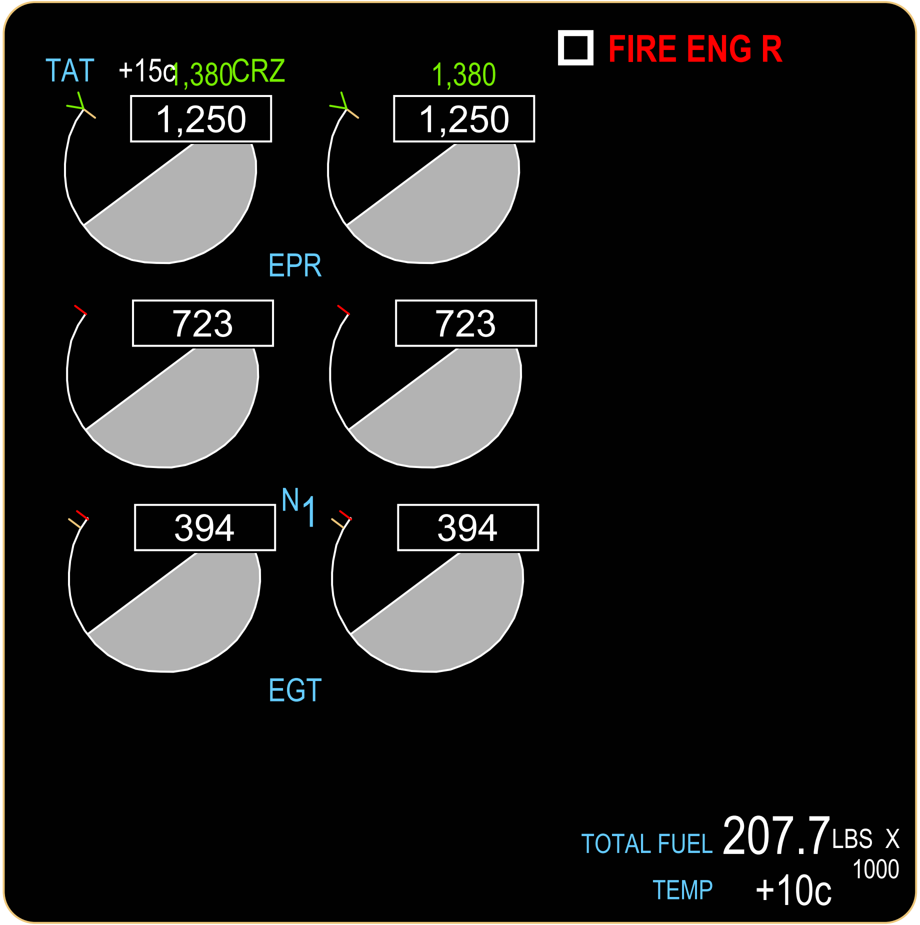
Slope of SOC curve = cost ratio

Courtesy: Jim Kuchar

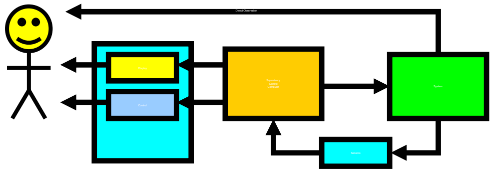


Engine Fire Alerting

- C(FA) high on takeoff
- Alerts suppressed during TO



Now let's take a quick look at non-normal checklists.
The 777 EICAS message list is similar to other Boeing EICAS airplanes.
[*For 747-400 operators*: It doesn't use the "caret" symbol to indicate a checklist with no QRH items, like the 747-400s do.]
But it has an additional feature, called the "checklist icon". The icon is displayed next to an EICAS message whenever there is an ECL checklist that needs to be completed. Once the checklist is fully complete, the icon is removed from display next to the message. This helps the crew keep track of which checklists remain to be completed.



Crew Alerting Levels

Non-Normal Procedures

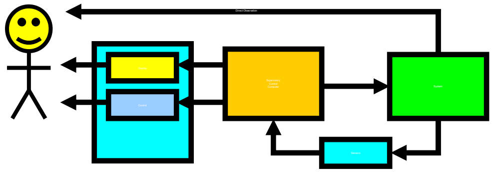
Time Critical	**Operational condition that requires immediate crew awareness and immediate action**
Warning	**Operational or system condition that requires immediate crew awareness and definite corrective or compensatory action**
Caution	**Operational or system condition that requires immediate crew awareness and possible corrective or compensatory action**
Advisory	**Operational or system condition that requires crew awareness and possible corrective or compensatory action**

Alternate Normal Procedures

Comm	**Alerts crew to incoming datalink communication**
Memo	**Crew reminders of the current state of certain manually selected normal conditions**

Source: Brian Kelly Boeing

Don’t have time to discuss these levels.
Important thing to know is that we rigorously define and defend these levels
We apply them across all the systems.
The indications are consistent for all alerts at each level.
Thus the pilots instantly know the criticality and nature of an alert even before they know what the problem is

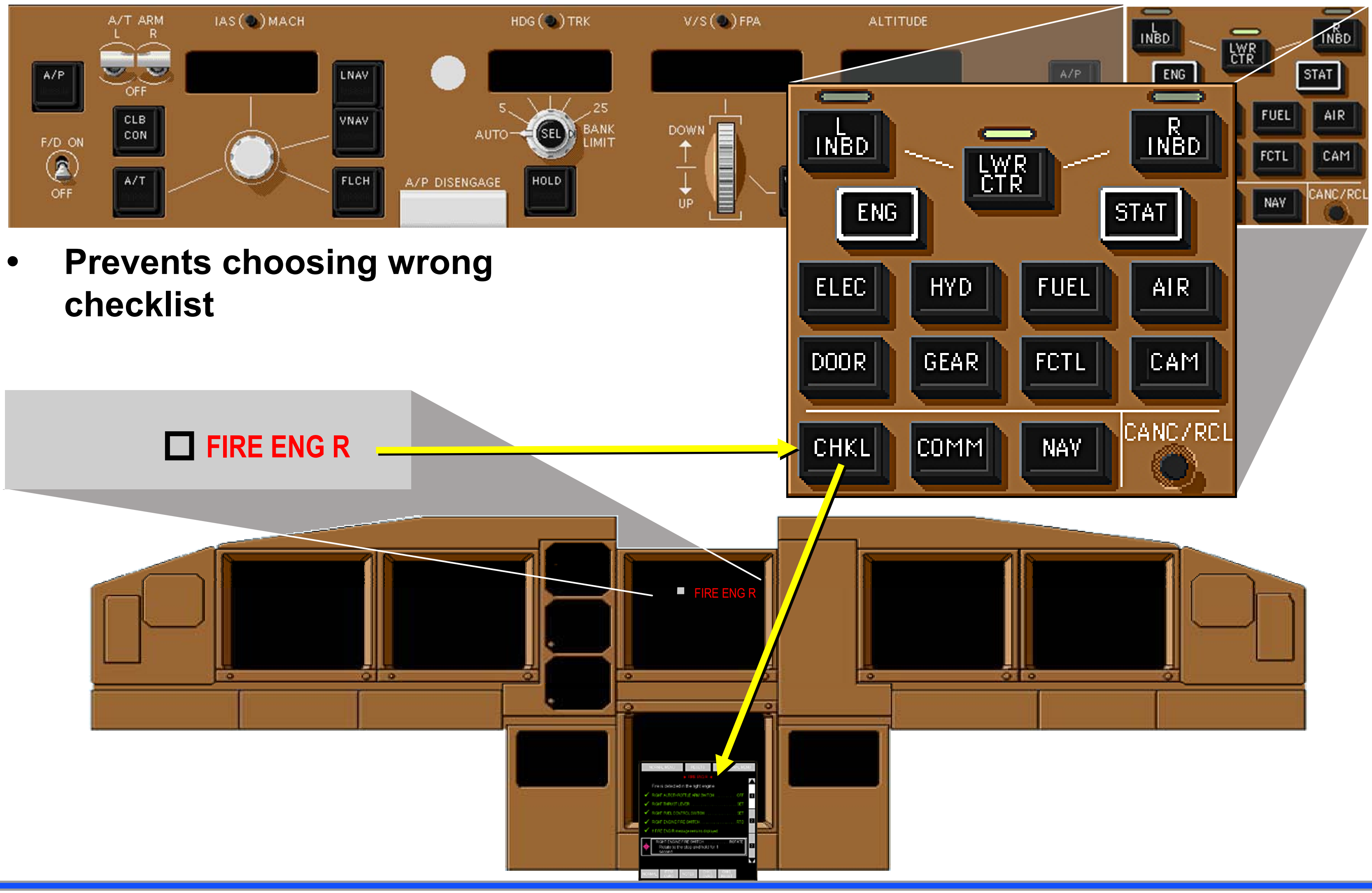


Boeing Color Use Guides

Red	Warnings, warning level limitations
Amber	Cautions, caution level limitations
White	Current status information
Green	Pilot selected data, mode annunciations
Magenta	Target information
Cyan	Background data

Again, we don't have time to describe these definitions in detail.
The important thing to note is that our philosophy is definite, and as simple as practical.
It fits on one page, in big font no less.

Access To Non-Normal Checklists



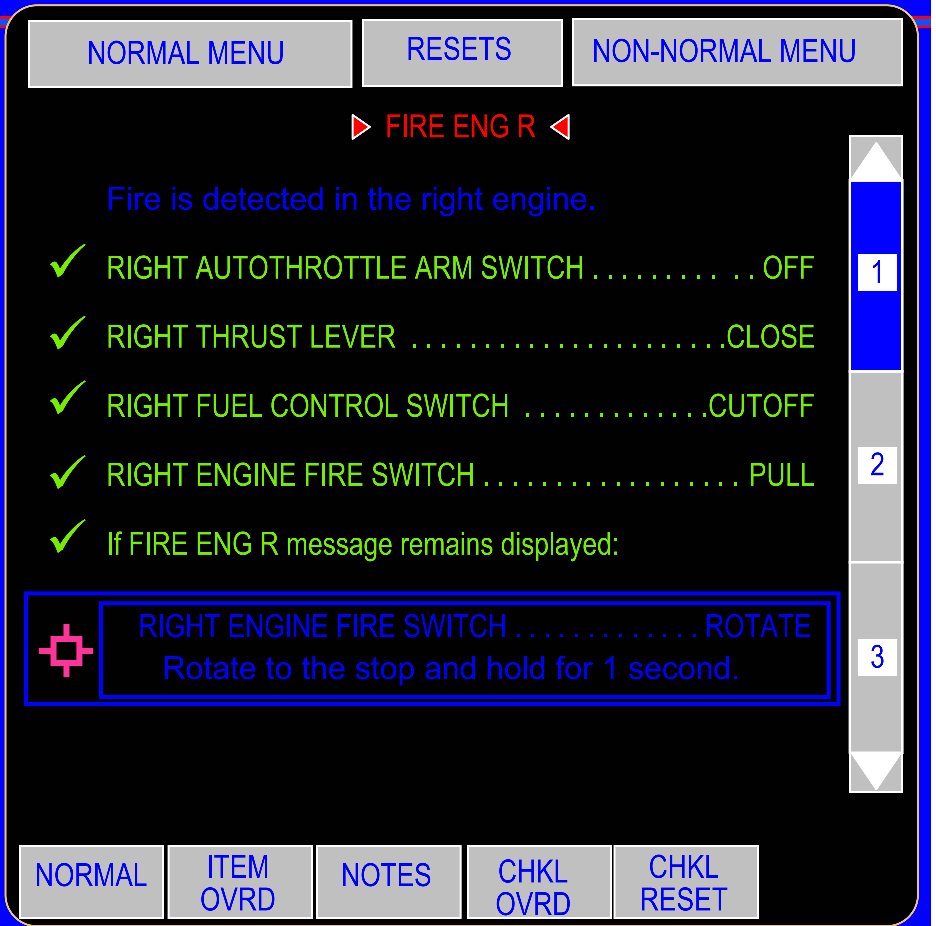
- **Prevents choosing wrong checklist**

When an alert message is displayed, the pilot simply pushes the CHKL button and the correct non-normal checklist is displayed. This prevents the crew from accidentally choosing the wrong checklist.

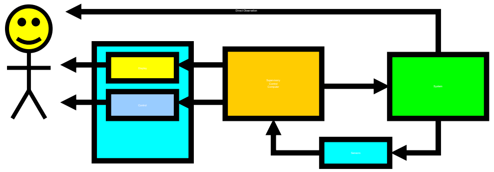
The non-normal checklists have priority over the normal checklists.

Non-Normal Checklists

- Checklist specific to left or right side
- Exact switch specified
- Memory items already complete
- Closed-loop conditional item
- Page bar



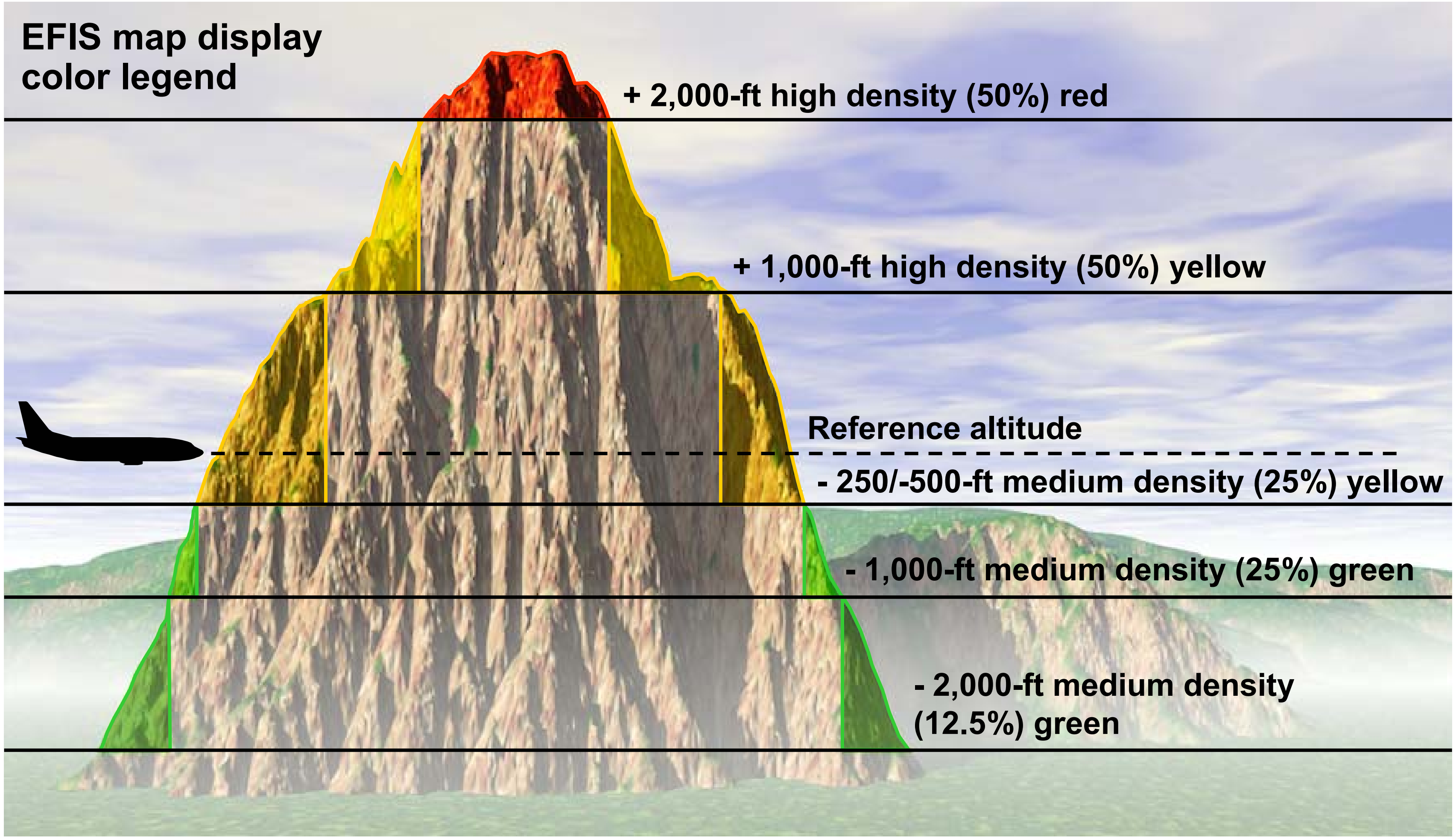
This is what a typical normal checklist looks like. This is the Preflight checkist.
There are two kinds of line items, which we call open-loop and closed-loop items. The open-loop items have a gray check-box in front of them. These are items that the airplane systems cannot sense. The pilot determines whether the items have been completed and clicks the CCD thumbswitch when each item is complete.
Closed-loop items are for switches and selectors that are sensed by the airplane systems. They automatically turn green when the switch has been positioned correctly. If the crew actuates the wrong switch, the closed-loop item will not turn green and the crew will catch their error. In this example, the procedure was already complete, so the last two items are shown in green as soon as the checklist is displayed.
The white current line item box leads the pilot through the checklist and prevents accidentally skipping a line item.
Color is used to indicate line item status. Incomplete items are displayed white and complete items are displayed green. Cyan (or blue) indicates an inapplicable item, or an item that has been intentionally overridden by the crew using the ITEM OVRD button. In this example, the flight is dispatching with autobrakes inoperative, so the crew has overridden the AUTOBRAKE item. Overriding the item allows the checklist to be completed.

