

National Aeronautics and Space Administration



# ***Aircraft Loss of Control: Research and Technology Summary & Future Directions***

**Assuring Safe and Effective Control  
under Hazardous Conditions**

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Briefing to Aviation Safety Working Group  
February 11, 2015

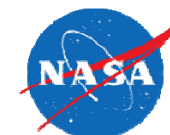
[www.nasa.gov](http://www.nasa.gov)

# Outline

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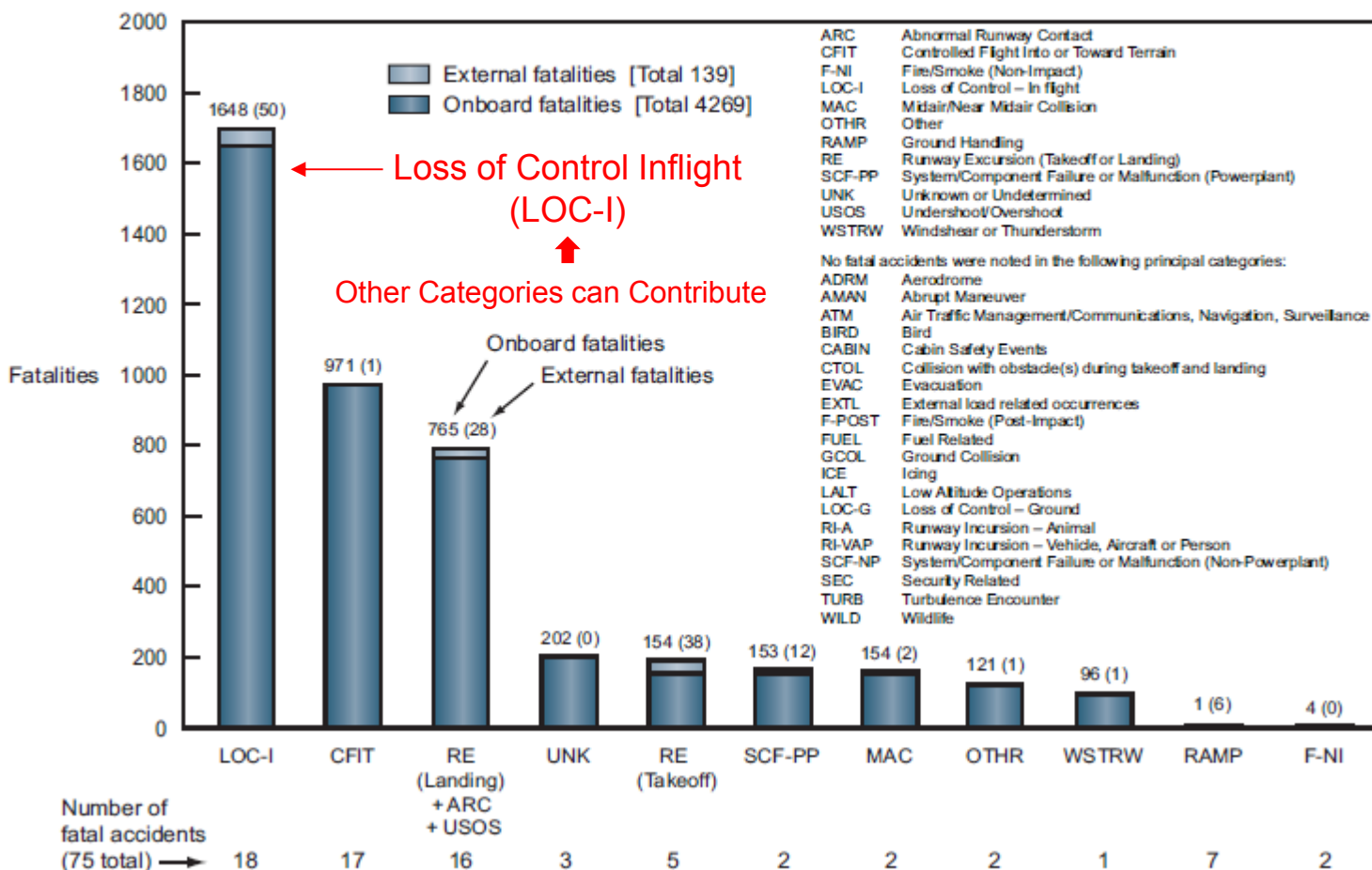
- Introduction: Aircraft Loss of Control (LOC)
- Research Approach
- Selected Research Results
  - LOC Hazards Analysis
  - Vehicle Dynamics Modeling
  - Guidance, Control, & Systems
  - Technology Validation
- Future Research Directions
- Summary & Concluding Remarks



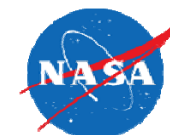
# LOC Overview: Relevance to Accident Statistics

## Fatalities by CAST/ICAO Common Taxonomy Team (CICTT) Aviation Occurrence Categories

Fatal Accidents – Worldwide Commercial Jet Fleet – 2003 Through 2012



*Note: These statistics apply to jet transport aircraft ≥ 60,000 lbs.*



# LOC Problem Definition

## LOC Characteristics

**LOC: aircraft motion that is characterized by one or more of the following:**<sup>1,2</sup>

- outside normal envelopes (adjusted for flight phase)
- not predictably altered by pilot control inputs (i.e. aircraft response is no longer predictable to the pilot)
- characterized by nonlinear effects that degrade handling qualities
  - kinematic / inertial coupling
  - disproportionately large responses to small state variable changes,
  - oscillatory / divergent behavior
- likely to result in high angular rates / displacements,
- characterized by the inability to maintain heading, altitude, and wings-level flight
- flight path is outside of acceptable tracking tolerances and cannot be predictably controlled by pilot (or autoflight system) inputs

Note: LOC need not be unrecoverable

## Primary Causes

1. Entry into vehicle upset condition (e.g., Stall / Departure)
2. Reduction or loss of control effectiveness
3. Changes to vehicle dynamic response and handling / flying qualities (including asymmetric effects)
4. Combinations of the above (1-3)

## Causal & Contributing Factors

- **Adverse onboard conditions:**
  - **vehicle impairment**
    - » Inappropriate vehicle configuration, contaminated airfoil, improper loading, vehicle damage to airframe and engines
  - **system faults, failures, and errors**
    - » Control component, engine, sensor system, flight deck instrumentation, non-control component
  - **inappropriate crew action / inaction**
    - » Loss of aircraft attitude, energy, or system state awareness, aggressive maneuver, abnormal control input, ineffective recovery, improper procedure, crew fatigue / impairment
- **External hazards and disturbances:**
  - **inclement weather & atmospheric disturbances**
    - » wind shear, turbulence, rain / thunderstorms, snow / icing, wake vortices
  - **poor visibility** (fog / haze, night)
  - **obstacle** (fixed or moving)
- **Abnormal dynamics & vehicle upsets:**
  - abnormal vehicle dynamics & control response
  - abnormal attitude, airspeed, angular rates, asymmetric forces, or flight trajectory
  - uncontrolled descent (including spiral dive)
  - stall/departure from controlled flight

**LOC Usually Results from Multiple Causal & Contributing Factors**

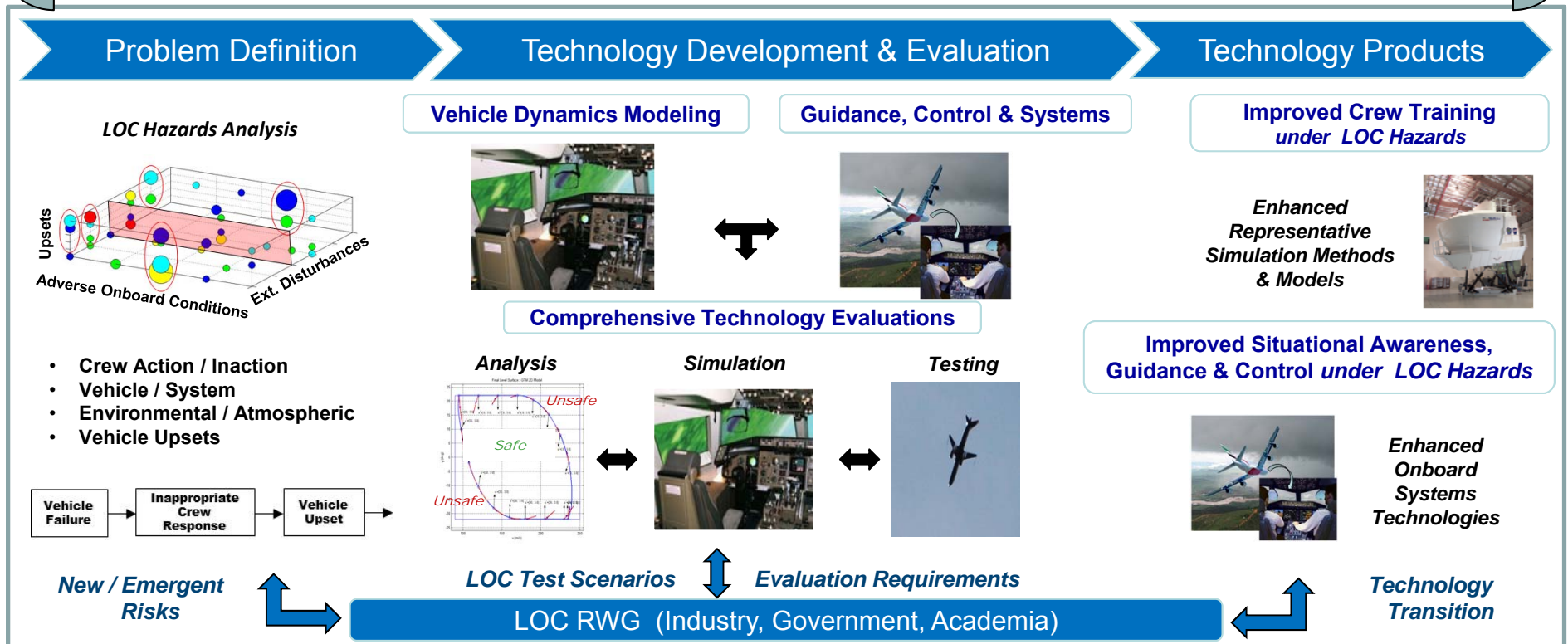
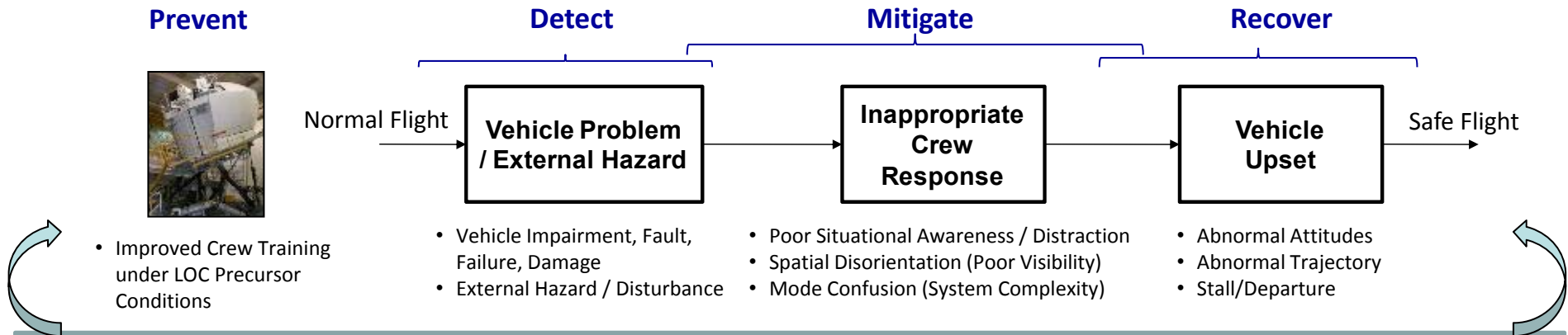
<sup>1</sup> Wilborn, J. E. and Foster, J. V., "Defining Commercial Aircraft Loss-of-Control: a Quantitative Approach," AIAA Atmospheric Flight Mechanics Conference and Exhibit, Providence, Rhode Island, 16-19 August 2004.

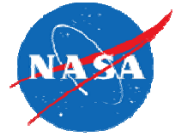
<sup>2</sup> Lambregts, A. A., Nesemeier, G., Wilborn, J.E., Newman, R. L., "Airplane Upsets: Old Problem, New Issues," AIAA Modeling and Simulation Technologies Conference and Exhibit, Honolulu, Hawaii, 18-21 August 2008

# LOC Research Approach



## Holistic Approach to Breaking LOC Precursor Sequences:





# LOC Hazards Analysis (1)

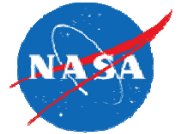
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## LOC Accident / Incident Data Set

- Data Sources
  - Aircraft Accident Reports on DVD (R. Dorsett, 2006)
  - Australian Transport Safety Bureau (ATSB)
  - Aviation Safety Network (ASN)
  - Canadian Transportation Safety Board (TSB)
  - Flightglobal (Ascend Database)
  - French Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile (BEA)
  - German Bundesstelle für Flugunfalluntersuchung (BFU)
  - International Civil Aviation Organization (ICAO)
  - Irish Air Accident Investigation Unit (AAIU)
  - National Transportation Safety Board (NTSB)
- Search Criteria
  - “loss-of-control”
  - “upset”
  - “unusual attitude”
  - “stall”
  - “uncontrolled”

**275 Accidents and Incidents (1996 – 2010)**  
**7185 Onboard Fatalities, 235 Ground Fatalities**

# LOC Hazards Analysis (2)



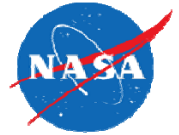
Adverse Onboard Conditions	External Hazards & Disturbances	Abnormal Vehicle Dynamics & Upsets
<b>Vehicle Impairment</b>	<b>Inclement Weather &amp; Atmospheric Disturbances</b>	<b>Abnormal Vehicle Dynamics</b>
Improper Maintenance Action / Inaction / Procedure	Thunderstorms / Rain	Uncommanded Motions
Inappropriate Vehicle Configuration	Wind Shear	Oscillatory Response (Includes PIO)
Contaminated Airfoil	Wind / Turbulence	Abnormal Control for Trim / Flight and/or Control Asymmetry
Smoke / Fire / Explosion	Wake Vortex	Abnormal / Counterintuitive Control Response
Improper Loading: Weight / Balance / CG	Snow / Icing	
Airframe Structural Damage		
Engine Damage (FOD)		
<b>System &amp; Component Failure / Malfunction</b>	<b>Poor Visibility</b>	<b>Vehicle Upset Conditions</b>
System Design / Validation Error / Inadequacy	Fog / Haze	Abnormal Attitude
System SW Design / Verification Error / Inadequacy	Night	Abnormal Airspeed / Energy
Control Component Failure / Malfunction		Abnormal Angular Rates
Engine Failure / Malfunction		Undesired Abrupt Response
Sensor System Failure / Malfunction		Abnormal Flight Trajectory
Flight Deck Instrumentation Malfunction / Inadequacy		Uncontrolled Descent (Includes Spiral Dive)
System Failure / Malfunction (Non-Control Component)		Vmc / Departure
<b>Crew Action / Inaction</b>	<b>Obstacle</b>	<b>Stall / Departure (Includes Falling Leaf, Spin)</b>
Loss of Attitude State Awareness / SD	Fixed	
Loss of Energy State Awareness	Moving	
Lack of Aircraft / System State Awareness		
Aggressive Maneuver		
Abnormal / Inadvertent Control Input		
Improper / Ineffective Recovery		
Inadequate Crew Resource Monitoring / Management		
Improper / Incorrect / Inappropriate Procedure / Action		
Fatigue / Impairment / Incapacitation		

Precursor Categories

Precursor Sub-Categories

Precursors / Hazards

# LOC Hazards Analysis (3)



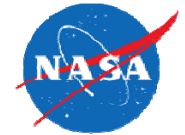
## Preliminary Analysis Results

### Individual LOC Hazards Statistics: Category & Sub-Category Level

Hazard Category / Sub-Category	Accidents / Incidents	%	Fatalities	%
<b>Adverse Onboard Conditions</b>	<b>240</b>	<b>87.3</b>	<b>6750</b>	<b>94.0</b>
Vehicle Impairment	86	31.3	2576	35.8
System & Component Failures / Malfunctions	117	42.6	3150	43.8
Inappropriate Crew Action / Inaction	160	58.2	4444	61.8
<b>External Hazards &amp; Disturbances</b>	<b>101</b>	<b>36.7</b>	<b>3036</b>	<b>42.2</b>
Inclement Weather & Atmospheric Disturbances	65	23.6	1741	24.2
Poor Visibility	30	10.9	1324	18.4
Obstacle	16	5.8	601	8.4
<b>Abnormal Dynamics &amp; Vehicle Upset Conditions</b>	<b>220</b>	<b>80.0</b>	<b>5416</b>	<b>75.4</b>
Abnormal Vehicle Dynamics	47	17.1	312	4.3
Vehicle Upset Conditions	188	68.4	5315	74.0

