



MIT International Center for Air Transportation

Supporting Pilots' Time-Dependent Information Needs During Operations in Adverse Weather

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- **Adverse Weather Significantly Impacts Flight Operations**

- Safety -- 22.5% All US Accidents
- Efficiency -- 17% / \$1.7B per year Avoidable Weather Delays (Source: FAA)

(Courtesy of NASA)



Convective Weather



Icing



Turbulence



Ceiling & Visibility

- **Multiple efforts to develop new weather information tools**

- Cockpit weather datalink

- **In order to develop *safe* and *effective* decision-support tools, it is important to:**

- Understand users' information needs and cognitive tasks
- Understand the implications and limitations of supporting their tasks

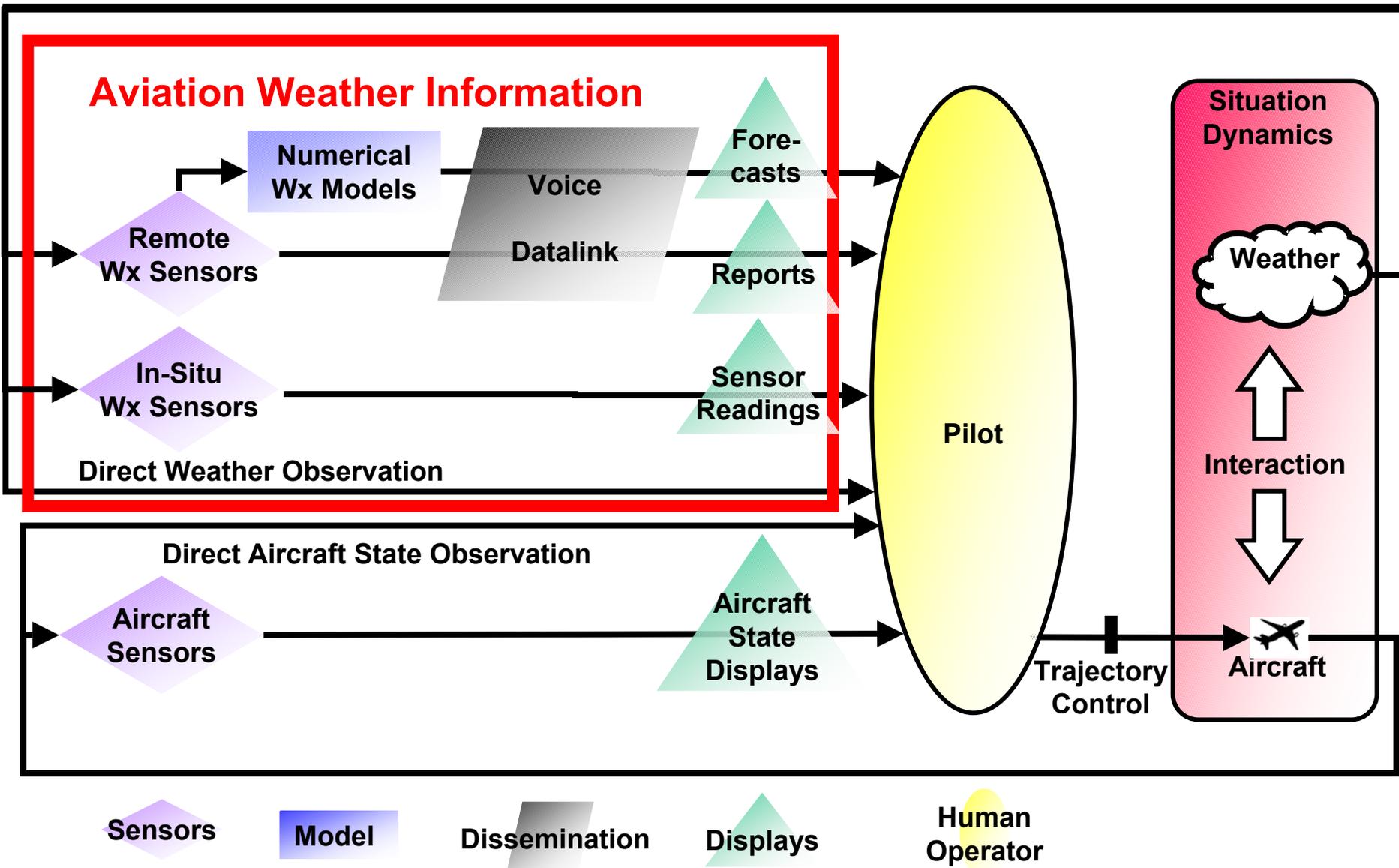
Methodology



- **Cognitive Analysis of Pilots Decisions**
- **Temporal Representation Framework**
 - Deterministic Regime
 - Stochastic Regime

Human-Centered Approach

Closed Loop Feedback Process



Planning Tasks of Pilots

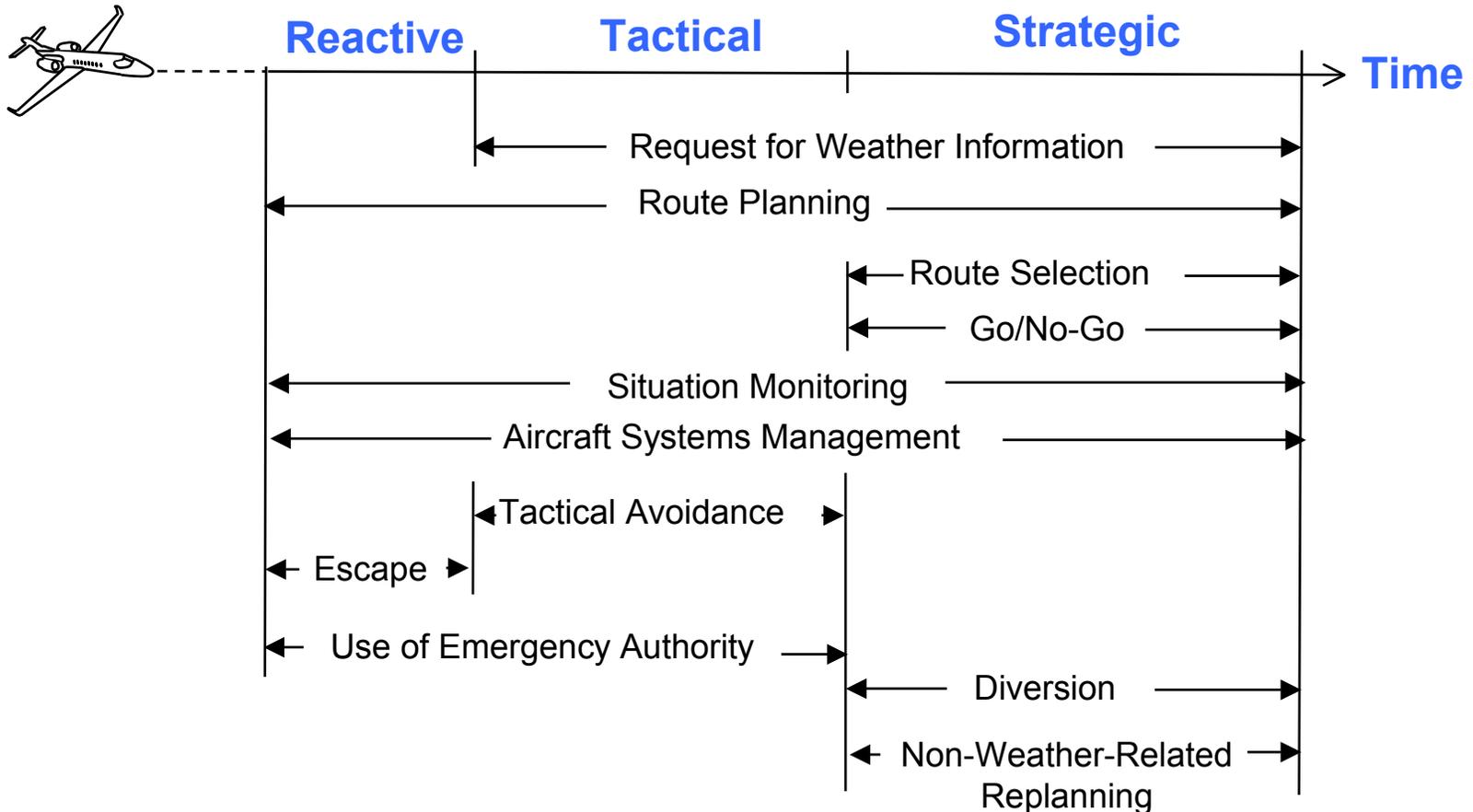
Weather-Related Decisions



Short-term planning where safety goals dominate the decisions

Planning based on the main goals without considering the entire remainder of the flight

Planning for the remainder of the flight considering the main goals: safety, legality, efficiency, satisfactory level of comfort and service

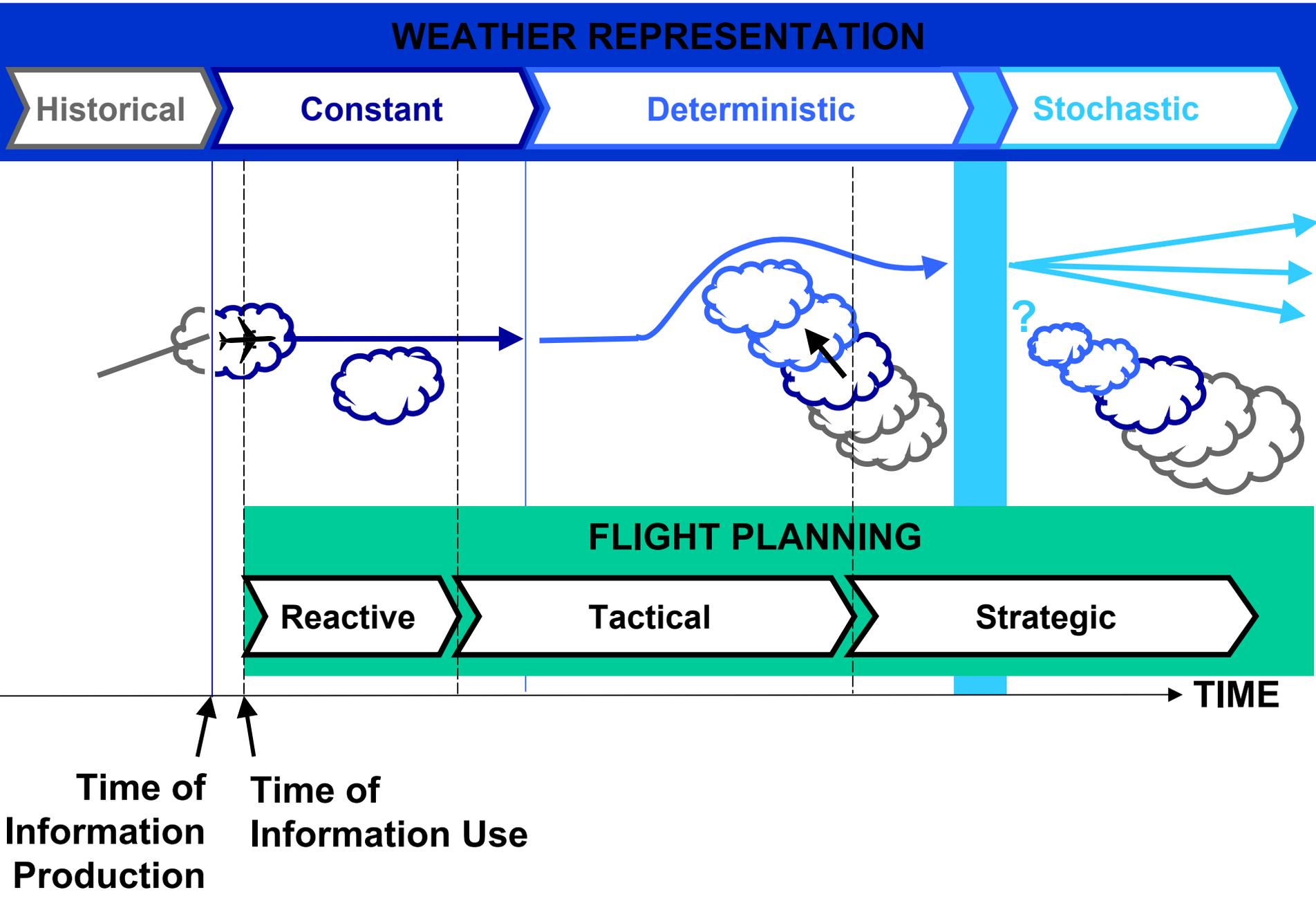


Methodology



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Temporal Regimes of Cognitive Processes