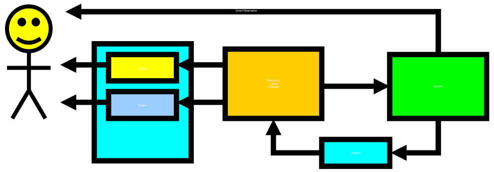


Internal vs External Threat Systems

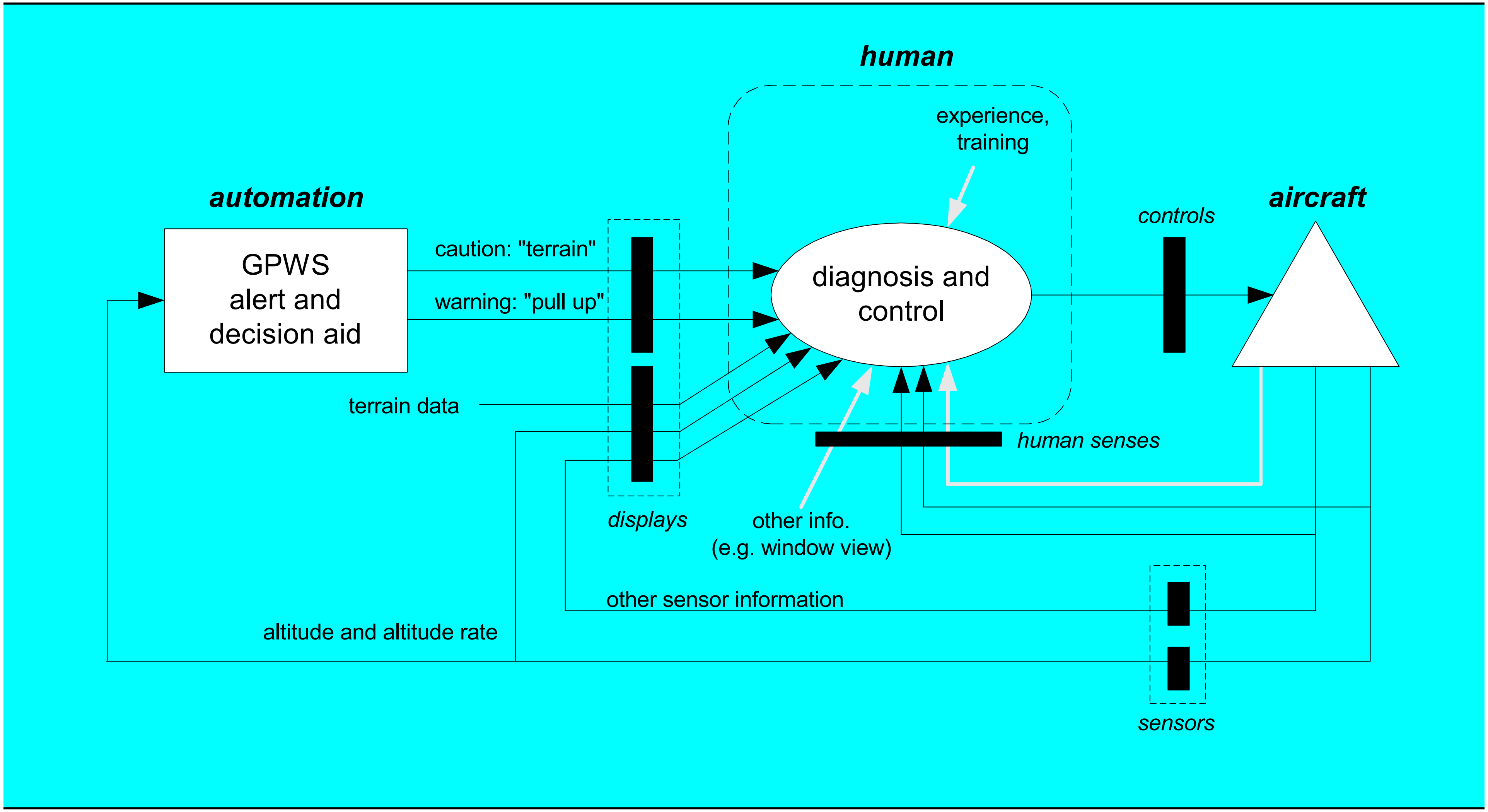
- **Internal**
  - ☐ System normally well defined
  - ☐ Logic relatively static
  - ☐ Simple ROC approach valid
  - ☐ Examples (Oil Pressure, Fire, Fuel, ...)
- **External**
  - ☐ External environment may not be well defined
    - ◆ Stochastic elements
  - ☐ Controlled system trajectory may be important
    - ◆ Human response
  - ☐ Need ROC like approach which considers entire system
  - ☐ System Operating Characteristic (SOC) approach of Kuchar
  - ☐ Examples (Traffic, Terrain, Weather, …)

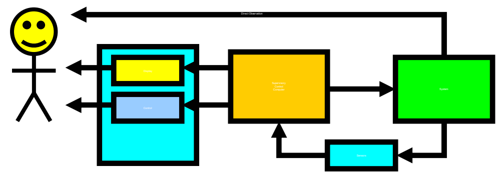
Enhanced GPWS Improves Terrain/Situational Awareness



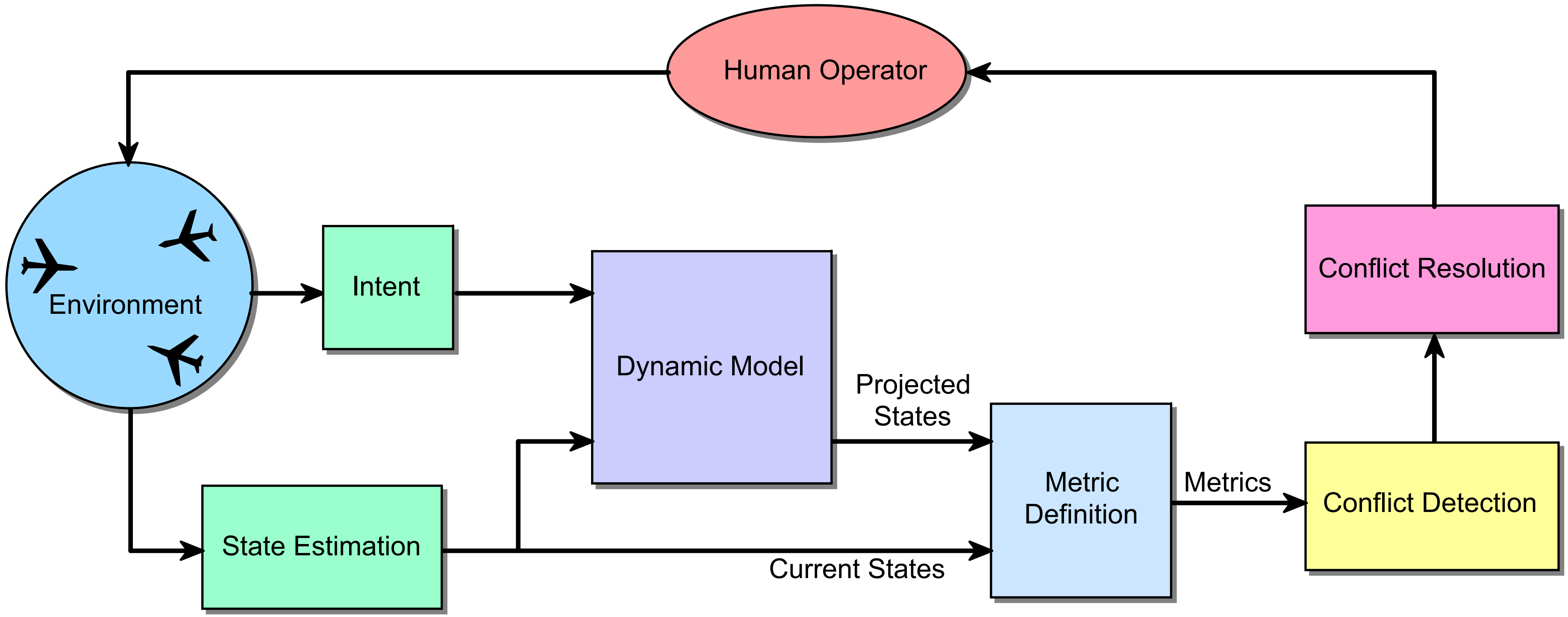


Aircraft Collision Avoidance



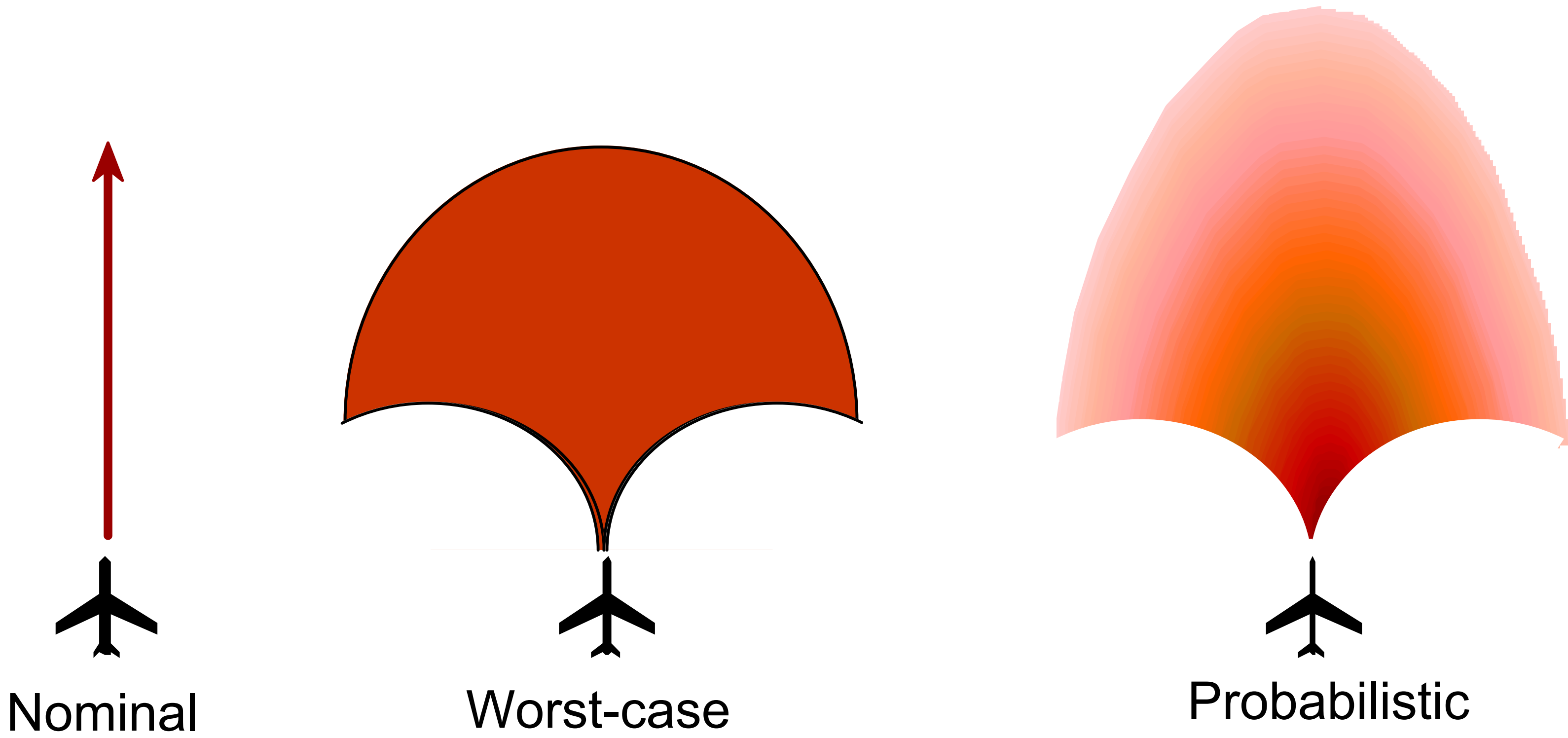


Conflict Detection and Resolution Framework

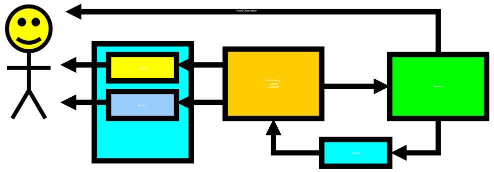


Courtesy: Jim Kuchar

Trajectory Modeling Methods

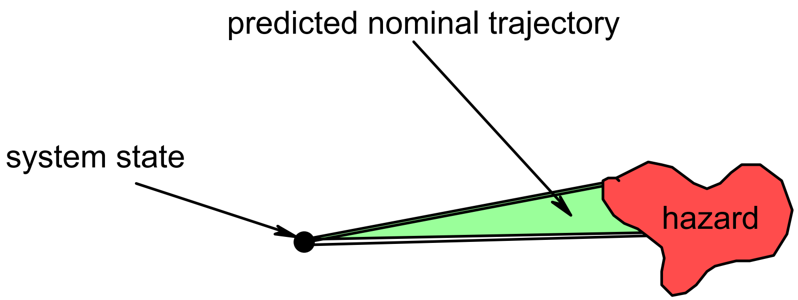


Courtesy: Jim Kuchar



Nominal Trajectory Prediction-Based Alerting

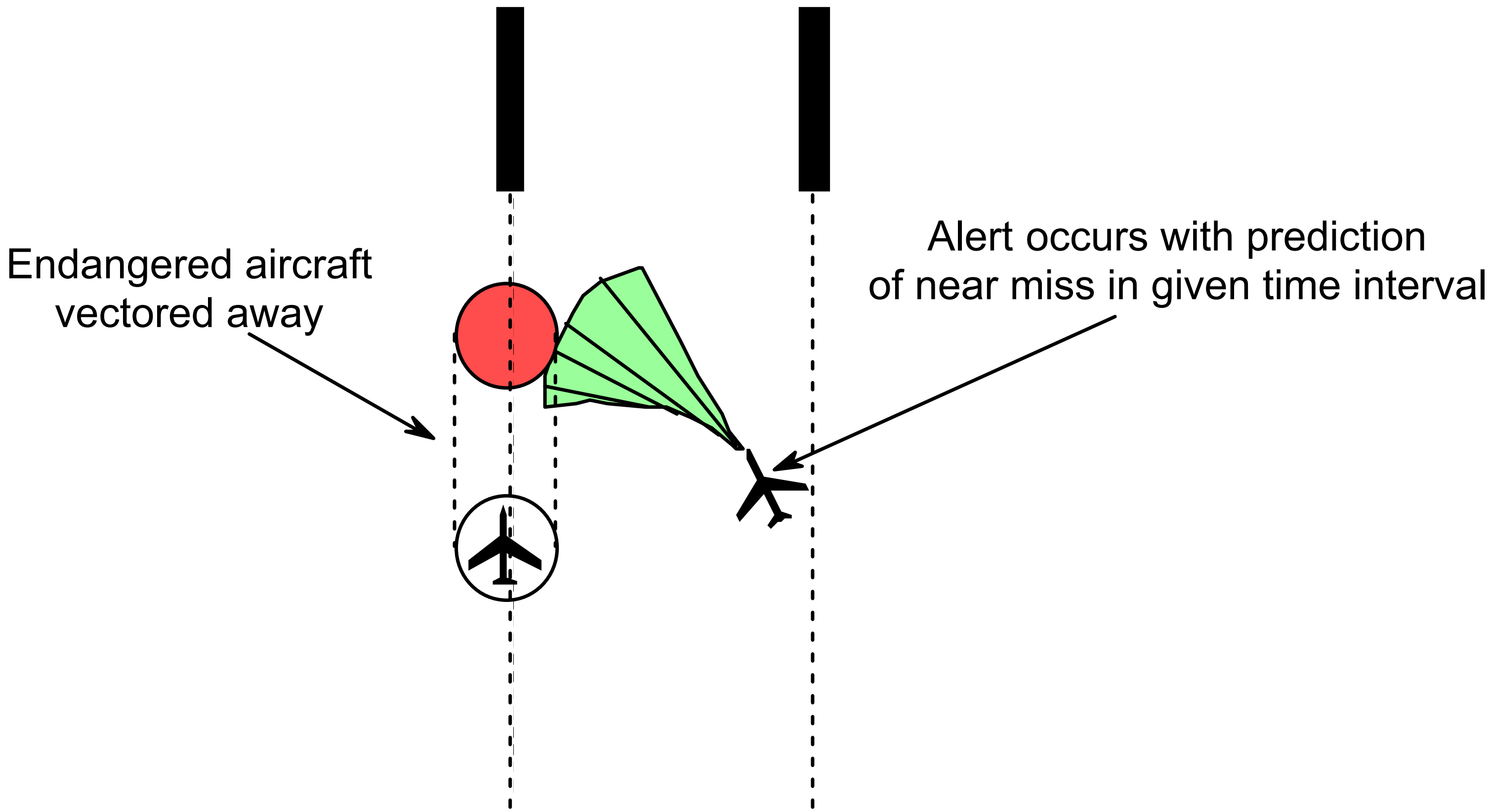
- **Alert when projected trajectory encounters hazard**



- **Look ahead time and trajectory model are design parameters**
- **Examples: TCAS, GPWS, AILS**

Courtesy: Jim Kuchar

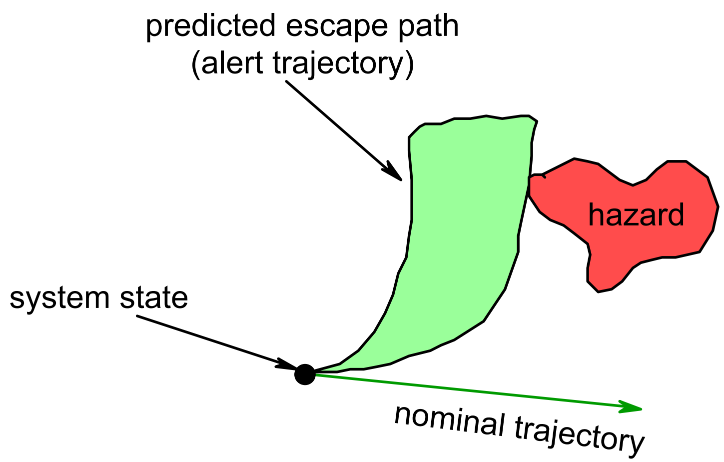
Airborne Information for Lateral Spacing (AILS) (nominal trajectory prediction-based)



Courtesy: Jim Kuchar

Alert Trajectory Prediction-Based Alerting

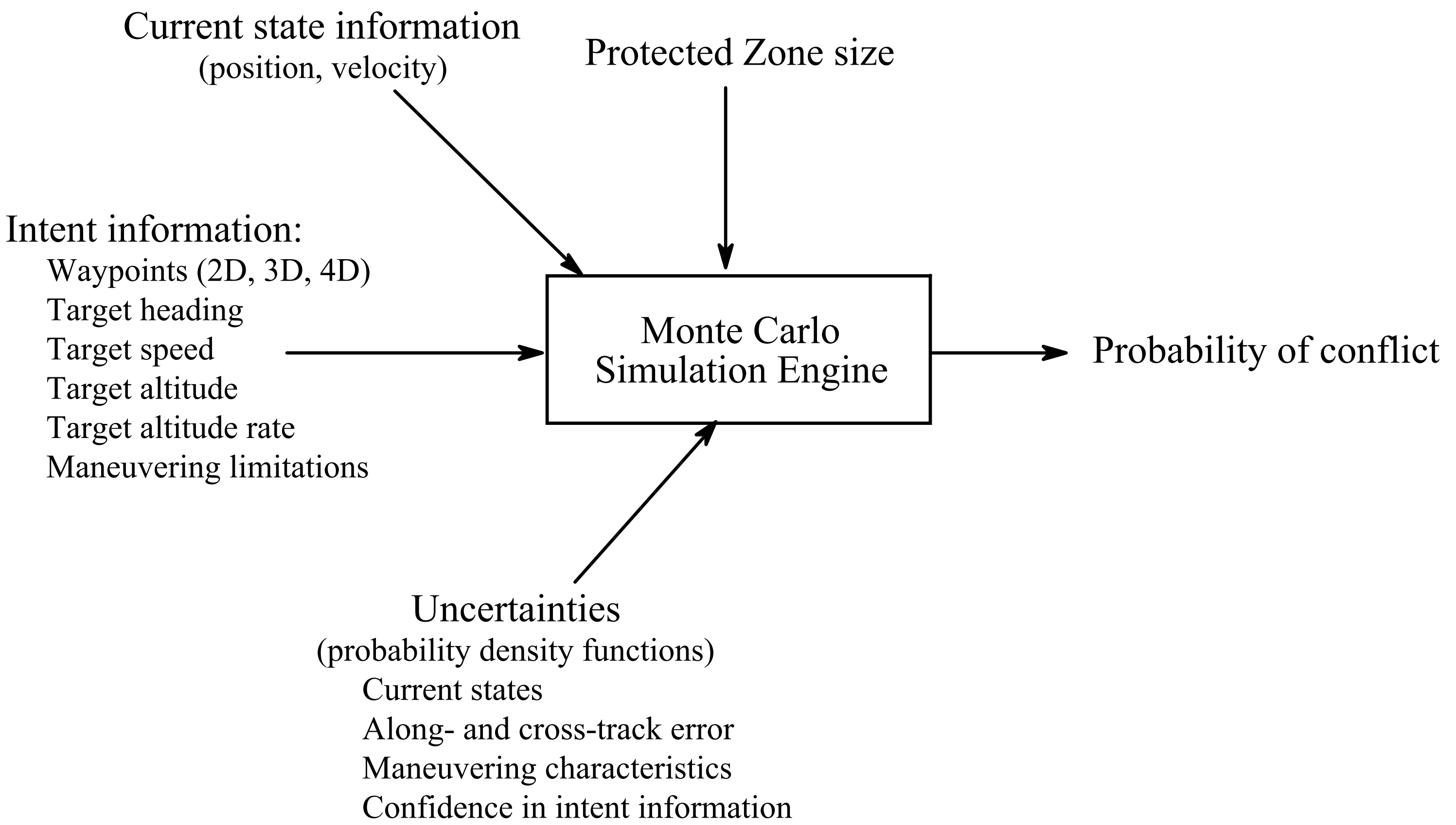
- **Alert is issued as soon as safe escape path is threatened**