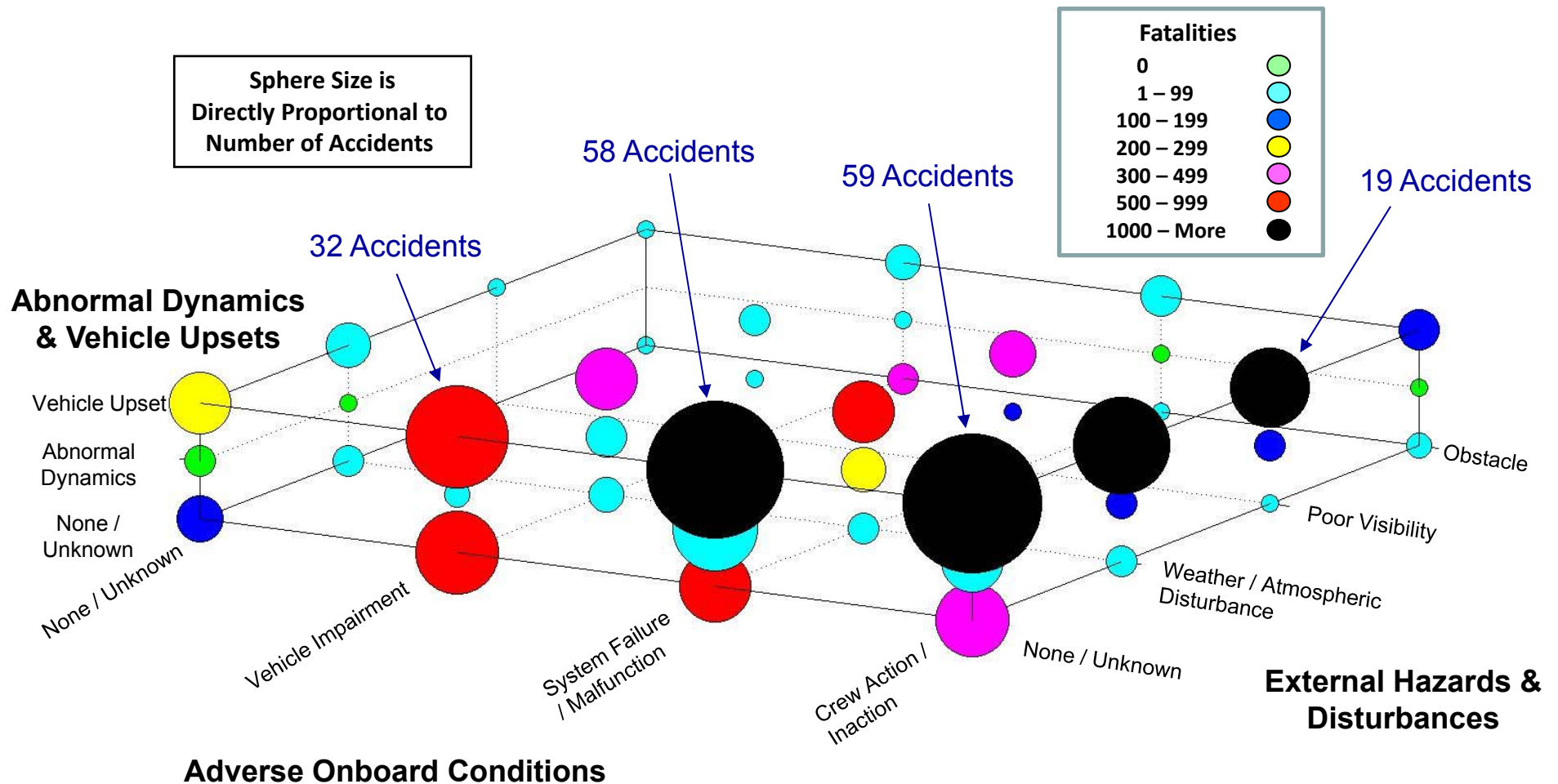
Individual Precursor Contributions are Provided in the 2014 SciTech Paper

# LOC Hazards Analysis (4)



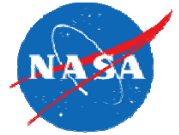
## Preliminary Analysis Results

### Worst-Case Hazards Combinations (1)



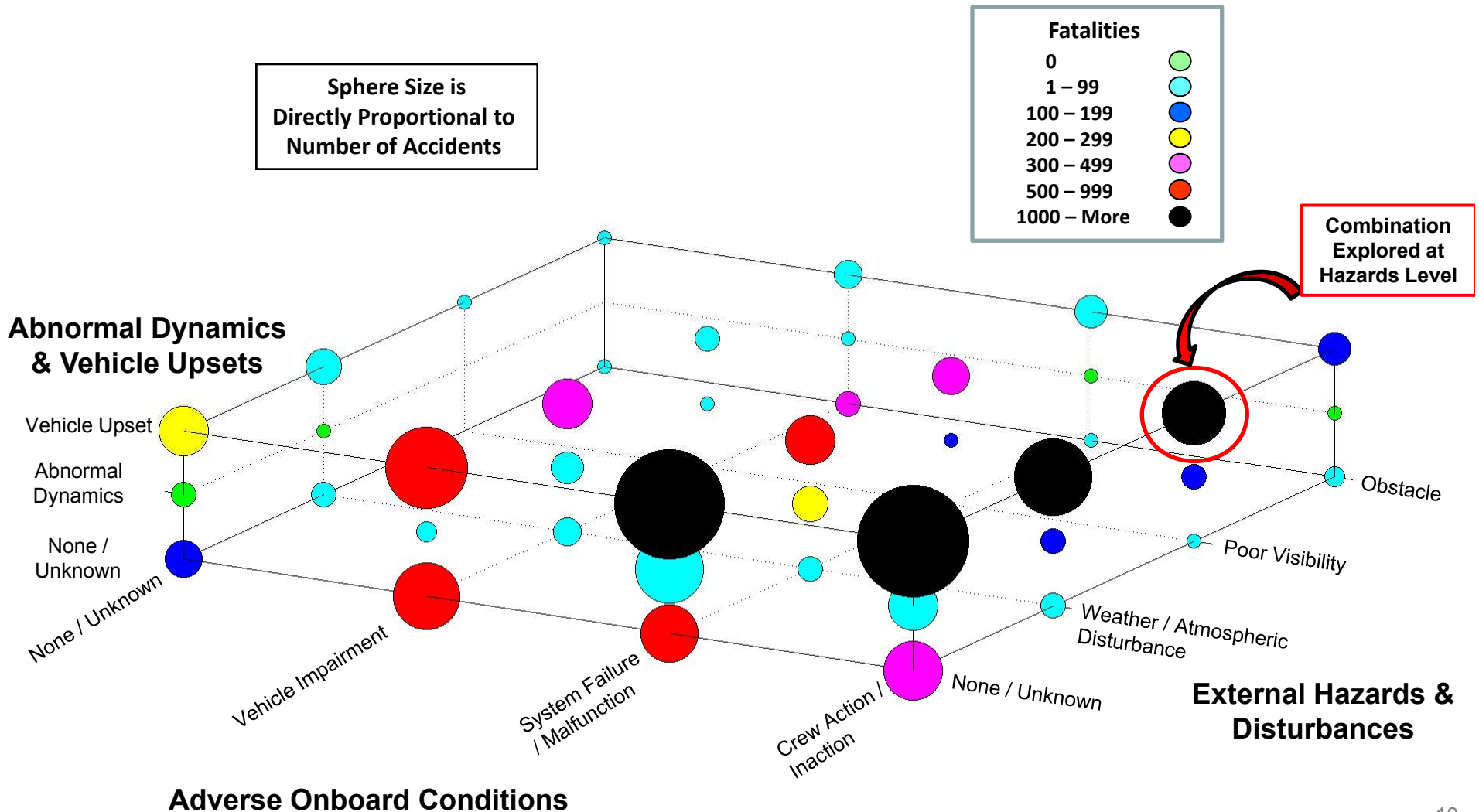
Preliminary Worst-Case Analysis Performed at Sub-Category Level

# LOC Hazards Analysis (5)

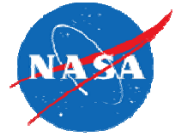


## Preliminary Analysis Results

### Worst-Case Hazards Combinations (2)



# LOC Hazards Analysis (6)



## Preliminary Analysis Results

### Precursor Combinations for Crew Action / Inaction – Poor Visibility – Vehicle Upset

Sphere Size is Directly Proportional to Number of Accidents

Fatalities	
0	<span style="color: green;">●</span>
1 – 99	<span style="color: cyan;">●</span>
100 – 199	<span style="color: blue;">●</span>
200 – 299	<span style="color: yellow;">●</span>
300 – 499	<span style="color: magenta;">●</span>
500 – 999	<span style="color: red;">●</span>
1000 – More	<span style="color: black;">●</span>

#### Vehicle Upsets

- Stall / Departure
- Uncont. Descent
- Abnorm. Traject.
- Undes. Abrpt. Resp.
- Abnorm. Ang. Rates
- Abnorm. Airspeed
- Abnorm. Attitude

- Loss of Attitude State Awareness / SD
- Loss of Energy State Awareness / Inappropriate Energy Mgmt.
- Lack of Aircraft / System State Awareness / Mode Confusion
- Aggressive Maneuver
- Abnormal / Inadvertent Control Input
- Improper / Ineffective Recovery
- Inadequate Crew Resource Monitoring / Management
- Improper Procedure
- Crew Fatigue / Impairment

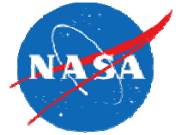
Night

Poor Visibility

Fog / Haze

Inappropriate Crew Action / Inaction

# LOC Hazards Analysis (7)



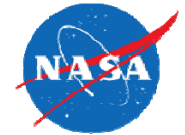
## Preliminary Analysis Results

### Temporal Sequencing: Category & Sub-Category Totals

Precursor	1st	2nd	3rd	4th	5th	6th	7th
<b>Adverse Onboard Conditions</b>	<b>167</b>	<b>153</b>	<b>88</b>	<b>39</b>	<b>10</b>	<b>3</b>	<b>0</b>
Vehicle Impairment	41	32	11	4	3	0	0
System & Component Failures / Malfunctions	84	35	10	5	1	0	0
Inappropriate Crew Action / Inaction	42	86	67	30	6	3	0
<b>External Hazards &amp; Disturbances</b>	<b>86</b>	<b>16</b>	<b>4</b>	<b>2</b>	<b>0</b>	<b>1</b>	<b>0</b>
Inclement Weather & Atmospheric Disturbances	58	6	1	1	0	0	0
Poor Visibility	19	6	2	0	0	0	0
Obstacle	9	4	1	1	0	1	0
<b>Abnormal Dynamics &amp; Vehicle Upset Conditions</b>	<b>0</b>	<b>89</b>	<b>78</b>	<b>55</b>	<b>33</b>	<b>11</b>	<b>3</b>
Abnormal Vehicle Dynamics	0	23	14	8	4	1	0
Vehicle Upset Conditions	0	66	64	47	29	10	3
<b>Unknown Precipitating Events</b>	<b>22</b>	-	-	-	-	-	-
<b>TOTALS</b>	<b>275</b>	<b>258</b>	<b>170</b>	<b>119</b>	<b>43</b>	<b>15</b>	<b>3</b>

Precursor Sequence Information is Provided in the 2014 SciTech Paper

# LOC Hazards Analysis (8)



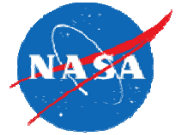
## Preliminary Analysis Results

### Sequence Diagrams – Example: Initiated by Poor Visibility

		Events	Fatalities	
Poor Visibility Total		19	832	
NORMAL FLIGHT →	Poor Visibility	→ Inappropriate Crew Action / Inaction → Vehicle Upset Conditions → LOC	11	529
		→ Inappropriate Crew Action / Inaction → Inappropriate Crew Action / Inaction → Vehicle Upset Conditions → LOC	1	143
		→ Unknown Abnormal Dynamics & Vehicle Upset Conditions → LOC	1	3
		→ System & Component Failures / Malfunctions → Inappropriate Crew Action / Inaction → Vehicle Upset Conditions → LOC	2	3
		→ System & Component Failures / Malfunctions → Vehicle Upset Conditions → LOC	1	1
		→ Vehicle Upset Conditions → LOC	1	1
		→ Abnormal Vehicle Dynamics → Inappropriate Crew Action / Inaction → LOC	1	0
	→ Inclement Weather & Atmospheric Disturbances → Inappropriate Crew Action / Inaction → Vehicle Upset Conditions → LOC	1	152	

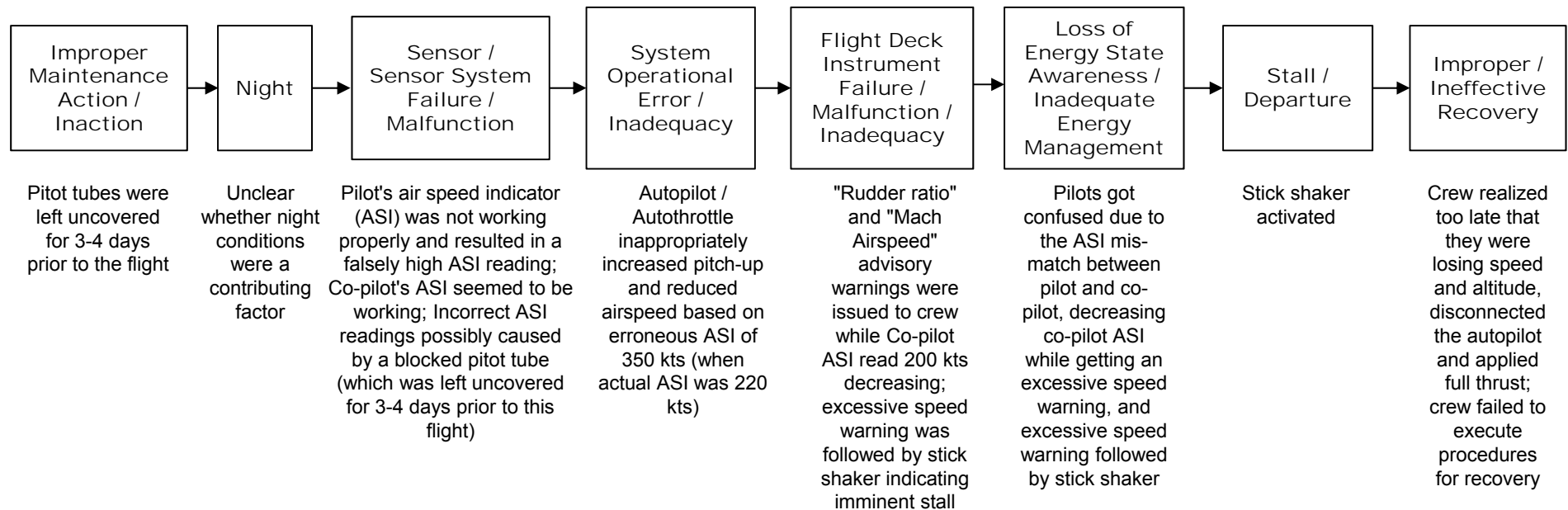
Sequence Diagrams at Category & Sub-category Level are Provided in Appendix B of the 2014 SciTech Paper 13