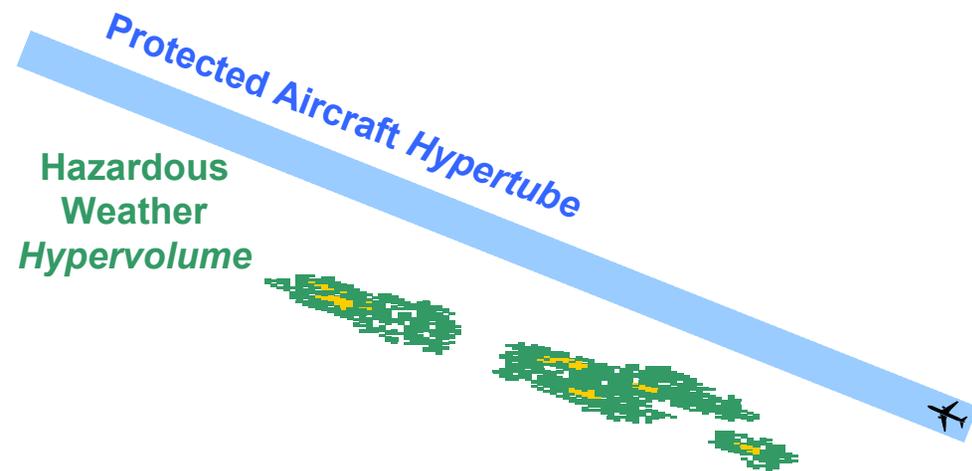
Methodology



- **Cognitive Analysis of Pilots Decisions**

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 - Stochastic Regime

Pilots' Perception of Forecast Quality



CONTINGENCY MATRIX

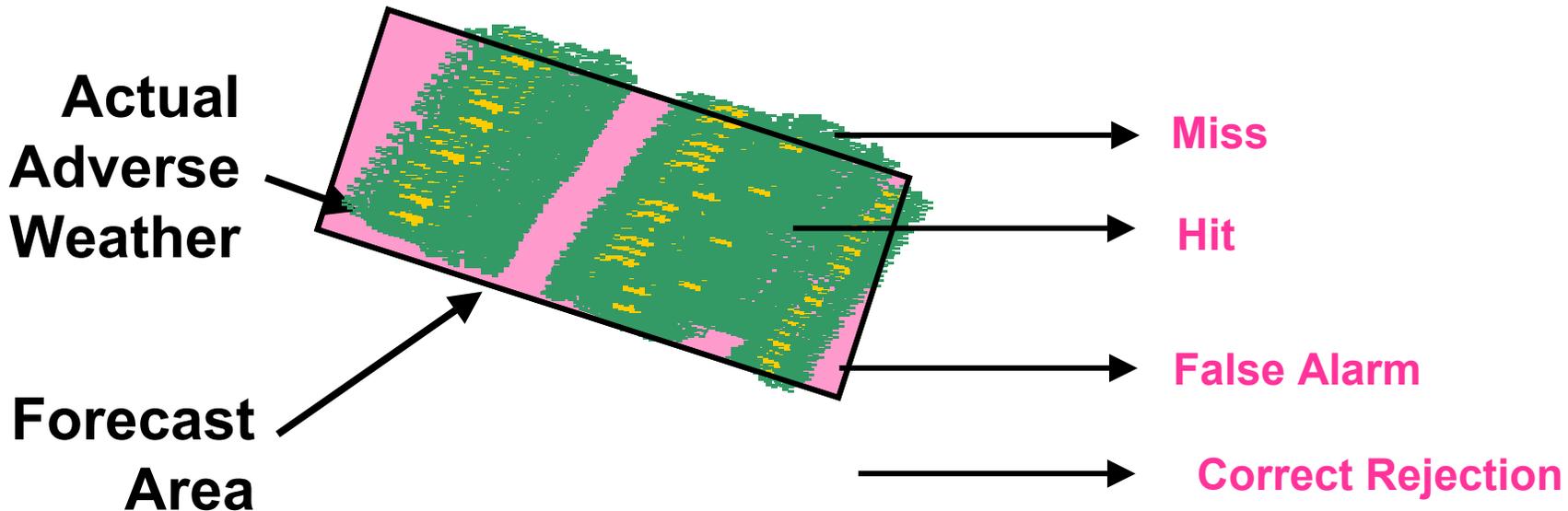
Prediction of 4-D Intersection*

	Y	N
Y	Hit	Miss
N	False Alarm	Correct Rejection

Occurrence of 4-D Intersection*

*Between Protected Aircraft Hypertube and Hazardous Weather Hypervolume

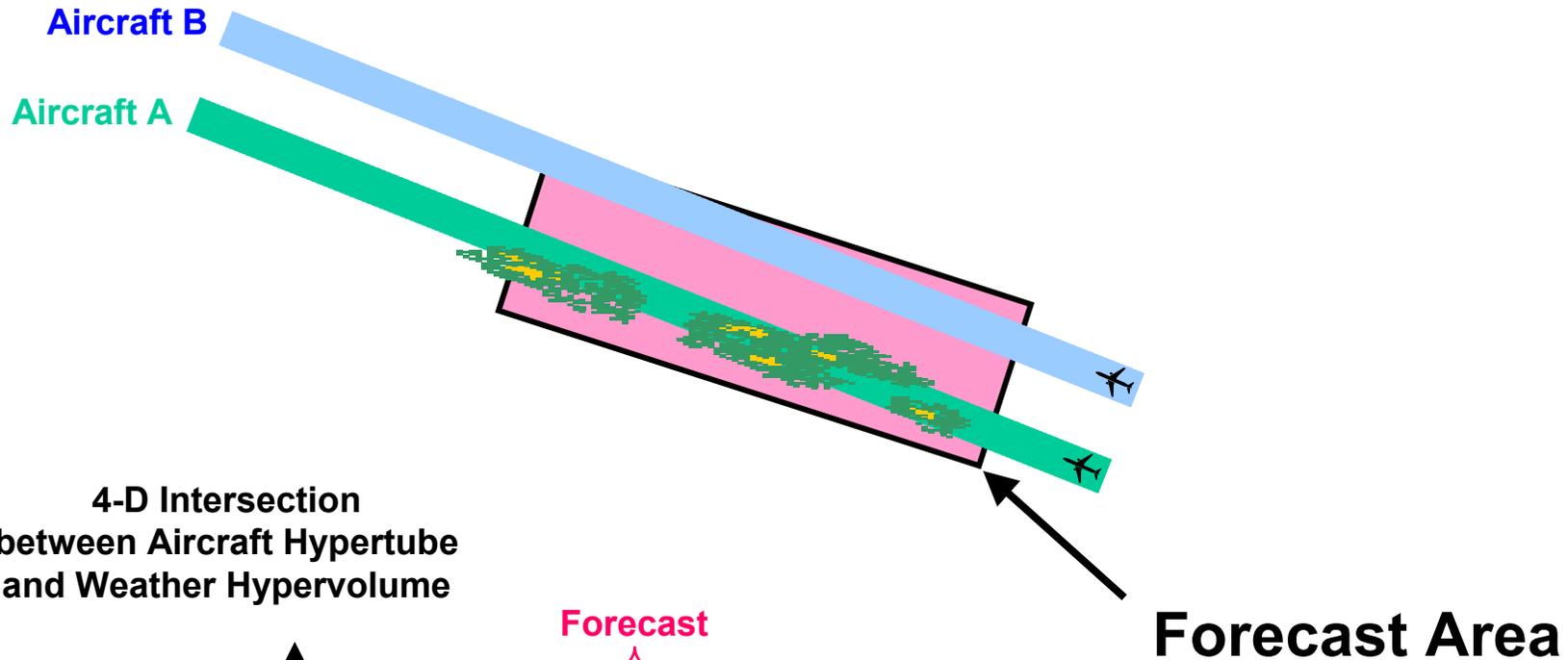
Traditional Forecast Verification Methodology for ΔT Hours



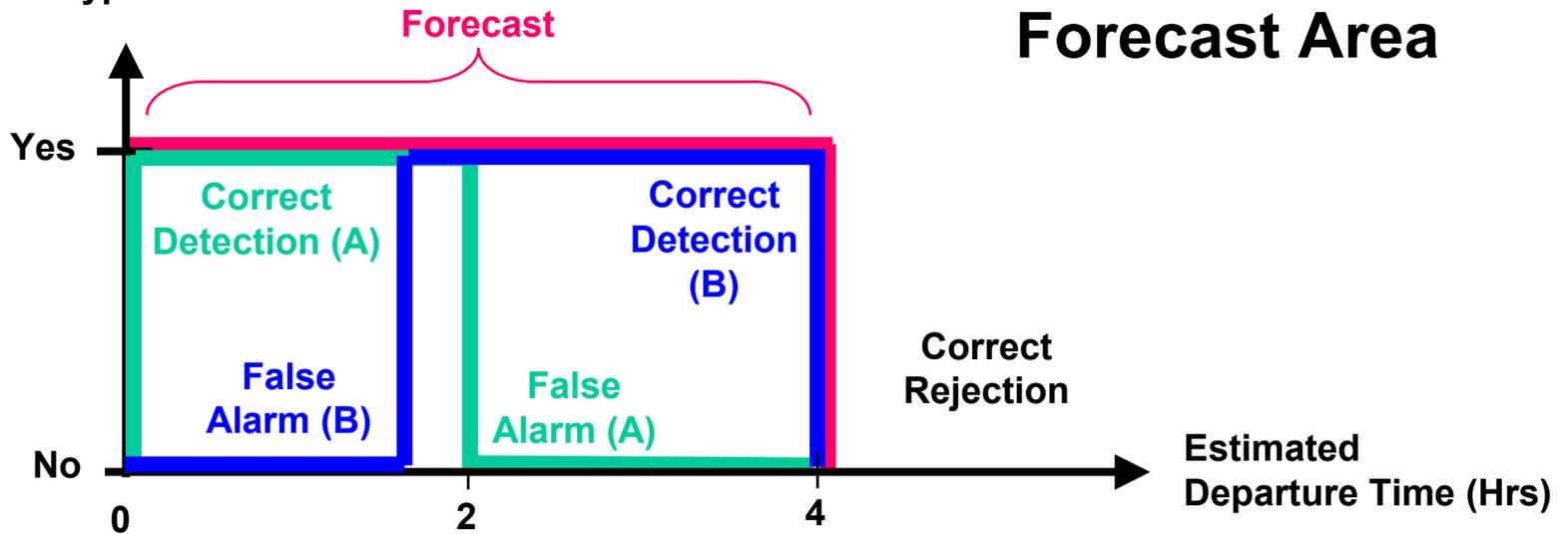
Scores Based on Contingencies

Critical Success Index	73%
Signal Detection Theory Hit Rate	89%
Signal Detection Theory False Alarm Rate	17%
Mean Square Error	14%

Sensitivity of 4-D Intersection Test to Timing (e.g., ETD)



4-D Intersection
between Aircraft Hypertube
and Weather Hypervolume



Trajectory-Based Weather Forecasting



- **Opportunity**

- Route Availability Planning Tool (RAPT) with MIT Lincoln Lab
 - ▲ *Uses convective weather forecast + airline schedule*
 - ▲ *Predicts clear/blocked/impacted status of departure routes*
 - ➔ *Essentially 4-D intersection test*
- Key Questions
 - ▲ *What interface to provide to ATC users?*
 - ▲ *How to manage/communicate uncertainty?*
 - ➔ *Weather growth/decay*
 - ➔ *Aircraft trajectory*
 - ➔ *EncounterTiming*

- **Analytical approach**

- Understand and model uncertainty in situation dynamics
- Characterize the geometry/kinematics of encounter
- Identify
 - ▲ *Implications for available decisions*
 - ▲ *Opportunities for support the identification of options*
- Provide recommendations for RAPT team & other tool development efforts

Summary of Analysis



- **Relative Aircraft Track Angle**

- Upstream: Aircraft trajectory toward boundary line
- Downstream: Aircraft trajectory away from boundary line

- **Aircraft-Weather Encounter Situation**

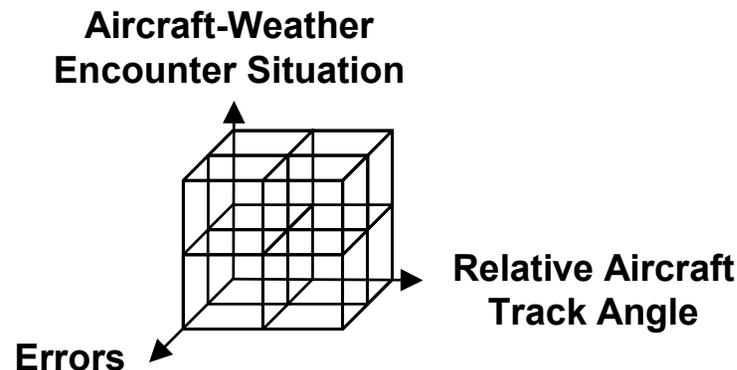
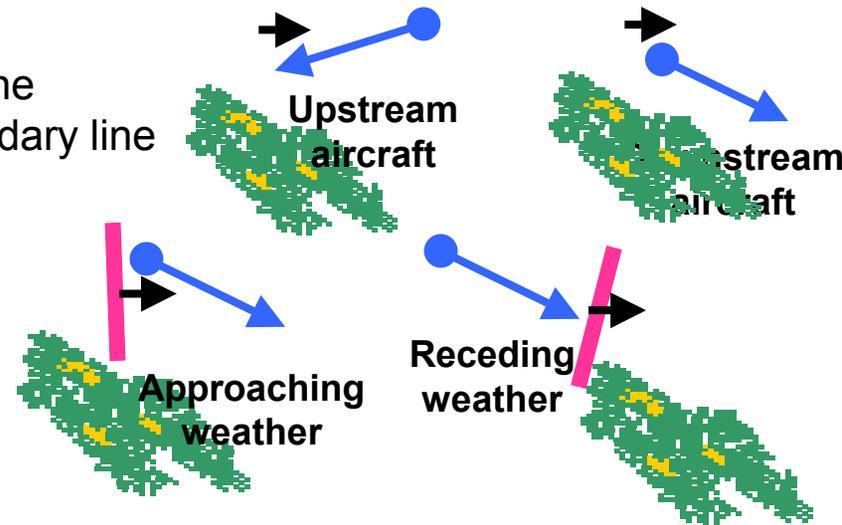
- Approaching weather boundary
- Receding weather boundary

- **Error (Trajectory-Based)**

- False alarms (FA)
 - ▲ *Adverse weather is forecast to impact aircraft trajectory but does not*
- Missed detections (MD)
 - ▲ *Adverse weather is not forecast not to impact aircraft trajectory but does*