- **Attempt to ensure minimum level of safety**
- **Some loss of control over false alarms**
- **Example: Probabilistic parallel approach logic (Carpenter & Kuchar)**

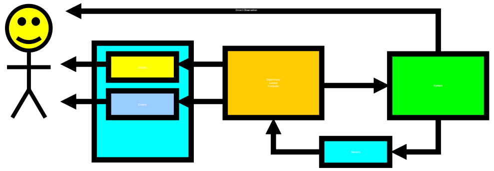
Courtesy: Jim Kuchar

Monte Carlo Simulation Structure



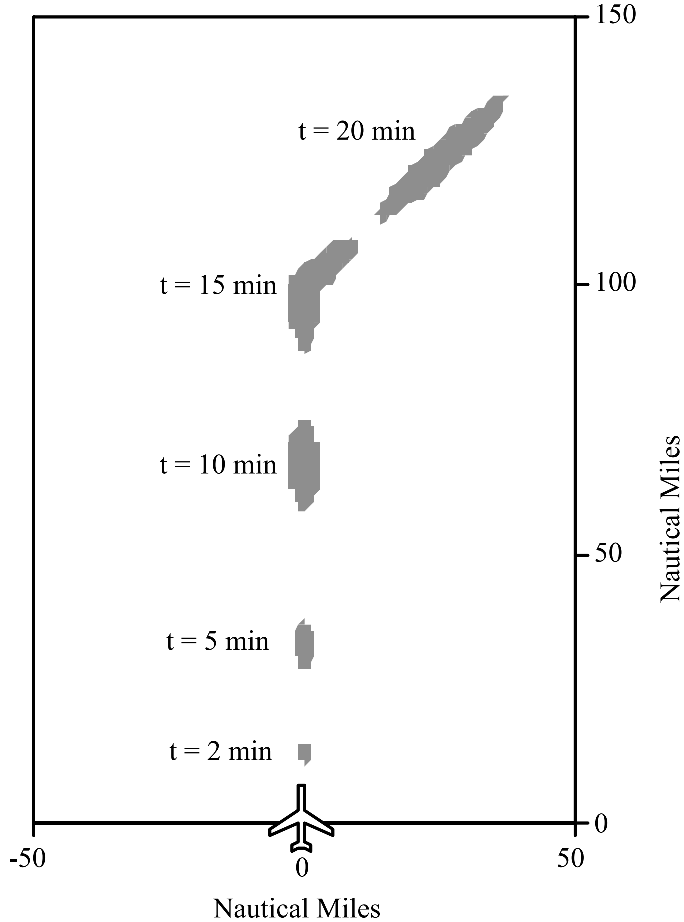
Implemented in real-time simulation studies at NASA Ames
Computational time on the order of 1 sec

Courtesy: Jim Kuchar



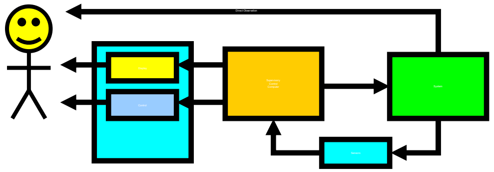
Example State Uncertainty Propagation

Computed via Monte Carlo

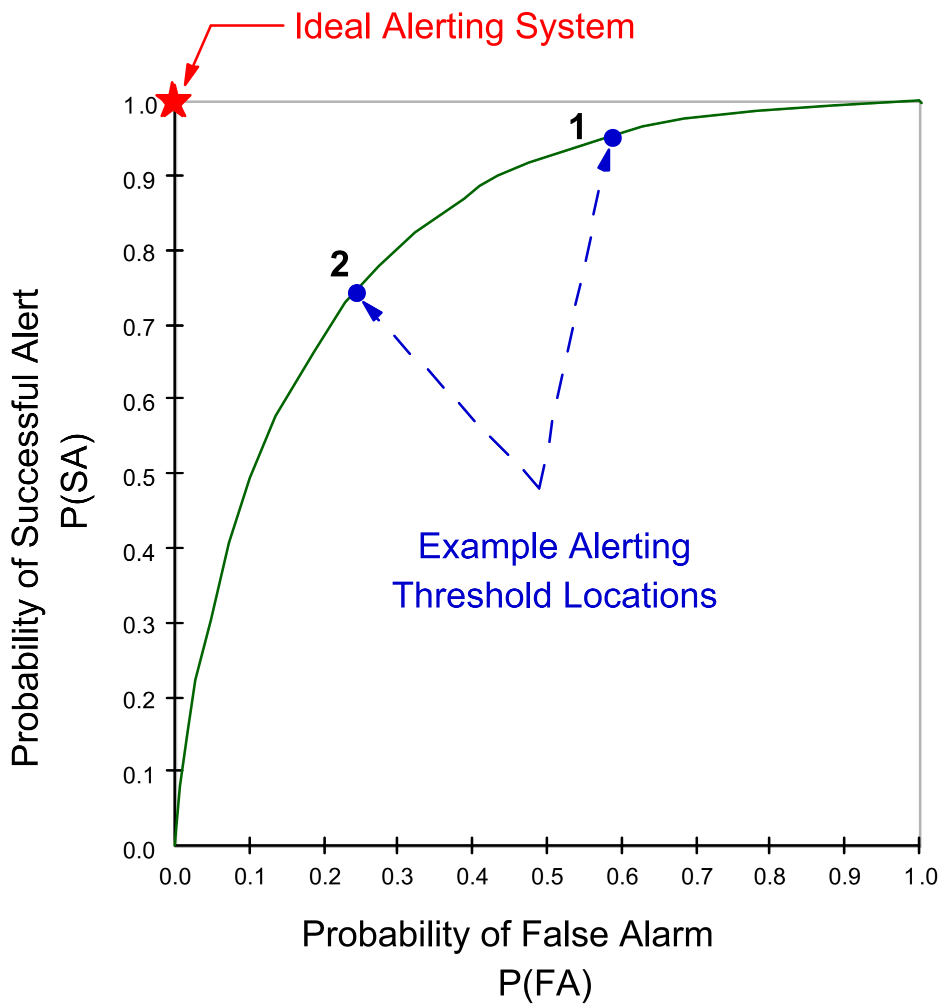


along-track σ = 15 kt
cross-track σ = 1 nmi
(from NASA Ames)

Courtesy: Jim Kuchar

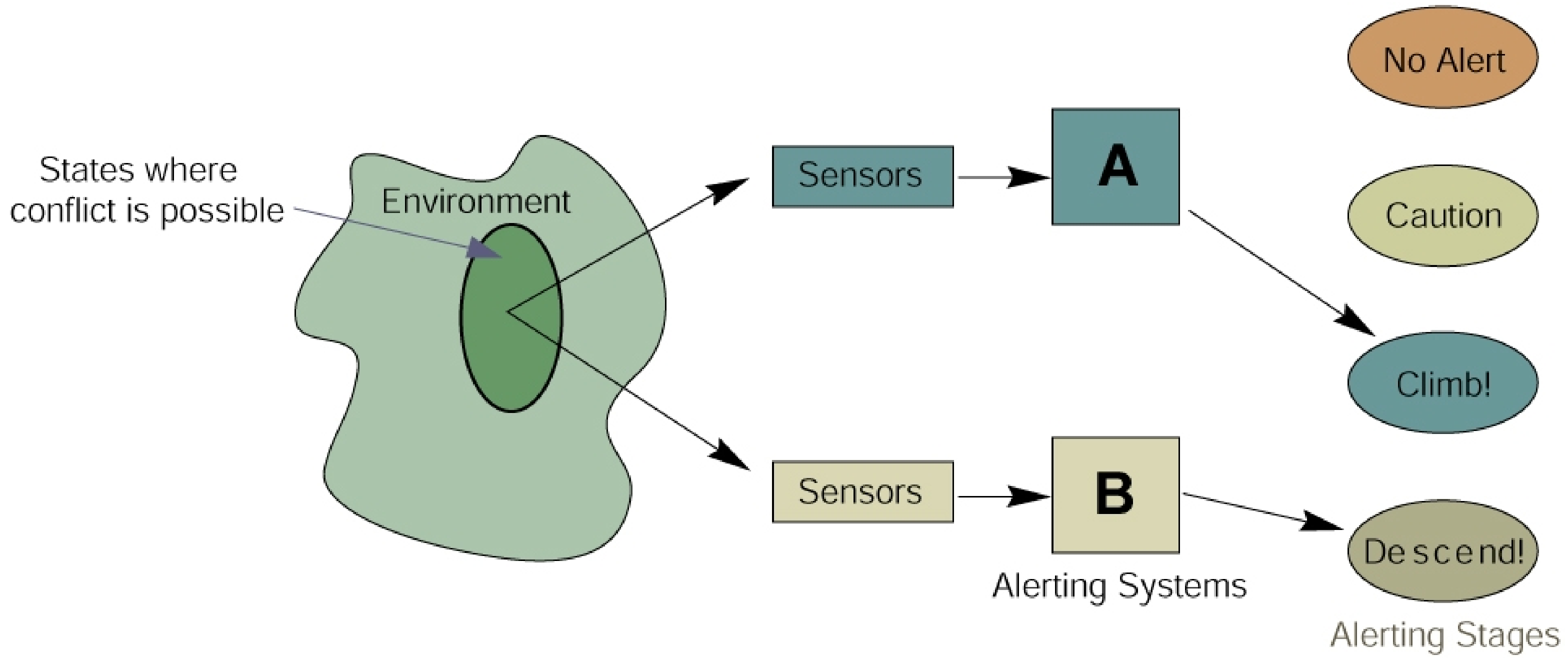


Generating the System Operating Characteristic Curve



Courtesy: Jim Kuchar

Multiple Alerting System Disonance

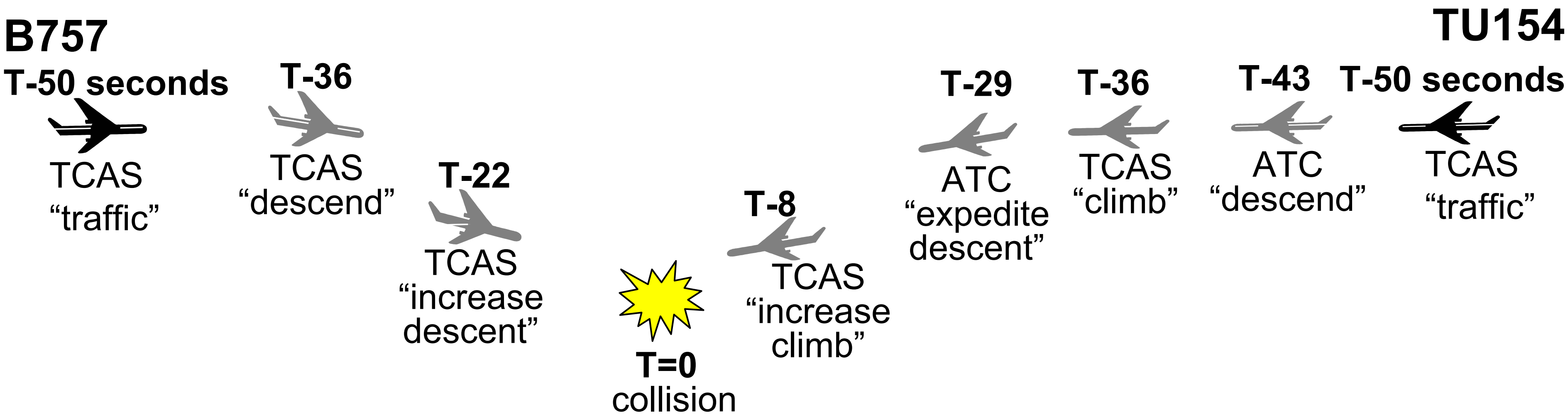


Adapted from Jim Kuchar and Lixia Song.

- **Already occurred with on-board alerting system & air traffic controller**
  - ❑ mid-air collision and several near misses

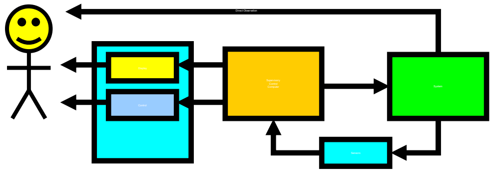
    Germany, July 1st,2002; Zurich, 1999; Japan, 2001
- **Potential for automation/automation dissonance is growing**

Example: Russian (TU154) and a DHL (B757) collide over Germany On July 1st, 2002



TCAS: on-board collision avoidance system

ATC: Air Traffic Controller



Dissonance

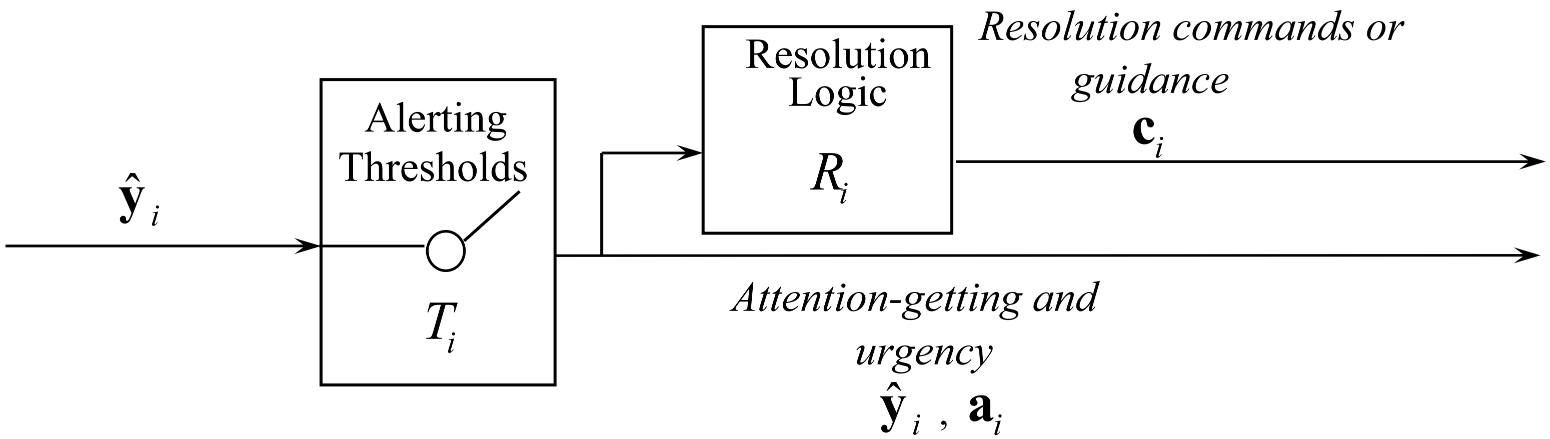
- **Indicated Dissonance: mismatch of information between alerting systems**
  - ❑ alert stage
  - ❑ resolution command

- **Indicated dissonance may not be perceived as dissonance**
  - ❑ Human operator knows why dissonance is indicated

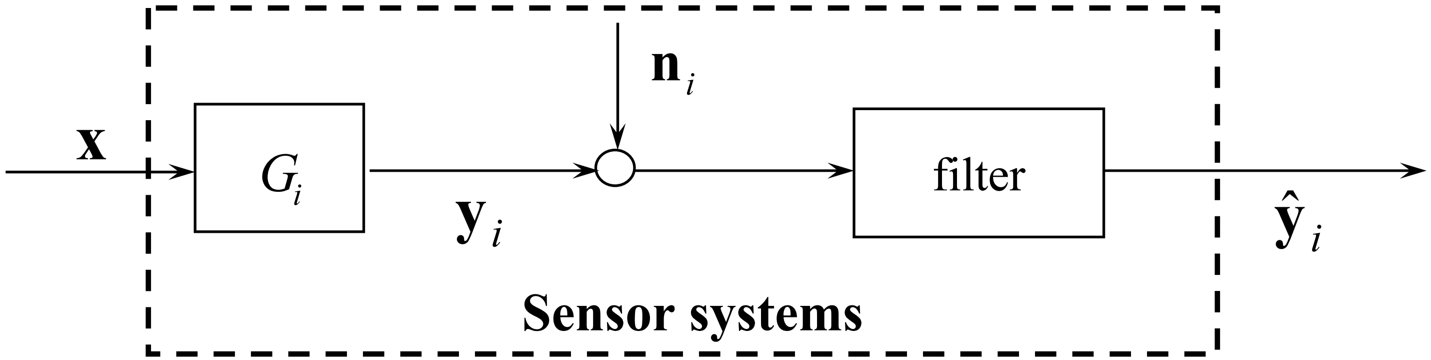
- **Indicated consonance may be perceived as dissonance**