# LOC Hazards Analysis (9)

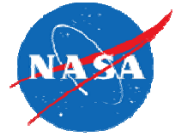


## Example Detailed Precursor Sequence:

### 2/6/1996: Birgenair 301 (B-757) En Route, Near Puerto Plata, Dom. Republic (189 Fatalities)



**Example Result from Ongoing Civil Transport Accident Analysis**

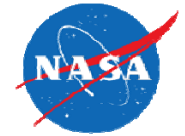


# LOC Hazards Analysis (10)

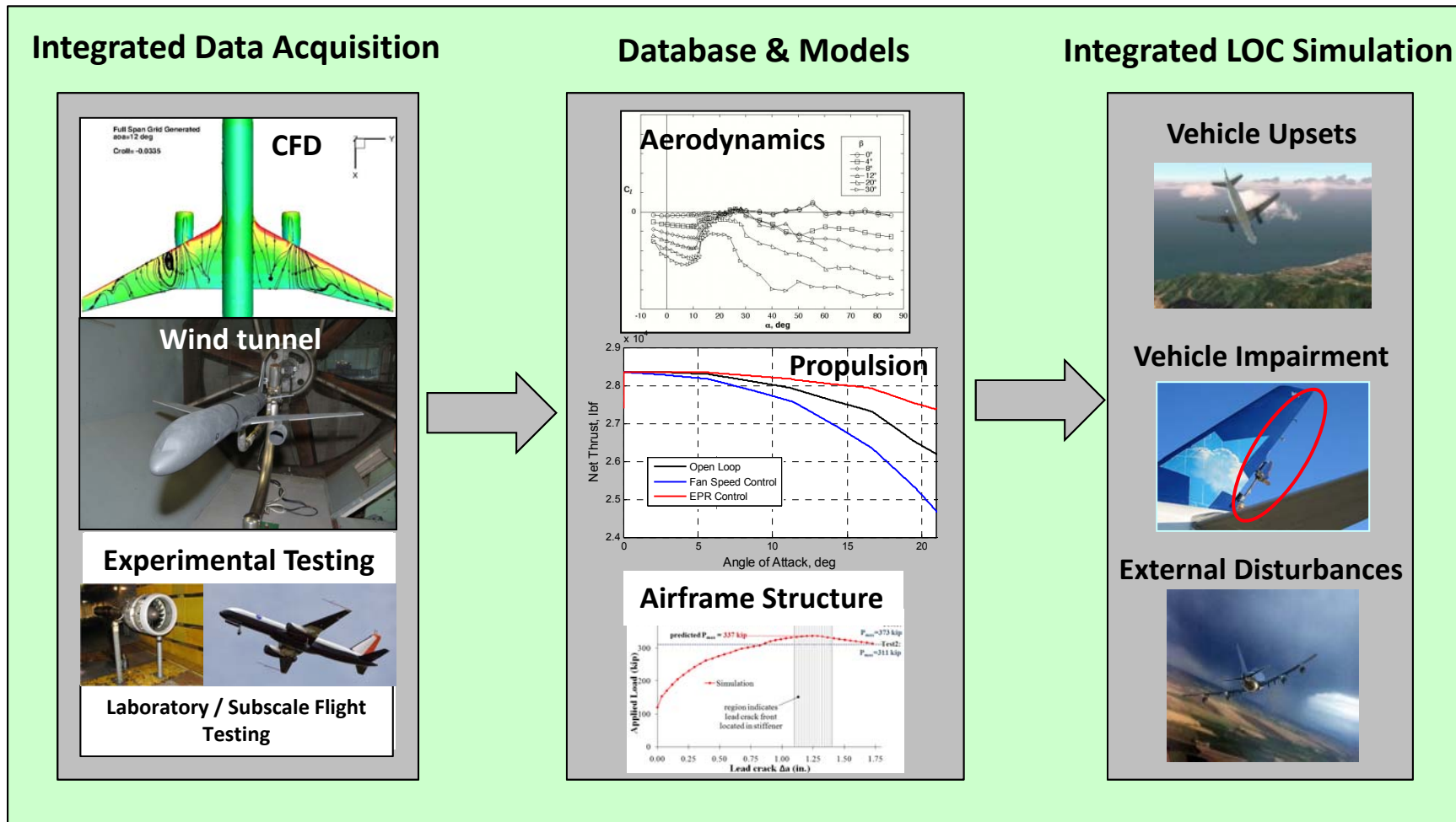
## *Summary:*

- Comprehensive Set of Accidents / Incidents Compiled for 1996 – 2010
    - 10 International Databases Searched for LOC
    - Commercial transports at or above 12,500 lbs
    - 275 accidents & incidents identified resulting in 7185 fatalities
  - Preliminary Analysis Results Obtained
    - Based on Six Accident / Incident Subsets (45-46 Events)
    - Individual Precursor Statistics
    - Worst-Case Precursor Combinations
    - Temporal Sequencing
  - Ongoing Research
    - Re-Evaluation Based on Team Consensus Approach (In Progress)
    - Definition of Future LOC Risks (To be Coordinated with CAST / ATLAS)
    - Development of LOC Test Scenarios
    - Final Results to be Submitted for NASA TP and/or Journal Publication
- Analysis results and test scenarios can be used in the development and evaluation of technology solutions for LOC prevention and recovery (e.g., Resilient Systems)
    - LOC test scenarios also provide engineering simulation requirements
  - Potential for wider application of this research to broader applications
    - **Initiating UAS Mishap Analysis (Coordinated with DoD Safety Centers) for NAS operations**
    - Resilience testing / evaluation of autonomous aircraft systems under hazardous conditions

# Vehicle Dynamics Modeling Technologies (VDMT) for Characterizing Effects of LOC Hazards



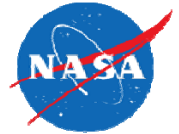
## Representative Modeling Research Approach



**Class-Representative Integrated LOC Simulations (Upsets, Impairment, External Disturbances)**

**NRA Partner: Boeing**

# VDMT Accomplishments Summary

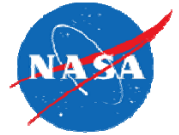


- Vehicle Upset Modeling
  - Aerodynamic Effects
  - Engine Effects
  - Airframe Structure Effects
- Vehicle Impairment Modeling
  - Icing Effects (Partnered with NASA GRC)
    - » Airframe
    - » Engine
  - Damage (Partnered with JASP)
    - » Airframe
    - » Engine
  - System Failures
    - » Control Components
    - » Collateral Damage Effects (Partnered with JASP)
    - » Engine
- Integration of Existing Atmospheric Disturbance Models
  - Wind Shear
  - Wake Vortices
  - Turbulence
- Integrated Real-Time Simulation Development
  - Multidisciplinary Hazard Effects
  - Multiple Hazards that can Lead to LOC



*Integrated Multidisciplinary Real-Time Simulation of Vehicle Dynamics & Control Effects under LOC*

# Guidance, Control, and Systems Technologies (GCST) for LOC Prevention and Recovery

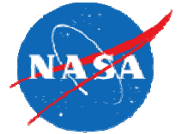


## Research Objectives

- Goal: Develop and evaluate onboard systems technologies that provide improved real-time situational awareness, guidance, and control under hazards that can lead to LOC
- Research Objectives:
  - Develop an integrated system architecture and technologies that provide
    - » Hazards detection and flight safety impacts assessment
    - » Upset prevention, detection and recovery
    - » Multiple hazards mitigation (system failures, icing, wakes / wind shear)
  - Develop preliminary crew interface concepts that provide
    - » Improved situational awareness specific to LOC
    - » Anticipatory guidance for LOC prevention
    - » Control cueing for recovery
  - Evaluate GCST technologies using
    - » Analysis
    - » Simulation
    - » Experimental Testing



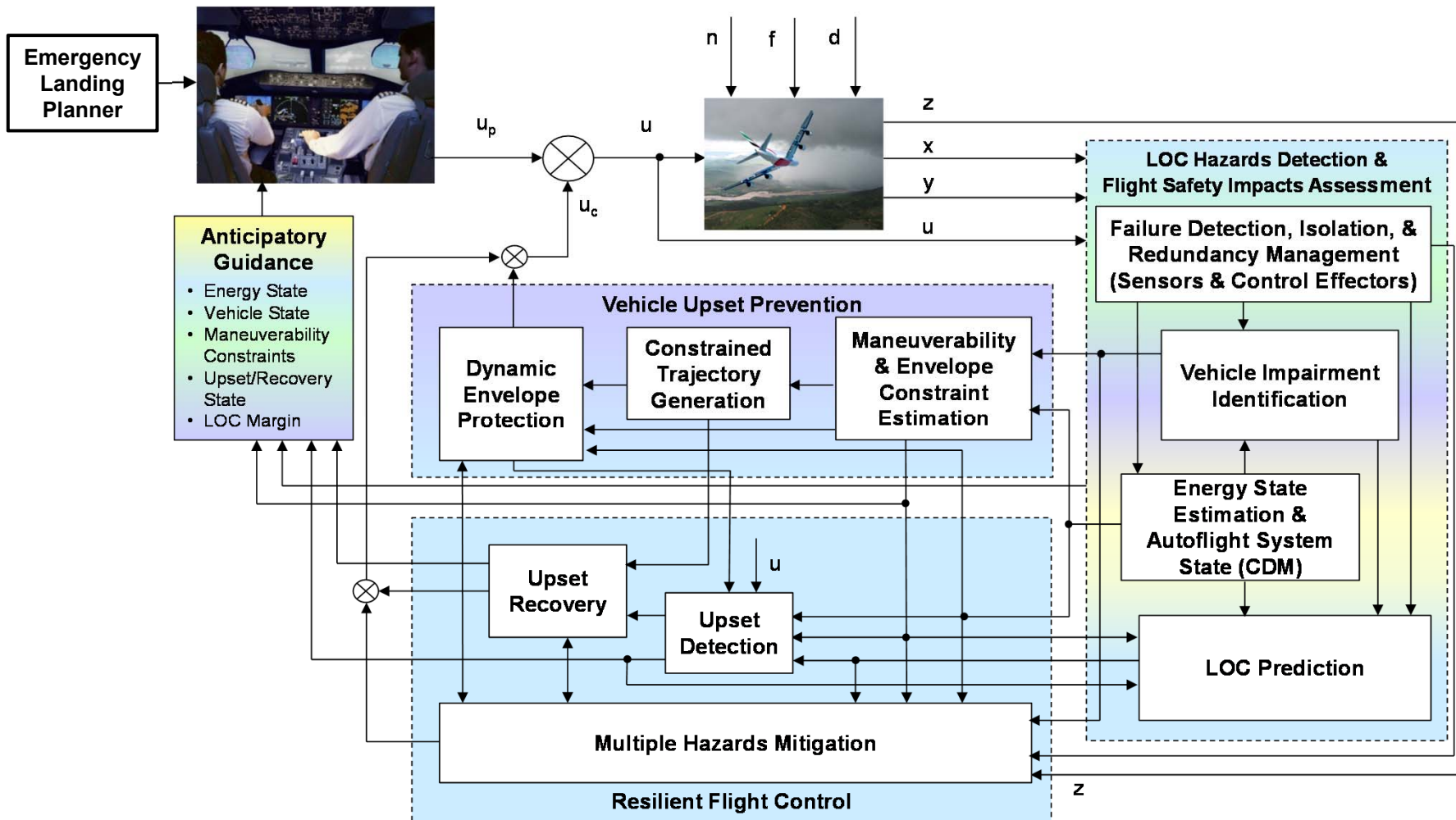
# Guidance, Control, and Systems Technologies (GCST) for Safe & Effective Control under LOC Hazards



■ Crew Decision Making (CDM)

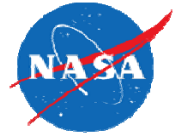
■ Maintaining Vehicle Safety (MVS)

■ Assuring Safe Control (ASC)



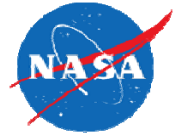
*Enables LOC Prevention and Recovery under Multiple Hazards*

# GCST Accomplishments Summary

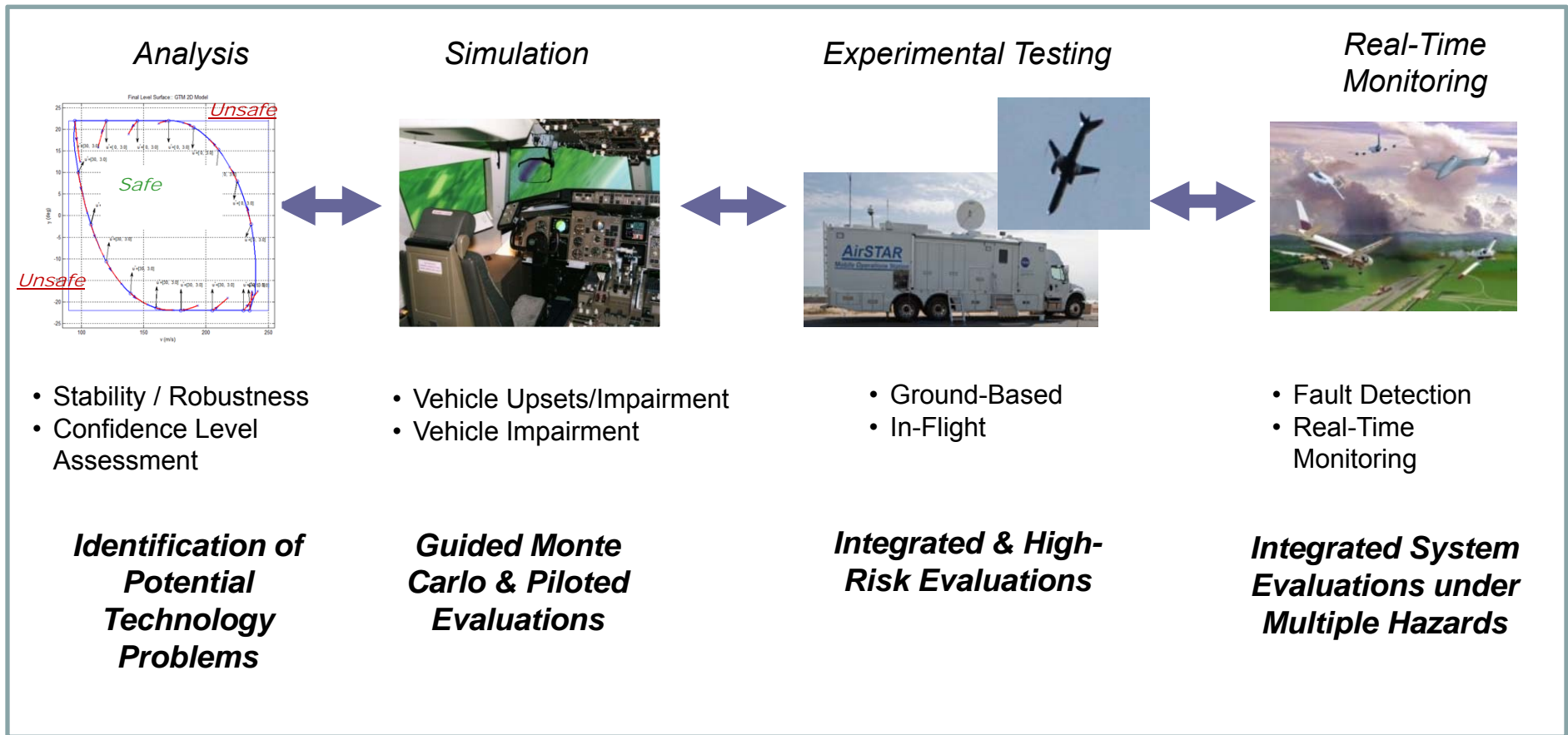


- Real-Time Hazards Effects Detection, Identification, & Mitigation (Dynamics and Control Effects)
  - System Failures
    - » Sensor (Focus on Dynamics & Control) Failures - FDI & Sensor Integrity Management
    - » **Control Actuator Failures – FDI & Control Mitigation**
    - » Propulsion System
  - Vehicle Impairment
    - » Icing
      - Airframe
      - Engine
    - » Damage
      - Airframe Structure (Longer Term)
      - Propulsion System
  - External Hazards
    - » Turbulence
    - » Wind Shear
    - » Wake Vortices
  - Inappropriate Crew Actions / Inaction
    - » Inappropriate / Ineffective Control Inputs
    - » Ineffective Recovery
- Real-Time Vehicle Level Effects Prediction / Detection
  - LOC Prediction / Prevention (Includes Upset Detection & Dynamic Envelope Protection)
  - **System Identification under Vehicle Upset** and Impairment Conditions
  - Safe Flight Envelope Estimation
  - Flight Safety Estimation / Prediction (Longer Term)

# Comprehensive Technology Evaluation (CTE)

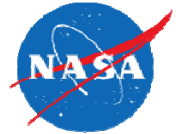


## Comprehensive Technology Evaluation using Realistic Hazards Test Scenarios



**Assess Effective Hazards Coverage, and Identify System Limitations & Weaknesses**

**NRA Partners: University of Minnesota, University of West Virginia, Georgia Institute of Technology (Bristol University and Drexel University)**

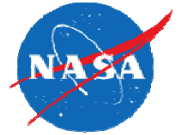


# CTE Accomplishments Summary

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- Analysis Methods
  - Nonlinear Analysis Methods (Bifurcation, etc.)
  - Robustness Analysis for Nonlinear Uncertain Systems
    - » Deterministic
    - » Stochastic
  - Analysis for Fusion-Based Stochastic Estimation Systems
  - Analysis of Pilot-Vehicle Systems
  - Analysis of Pilot-Automation Systems
  - Analysis of Complex Integrated Systems
- Simulation Methods (Based on Enhanced LOC Hazards Simulation)
  - Batch / Monte Carlo
  - Real-Time Piloted Evaluations
- Experimental Test Methods
  - **AirSTAR Testbed (In-Flight High-Risk Vehicle-Level Testing under LOC Conditions)**
    - » Conventional Transports within Visual Range
    - » Modular T-Tail Transport (Developed research aircraft via SBIR I & II)
    - » Beyond Visual Range (Under Development – Nearly Complete)
    - » Developed to Support Vehicle Dynamics & Resilient Control Testing
    - » Applicable to UAS Safety & Autonomy Research
  - SAFETI Lab (Potential for Integrated System Vehicle-Level Testing)
- LOC Test Scenarios Development
  - Preliminary Test Scenarios Developed (2012)
  - Final Set to be Developed (2015 - 2016)

# Airborne Subscale Transport Aircraft Research (AirSTAR) Testbed: Overview



**Objective: Provide an In-Flight Test Capability for High-Risk Conditions Leading to Aircraft Loss-of-Control**

## Research Aircraft



## Mobile Operations Station

### Base Research Station



### Research Pilot Station



### Researcher Station



## RESEARCH AIRCRAFT

- Current: 5.5% Dynamically Scaled Generic Transport Model (GTM); 16% Generic Modular Aircraft with T-Tail (GMA-TT)
- Future: Unconstrained
- Split Control Surfaces (Failures / Damage)
- Research Quality Instrumentation