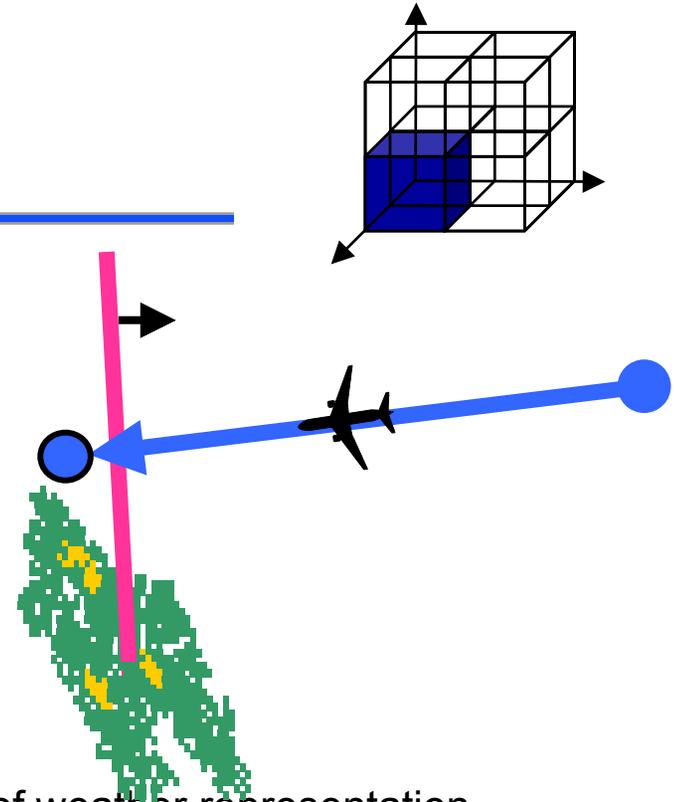
- **8 Scenarios**

- Potential causes
- Characterization
- Implications
- Adjustment options



Example Worse Case

- **Missed detection** of **approaching** weather boundary for **upstream** aircraft trajectory
- **Potential causes**
 - Front velocity underestimation
 - Initiation/growth underestimation
 - Aircraft velocity overestimation
- **Characterization**
 - Transition to reduced capacity along route
 - Associated with *too late* scenario
 - Aircraft launch decision made in *stochastic regime* of weather representation
- **Implications - Strategic**
 - Aircraft already in flight may have to divert
 - Aircraft not already launched may have to delay departure for a long time
- **Adjustment options - Tactical**
 - ATC: Identify aircraft trajectories around or above front
 - Pilots: Identify gaps in front line
- **Adjustment support**
 - ATC: Pre-negotiation between controllers for deviating aircraft flows
 - Pilots: Support weather information update



Conclusions



- **Weather decision-support requires addressing users' time-dependent information needs**
 - Planning tasks
 - Weather representation
- **Under *deterministic regime*, trajectory-based weather forecasting has the potential to help support key decisions**
 - Matches users' perspective and information needs for dynamics assessment
 - ▲ *Pilots*
 - ▲ *ATC*
 - Aircraft-weather encounter analysis points to key risk adjustment strategies

AIRLINE PILOTS

WEATHER FORECASTING STONE

CONDITION	FORECAST
Stone is Wet	Rain
Stone is Dry	Not Raining
Shadow on Ground	Sunny
White on Top	Snowing
Can't see Stone	Foggy
Swinging Stone	Windy
Stone Jumping Up & Down	Earthquake
Stone Gone	Tornado





Backup

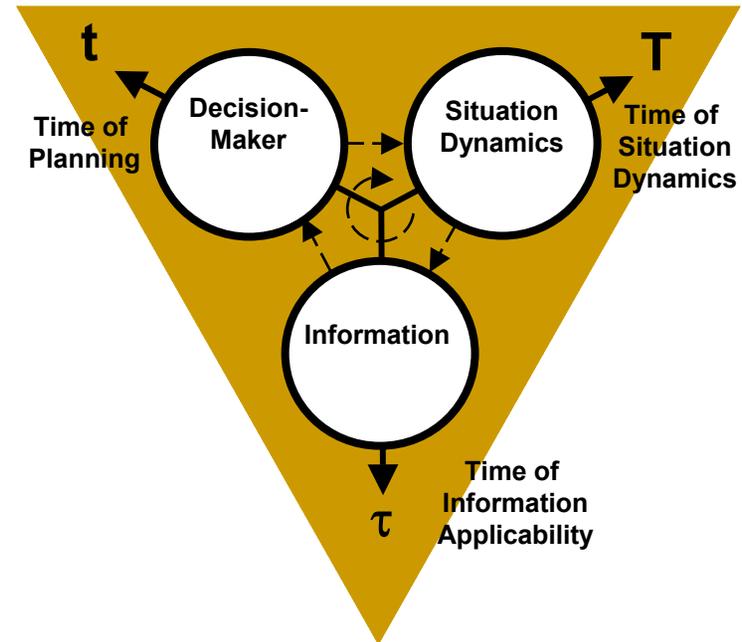
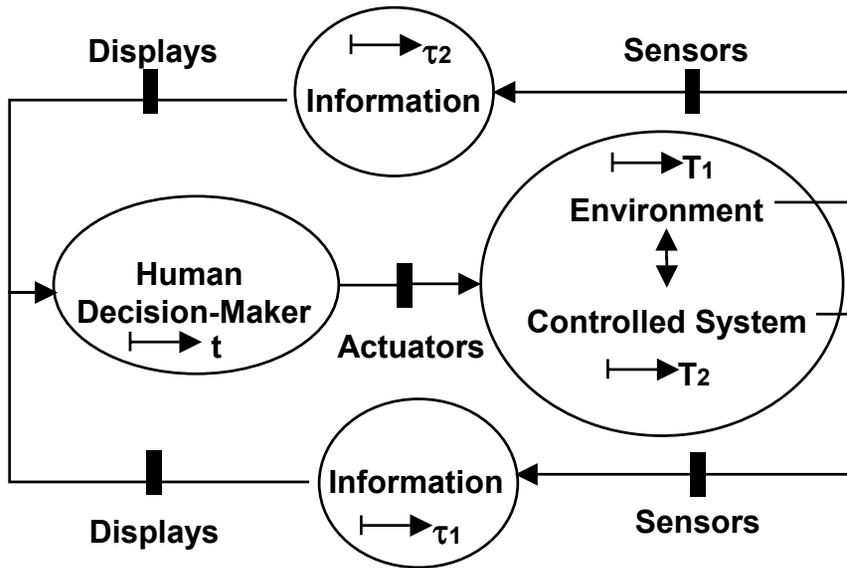
Motivation

Pilots' information needs change over time



*Pilots' functions
vary over time*

Weather is chaotic

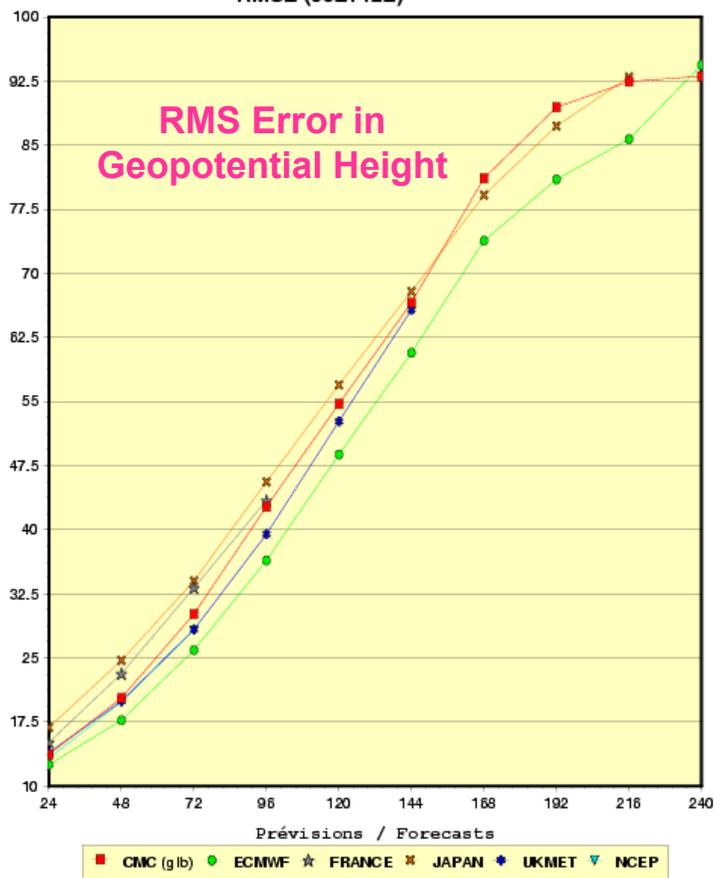


*Forecast accuracy decreases with
forecast horizon
Information is not sampled and
provided continuously*

Uncertainty Growth with Forecast Horizon



VERIFICATION vs RADIOSONDES
GZ 500 hPa 06/2002
Hémisphère Nord/Northern Hemisphere
RMSE (00Z+12Z)

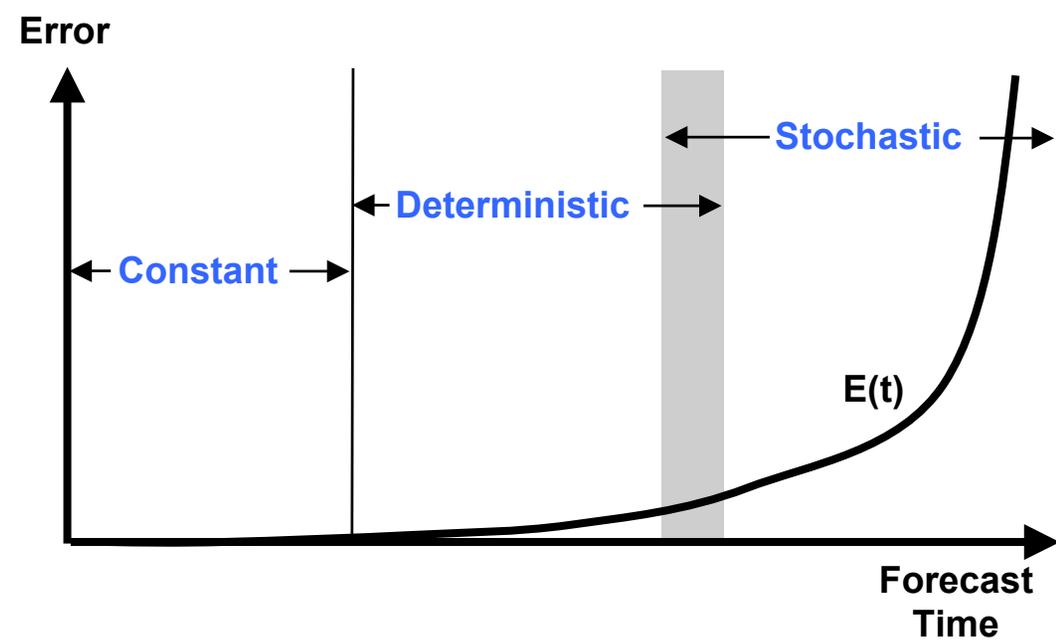


CMC

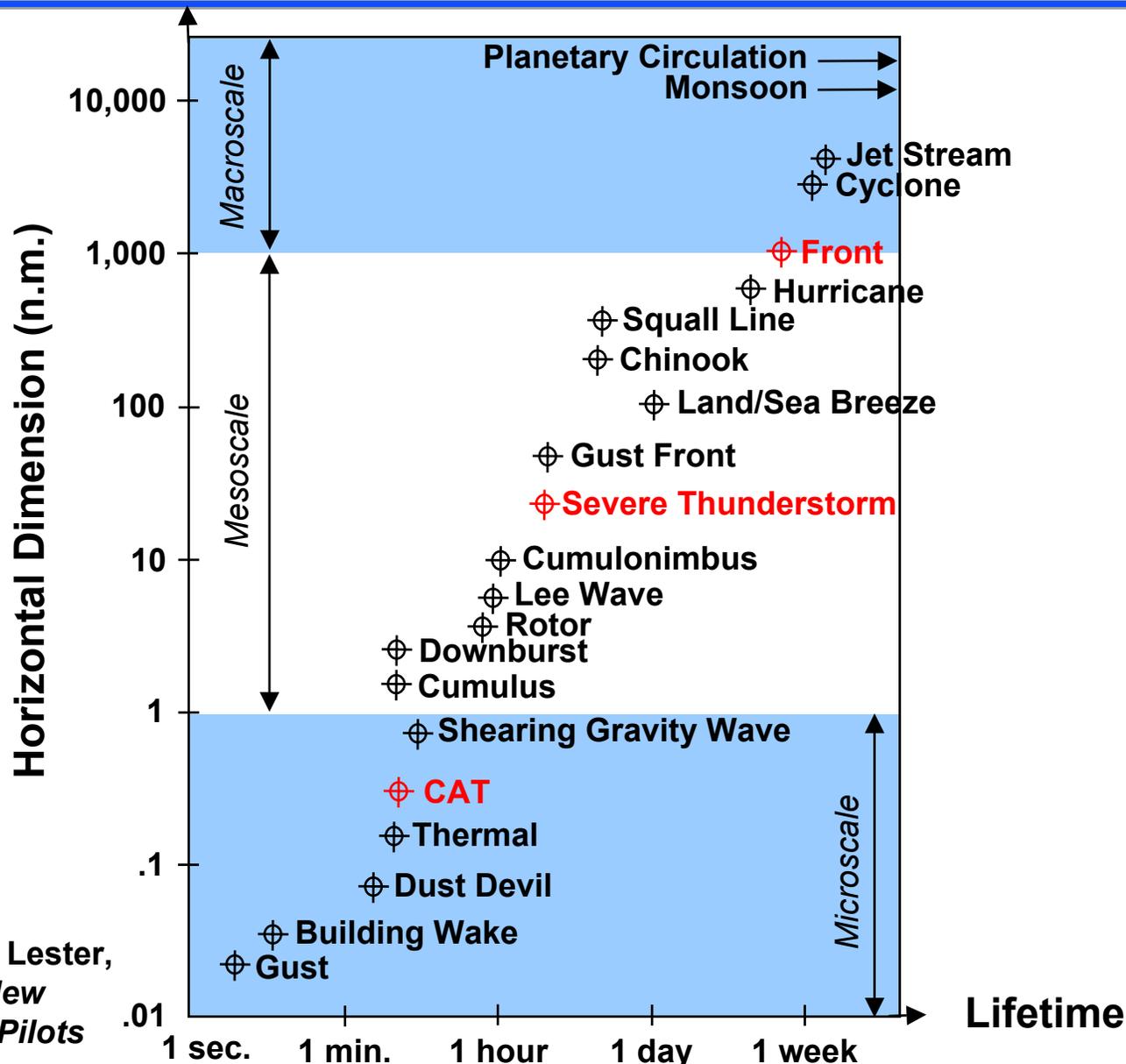
Weather representation based on observation over a time period where conditions do not significantly change