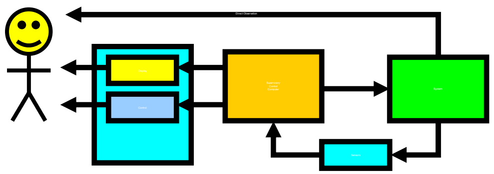
Causes of Indicated Dissonance

- **Different alerting threshold and/or resolution logic**

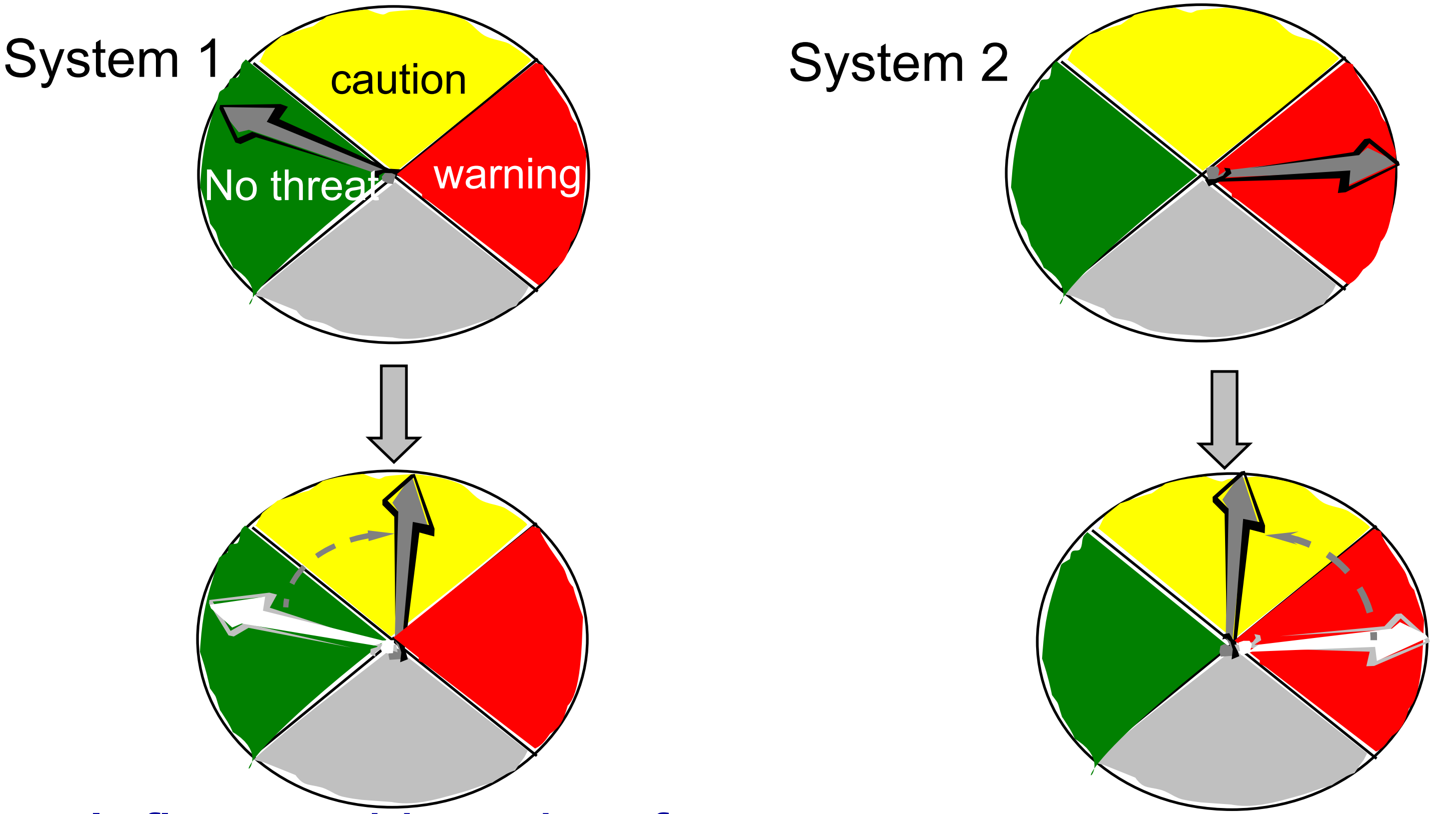


- **Different sensor error or sensor coverage**





Example Perceived Dissonance

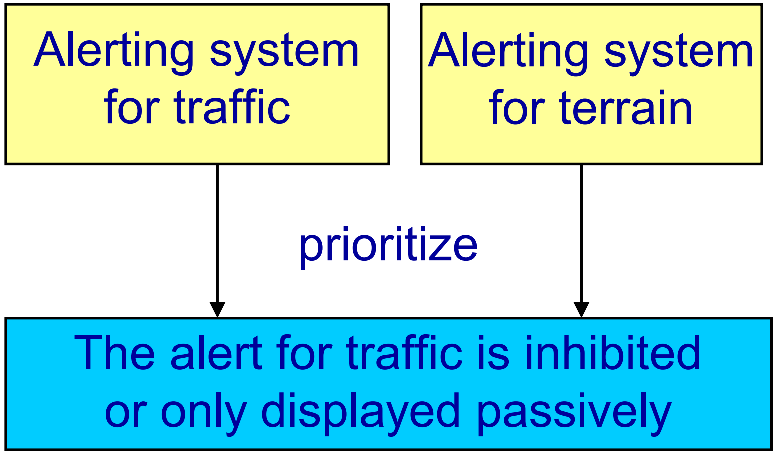


- Influenced by other factors

(system dynamics, trend data, nominal information, human mental model, etc.)

Current Mitigation Methods

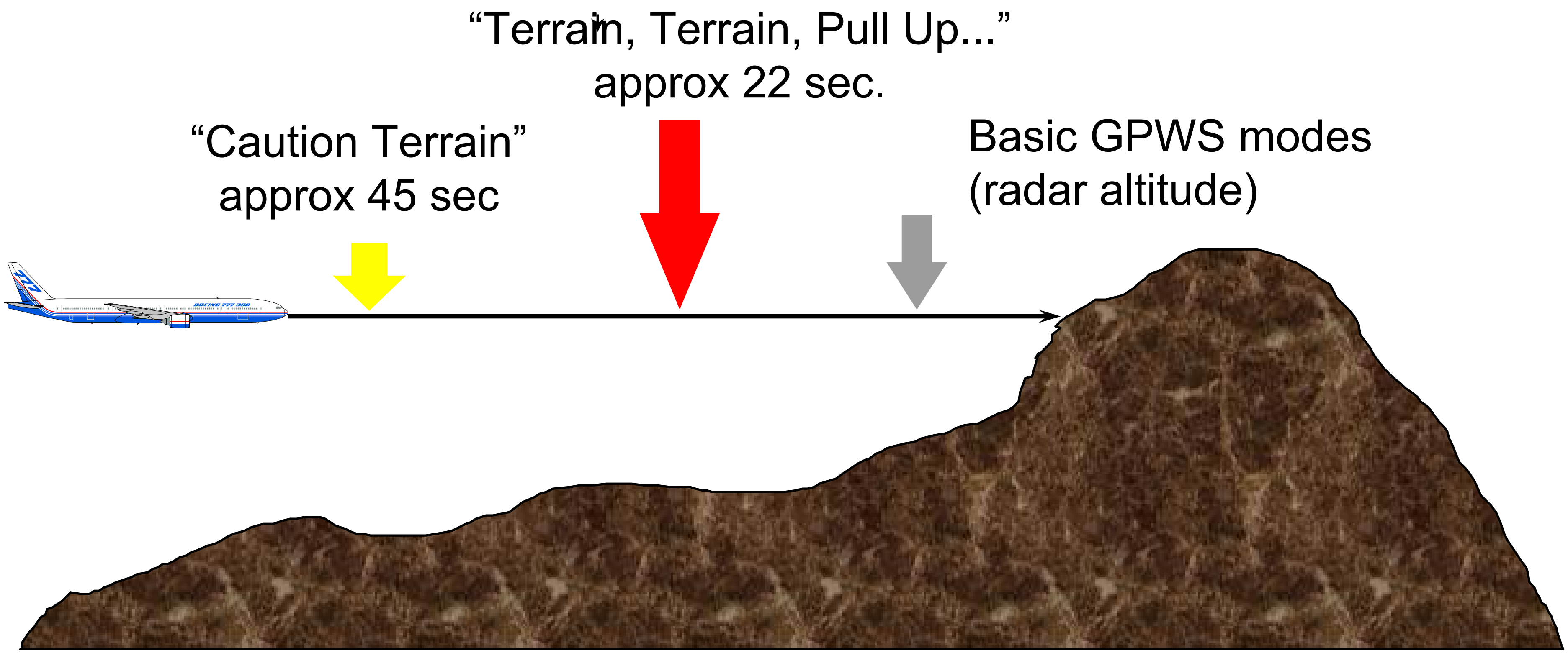
- Prioritization



- Procedures for responding to dissonance
  - Human operator can be trained to know how the alerting systems work and how to deal with dissonance
  - Training may be inadequate
    - 2 B-757 accidents in 1996, dissonant alert from airspeed data systems

Terrain Alerting

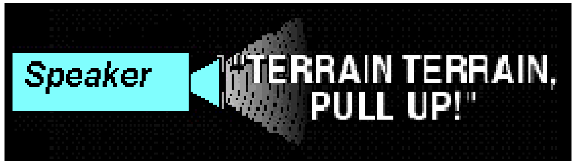
TAWS Look-Ahead Alerts
(Terrain Database)

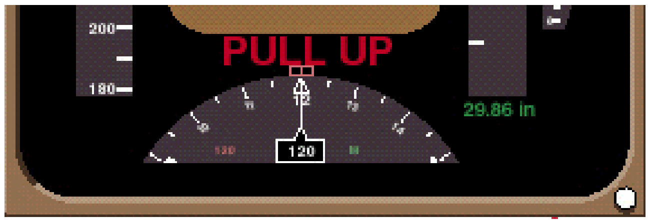


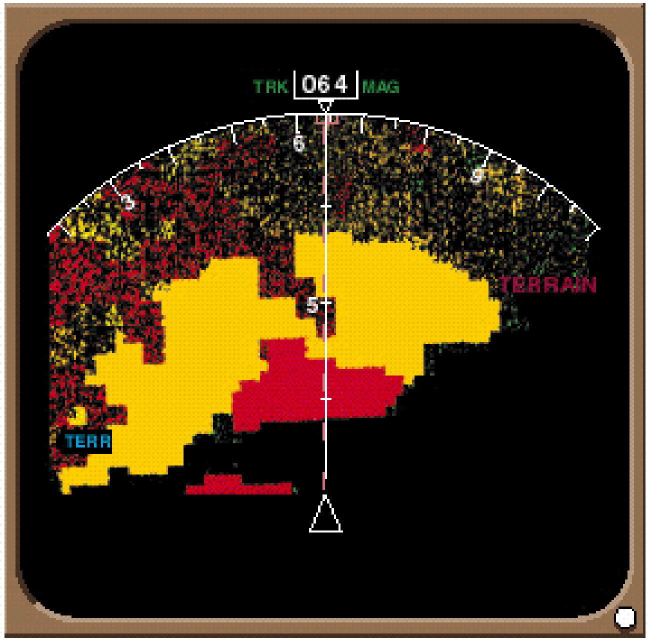
Courtesy: Brian Kelly, Boeing

TAWS Look-ahead Warning

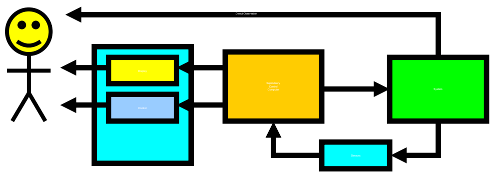
- Threat terrain is shown in solid red
- “Pull up” light or PFD message
- Colored terrain on navigation display





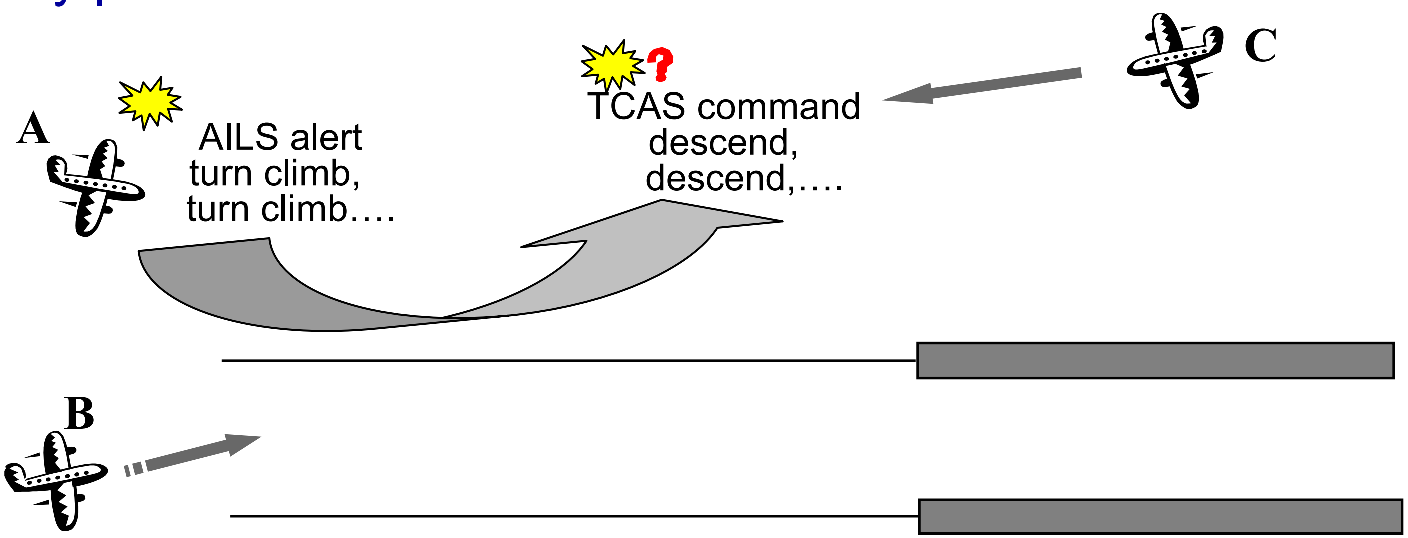


Courtesy: Brian Kelly, Boeing

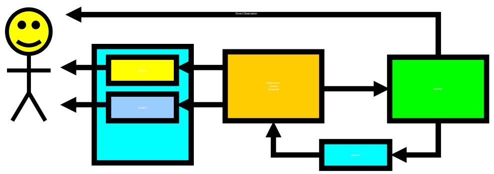


Current Mitigation Methods (2)

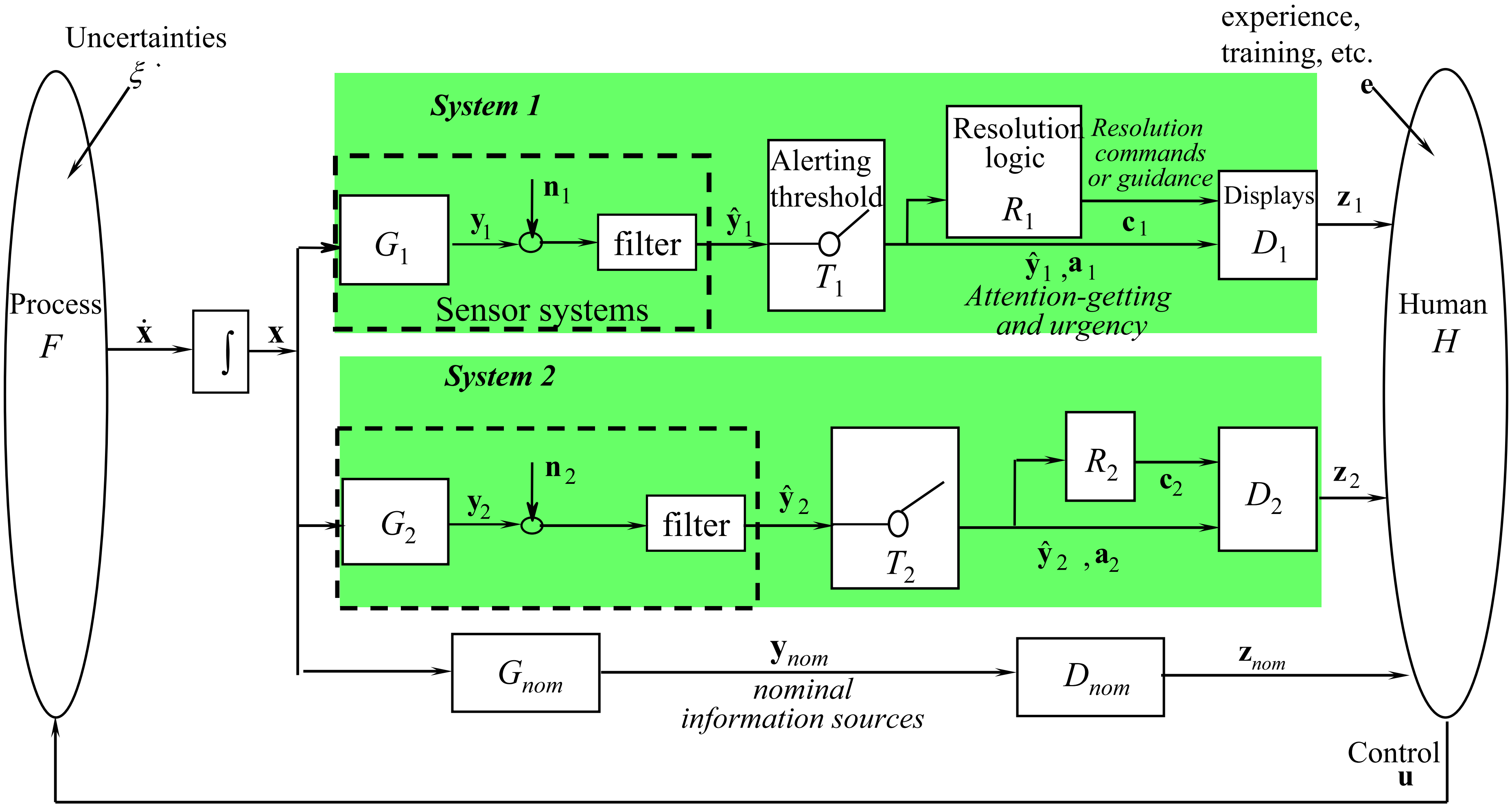
- Modify procedures to avoid dissonance



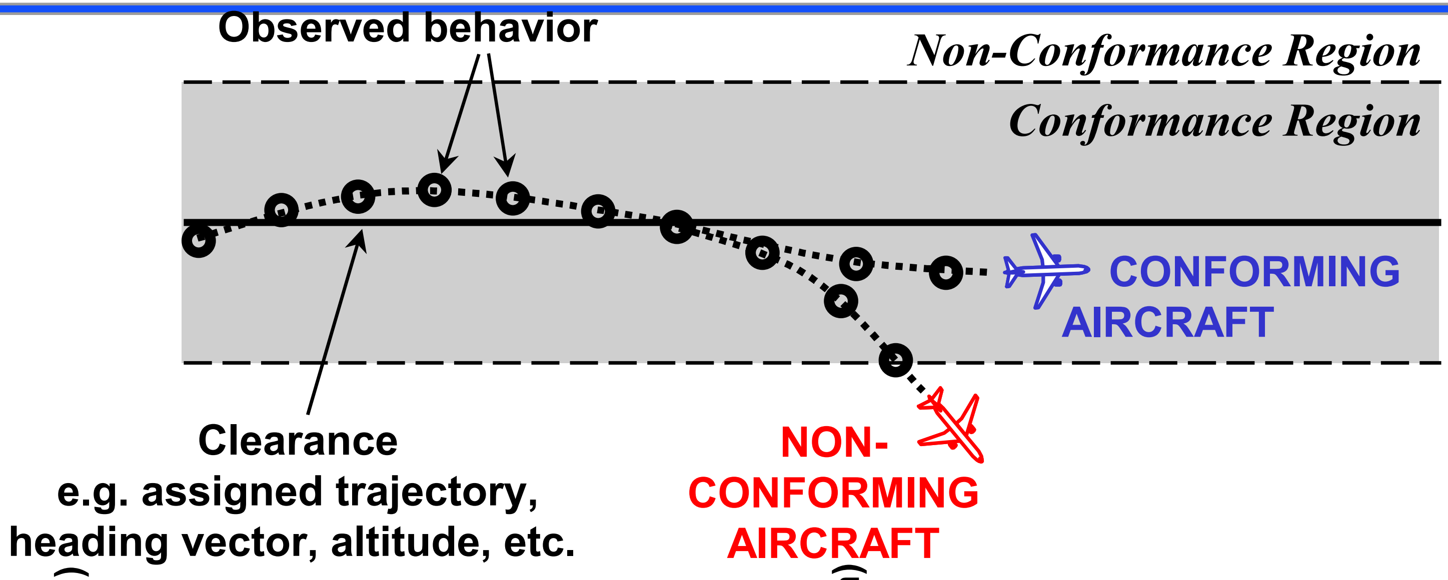
- AILS --- Airborne Information for Lateral Spacing parallel approach
  —— Special alerting system for closely-spaced runway approaches
- TCAS --- Traffic alert and Collision Avoidance System
  —— Warns the pilots to an immediate collision with other aircraft
- Modify air traffic control procedures to reduce the likelihood of a simultaneous TCAS alert and parallel traffic alert
- Changing operation procedure may largely reduce the efficiency of the airspace around the airport