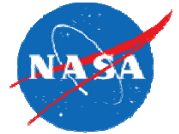
## GROUND FACILITIES

- Base Research Station (BRS)
- Mobile Operations Station (MOS)
  - » Research Pilot cockpit with synthetic vision
  - » Multiple researcher stations
  - » Data telemetry to / from aircraft

## UNIQUE CAPABILITIES

- Research Quality Data under High-Risk Test Conditions
- Supports Wide Range of Research
  - » Vehicle Dynamics Modeling
  - » LOC Prevention / Recovery Systems
  - » UAS Operations / Safety / Autonomy

# AirSTAR Testing under Vehicle Impairment



## Example Result: Offset Landing with Emulated Destabilizing Failure:

- Initial offset: 90 ft. lateral, 1800 ft. downrange, 100 ft. above the runway
- Pitch Stability degraded by 2 inboard elevator segments → 50% reduction in pitch control effectiveness
- Roll Damping Stability degraded by spoilers
- Flying qualities ratings taken for nominal, neutrally stable, unstable airplane

Note: Subscale Test Vehicle Response is 4.25X Faster than Full-Scale Aircraft

### September 2010 Deployment, Ft. Pickett, VA



Open-Loop Aircraft



L1 Adaptive Control System

Nominal

CHR 4 (FQ L2)

CHR 3 (FQ L1)

Neutrally Stable

CHR 10 (Uncontrollable)

CHR 5 (FQ L2)

Unstable

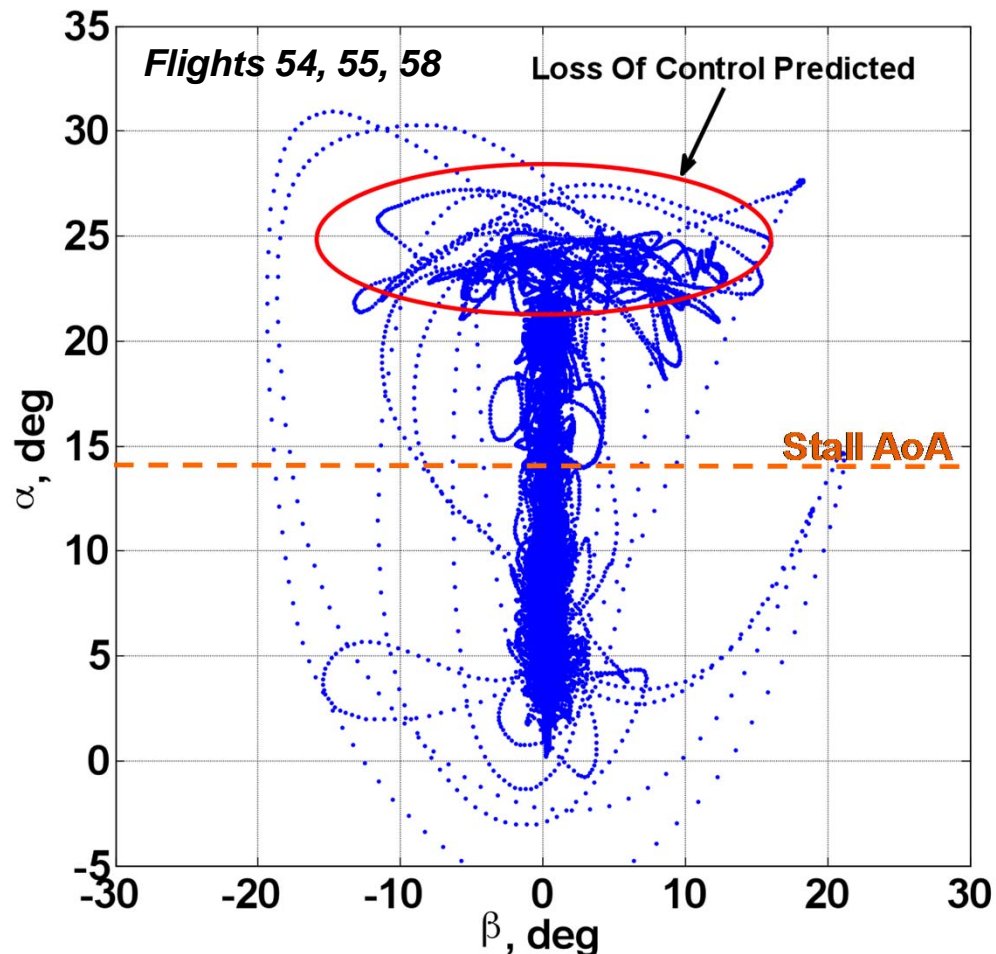
CHR 7 (FQ L3)

# AirSTAR Testing: System Identification under Vehicle Upset



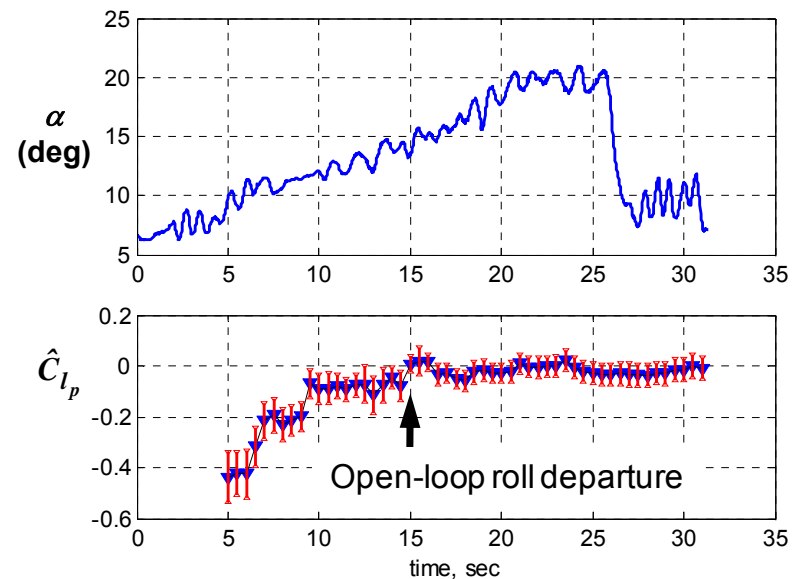
Example Result: Upset Test Condition - Stall / Departure (Pilot + Advanced Control System)

May 2011 Deployment, Ft. Pickett, VA



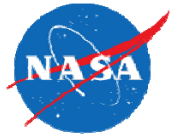
Demonstrated real-time stability and control characterization during approach to stall, through departure and recovery.

Example Result: T2 FLT 58 C14 WT02a



Applied L1 adaptive control to lengthen time on condition with stabilization that allowed slow transition through stall boundary and improved stall/departure recovery

# AirSTAR Testbed: Beyond Visual Range (BVR) Operations



- AirSTAR is developing the systems required for Beyond Visual Range (BVR) flight
  - Enables longer test period over larger test range
  - Enables going beyond the inner-loop in failure detection and accommodation
  - Enables extended envelopes, e.g. altitude for deep stall, spins
- BVR levies significant new instrumentation and operational requirements
  - Improved On-Board computational capability
  - Increased range of the telemetry link, secondary link for flight termination
  - Improved AGL sensing and video for remote piloted landings
  - Larger and more capable vehicle for aviation safety research
  - Operational changes



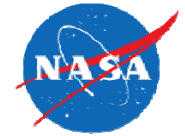
Beyond-Visual-Range  
System Integration Vehicle



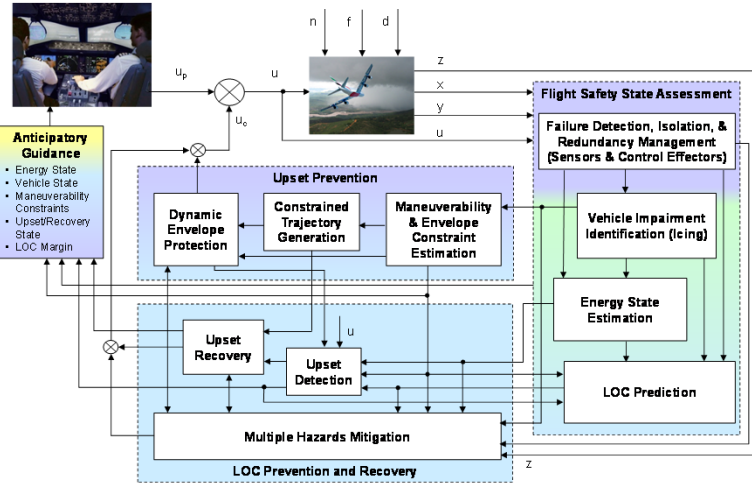
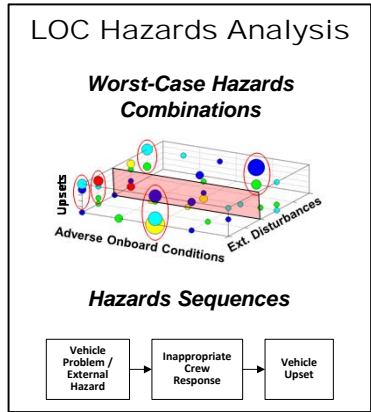
Wallops Test Range – 10 nm

*Upcoming BVR Deployment at NASA Wallops Flight Facility in April 2015*

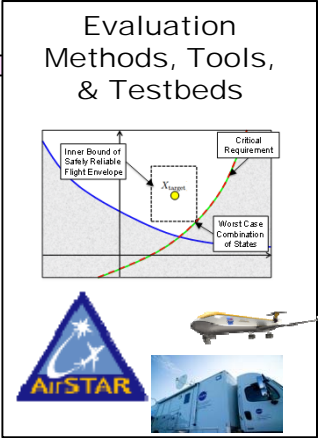
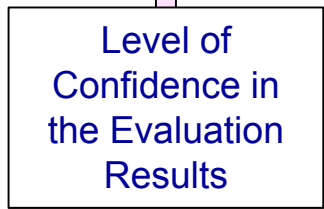
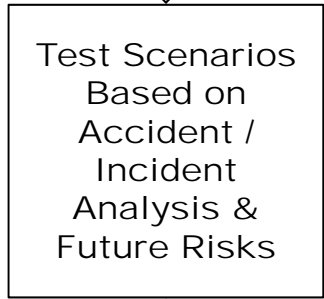
# LOC Research Integration



## Enhanced Systems Technologies for Improved Situational Awareness, Guidance & Control under LOC Hazards

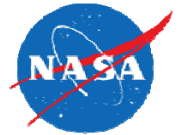


## Integrated LOC Hazards Effects Simulation



Level of Hazards Coverage      Degree of Technology Effectiveness      Technology Limitations & Constraints

# Future Research Directions: Safety-Assured Autonomy for Advanced Manned / Unmanned Aircraft



## Fully Autonomous Systems

Enable Safety-Assured Operations at All NAS Levels (Vehicles, Infrastructure, and Operations)



**Safety-Assured  
Autonomy**

*Pilot-Optional  
Aircraft*

- *Real-Time Safety Assurance*
- *Resilient Control & Mission Management*

## Variable Autonomy Systems

Enable Synergistic Dynamic Teaming Between Human and Intelligent Systems



*Single-Pilot Operations*

- *Resilient Control under LOC Hazards*
- *LOC Prediction, Prevention & Recovery*
- *Resilient Mission Planning*
- *Resilient Sense & Avoid*

## Resilient Systems

Provide Safety Augmentation, Guidance & Emergency Intervention to Support Baseline Systems and Human Operator



*Remotely Piloted  
UAS*

- *Dynamic Envelope Protection*
- *Resilient Control under Off-Nominal Conditions*
- *Upset Detection & Recovery*
- *Automatic Collision Avoidance*
- *Emergency Landing Planning*

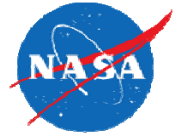
## Baseline:

Technology Used to Automate Routine Operations under Nominal Conditions and Provide Information & Alerts



*Current Operations*

Baseline: Altitude Hold, Autoland, Nominal Envelope Protection, TCAS, EGPWS, No Significant Warnings or Guidance under LOC Hazards

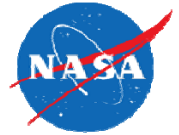


# Summary & Concluding Remarks

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- Aircraft LOC Contributes Significantly to Accidents & Fatalities
  - Largest Fatal Accident Category
  - Most Complex Accident Category (Many Causal & Contributing Factors)
- NASA is Conducting Unique Hazards Analysis of LOC Accidents / Incidents (Civil Transports / UAS)
  - Large Accident / Incident Set
  - Worst-Case Hazards Combinations
  - Detailed Hazards Sequences
  - Comprehensive LOC Test Scenarios
- NASA Research on LOC Prevention & Recovery Provides Holistic Solution
  - Vehicle Dynamics Modeling & Simulation of LOC Precursor Conditions
  - Guidance, Control, & Systems for LOC Prevention / Recovery
  - Improved Crew Situation Awareness, Guidance, & Cueing under LOC Hazards
  - Validation of Safety-Critical Technologies Developed for LOC Prevention / Recovery
- Future Research Direction towards Resilient Autonomous Aircraft for Safety-Critical Applications
  - Resilient Systems
  - Variable Autonomy Systems
  - Fully Autonomous Systems

***NASA LOC Research Directly Extends to Military Aircraft Applications***



# Potential Areas of Mutual Interest

---

- UAS Mishap Analysis & Hazards-Based Test Scenario Development
  - Large & Small UAS
  - Hazards Combinations & Sequences Leading to LOC (Includes Lost Link for UAS)
  - Resilience Testing under Uncertain, Unexpected, & Hazardous Conditions
- Modeling & Simulation of Key UAS Vehicle Configurations under LOC Hazards
  - Large / Small UAS
  - Realistic LOC Effects Characterization
- Resilient Control for LOC Prevention & Recovery (Including Lost Link Conditions)
  - Remotely Piloted UAS (e.g., Recovery Guidance under transport delays & without motion cues)
  - Autonomous UAS (Autonomous LOC Prevention & Recovery and Mission Planning & Execution)
- UAS Experimental Testing & Research
  - Lost Link Mitigation
    - » Safe Mission / Flight Termination
    - » Autonomous LOC Prevention & Recovery
    - » Autonomous Mission Planning & Execution
  - Transport Delay Effects in Recovery Guidance & Cueing of Remotely Piloted UAS
  - LOC Model & Technology Validation for UAS Vehicles

*Potential Upcoming Opportunity for NASA / DoD Cost Sharing*

## Contact Information:

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Resilient Control under Hazardous Conditions  
Dynamic Systems and Control Branch

8 Langley Boulevard, MS 308  
NASA Langley Research Center  
Hampton, VA 23681

757-864-4035

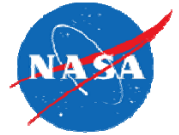
[christine.m.belcastro@nasa.gov](mailto:christine.m.belcastro@nasa.gov)

# Backup

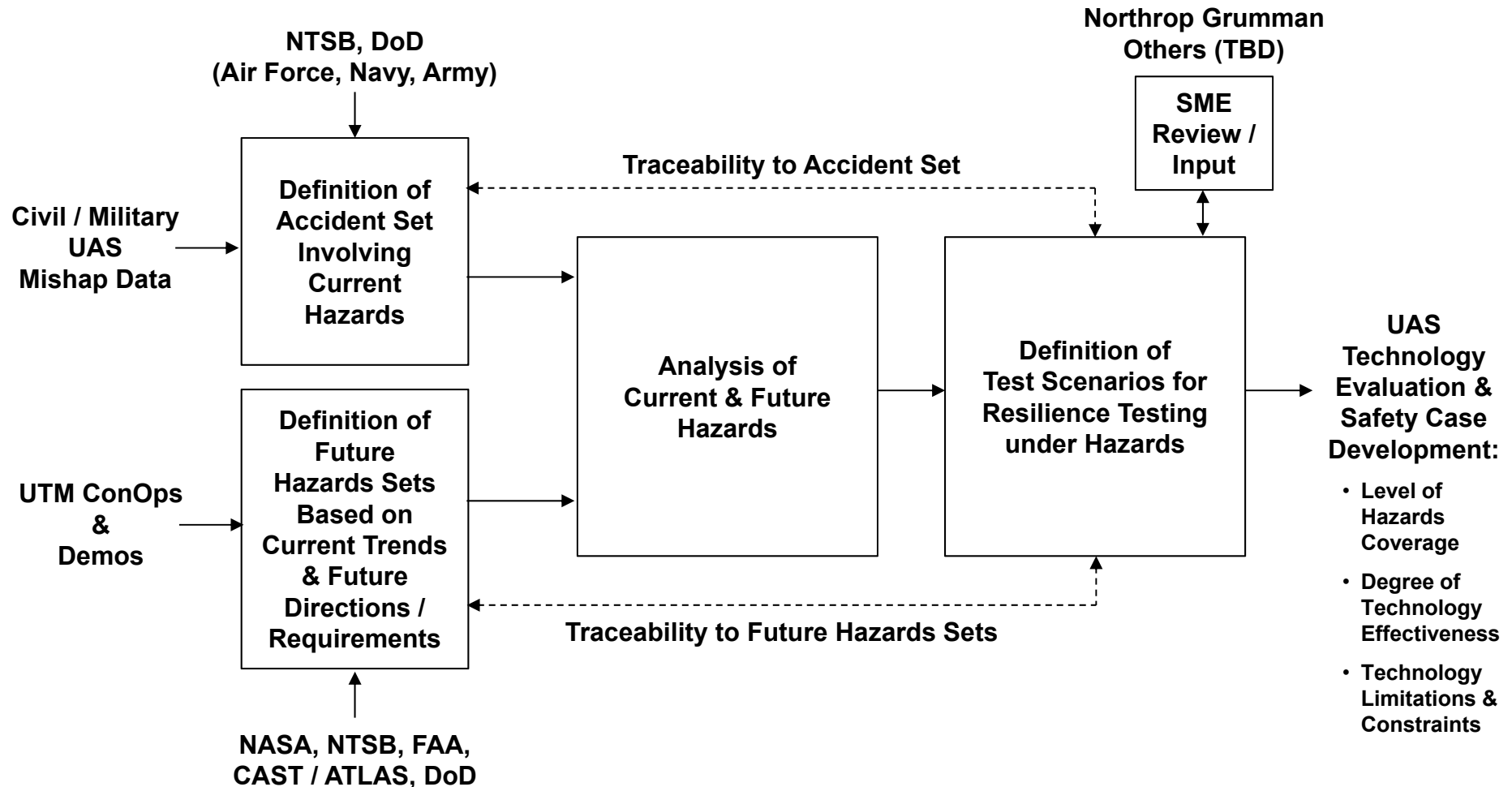
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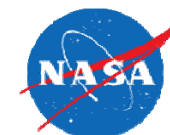