Weather representation based on deterministic forecast of "acceptable" accuracy

Weather representation at time in future beyond "predictability limit"



Predictability Horizon Linked to Weather Phenomenon Lifetime

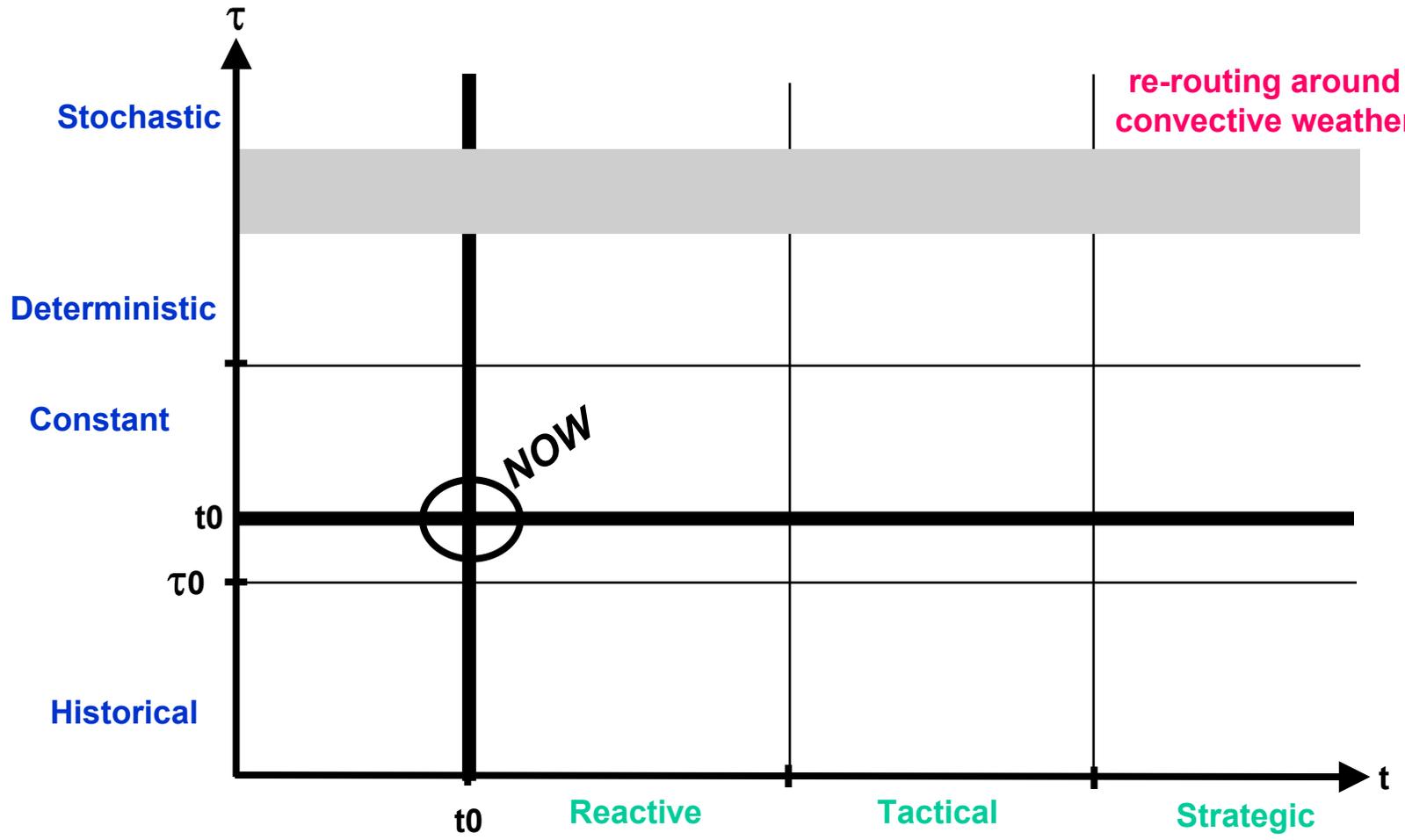


Reference: P. F. Lester, *Turbulence, A New Perspective for Pilots*

Matrix of Temporal Regimes of Cognitive Processes of Cognitive Processes



Temporal Regimes of Weather Representation

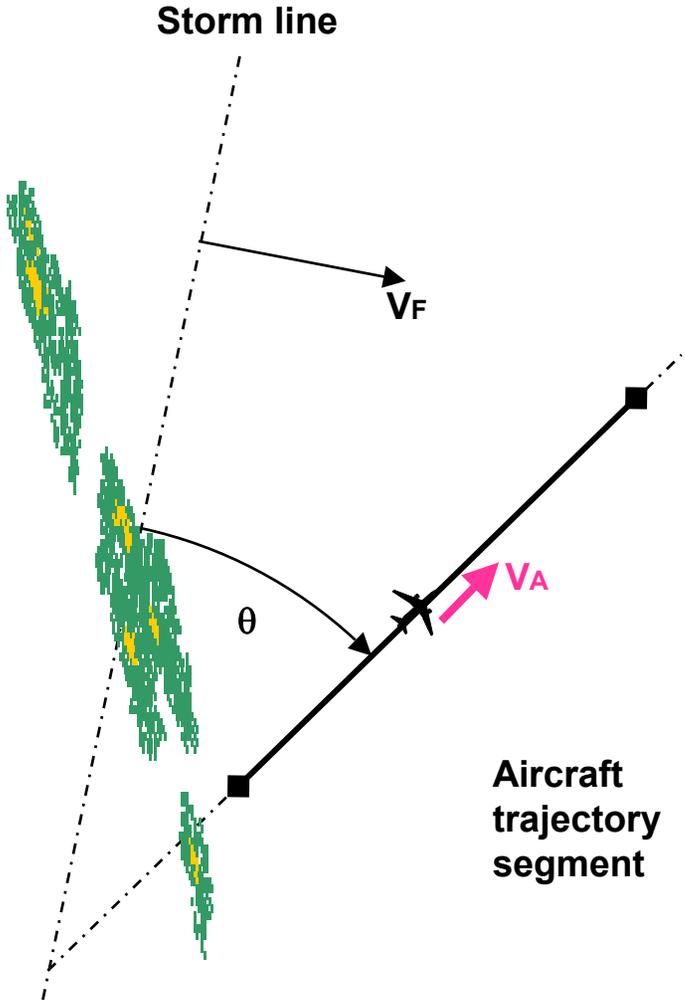


t_0 : time of information use

τ_0 : time of information production

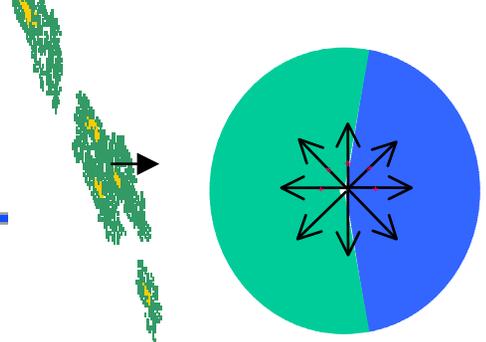
Temporal Regimes of Flight Planning

Scenario Analysis Model



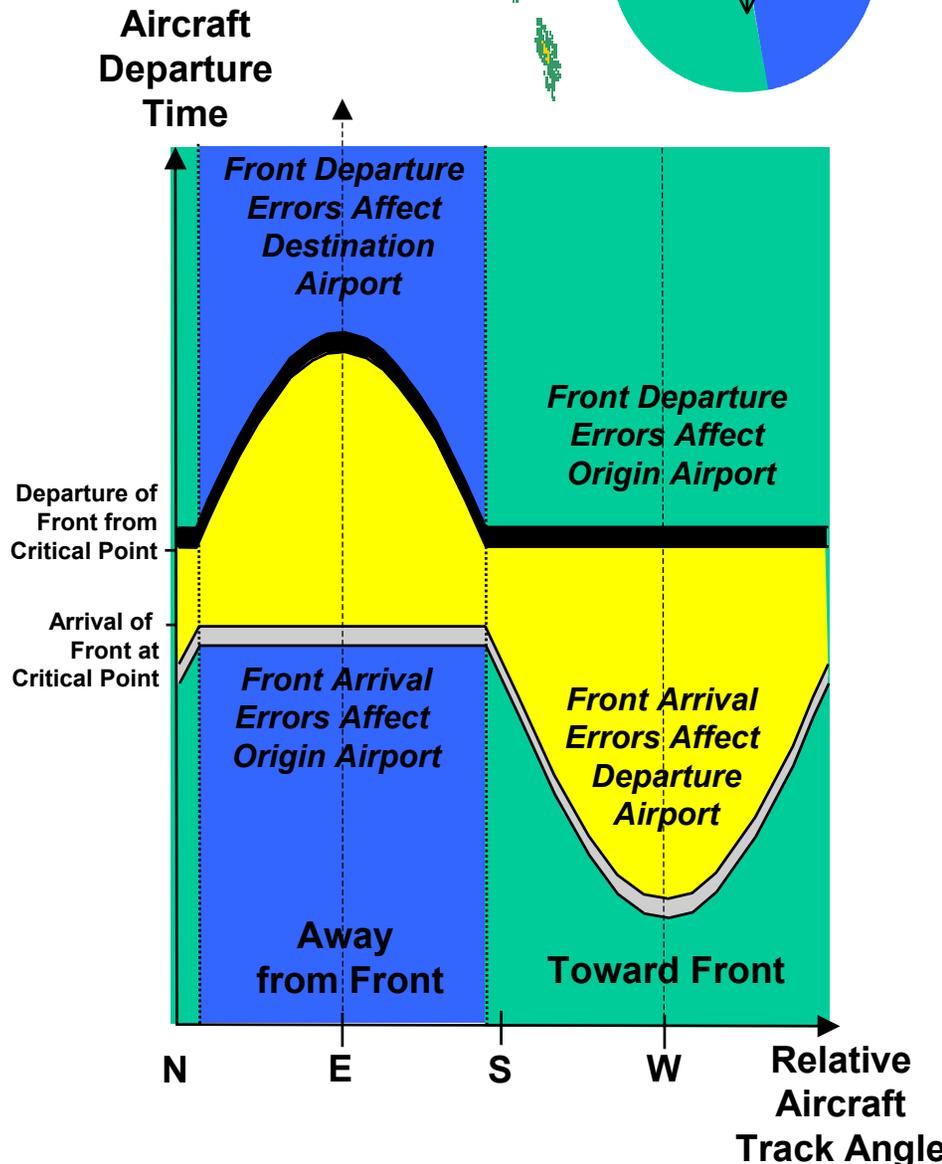
- V_A Aircraft velocity
- V_F Front velocity perpendicular to the front line
- θ Angle between weather front line and aircraft track