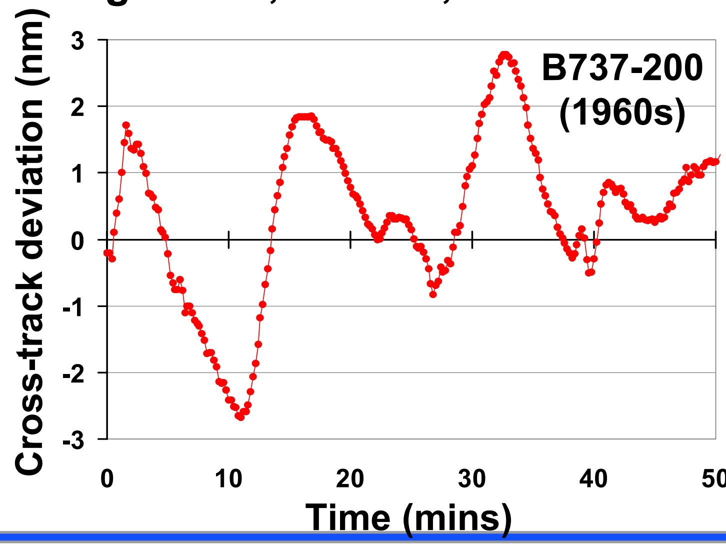


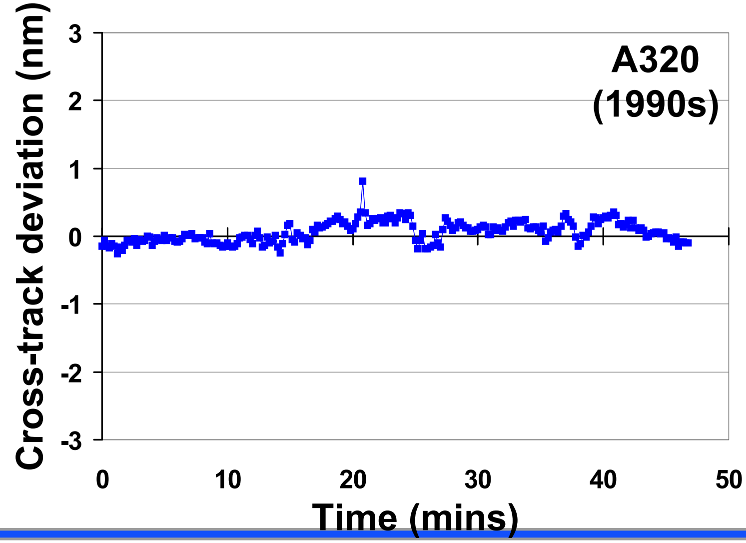
Multiple Alerting System Representation



SIMPLE REPRESENTATION OF CONFORMANCE MONITORING

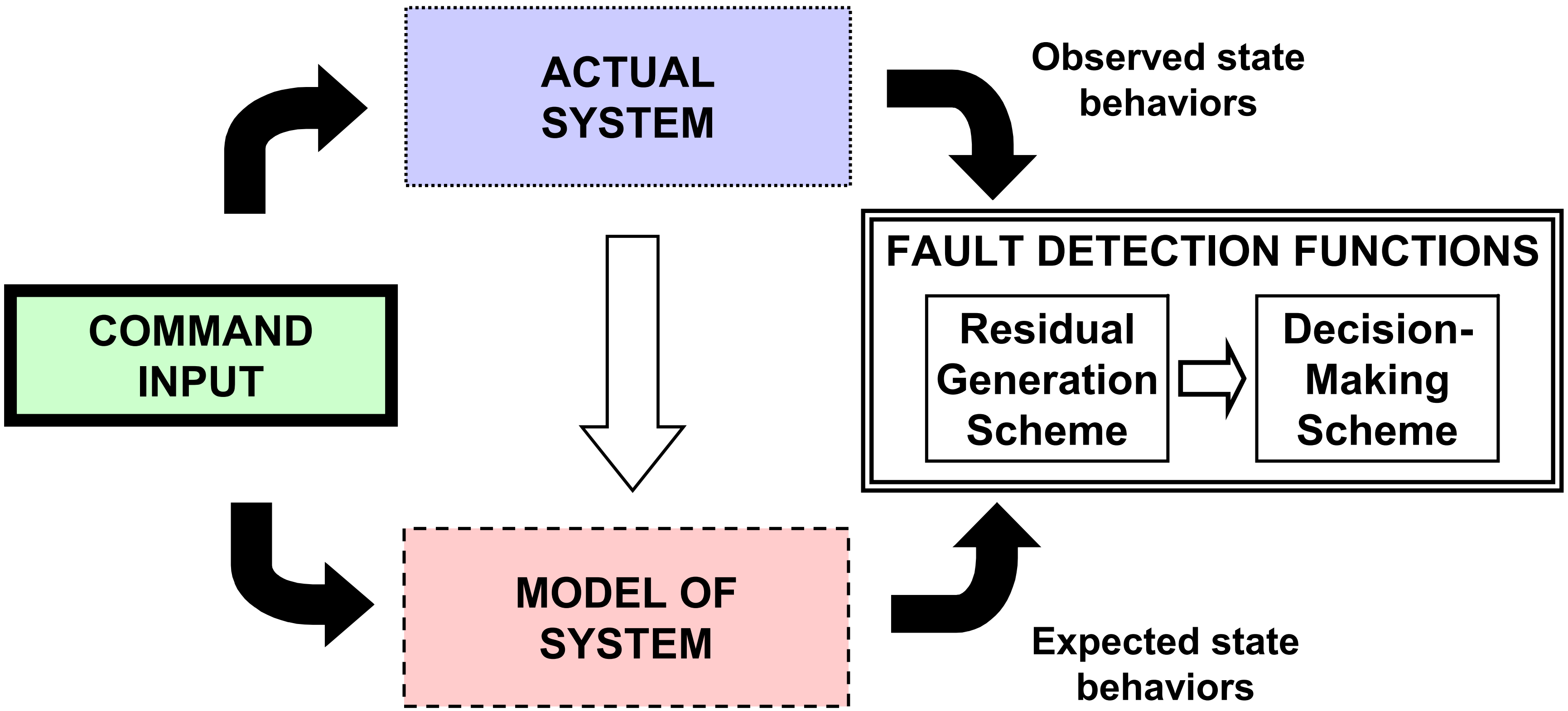


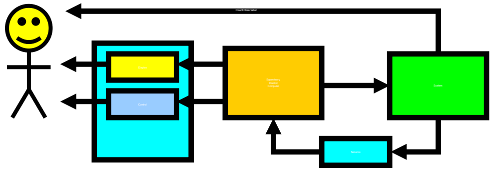




CORE RESEARCH APPROACH

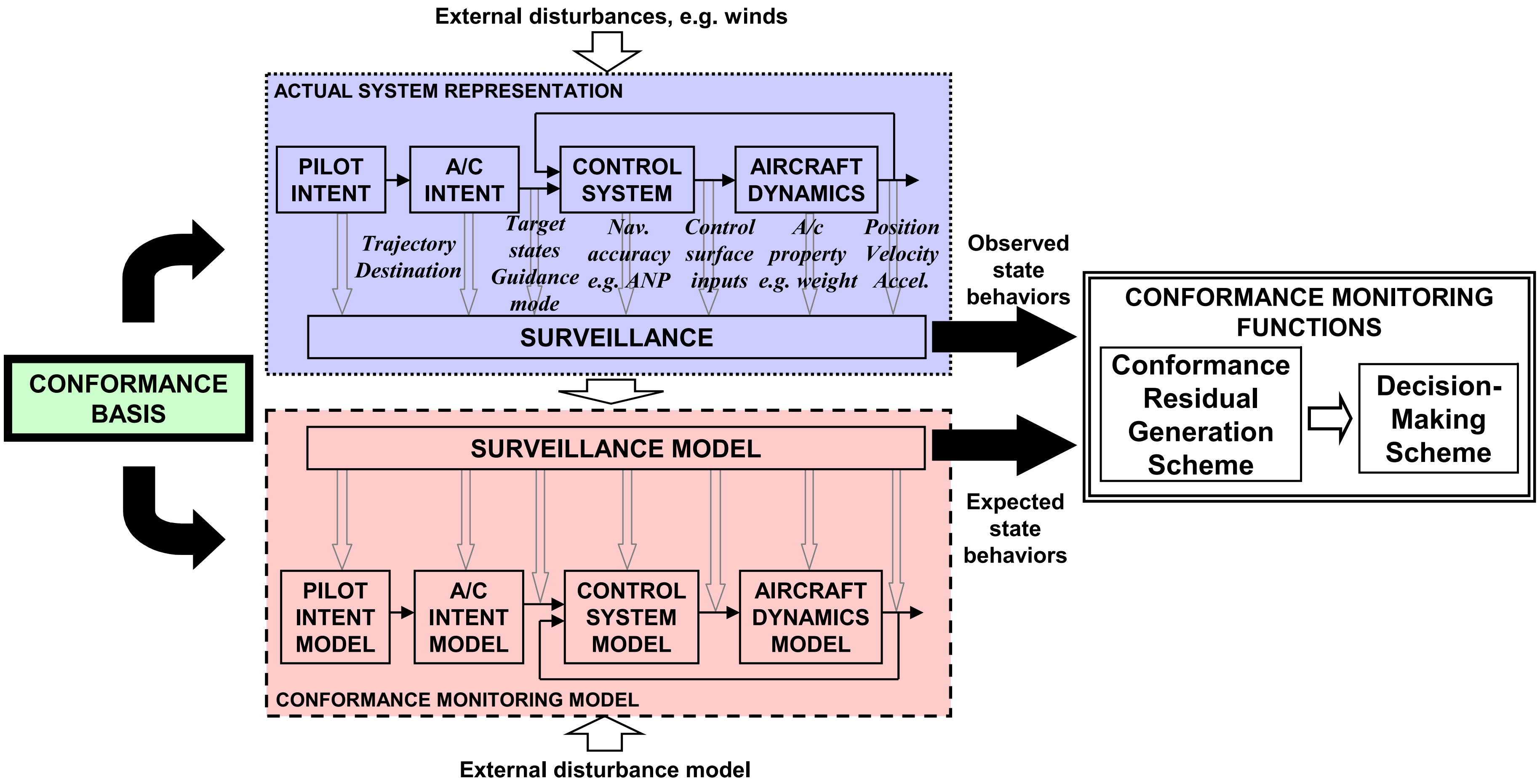
- **Conformance Monitoring as “fault detection”**
  - Aircraft non-conformance a “fault” in ATC system needing to be detected
  - Existing fault detection techniques can be used for new application





CONFORMANCE MONITORING ANALYSIS FRAMEWORK

- **Fault detection framework tailored for conformance monitoring**



INTENT REPRESENTATION IN ATC

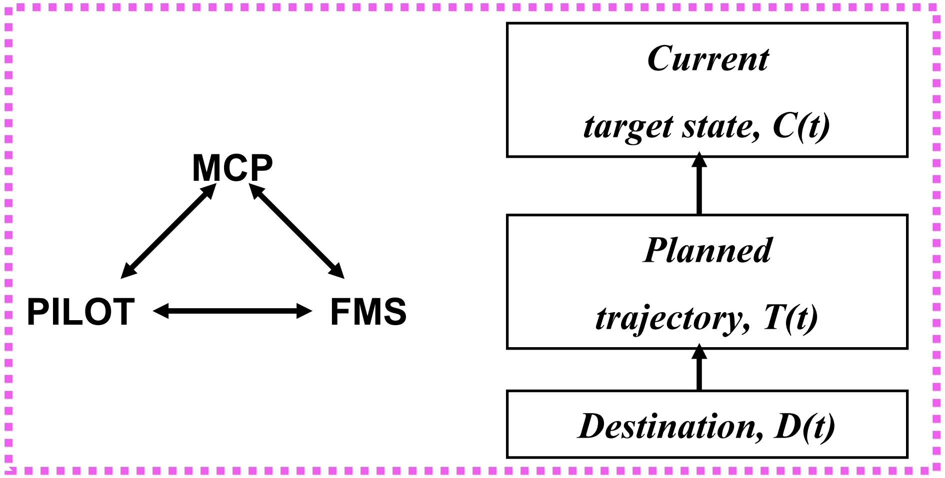
- **Intent formalized in "Surveillance State Vector"**

$$\text{Surveillance State Vector, } \underline{\boldsymbol{X(t)}} = \left\{ \begin{array}{c} \textit{Position states, } P(t) \\ \textit{Velocity states, } V(t) \\ \textit{Acceleration states, } A(t) \\ \textit{Current target states, } C(t) \\ \textit{Planned trajectory states, } T(t) \\ \textit{Destination states, } D(t) \end{array} \right.$$

Traditional dynamic states (Position, Velocity, Acceleration)

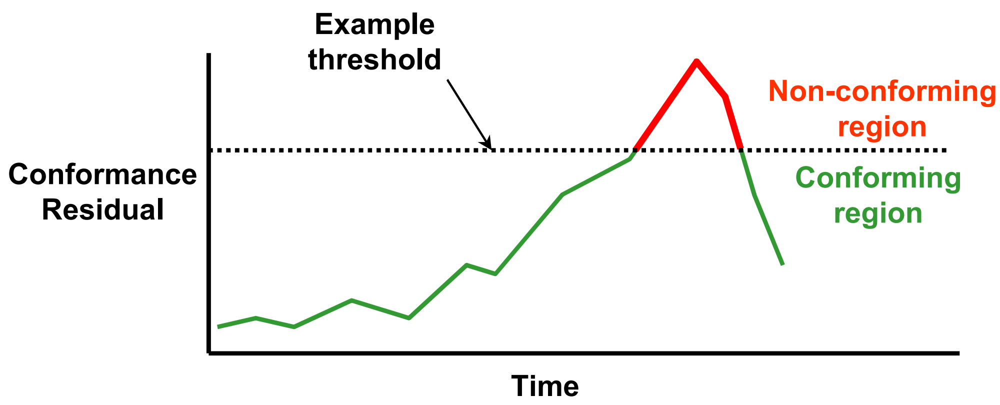
Defined intent states (Current target, Planned trajectory, Destination)

- **Accurately mimics intent communication & execution in ATC**

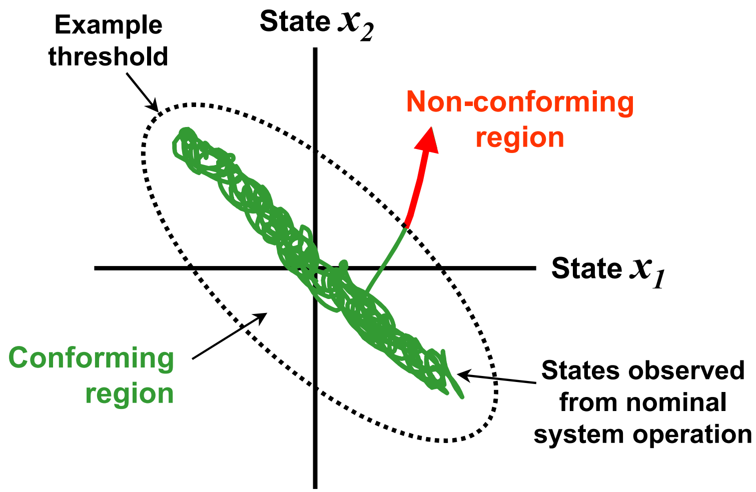


DECISION-MAKING SCHEME

- Consider evidence in Conformance Residual to make best determination of conformance status of aircraft
- Simple/common approach uses threshold(s) on Conformance Residuals