# UAS Mishap Analysis & Test Scenarios Development



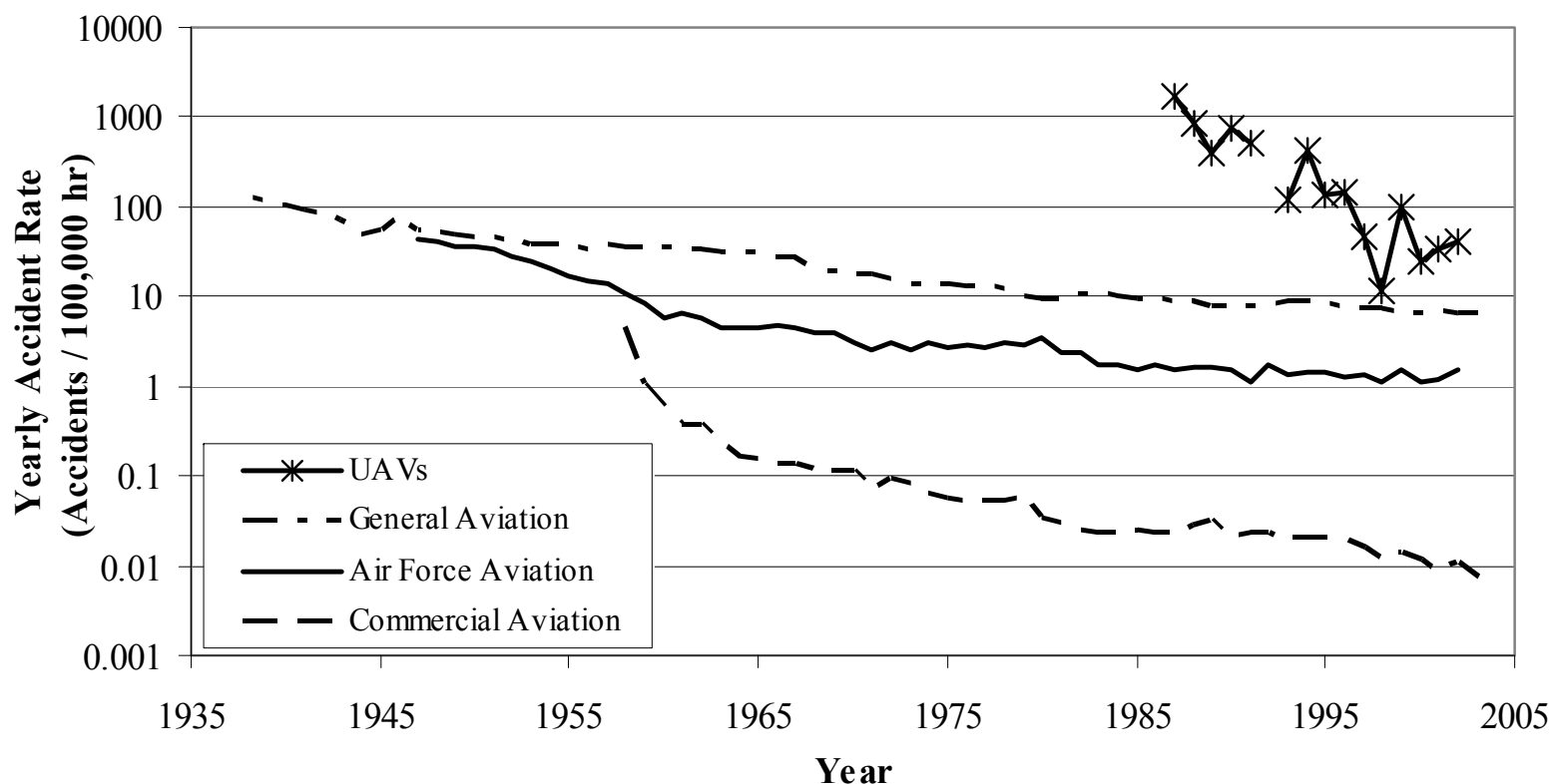
## Technical Approach





# Accident Rate Comparison for UAVs\* (1)

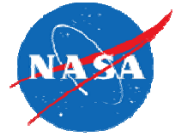
## Historical Accident Rate Trends by Year of Introduction



### Notes:

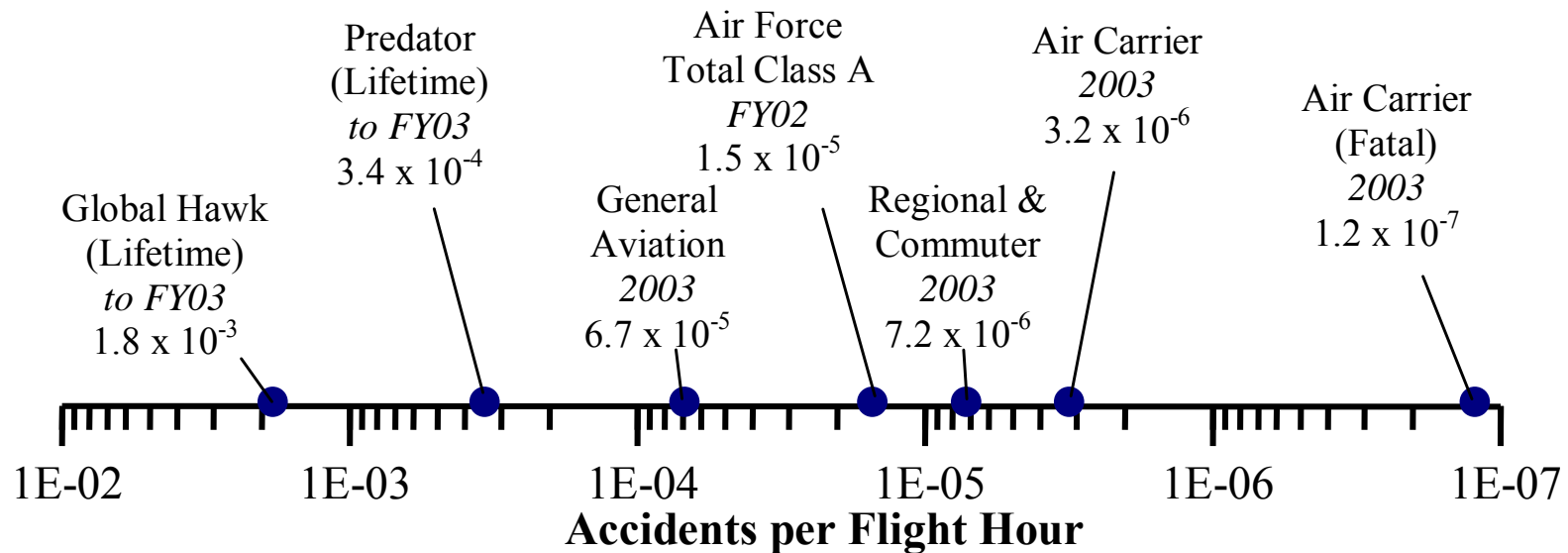
- 1) Commercial Aviation accident statistics are from the Bureau of Transportation Statistics and Aviation-Safety.net
- 2) Historical General Aviation Statistics are from AOPA
- 2) Air Force Aviation Class A mishap rates were published in an Air Force Safety Center presentation. UAVs are included in the category of Air Force Aviation
- 3) UAV Accident rates are averaged across the Pioneer, Hunter, and Predator UAVs from a DoD reliability study
- 3) Accident definitions vary between commercial & civil aviation

\*Ref: MIT International Center for Air Transportation, Accidents & Safety Briefing, 2005



# Accident Rate Comparison for UAVs\* (2)

## Accident Rate Comparison



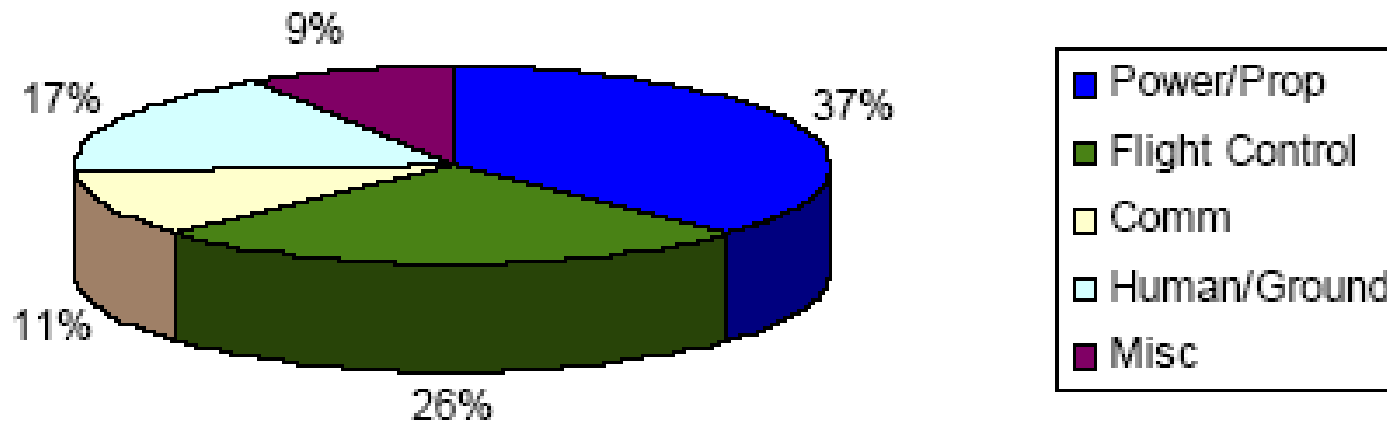
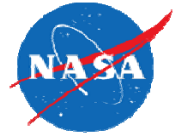
### Notes:

- 1) UAV Accident Rates and manned Air Force Aviation rates are Class A mishap rates reported by the Air Force Safety Center
- 2) Air Carrier, Regional & Commuter, and General Aviation accident rates were reported by the NTSB

\*Ref: MIT International Center for Air Transportation, Accidents & Safety Briefing, 2005

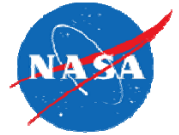


# Sources of System Failures\*



Source: Feb. 2003 Office of Secretary of Defense (OSD) UAV Reliability Study

\*Ref: MIT International Center for Air Transportation, Accidents & Safety Briefing, 2005



# LOC Hazards Analysis (1)

## LOC Accident / Incident Data Set

- Data Sources
  - Aircraft Accident Reports on DVD (R. Dorsett, 2006)
  - Australian Transport Safety Bureau (ATSB)
  - Aviation Safety Network (ASN)
  - Canadian Transportation Safety Board (TSB)
  - Flightglobal (Ascend Database)
  - French Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile (BEA)
  - German Bundesstelle für Flugunfalluntersuchung (BFU)
  - International Civil Aviation Organization (ICAO)
  - Irish Air Accident Investigation Unit (AAIU)
  - National Transportation Safety Board (NTSB)
- Search Criteria
  - “loss-of-control”
  - “upset”
  - “unusual attitude”
  - “stall”
  - “uncontrolled”

Resulted in Broader LOC Accident Set than LOC-I, Including Accidents & Incidents Involving:

- Failure by crew to maintain control,
- Weather encounters,
- Abrupt maneuvers, and
- Reduced control capability due to equipment malfunction or failure



## LOC Example: Colgan Air Flight 3407

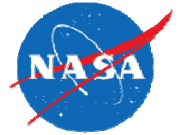
- Crashed During Approach to Landing (instrument landing system approach)
- Aircraft: Bombardier DHC-8-400, N200WQ; Date: February 12, 2009
- Clarence Center, New York (Near Buffalo-Niagara International Airport)



Note: This Aircraft (and many others involved in LOC accidents) < 60,000 lbs

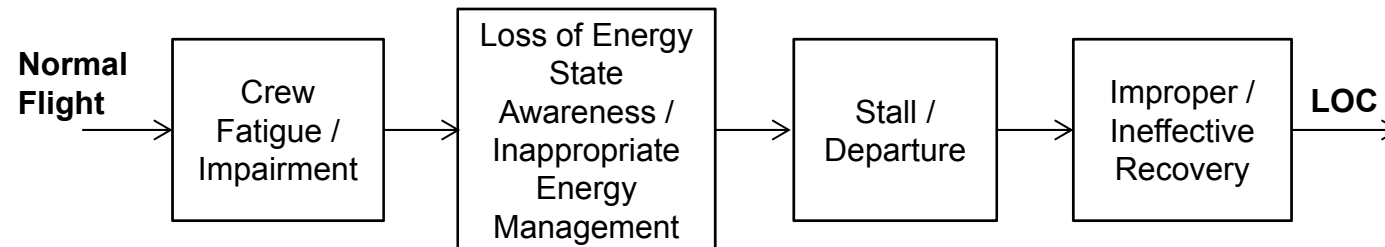
What is Aircraft LOC and what Causes it?

# LOC Hazards Analysis (9)



## *Preliminary Analysis Results*

Example Sequence at Precursor Level:  
Colgan Air 3407 (2/12/2009)



# LOC Hazards Analysis (2)



## 275 Accidents and Incidents (1996 – 2010)

7185 Onboard Fatalities, 235 Ground Fatalities

### LOC Events by 5-Year Intervals:

Timeframe	Events	On-Board Fatalities
1996 to 2000	102	2938
2001 to 2005	99	2143
2006 to 2010	74	2104
Total	275	7185

### LOC Events by Phase of Flight:

Flight Regime	Events	On-Board Fatalities
Takeoff	6	270
Initial Climb	79	1241
Climb	43	1697
Cruise	41	2008
Descent	17	156
Holding	22	0
Approach	34	1087
VFR Pattern	8	69
Circling	3	152
Final Approach	9	77
Landing	18	37
Go-around	8	15
Missed Approach	5	374
Maneuvering	2	2
Total	275	7185

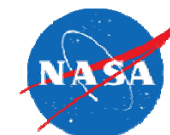
### LOC Events by Aircraft Classification:

Aircraft Classification	Events	On-Board Fatalities
Wide-body Turbojets	38	2224
Narrow-body Turbojets	96	3858
Business Jets	42	115
Turboprop Transports	44	615
Piston Transports	5	34
Commuter Airplanes	50	339
Total	275	7185

### LOC Events by Type of Operation:

Operation	Events	On-Board Fatalities
Scheduled Airlines	143	5803
Non-Scheduled	87	1234
Non-Revenue Operations	28	78
Executive Transportation	17	70
Total	275	7185

Accident Set is Provided in Appendix A  
of 2014 SciTech Paper



# Initial LOC Hazards Prioritization for Transports

Analysis of 64 Accidents with 2821 Fatalities from 2000 – 2009 (10 Years)

Multiple Hazards Guidance, Mitigation, & Upset Prevention / Recovery

### Crew-Related Hazards

- Loss of Aircraft State Awareness
  - Attitude / Energy
- Spatial Disorientation

### Vehicle/Environment-Related Hazards

- Control Component Failures
  - Icing Effects
  - Wakes / Wind Shear
- +/- Upsets & Crew Actions / Inactions

Sphere Size is Directly Proportional to Number of Accidents

Fatalities	
0	<span style="color: green;">●</span>
1 – 99	<span style="color: cyan;">●</span>
100 – 199	<span style="color: blue;">●</span>
200 – 299	<span style="color: yellow;">●</span>
300 - More	<span style="color: red;">●</span>

## Vehicle Upset Conditions

- Stall / Departure
- Uncontrolled Descent
- Abnormal Trajectory
- Ab. Va / Rates / Asym
- Abnormal Attitude
- None / Unknown

Inappropriate Crew Response

Vehicle Damage

System Faults / Failures

Vehicle Impairment

None / Unknown

None / Unknown

Poor Visibility

Wake Vortex

Wind Shear / Turb.