Trajectory-Based Forecast Errors

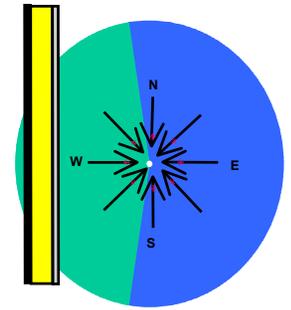


Stochastic
Regime

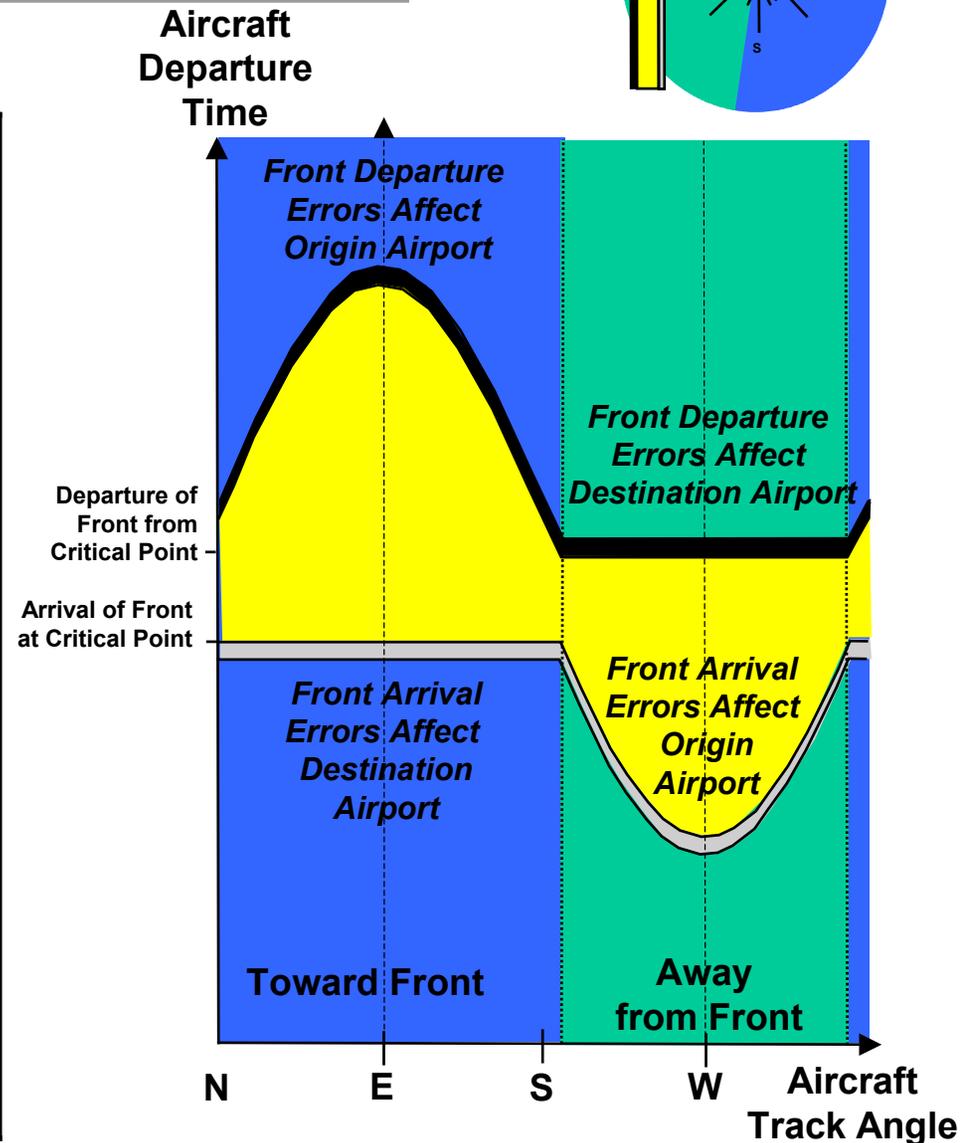
Front Departure Error	False Alarm	<i>Fly Faster</i> <i>More options</i> 7	<i>Take-off ASAP</i> <i>More options</i> 8
	Missed Detection	<i>Hold in air</i> <i>More options shortly</i> 5	<i>Hold on ground</i> <i>More options shortly</i> 6
Front Arrival Error	False Alarm	<i>Take-off ASAP</i> <i>No other</i> <i>options shortly</i> 4	<i>Fly faster</i> <i>No other options</i> <i>shortly</i> 3
	Missed Detection	<i>Hold on ground</i> <i>No other</i> <i>options</i> 2	<i>Divert</i> <i>No other options</i> 1
		Away from Front	Toward Front



Trajectory-Based Forecast Errors Types and Implications

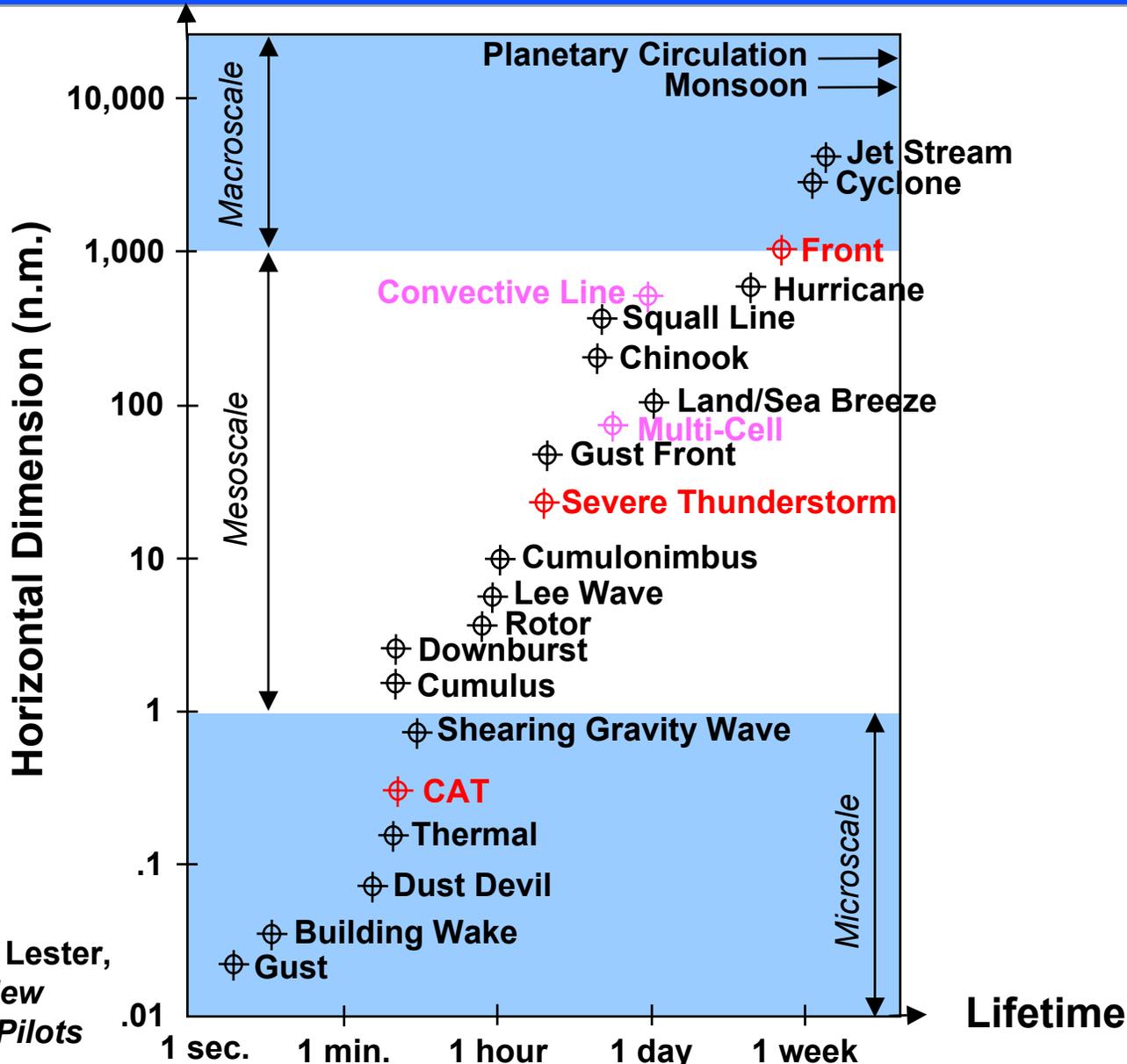


		Stochastic Regime	
Front Departure Error	False Alarm	Take-off ASAP More options	Fly Faster More options
	Missed Detection	Hold on ground More options shortly	Hold in air More options shortly
Front Arrival Error	False Alarm	Fly faster No other options shortly	Take-off ASAP No other options shortly
	Missed Detection	Divert No other options	Hold on ground No other options
		Toward Front	Away from Front



Accurate forecast has more value for longer impact time of adverse weather on aircraft route!

Predictability Horizon Linked to Weather Phenomenon Lifetime

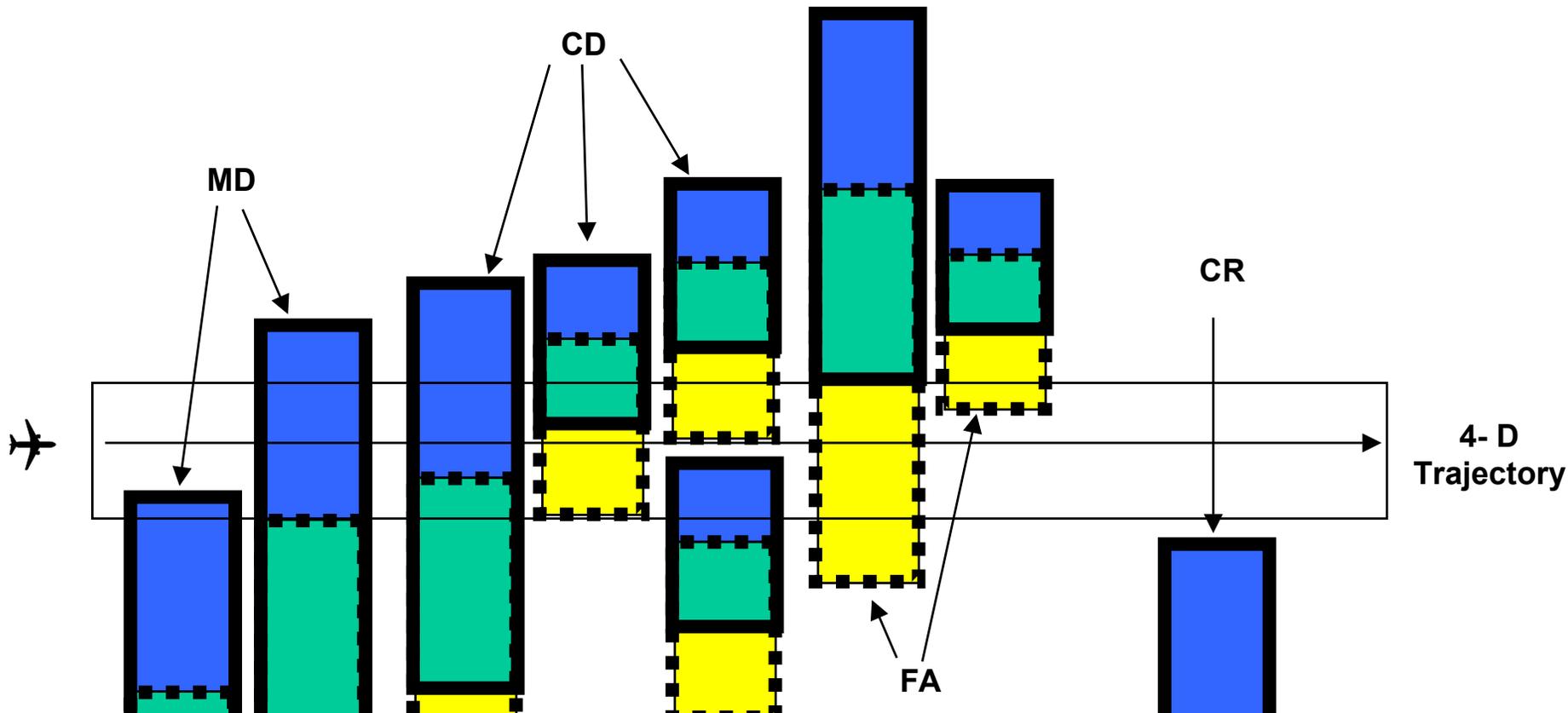
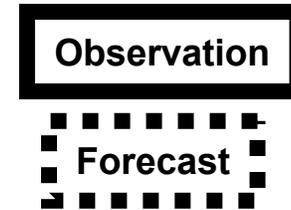
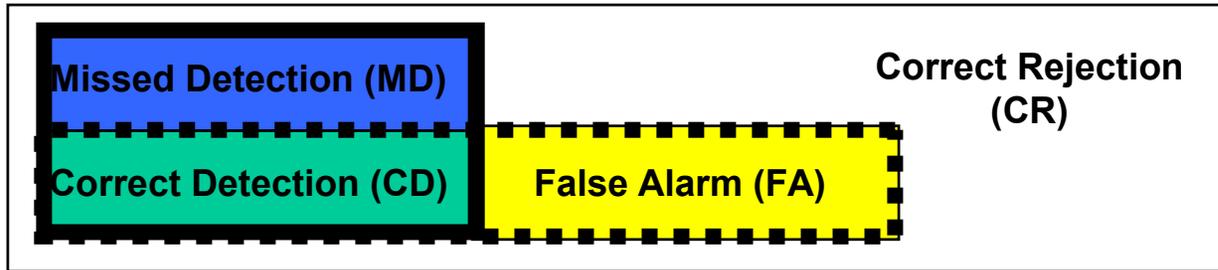