Scalar residual



Vector residual

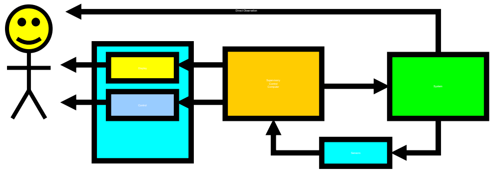
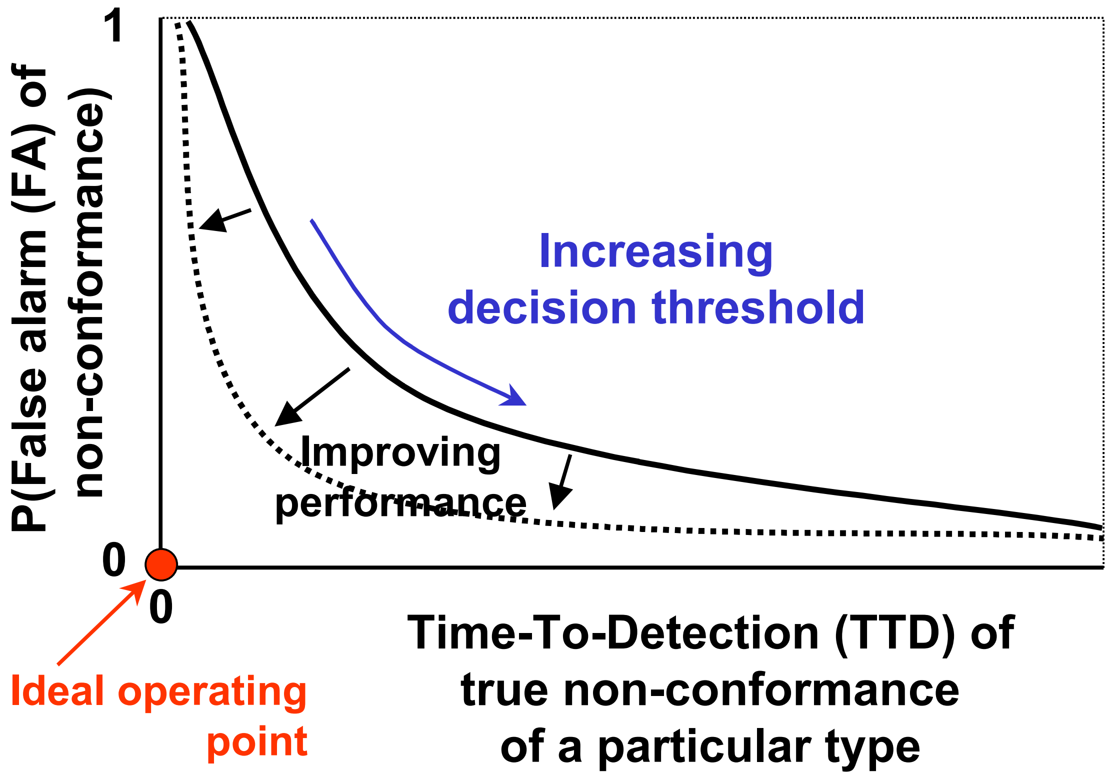


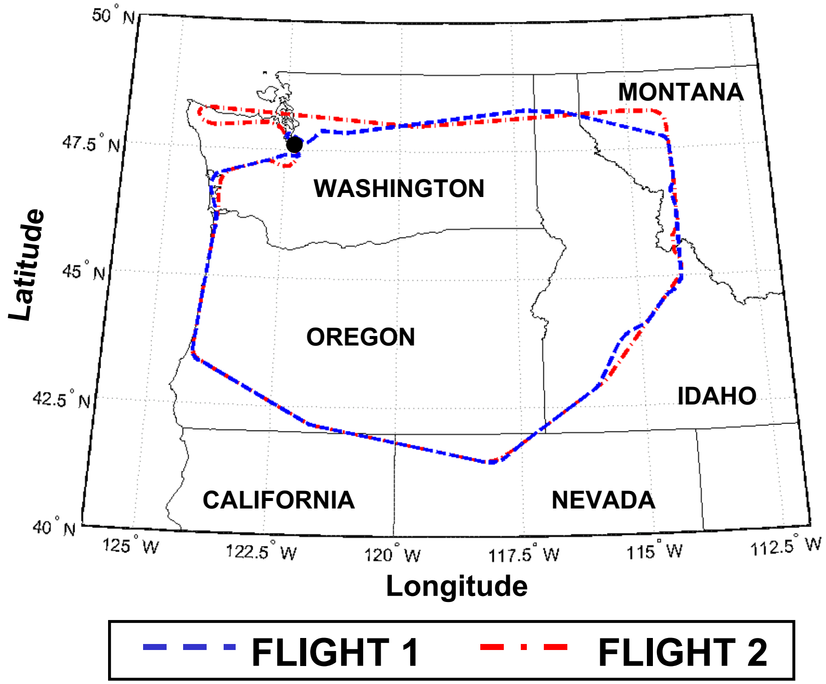
FIGURE OF MERIT TRADEOFFS

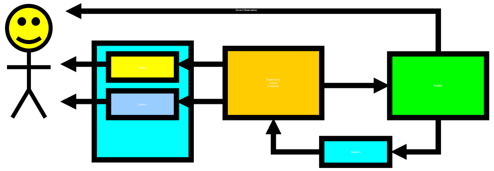
- **Use “figures of merit” to examine trade-offs applicable to application**
  - ☐ Time-To-Detection (TTD) of alert of true non-conformance
  - ☐ False Alarms (FA) of alert when actually conforming
  - ☐ FA/TTD tradeoff analogous to inverse System Operating Characteristic curve



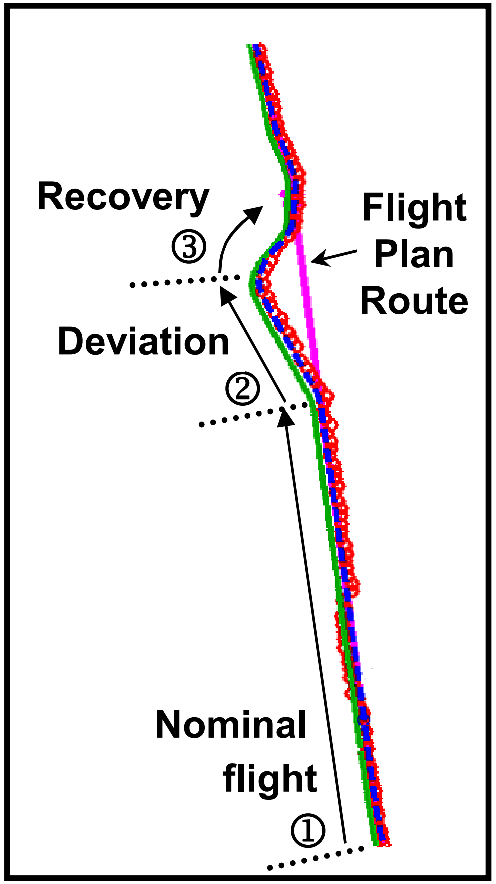
OPERATIONAL DATA EVALUATION

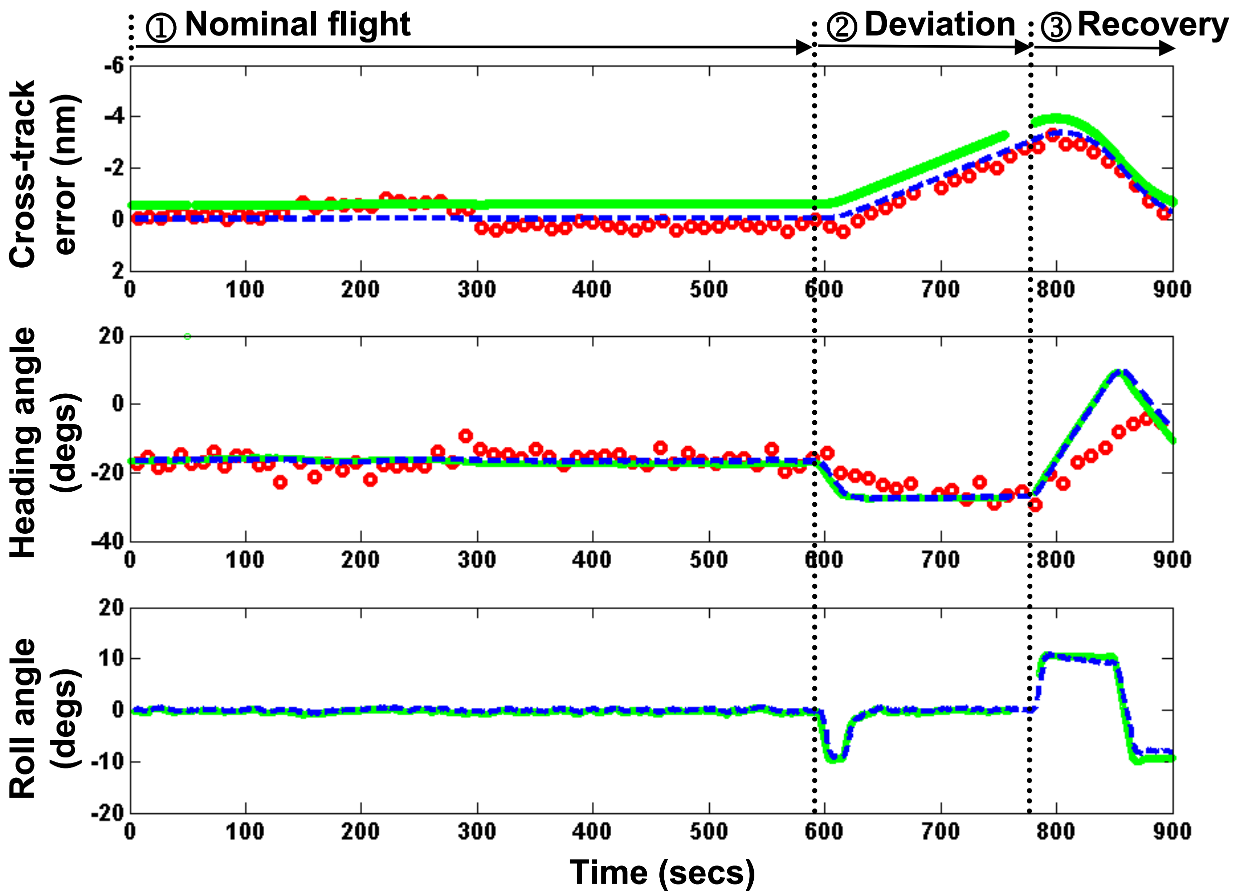
- **Boeing 737-400 test aircraft**
  - ☐ Collaboration with Boeing ATM
  - ☐ Two test flights over NW USA
  - ☐ Experimental configuration not representative of production model
- **Archived ARINC 429 aircraft states**
  - ☐ Latitude/longitude (IRU & GPS)
  - ☐ Altitude (barometric & GPS)
  - ☐ Heading, roll, pitch angles
  - ☐ Speeds (ground, true air, vertical, ...)
  - ☐ Selected FMS states (desired track, distance-to-go, bearing-to-waypoint)
- **Archived FAA Host ground states**
  - ☐ Radar latitude/longitude
  - ☐ Mode C transponder altitude
  - ☐ Radar-derived heading & speed
  - ☐ Controller assigned altitude
  - ☐ Flight plan route (textual)



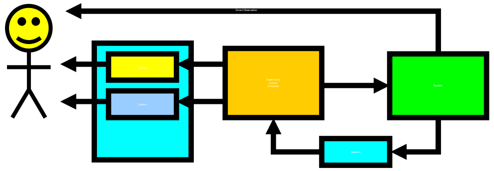


LATERAL DEVIATION TEST SCENARIO

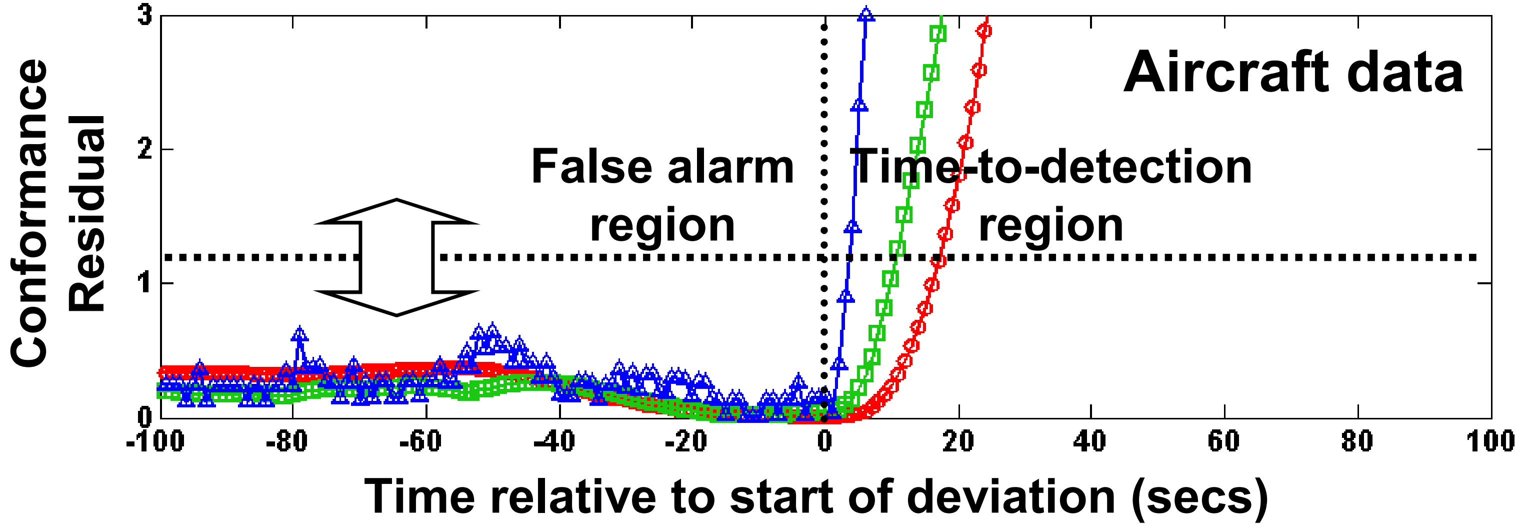


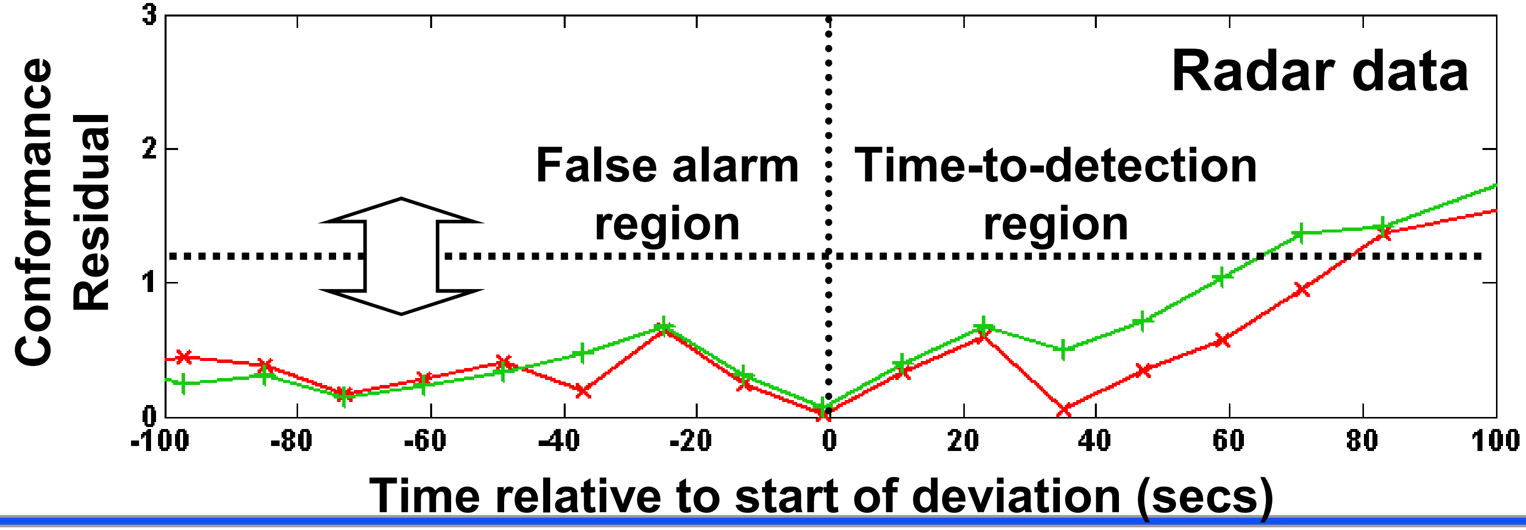


Databus data (0.1 sec) GPS data (1 sec) Radar data (12 sec)