Snow / Icing

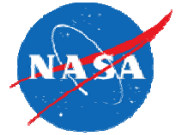
Collision

External Hazards / Disturbances

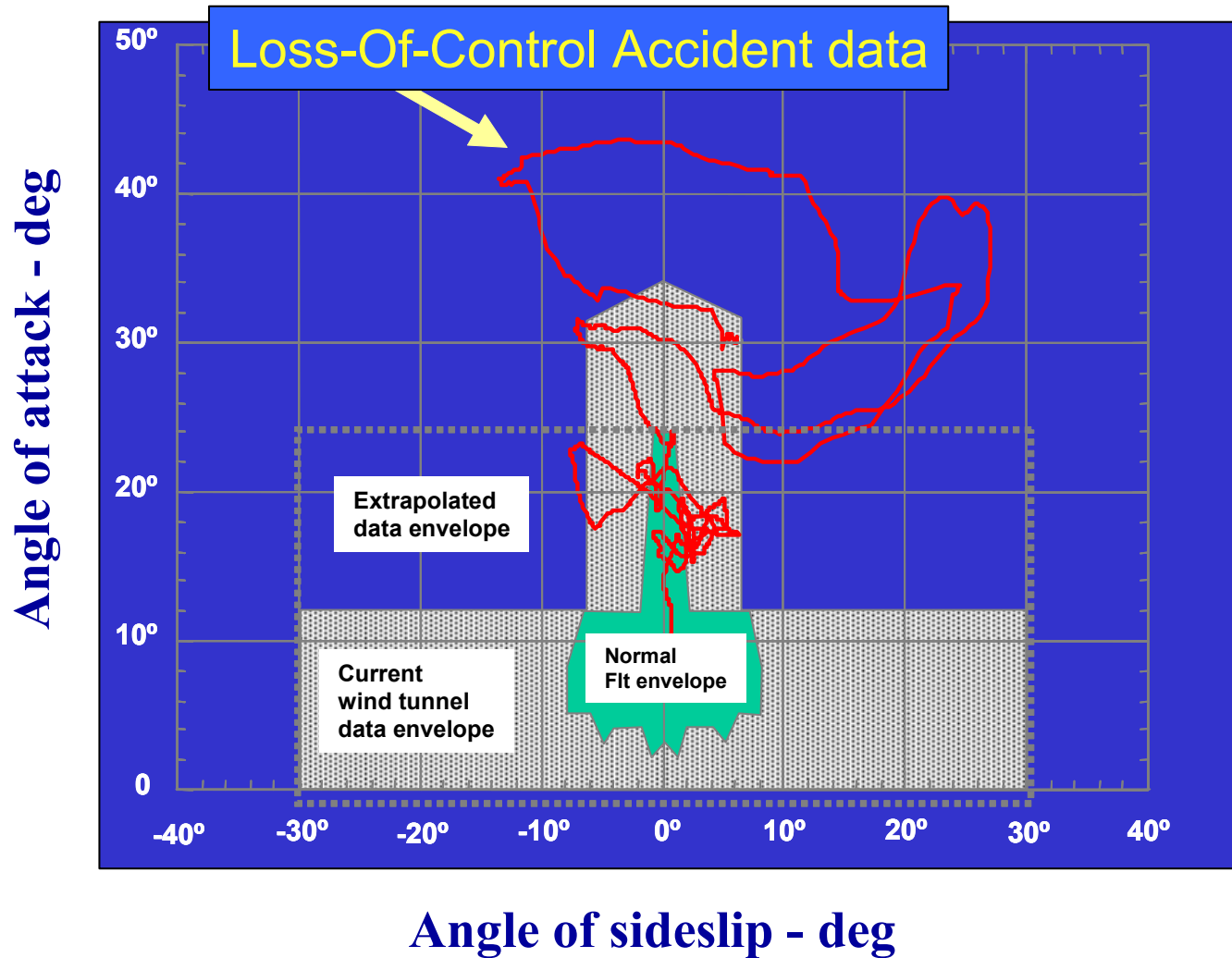
Adverse Onboard Conditions

Future High-Density Operations (Terminal Area)

# Vehicle Upset Modeling & Simulation (1)



## *Transport Simulation Assessment for Loss-of-Control Characterization*



*Loss-of-Control Events Occur Well Outside Normal Vehicle Operation*

# Integrated LOC Simulation (1)



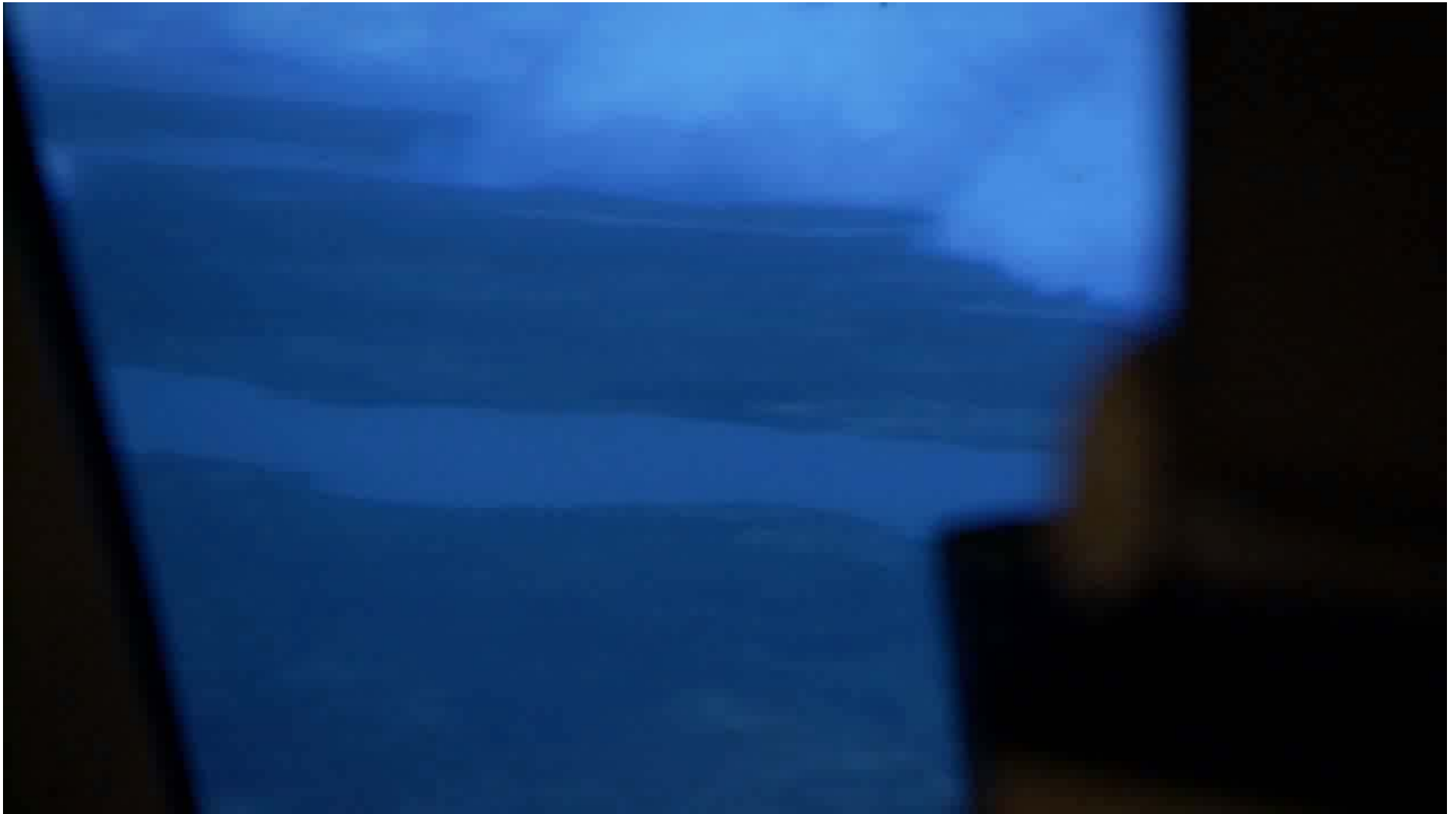
## *Enhanced Fixed-Base Simulation for Aircraft Upset Characterization: Stall / Departure*



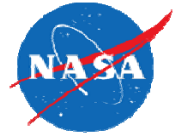
# Integrated LOC Simulation (2)



## *Enhanced Motion-Base Simulation for Aircraft Upset Characterization: Buffet*



# Upset/Stall Training Collaboration with NAVAIR



## Problem

- Upset models and simulations are needed for U.S. Navy upset prevention & recovery training for P-8 program
- Desire to leverage ongoing NASA upset modeling research to reduce costs and development time

## Objectives

- Develop & validate representative upset simulation models for U.S. Navy P-8 (B737-800)
- Support P-8 stall training research & development

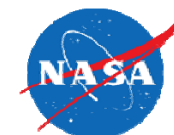
## Accomplishments

- Representative P-8 aerodynamic stall model developed from NASA aircraft upset database (developed for B-757)
- Operational Evaluation (OpEval) completed for 30+ U.S. Navy pilots of proposed P-8 upset training syllabus (Nov 2011)
- Preliminary validation of representative model completed using flight test data

## Significance

- Directly supports class-representative modeling and real-time simulation development for extension of upset models developed for one aircraft to other within-class aircraft
- Demonstrates applicability of upset modeling research for upset recovery training by other government agencies and industry

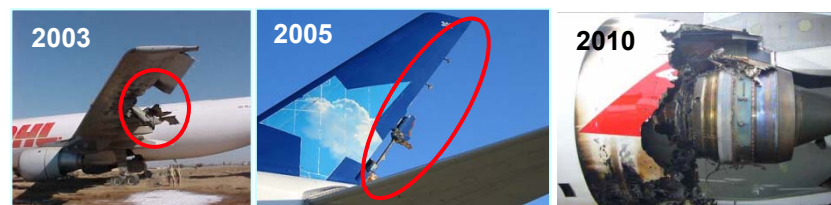




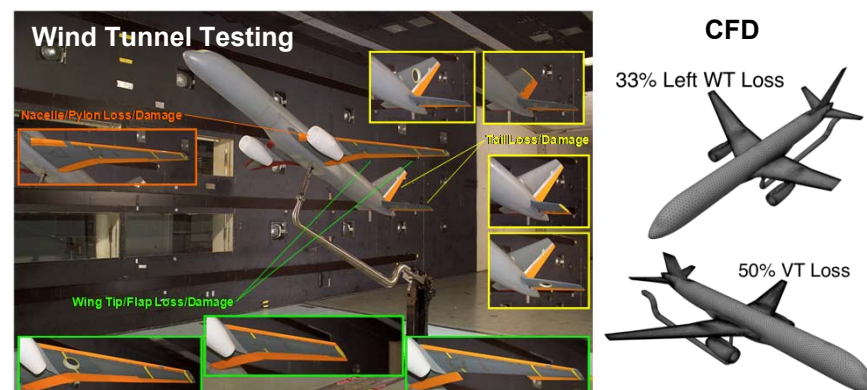
# Vehicle Impairment Modeling: Damage

- **Problem:** Vehicle damage can result from insipient fatigue crack growth (that reaches catastrophic failure) or a discrete source (e.g., uncontained engine failure). It can cause sudden changes in vehicle dynamics characteristics and control capability.
- **Objectives:** Develop simulation models that reflect realistic vehicle damage effects, including aerodynamic, propulsion, airframe structure, underlying systems, and control effectors.
- **Accomplishments:**
  - Developed preliminary aerodynamic damage effects database for parameterized loss of lifting and control surfaces using experimental and computational methods
  - Developed structural damage and crack propagation modeling methods and tools, and an approach for rapid modeling and analysis based on equivalent plate models
  - Developed a preliminary approach for assessing engine thrust degradation and impacts to underlying system failures as a result of airframe damage
- **Significance:** Enables the simulation of realistic airframe damage effects on aerodynamics and structural loads. This is important for upset prevention and recovery training as well as the development and evaluation of onboard system technologies for airframe damage effects detection and mitigation.

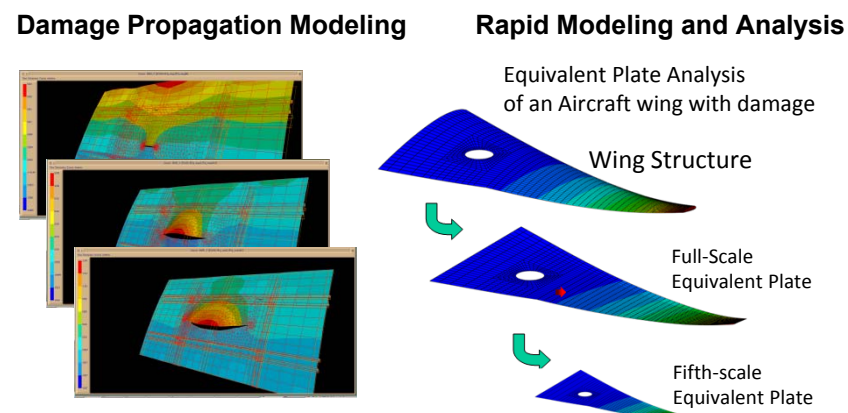
## Recent Occurrences of Vehicle Damage



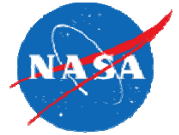
## Aerodynamics Effects Modeling



## Structural Effects Modeling



# Transport Damage Modeling

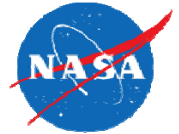


*Modeling and Simulation to evaluate survivability /continued-flight capability after MANPADS damage*

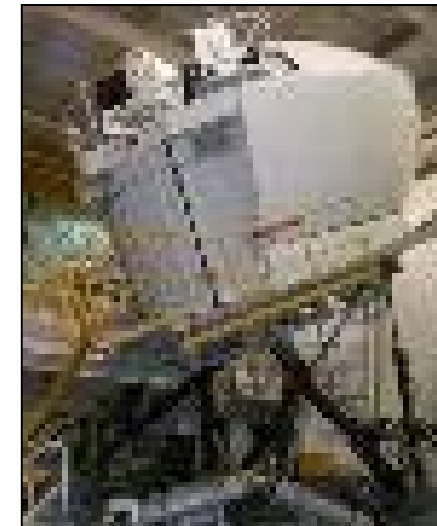
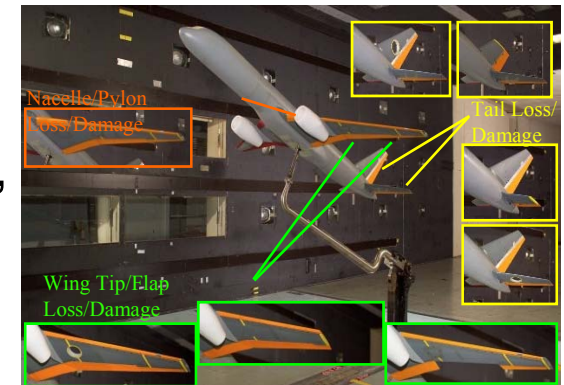
- NASA Aviation Safety Program
- Determine potential aerodynamic / flight control / propulsion effects due to damage
- Measure / Model effects in simulation
- Conduct real-time piloted simulation to evaluate controllability, landing capability
- Research efforts sponsored through DOD
  - Joint Aircraft Survivability Program
  - Joint Live Fire Program
- Live-fire testing, analysis, reporting
  - 46<sup>th</sup> TW - Eglin AFB, Wright-Patterson AFB – Control surface vulnerability to MANPADS
  - NAWCWD – China Lake – Engine/MANPADS damage