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Key Results

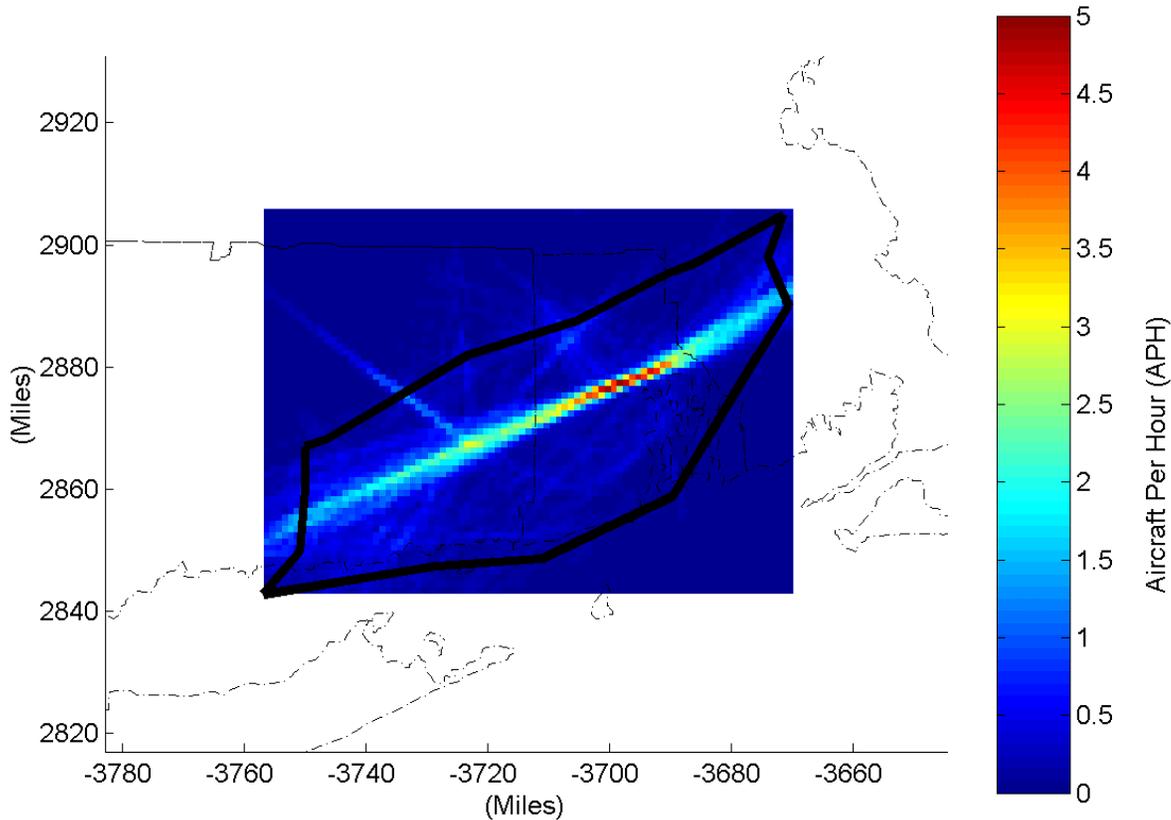
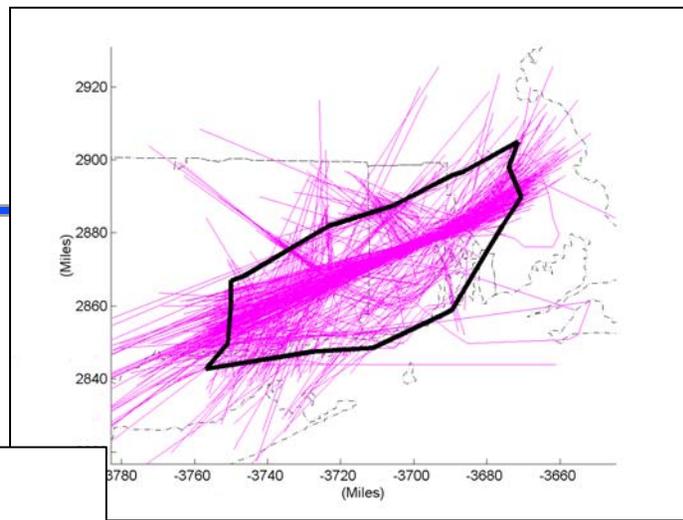


Area-based forecast assessment (top) vs. Trajectory-based forecast assessment (bottom)



Aircraft Trajectory Assessment for ATC Applications

- Aircraft Tracks inside Providence Sector
- 24 Hours – 1 mile grid



Courtesy of Jonathan Histon

Metrics of Interest



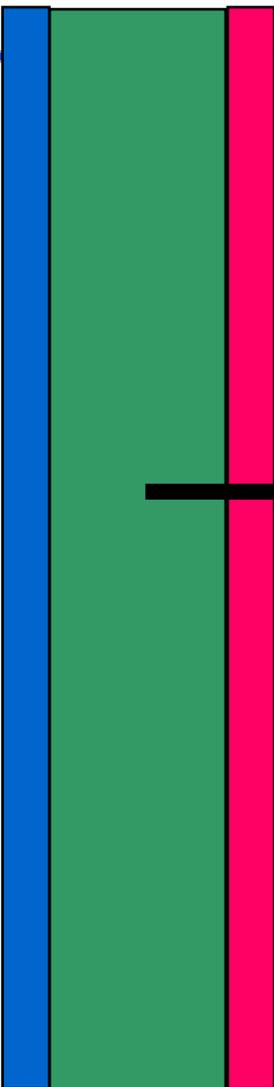
Missed Detection

Correct Detection

False Alarm



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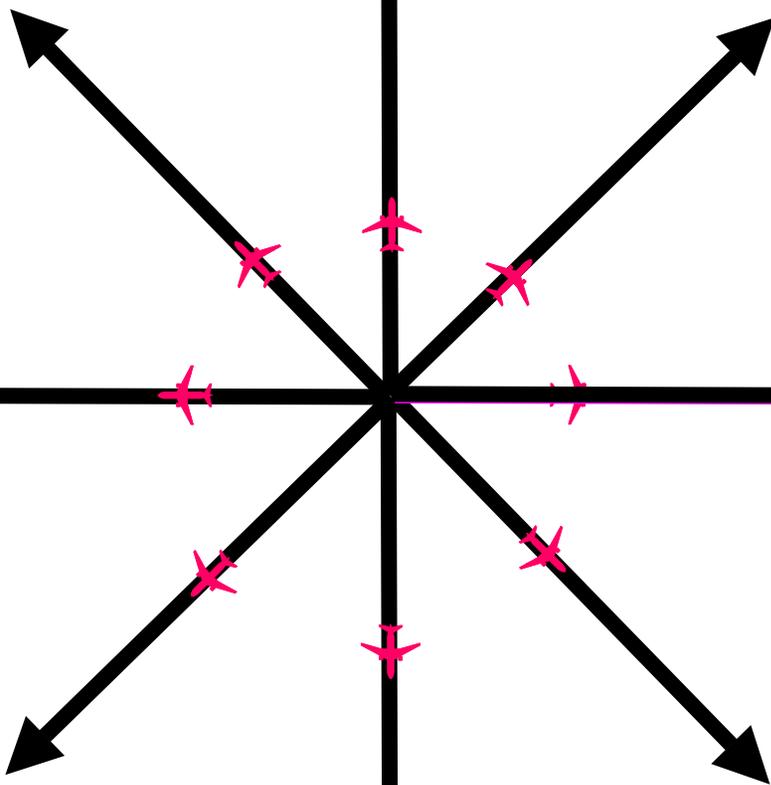
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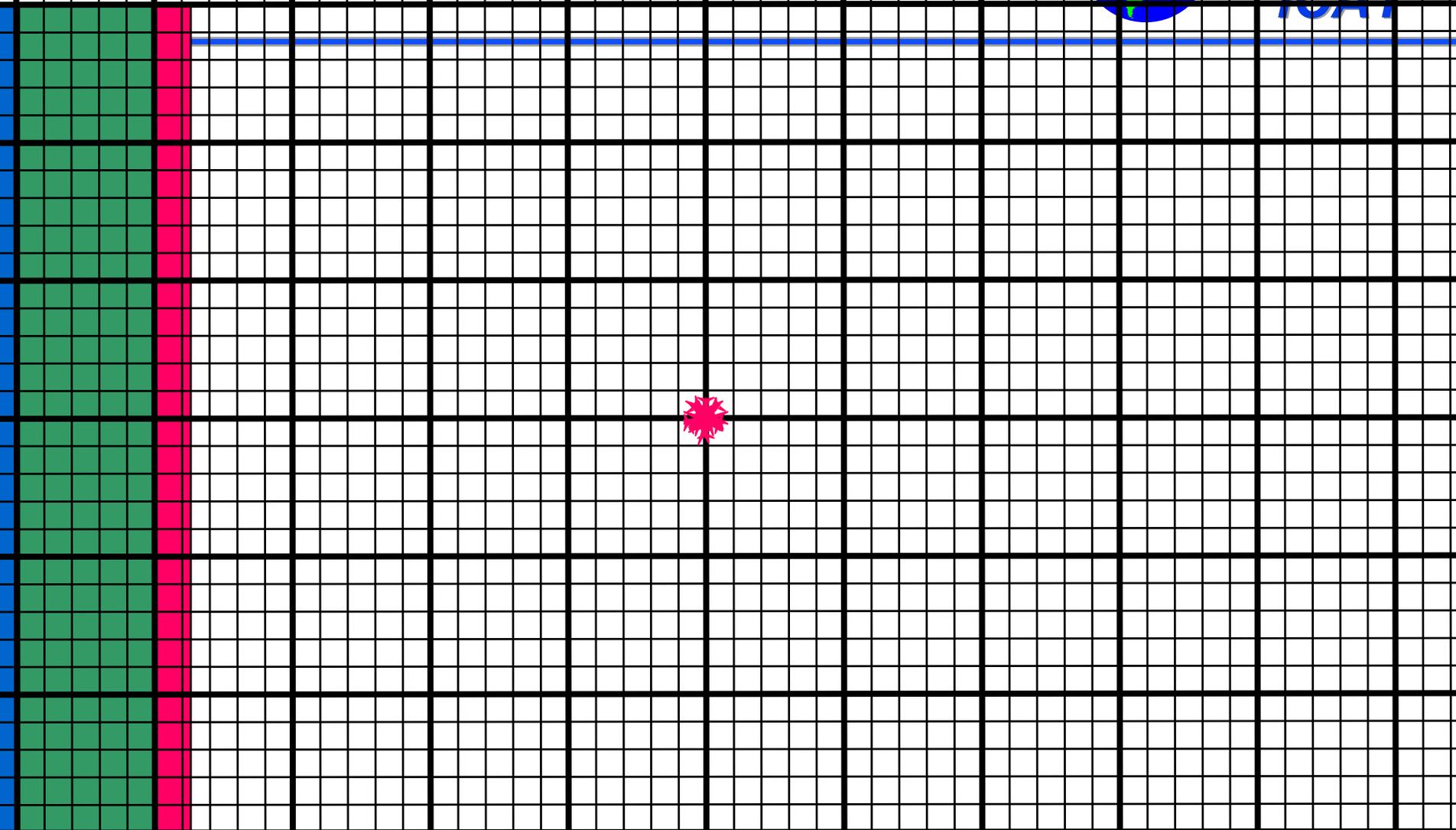
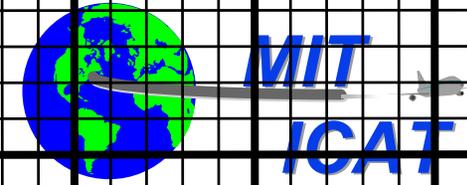


Along Weather-Track Errors

Missed Detection

Correct Detection

False Alarm



Along Weather-Track Errors

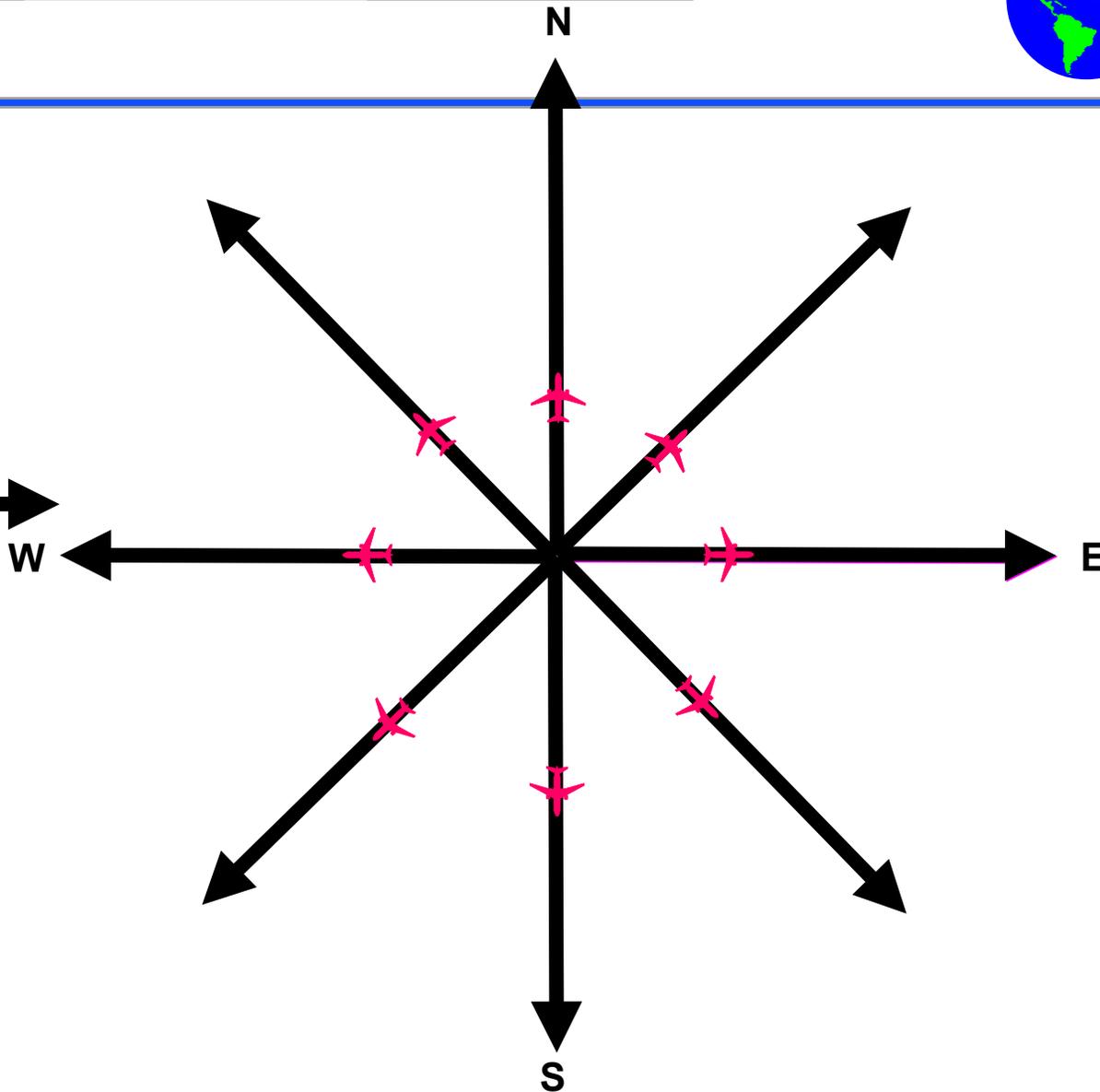
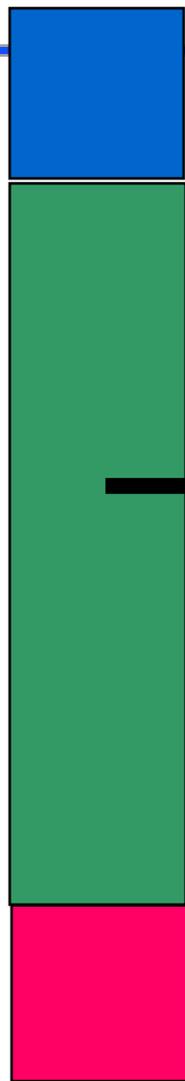
Missed Detection