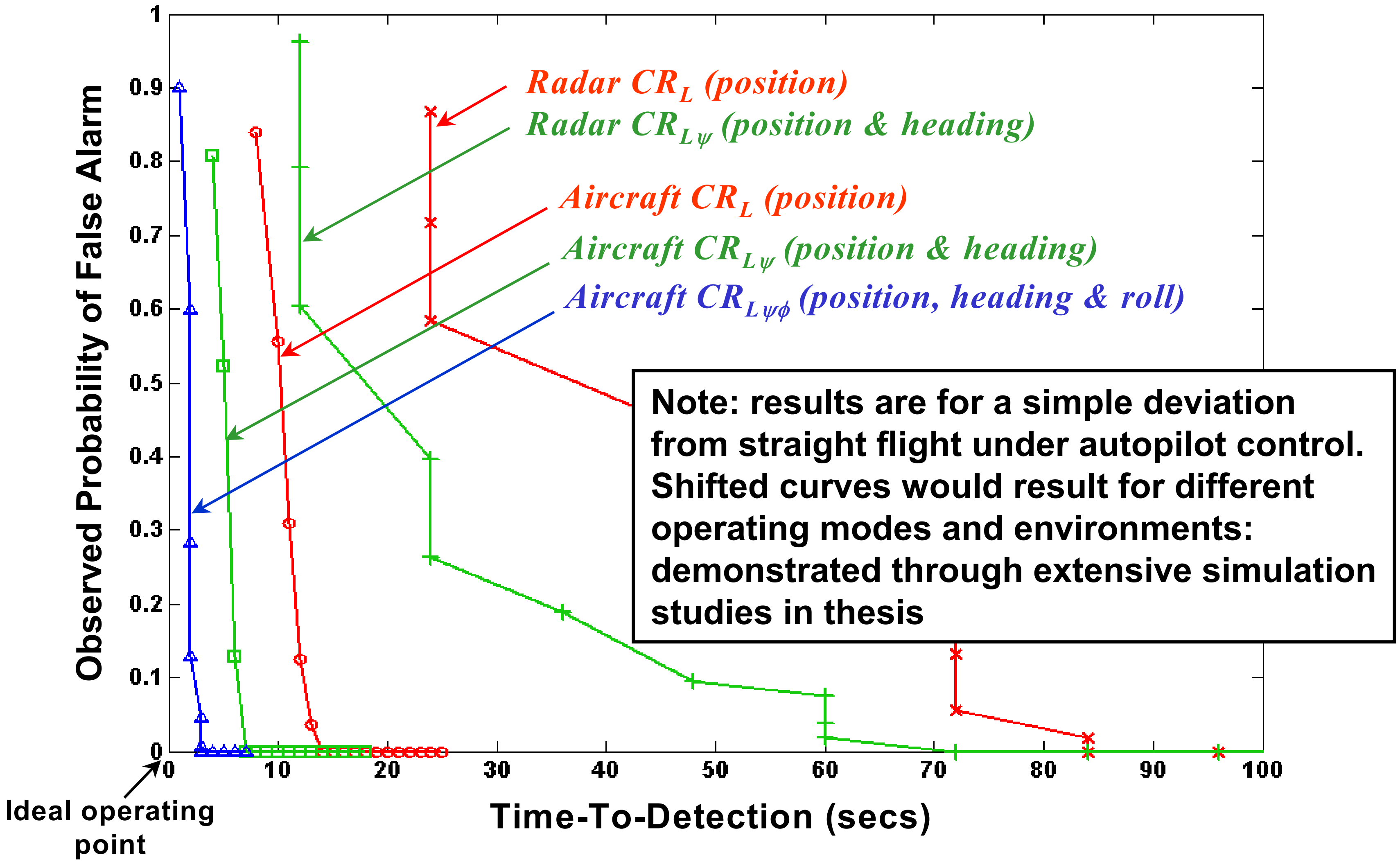


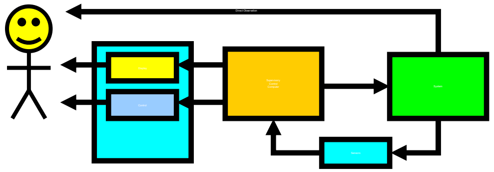
LATERAL DEVIATION DECISION-MAKING



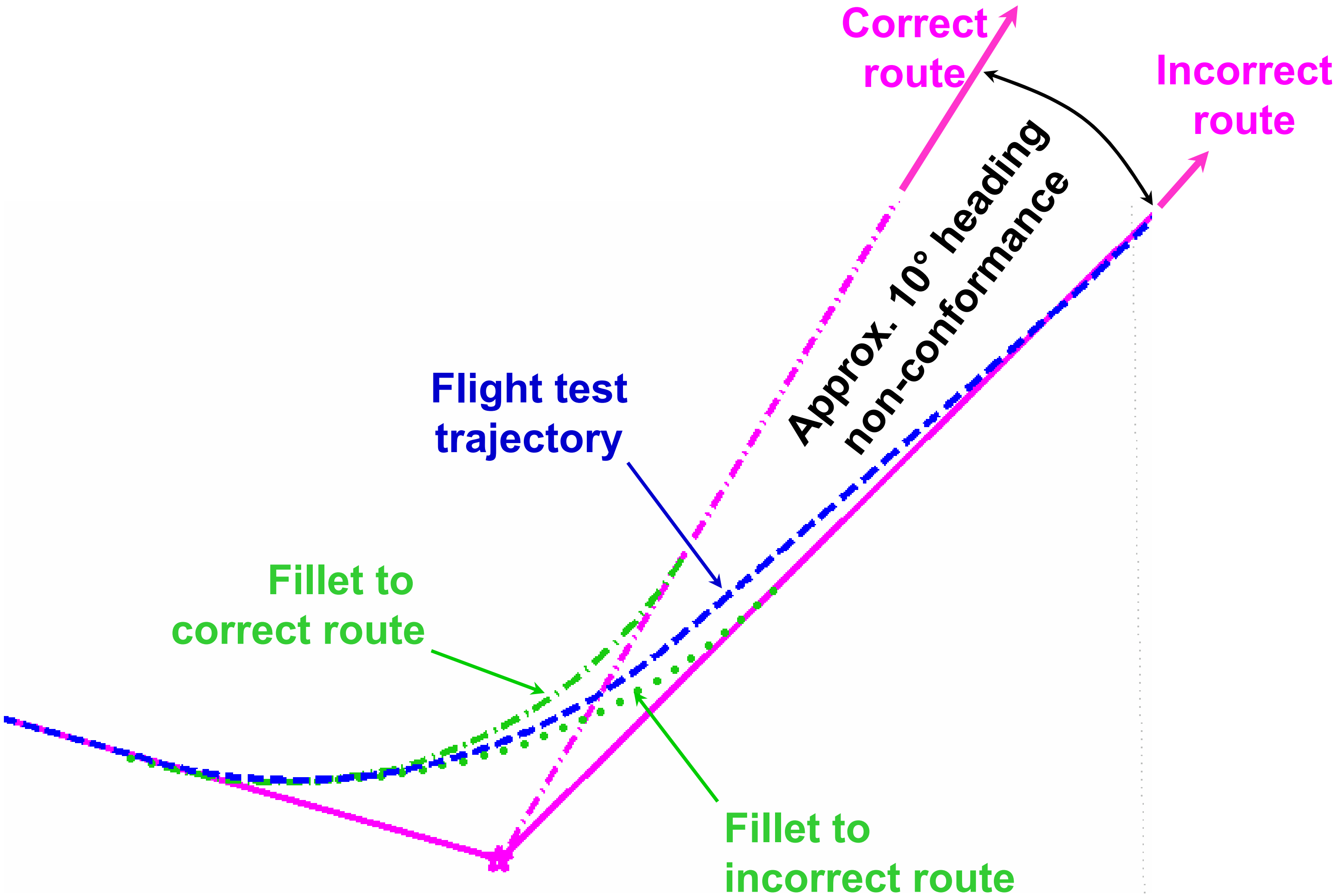


LATERAL DEVIATION FALSE ALARM / TIME-TO-DETECTION (2)

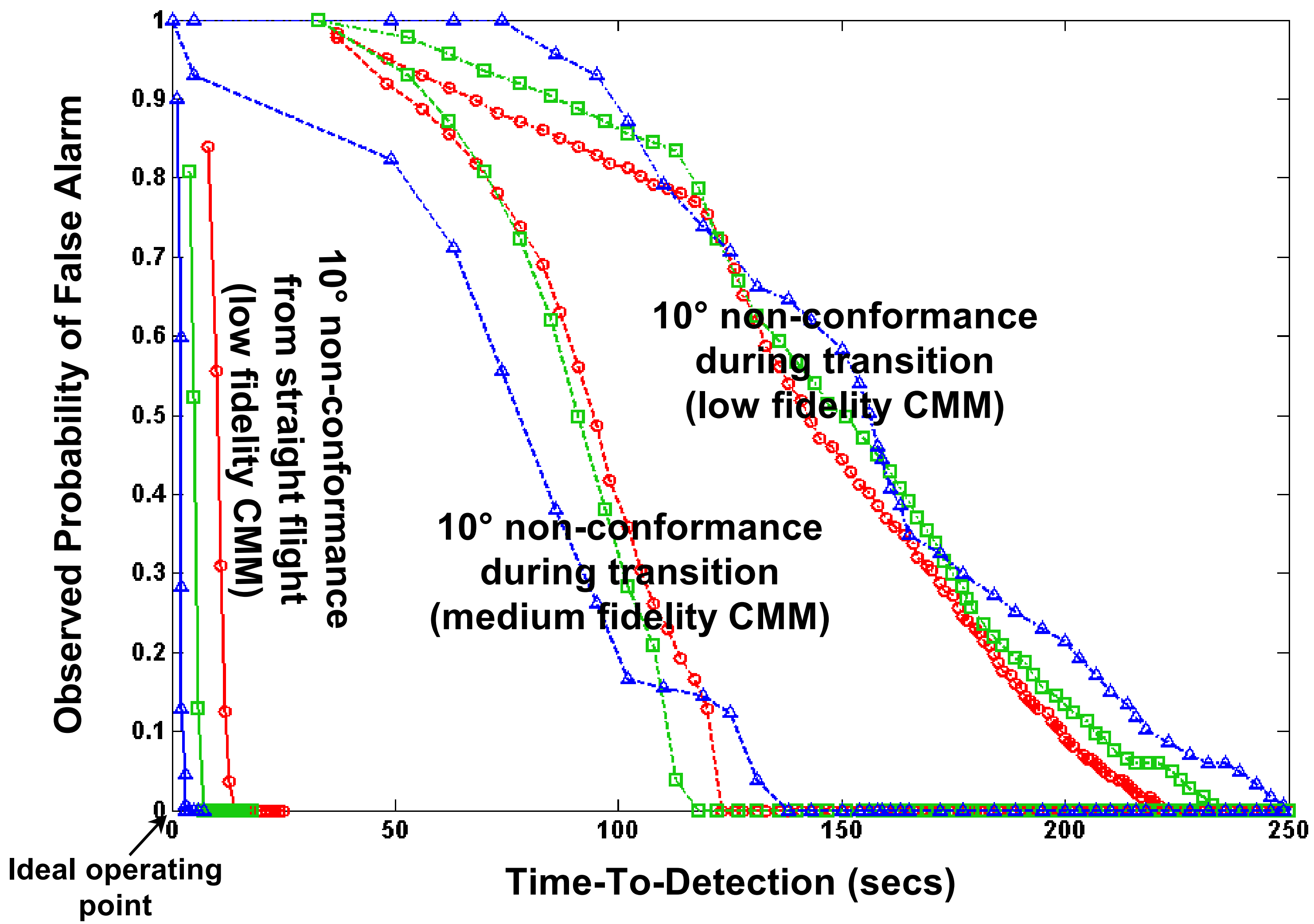


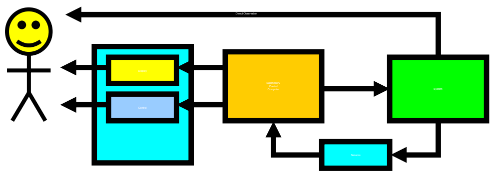


LATERAL TRANSITION NON-CONFORMANCE SCENARIO



LATERAL TRANSITION FALSE ALARM / TIME-TO-DETECTION



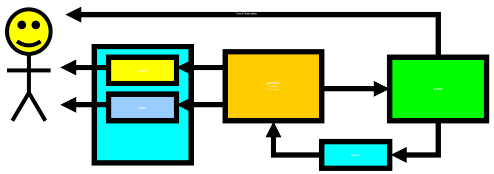


Design Principles for Alerting and Decision-Aiding Systems for Automobiles

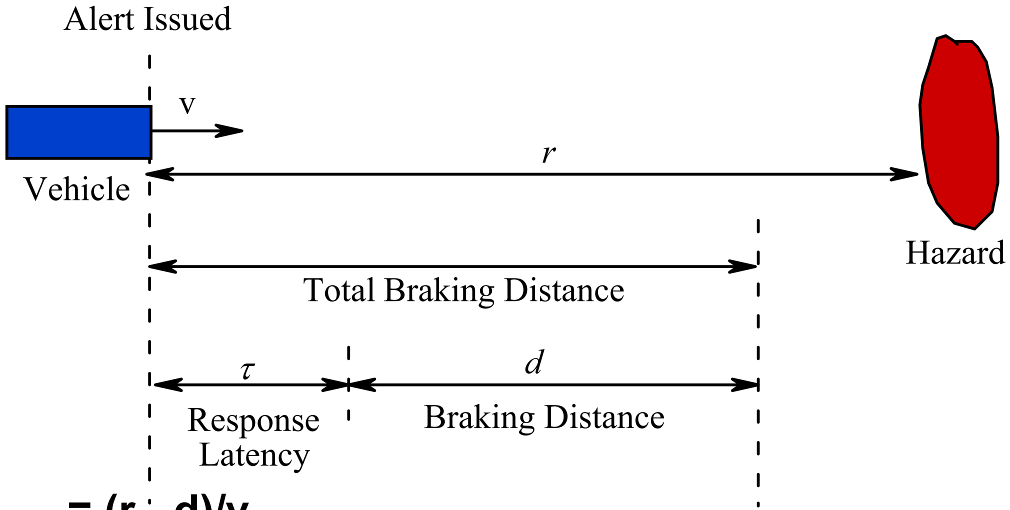
James K. Kuchar

Department of Aeronautics and Astronautics

Massachusetts Institute of Technology



Kinematics



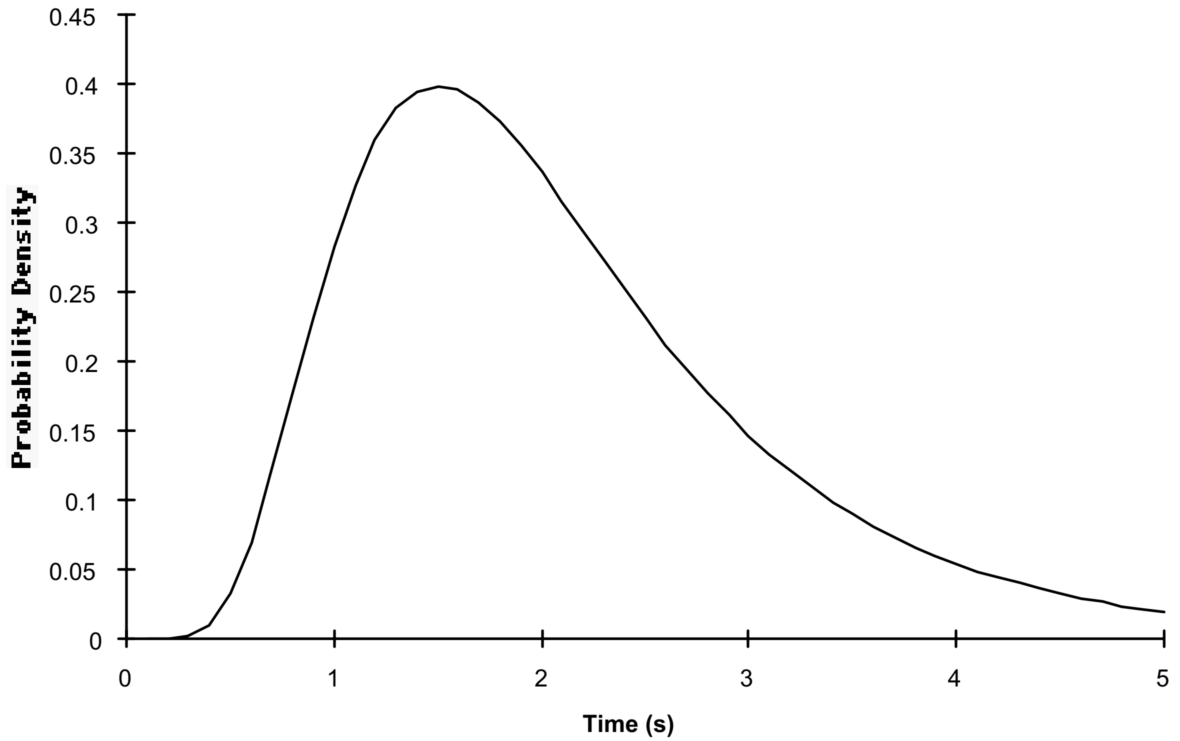
- **Alert time: $t_{alert} = (r - d)/v$**

  $t_{alert} = 0$ → braking must begin immediately

  $t_{alert} = \tau$ → alert is issued τ seconds before braking is required

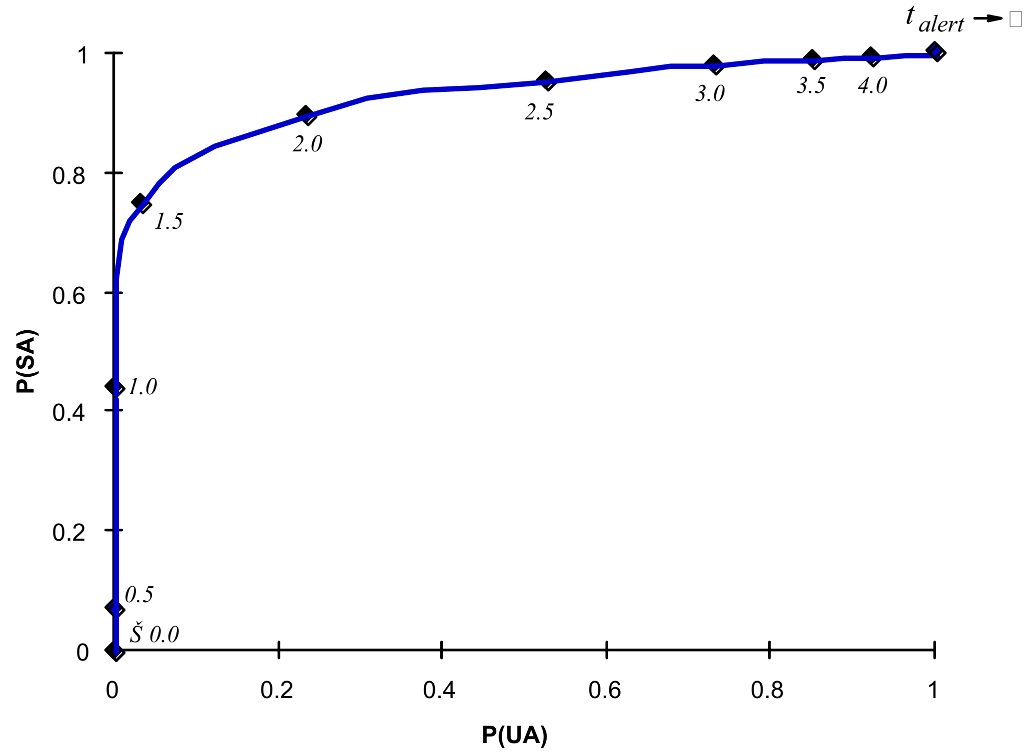
- **Determine P(UA) and P(SA) as function of t_{alert}**

Example Human Response Time Distribution

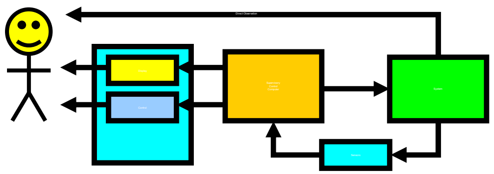


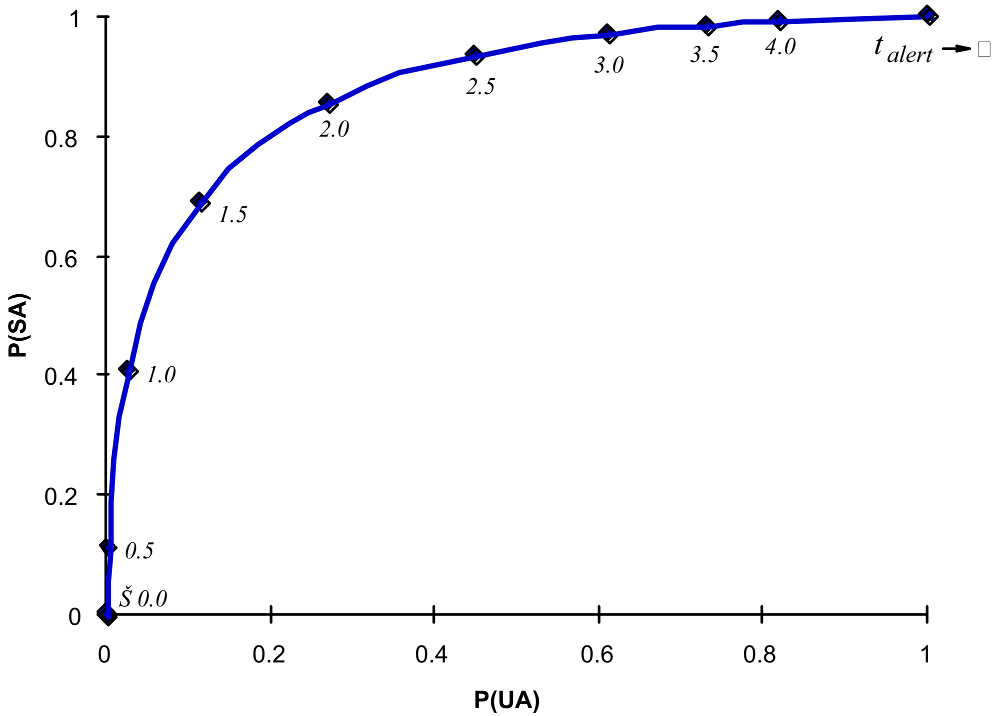
Lognormal distribution (mode = 1.07 s, dispersion = 0.49) [Najm et al.]