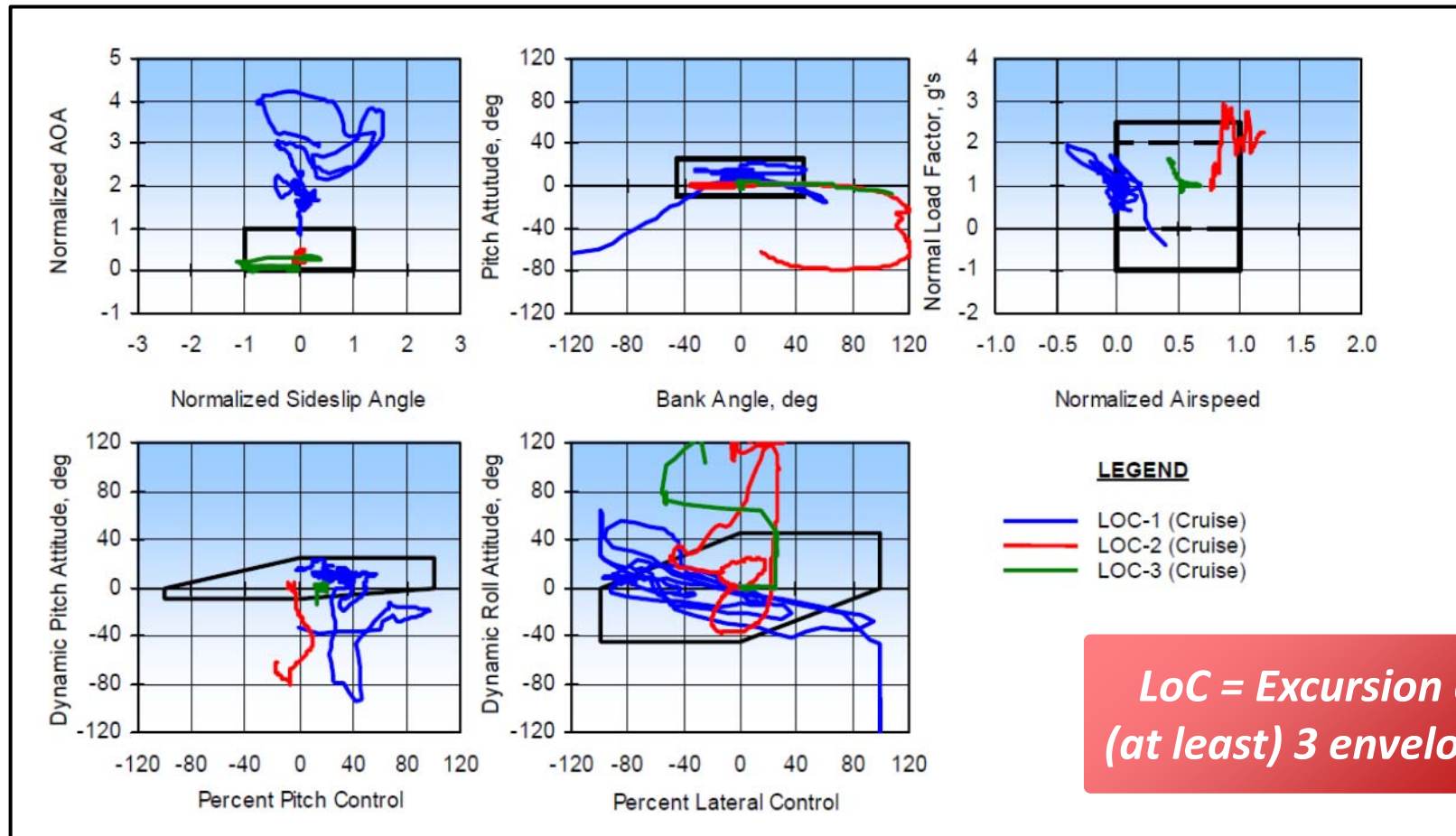
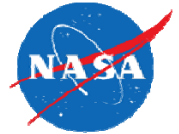
# Damage Modeling Technical Capability



- Extensive wind-tunnel-based dataset of damage characteristics
- Versatile, high-fidelity piloted simulation, multi-axis, multi-system damage effects
  - Aerodynamics, Flight Control degradations
  - Mass Properties changes
  - Thrust degradations
- Publications
  - JLF-TR-05-08, *Control Surface Vulnerability to MANPADS*, 2006
  - JASPO-TR-V-4-07-0001, *MANPADS Damage Effects on a Large Aircraft Engine*, 2007
  - AIAA-2008-6203, *Aerodynamic Effects and Modeling of Damage to Transport Aircraft*
  - JASP-M-10-03, *Flight Simulation of a Damaged Transport Aircraft*, 2010
  - JLF-09-13, *Large Engine Vulnerability To MANPADS*, 2013

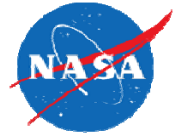


# LOC Prediction / Prevention (1)



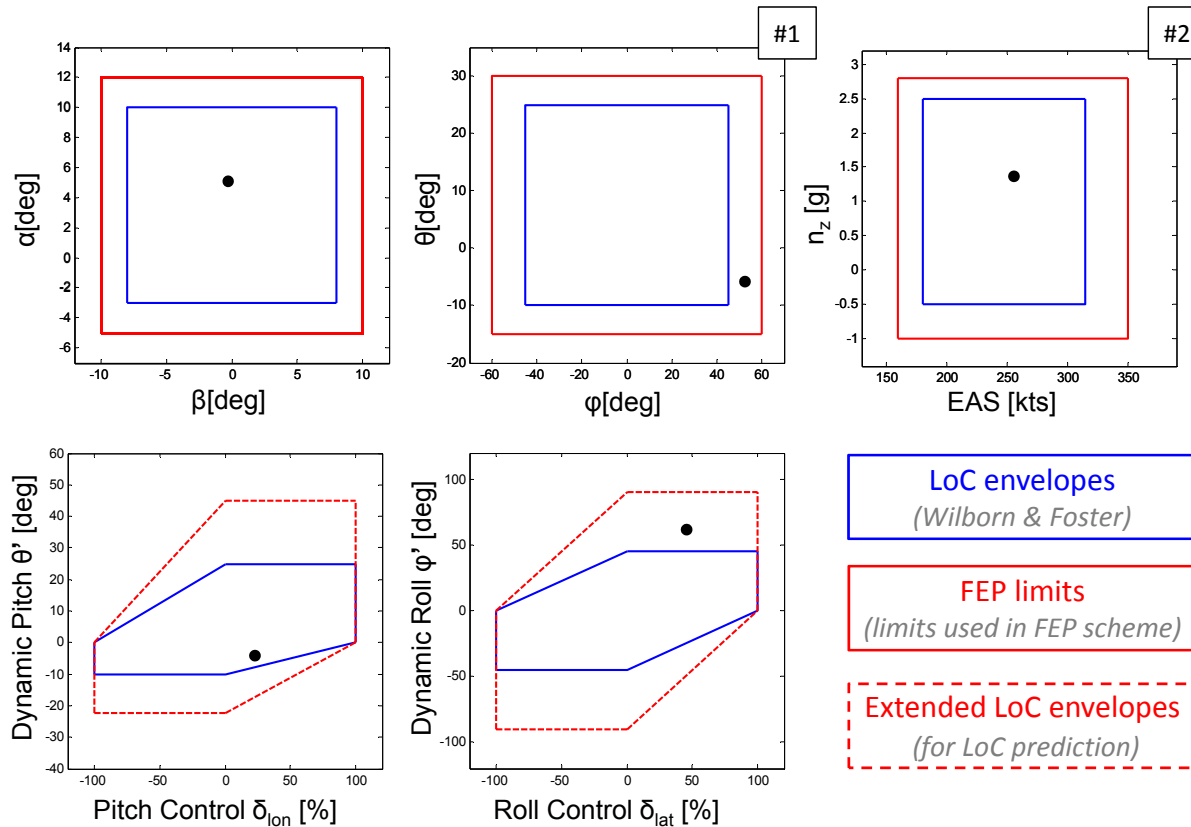
[1] Wilborn, J. E. and Foster, J. V., "Defining Commercial Aircraft Loss-of-Control: a Quantitative Approach," *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, Providence, RI, August 2004.

# LOC Prediction / Prevention (2)

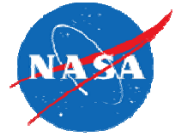


## Illustrative Example

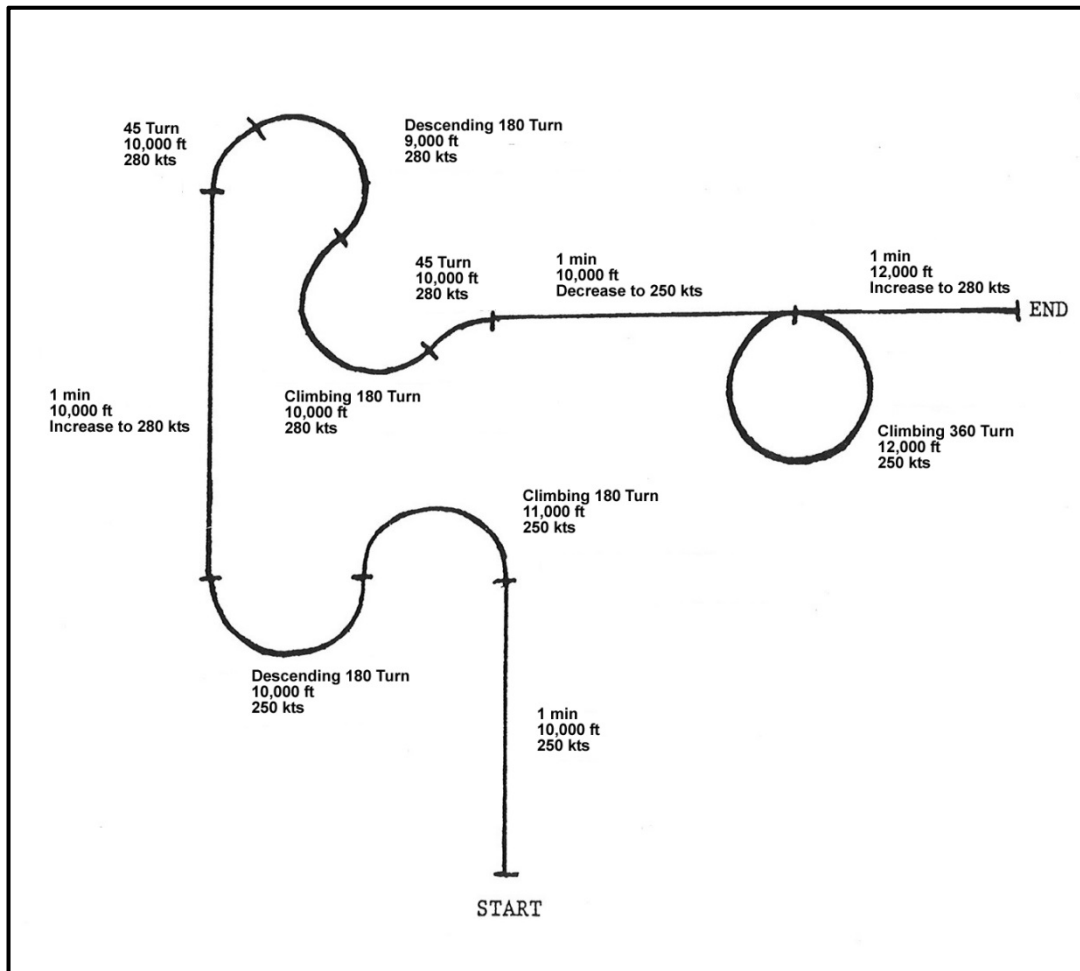
- **LoC Prediction:**
  - › Keep count of the number of LoC and extended LoC envelope excursions.
- **FEP-Limit Adjustment Logic:**
  - › Adjust FEP limits depending on the number of exceeded LoC envelopes.



# LOC Prediction / Prevention (3)



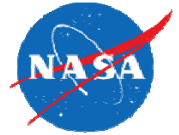
## Piloted Simulation Results: Nominal Operations



- **Execution of standard maneuvers in normal flight operation:**
  - › *Straight and level flight*
  - › *25-deg bank turns*
  - › *1,000-ft/min climbing turns and descents*
  - › *Increase/Decrease airspeed*
- **Range of operation:**
  - › *Alt: 9,000 – 12,000 ft.*
  - › *Bank angle: 0 to 25 deg*
  - › *Airspeed: 250 to 280 kts*

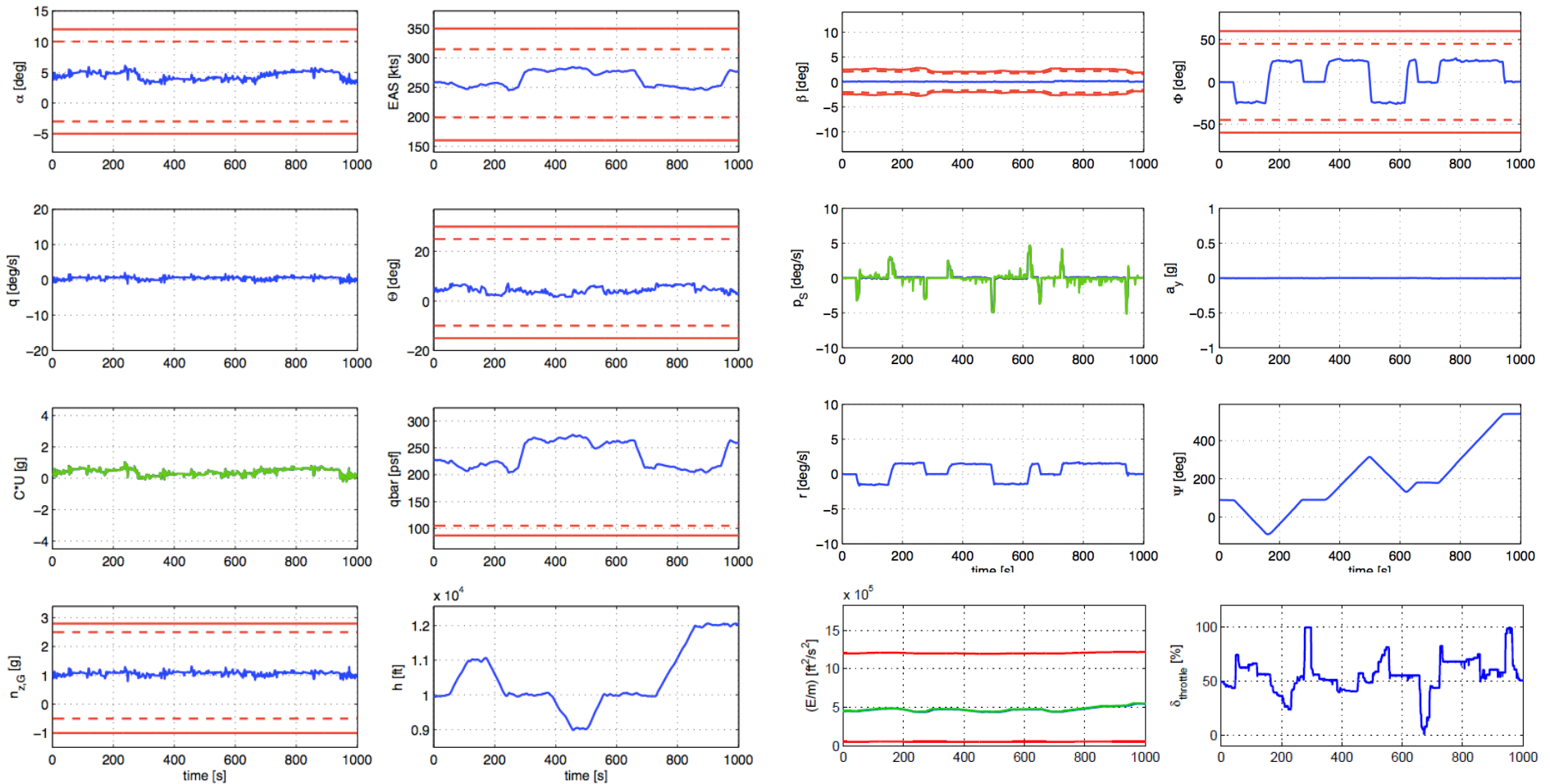
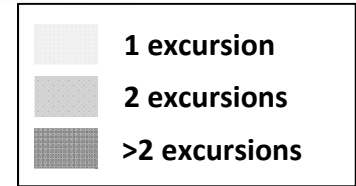
*All tests performed by a transport category certificated pilot*

# LOC Prediction / Prevention (4)



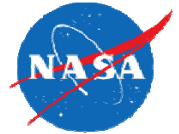
## Piloted Simulation Results: Nominal Operations

LoC prediction & prevention *active*

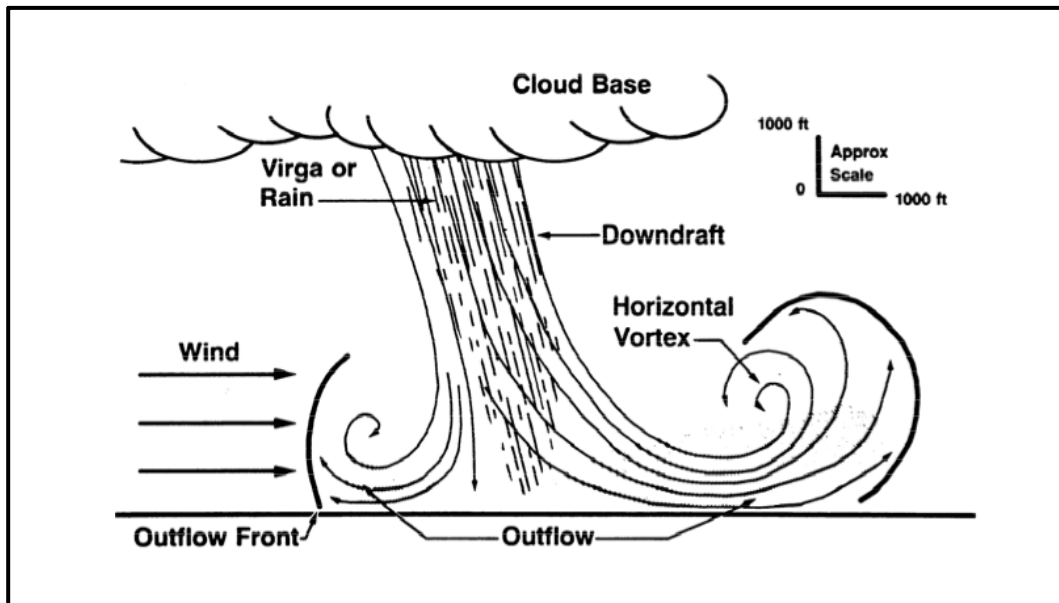


*Proposed System Does Not Appear to Affect Pilot Performance under Normal Operations*