Correct Detection

False Alarm



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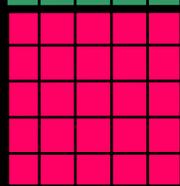
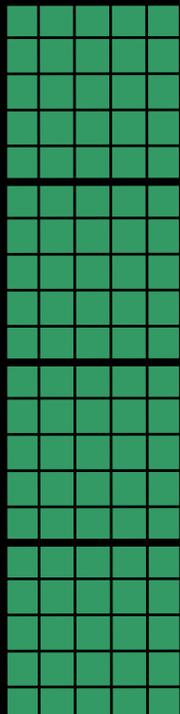
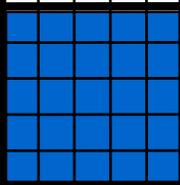
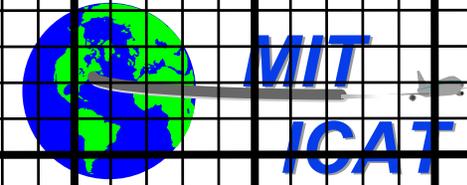


Across Weather-Track Errors

Missed Detection

Correct Detection

False Alarm

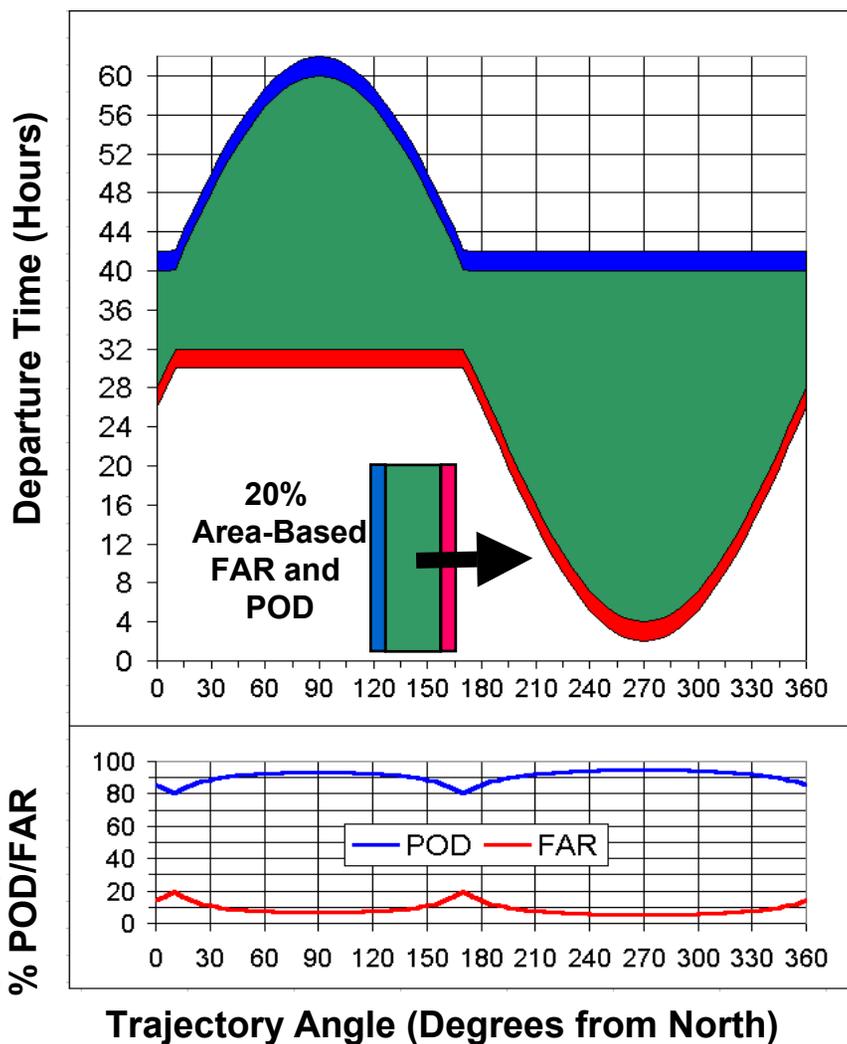


Across Weather-Track Errors

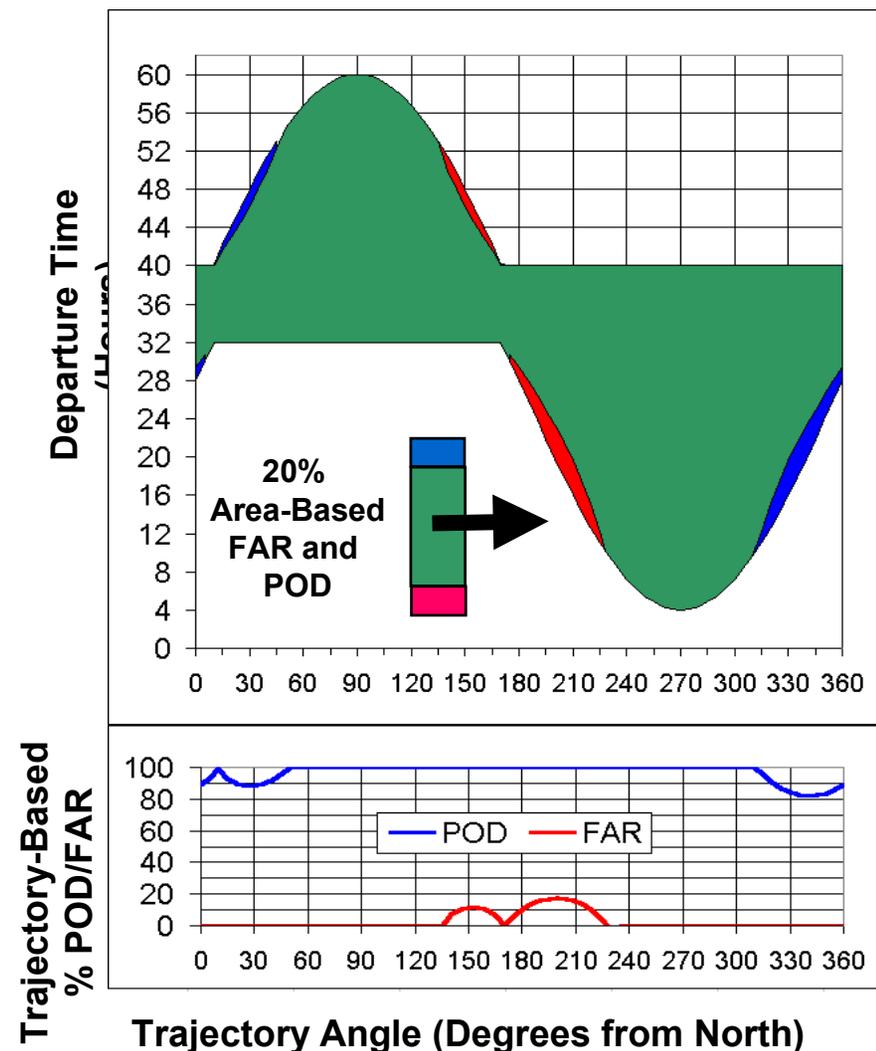
Sensitivity of Trajectory-Based to Area-Based Performance Assessment



Along Weather-Track Errors



Across Weather-Track Errors

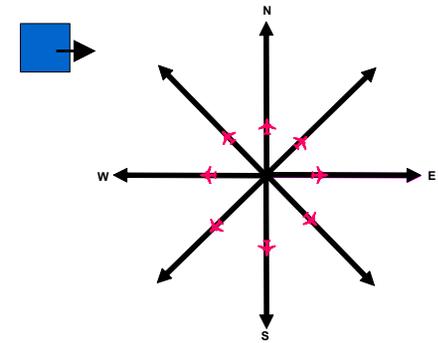


Sensitivity Analysis

Summary of Results

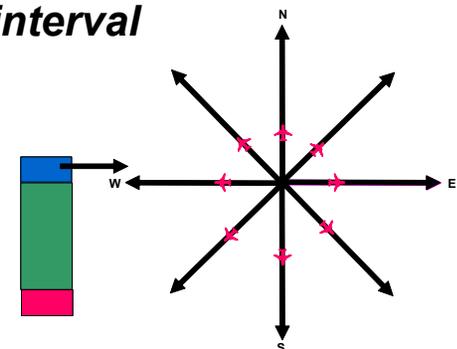


- Trajectory-based MD and FA correspond to 4-D intersections between 4-D aircraft hypertubes and FA/ MD hypervolumes
 - Except when there are 4-D intersections between aircraft and CD hypervolumes, since they correspond to CD



How should one measure ratios of POD or FAR?

- For fixed 4-D trajectories over departure time intervals?
 - ▲ *What time intervals are relevant?*
- For 2 simple cases investigated, the trajectory-based scoring will either look equal or better than the area-based statistics **over the full time interval**
 - ▲ *Many exceptions*



Sensitivity Analysis

Summary of Results



- **Trajectory-based errors depend on the geometry/kinematics**

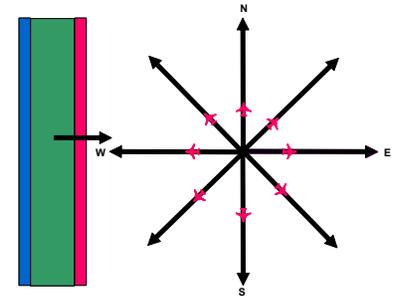
- Along weather-track errors are observed

- ▲ *At departure times when the weather is overhead the critical point*

- ▲ *FAR is worse for certain time intervals*

- ➔ *E.g., for trajectories with relative velocity ($V_a - V_w$) perpendicular to the weather track*

- ▲ *Linear relationship to timing error*

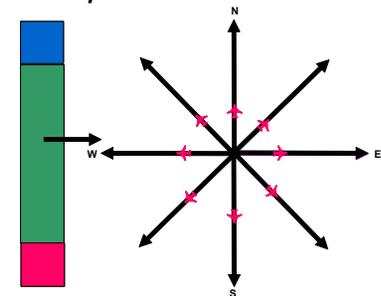


- Across weather-track errors are observed

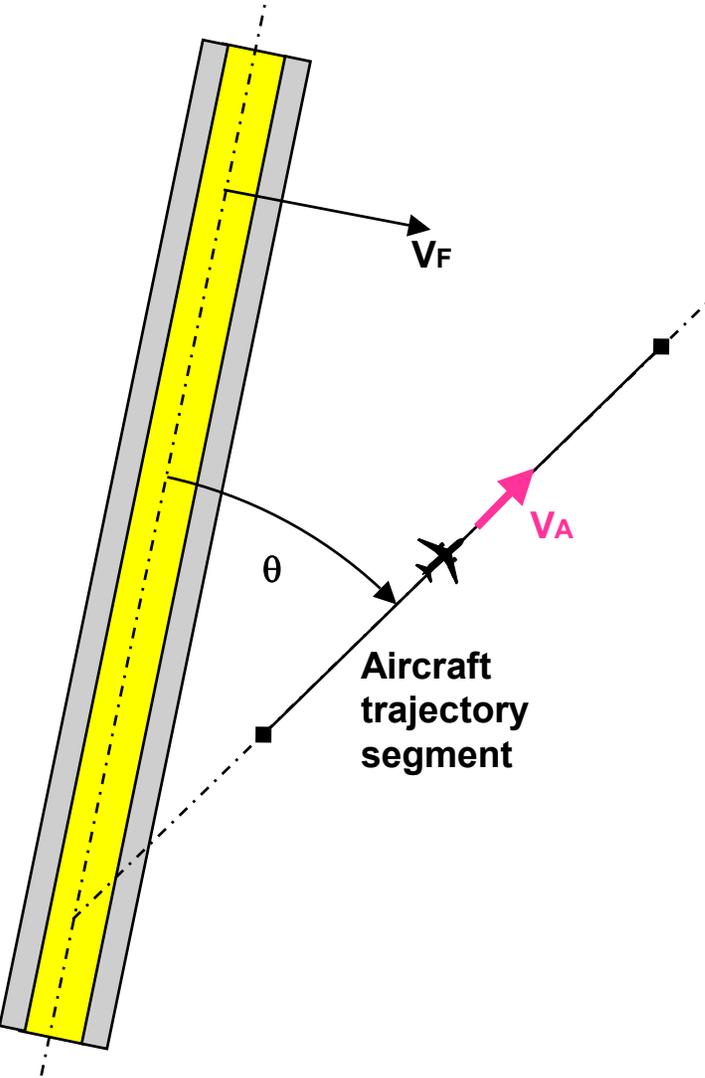
- ▲ *For trajectories that intersect the FA and MD hypervolumes*