Case 3: Add Response Delay Uncertainty

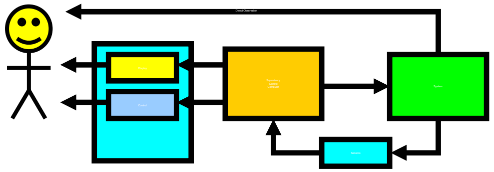


Case 4: Add Deceleration Uncertainty



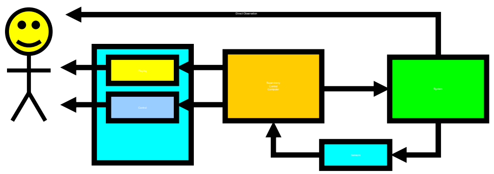


$\sigma_a = 3\ ft/s^2$



Conformance Monitoring for Internal and Collision Alerting

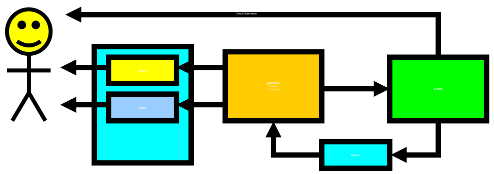
- **Simple Sensor Based Collision Alerting Systems Do Not Provide Adequate Alert Performance due to Kinematics**
  - SOC Curve Analysis
    - P(FA), P(MD) Performance
- **Enhanced Collision Alerting Systems Require Inference or Measurement of Higher Order Intent States**
  - Automatic Dependent Surveillance (Broadcast)
  - Environment Inferencing
    - Observed States



SURVEILLANCE STATE VECTOR

- **Aircraft Surveillance State Vector, $X(t)$ containing uncertainty & errors $\delta X(t)$ is given by:**
  - ☐ Traditional dynamic states
  - ☐ Intent and goal states

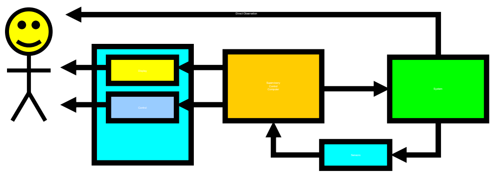
$$X(t) = \left\{ \begin{array}{c} \textit{Position}, R(t) \\ \textit{Velocity}, V(t) \\ \textit{Acceleration}, A(t) \\ \hdashline \textit{Intent}, I(t) \\ \textit{Goals}, G(t) \\ \vdots \end{array} \right\}, \qquad \delta X(t) = \left\{ \begin{array}{c} \delta R(t) \\ \delta V(t) \\ \delta A(t) \\ \hdashline \delta I(t) \\ \delta G(t) \\ \vdots \end{array} \right\}$$



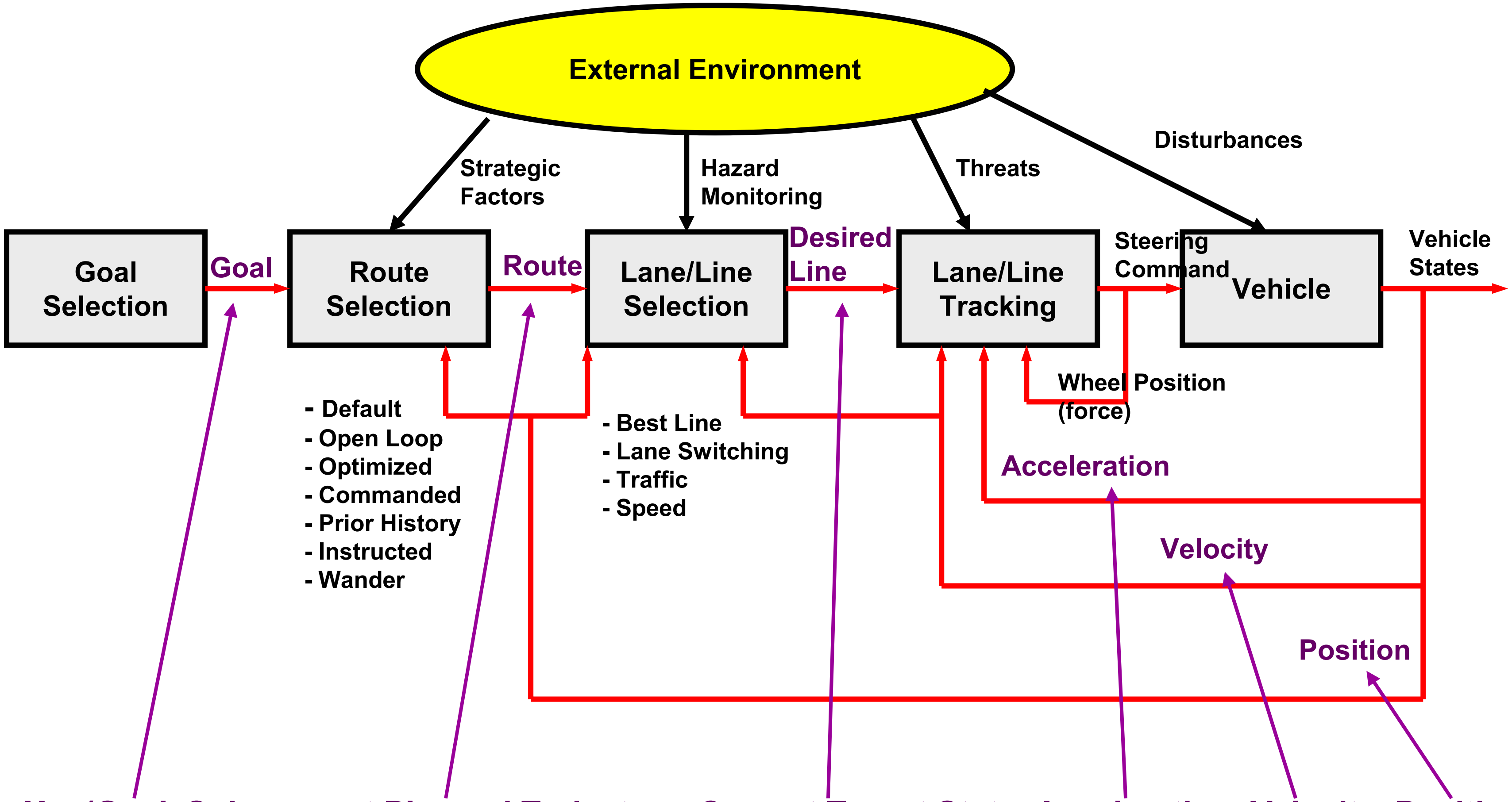
INTENT STATE VECTOR

- **Intent State Vector can be separated into current target states and subsequent states**

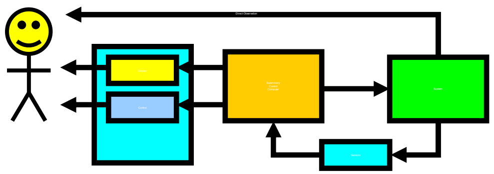
$$\boldsymbol{I}(\boldsymbol{t}) = \left\{ \begin{matrix} \boldsymbol{\mathit{Current\ target\ states}} \\ \boldsymbol{\mathit{Subsequent\ planned\ trajectory}} \end{matrix} \right\} \qquad \text{(Eqn. 3)}$$



Automobile Lateral Tracking Loop

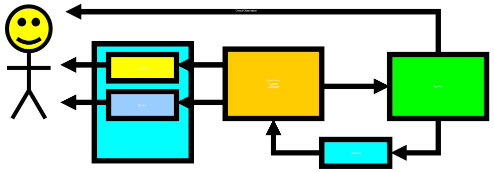


X = (Goal, Subsequent Planned Trajectory, Current Target State, Acceleration, Velocity, Position)

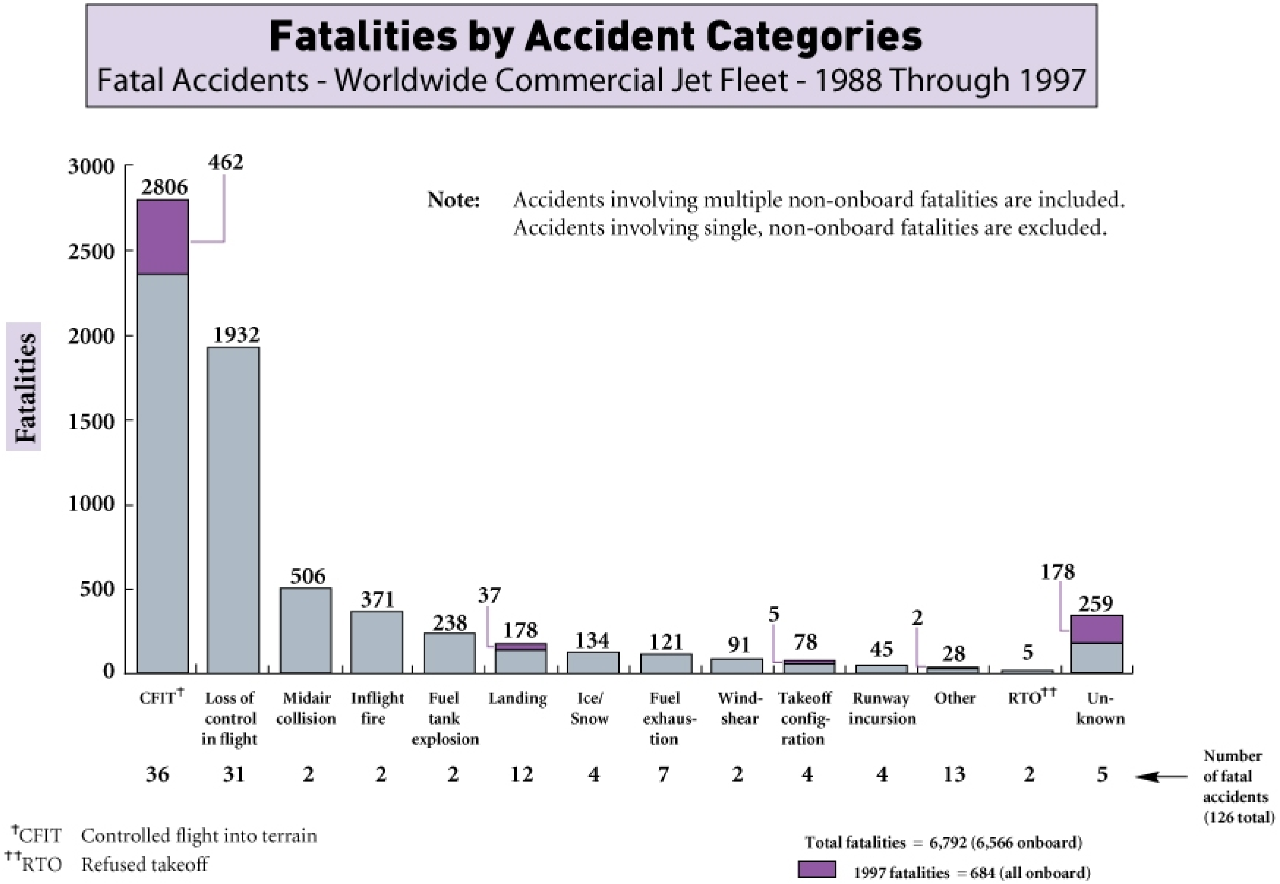


Intent Observability States

- **Roadway**
- **Indicator Lights**
  - ☐ Break Lights
  - ☐ Turn Signals
  - ☐ Stop Lights
- **Acceleration States**
- **GPS Routing**
- **Head Position**
- **Dynamic History**
- **Tracking Behavior**

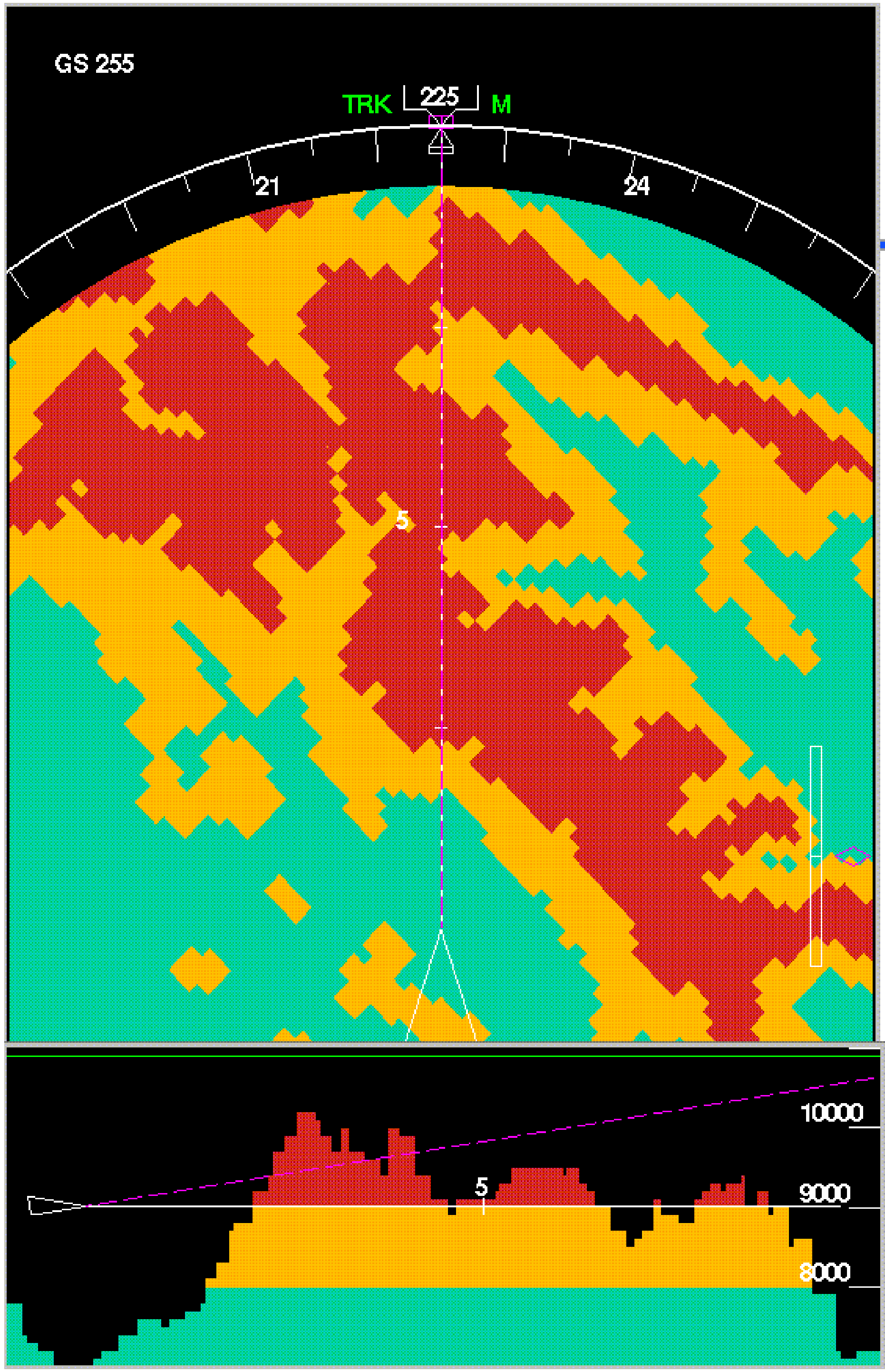


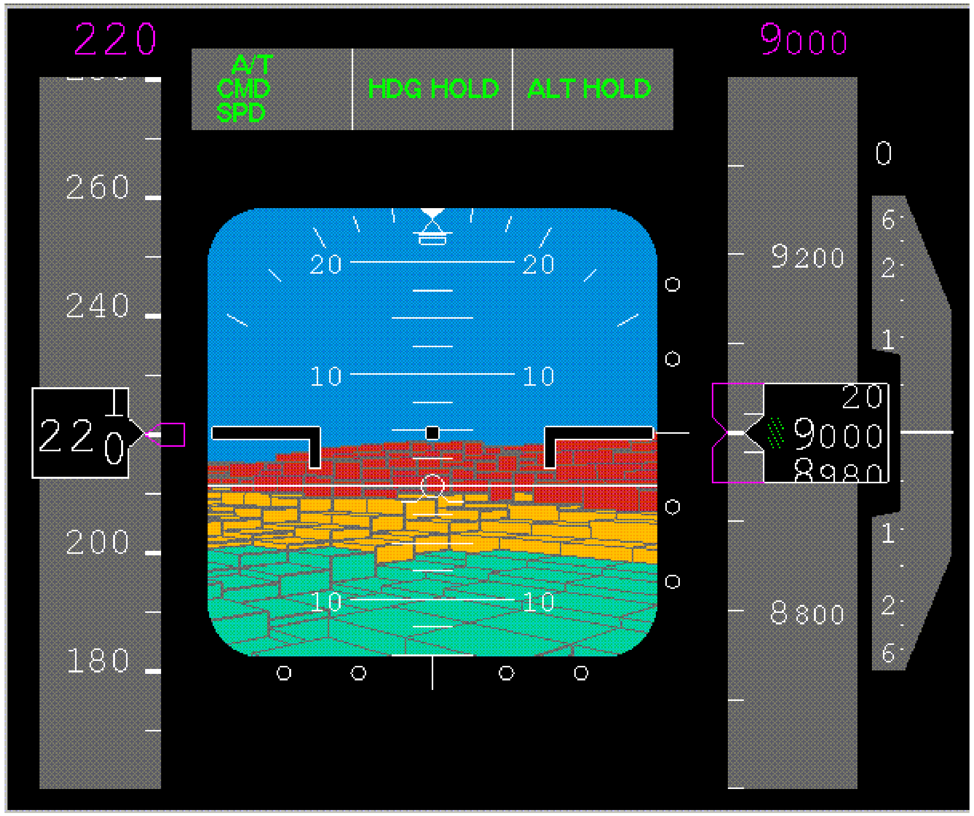
Fatal Accident Causes

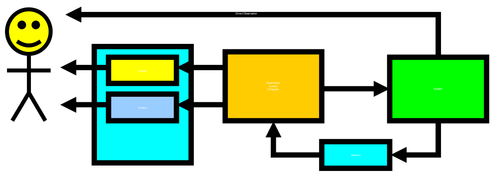


Adapted from The Boeing Company

Prototype MIT Terrain Alerting Displays







Alerting System Research

- **Kuchar, 1995**
  - Method for setting alert thresholds to balance False Alarms and Missed Detections
- **Yang, 2000**
  - Use of dynamic models to drive alerting criteria
- **Tomlin, 1998**
  - Hybrid control for conflict resolution
- **Lynch and Leveson, 1997**
  - Formal Verification of conflict resolution algorithm
- **Pritchett and Hansman, 1997**
  - *Dissonance* between human mental model and alerting system
    - Information that suggests different timing of alerts and actions to resolve the hazard
  - Suggested display formats to reduce dissonance