# LOC Prediction / Prevention (5)



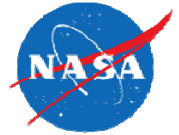
## Piloted Simulation Results: Microburst



*Tailwind, downdraft, and lateral gust modeled as “(1-cos)-shaped” time-varying velocity fields fixed with respect to the NED frame.*

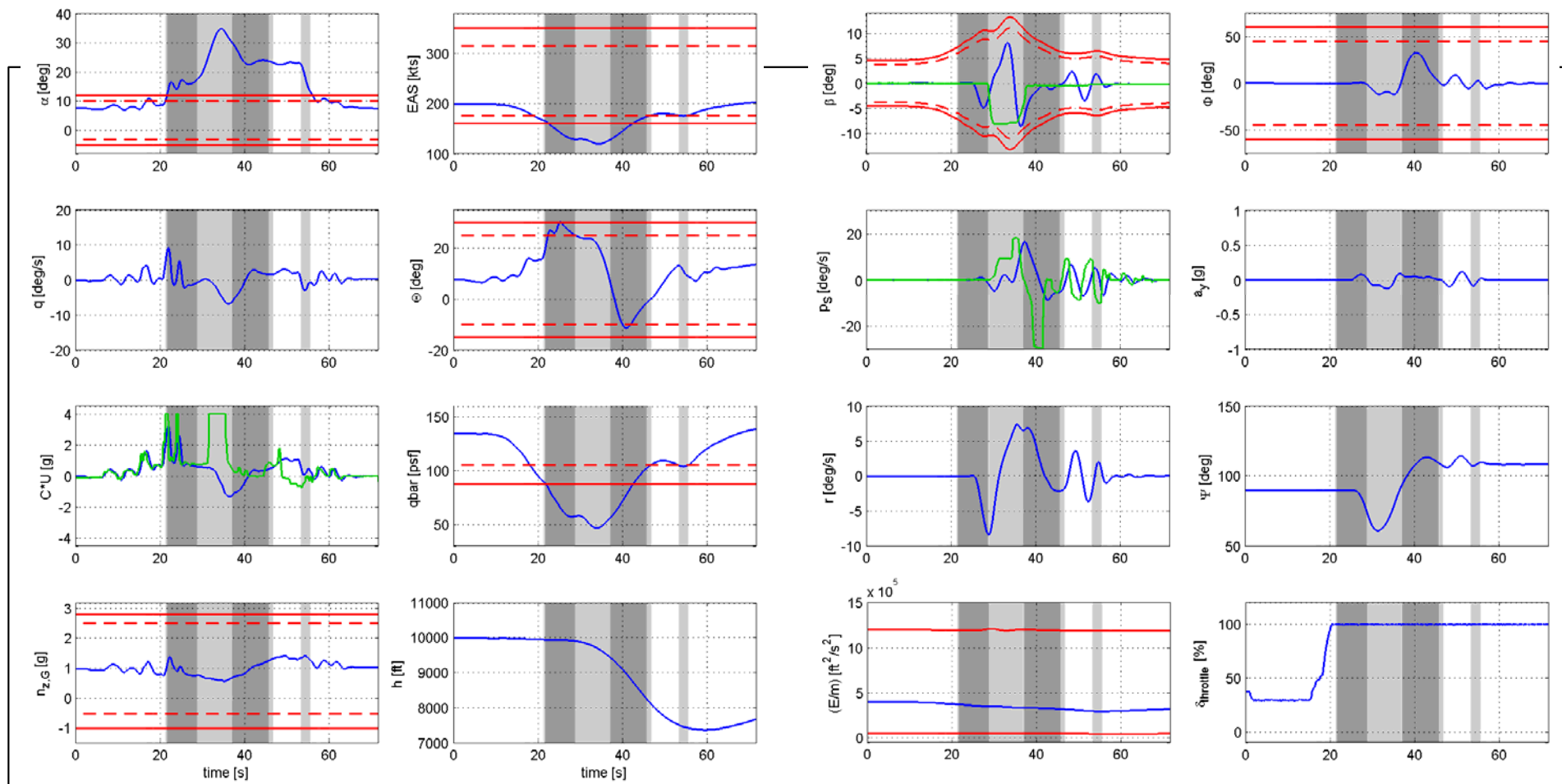
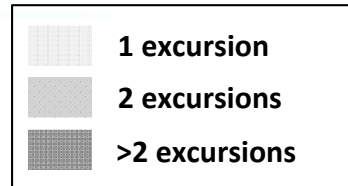
- **Test instructions:**
  - › *Maintain wings level at 200 KCAS*
  - › *Minimize altitude loss*
  - › *Maintain initial heading*

# LOC Prediction / Prevention (6)



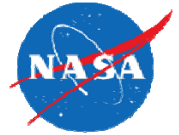
## Piloted Simulation Results: Microburst

*LoC prediction & prevention **not active***



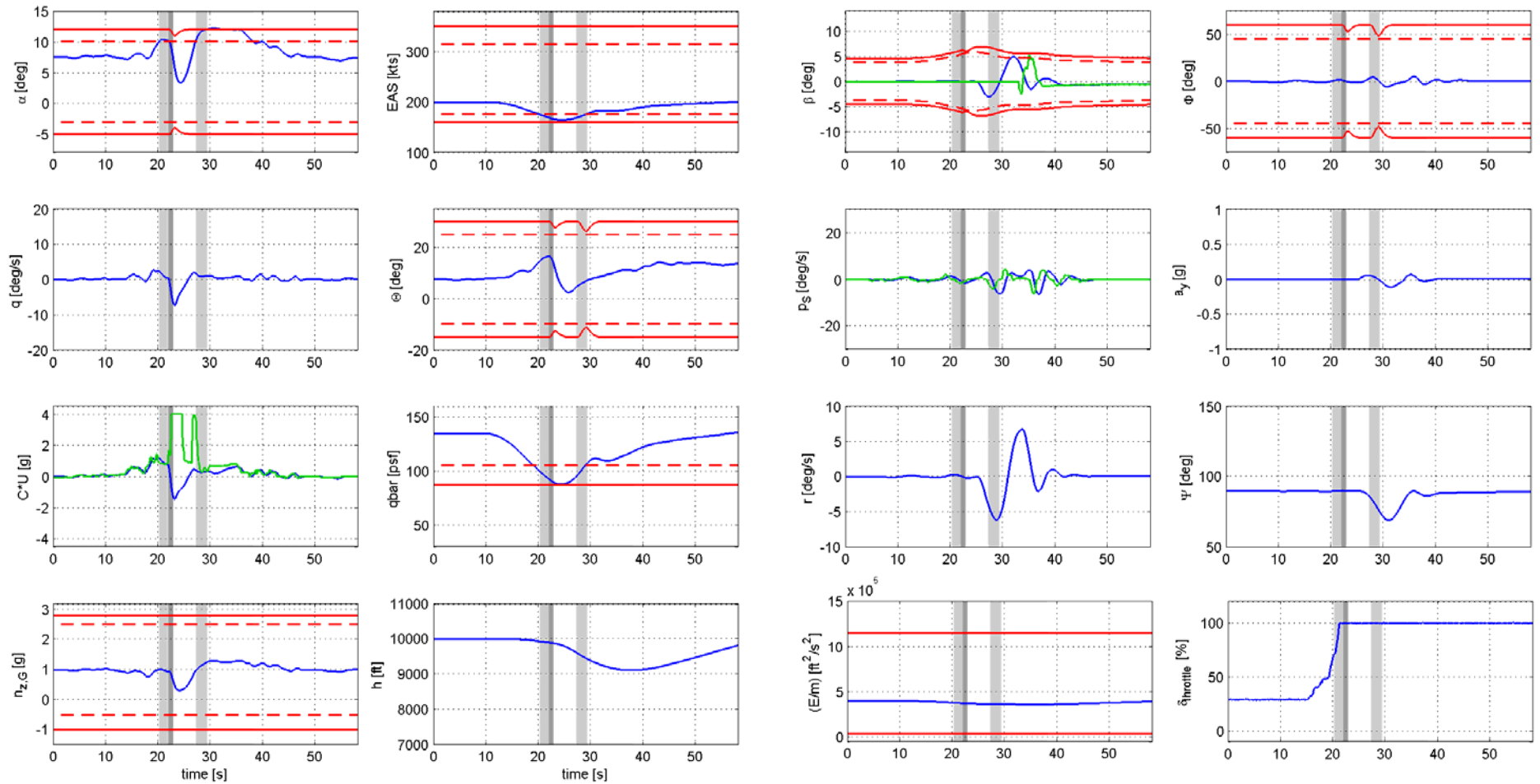
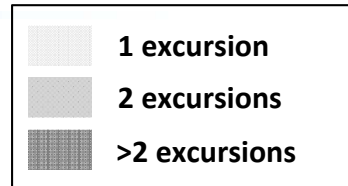
*LOC Conditions Occur for Substantial Amount of Time; Pilot Recovered after 2500 ft Altitude Loss*

# LOC Prediction / Prevention (7)



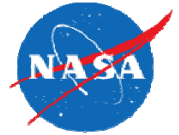
## Piloted Simulation Results: Microburst

*LoC prediction & prevention active*

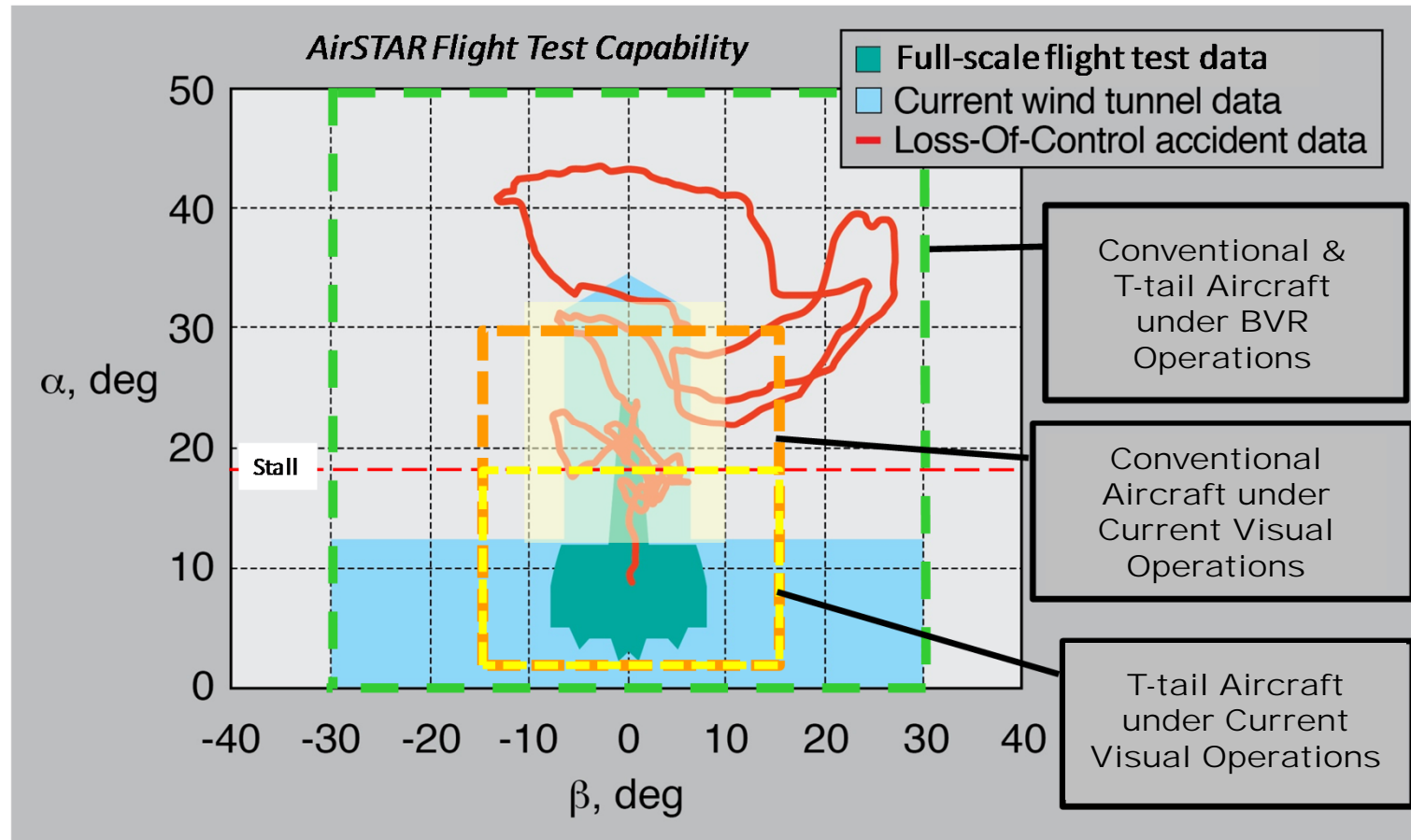


*Significant Reduction in LOC Conditions; Pilot Recovered after < 1000 ft Altitude Loss*

# Research Need for Beyond Visual Range (BVR) Operations

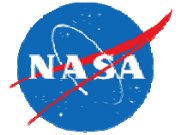


## 1. Vehicle Dynamics Modeling for Multiple Vehicle Configurations



## 2. Longer Research Maneuvers for Inner/Outer-Loop Systems

# Approach for Developing LOC Test Scenarios



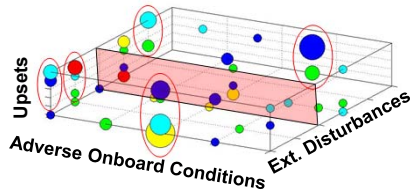
Hazards Analysis



Realistic Test Scenarios with Traceability to the Hazards Sets

Accident Data / Future Risks

Worst-Case Hazards Combinations



Scenario Set Number	Recommended Evaluation Methods	Scenario Description	Flight Condition	Adverse Onboard Conditions	Inappropriate Crew Response	External Hazards & Disturbances	Vehicle Upset Conditions
<i>Four Precursor LOC Scenarios: Vehicle Failure → Inappropriate Crew Response → Upset → Vehicle Damage</i>							
55	Analysis, Batch Simulation, Piloted Simulation	Engine Failure Followed by Crew Distraction Leading to Upset and Vehicle Damage	Cruise	1. Single Engine Failure (100% Thrust Loss); 4. Various Levels of Structural Damage with and without Loss of Control Effector	2. Crew Distraction Resulting in Delayed Response Followed by Excessive Response		3. Decreased Airspeed, Asymmetric Forces / Moments, Stall / Departure

### Crew Hazards

- Loss of Aircraft State Awareness
- Spatial Disorientation

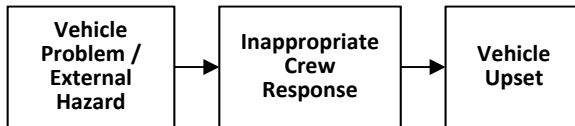
### Vehicle and Environmental Hazards

- Control Component Failures
- Icing Effects
- Wake Vortices

### Abnormal Flight / Upset Hazards

- Extreme Attitudes
- Abnormal Energy States
- Abnormal Control Response
- Stall / Departure

### Hazards Sequences



Unique & Generalized Sequences

Scenario Set Number	Generalized Sequence	Coverage of Hazards Based on Historical Data & Future Potential Risk Sets								
		Accidents from Data Set Covered by Scenario	Number of Accidents from Data Set Covered by Scenario	Future Risks Covered by Scenario	Number of Future Risks Covered by Scenario	% Coverage of Data Set		% Cumulative Coverage		
						Accidents	Future Risks	Accidents	Additional Future Risks Covered	Future Risks
1	D	56	1	3	1	0.79%	10%	0.79%	1	10%
2	D	62, 63	2	3	1	1.59%	10%	2.38%	0	10%
3	D	1, 15, 18, 41, 79	5	3	1	3.97%	10%	6.35%	0	10%
4	D, E	17, 20, 8, 113	4	3	1	3.17%	10%	9.52%	0	10%
5	D	13	1	3	1	0.79%	10%	10.32%	0	10%
6	D	7	1	3	1	0.79%	10%	11.11%	0	10%
7	D	3	1	10	1	0.79%	10%	11.90%	1	20%
8	D	2	1	3, 10	2	0.79%	20%	12.70%	0	20%
9	D	2, 110	2	3, 10	2	1.59%	20%	14.29%	0	20%
10	D	N/A	0	7	1	0.00%	10%	14.29%	1	30%
11	D	16	1	8	1	0.79%	10%	15.08%	1	40%
12	D	N/A	0	4	1	0.00%	10%	15.08%	1	50%

Partners: NTSB & NIA (CAST / ATLAS)