- FAR and POD

- ▲ *Highly dependent on the FA and MD hypervolume trajectories w.r.t. critical point*



Scenario Analysis Model

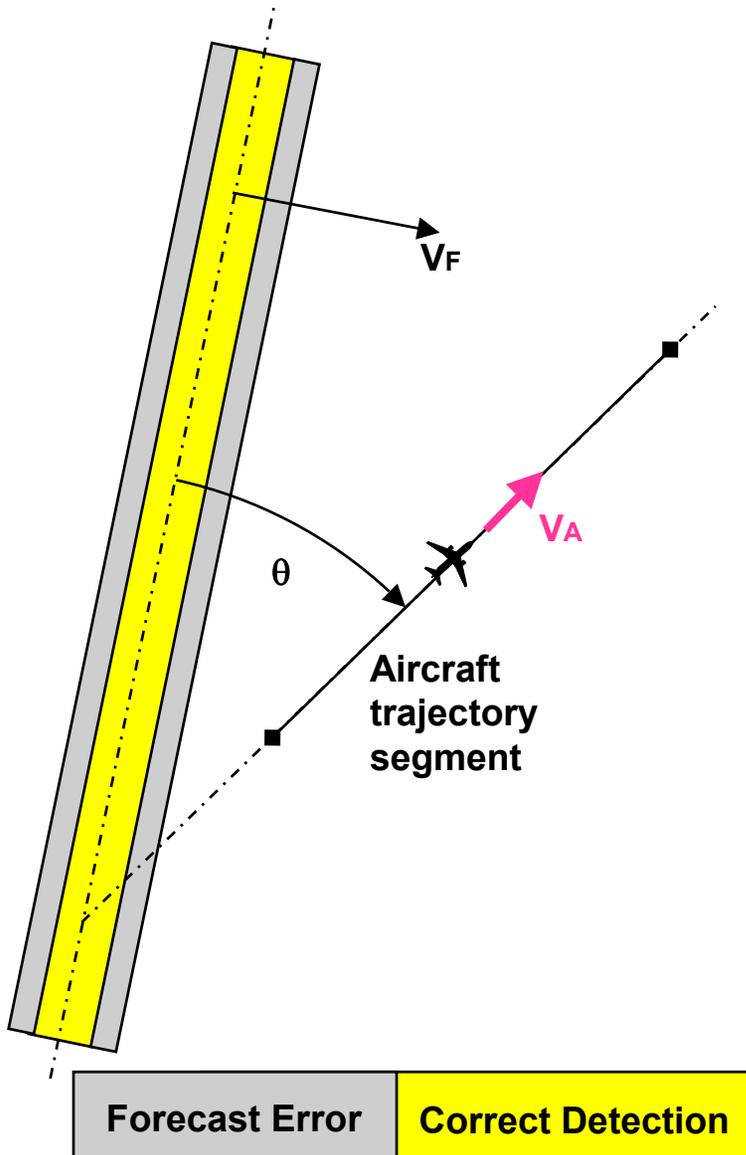


V_A Aircraft velocity

V_F Front velocity perpendicular to the front line

θ Angle between weather front line and aircraft track

Scenario Analysis



V_A Aircraft velocity

V_F Front velocity perpendicular to the front line

θ Angle between weather front line and aircraft track

Summary & Implications



- **Types of errors**
 - Front arrival
 - ▲ *Marks transition to “blocked trajectory” state*
 - Front departure
 - ▲ *Marks transition to “clear trajectory” state*
 - False Alarms
 - ▲ *Missed opportunity if tactical response not supported*
 - Missed detections
 - ▲ *Can be very disruptive*
 - ▲ *When related to front arrival errors, mean long ground hold or even diversion.*
- **Error type comparison**
 - Front arrival errors worse than front departure errors
 - Missed detection worse than false alarm
 - Worse when affecting destination airport
 - ▲ *Stochastic regime*
 - ▲ *Affected by:*
 - *Front arrival errors when flying toward front*
 - *Front departure errors when flying away from front*
- **Value of finding “pores”/gaps:**
 - Greatest for front arrival forecasts
 - Greatest for destination airports of aircraft

Opportunity for Applications



Methodology



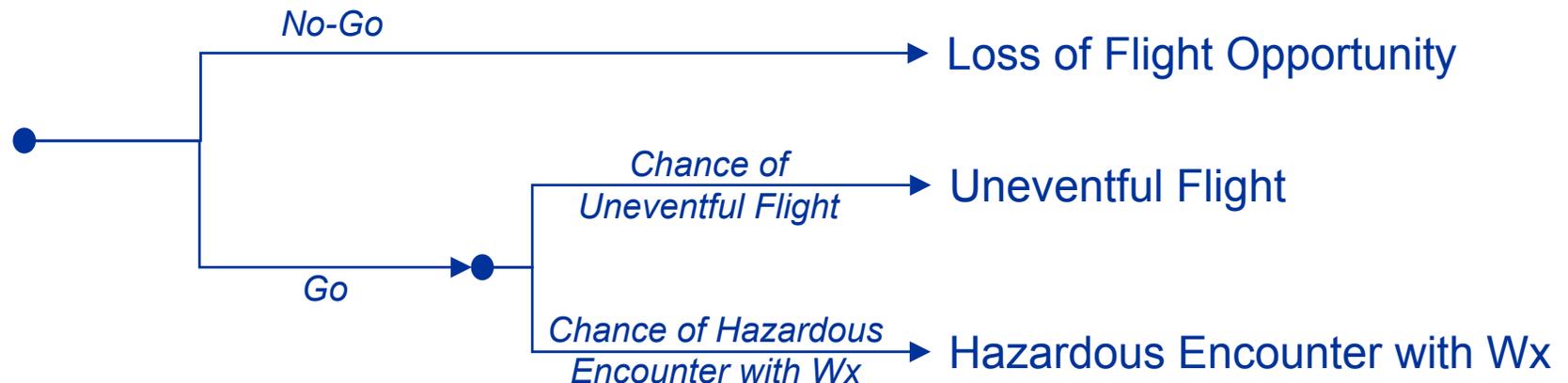
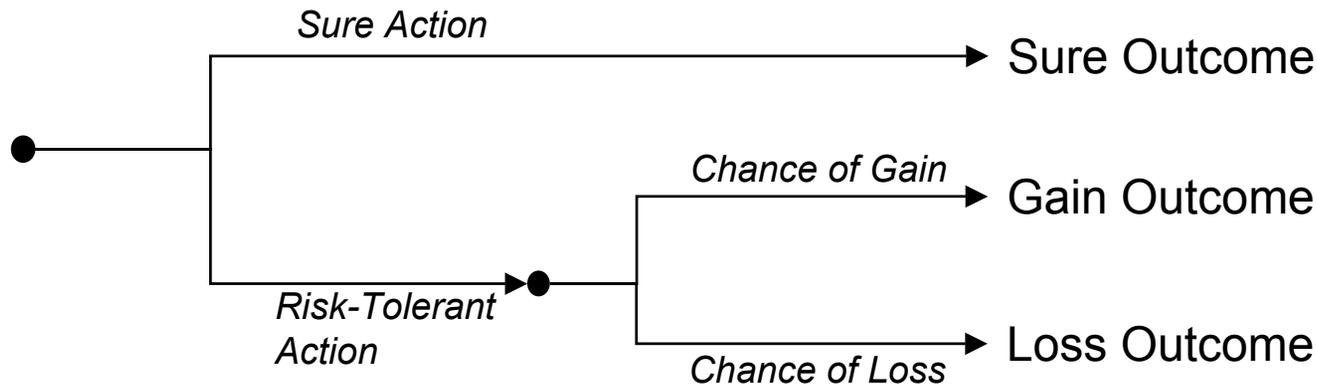
- **Cognitive Analysis of Pilots Decisions**
 - Feedback control loop
 - Decision-making models
 - Task analysis

- **Temporal Representation Framework**
 - Deterministic Regime

 - **Stochastic Regime**
 - ▲ *Beyond the “deterministic predictability limit”*
 - ▲ *Importance of “options”*
 - ▲ *How to support “options” identification in planning?*

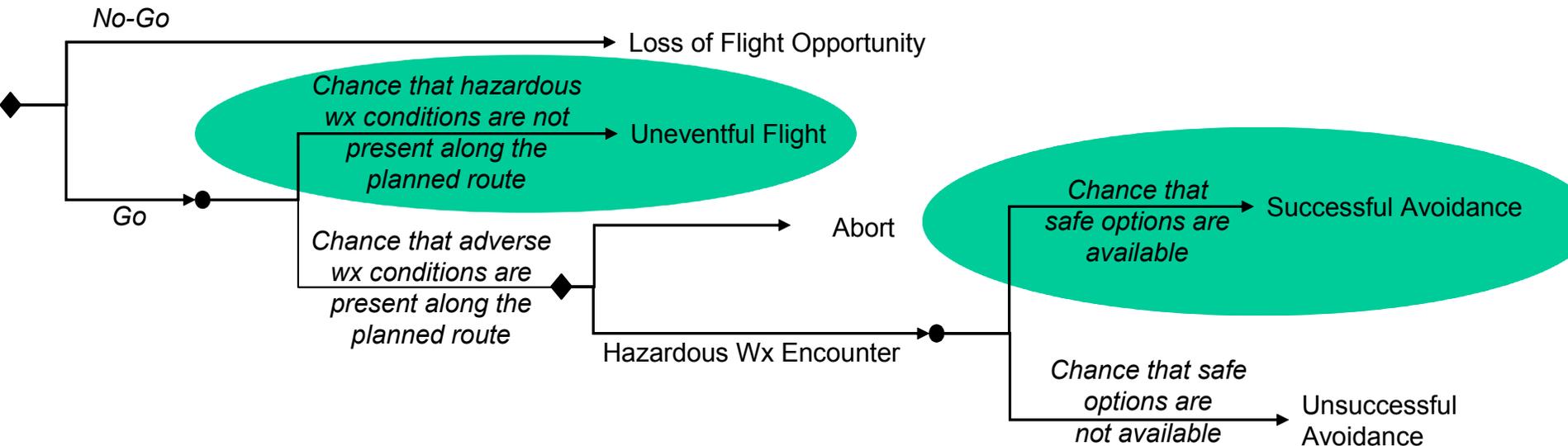
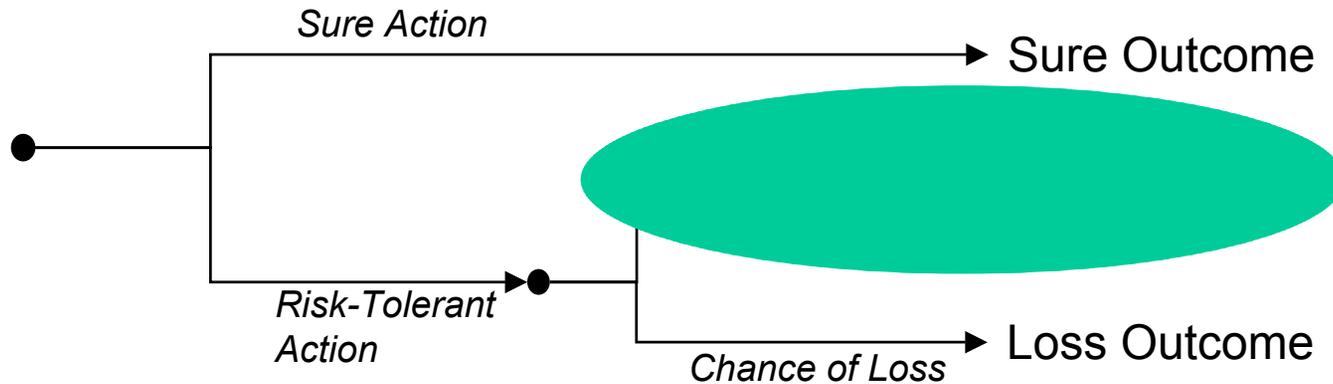


The “gain” option identification is important in potentially hazardous weather



If pilots frame the “no-go” decision as a *loss*, they will opt for the risk-tolerant “go” decision

The “gain” option identification is important in potentially hazardous weather



Implications

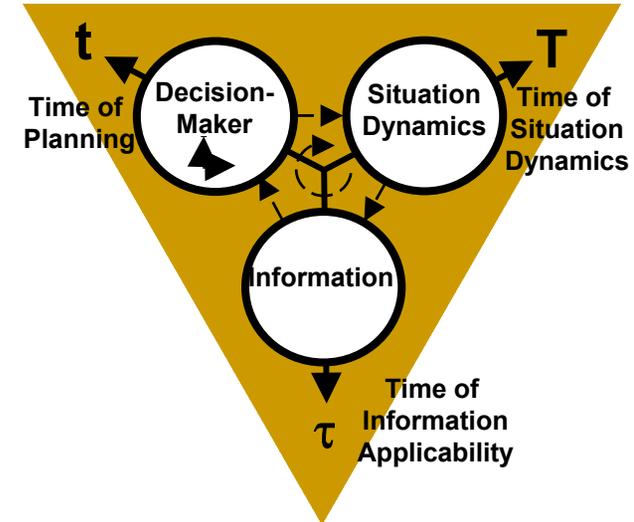


- The “options” identification is a key element of risk assessment
- Supporting the identification of “options” explicitly may add value to the decision-support information

Conclusions



- **How to improve time-varying decision-support**
 - Improve the “deterministic predictability limit”
 - Understand how the deterministic regime supports tactical vs. strategic planning
 - Understand how to support decision-making under the deterministic and stochastic regimes
- **Under deterministic representation**
 - Decision-makers wish to have information that supports their assessment of the situation dynamics
- **Under the stochastic representation**
 - Decision-makers wish to have information that supports their assessment of the availability of options



Back Up Slides