Emerging Technologies for Airplane State Awareness and Prediction

Stefan Schuet
Intelligent Systems Division
NASA Ames Research Center

Airline Operations Workshop
August 2-4

Main Contributors

NASA Ames:
Stefan Schuet (Co-lead)
John Kaneshige
Thomas Lombaerts
Kimberlee Shish
Vahram Stepanyan
Diana Acosta

Gordon Hardy (Test Pilot)

NASA LaRC:
Steven Young (Co-lead)
Taumi Daniels
Emory Evans

External:
Timothy Etherington
Rockwell-Collins, Inc.

Dr. Maarten Uijt de Haag
Ohio University

Capt. Daniel Kiggins
National Institute of Aerospace
American Airlines

Outline

- Motivation

- Technologies
  - Trajectory Prediction
  - Safe Flight Envelope Estimation
  - Predictive Alerting
  - Synoptic Displays
  - Stall Recovery Guidance

- Concluding remarks

Link to source material (shortened URL)

http://goo.gl/######
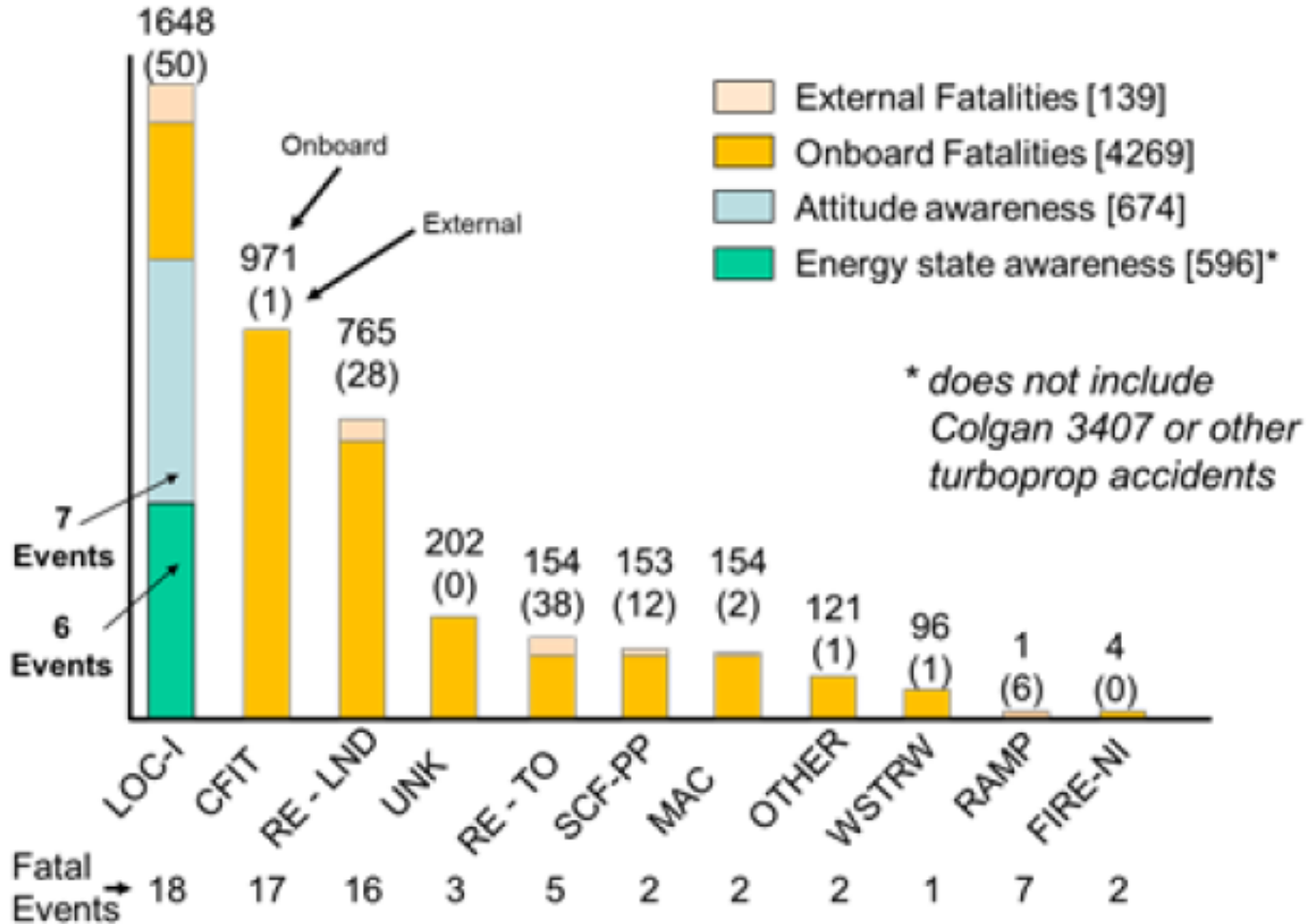
MOTIVATION

Commercial Aviation Safety Team (CAST)

Airplane State Awareness (ASA) Joint Safety Analysis Team (JSAT)

- Subject matter experts from industry and government

Final Report - Analysis and Results, June 2014

http://www.skybrary.aero/bookshelf/books/2999.pdf
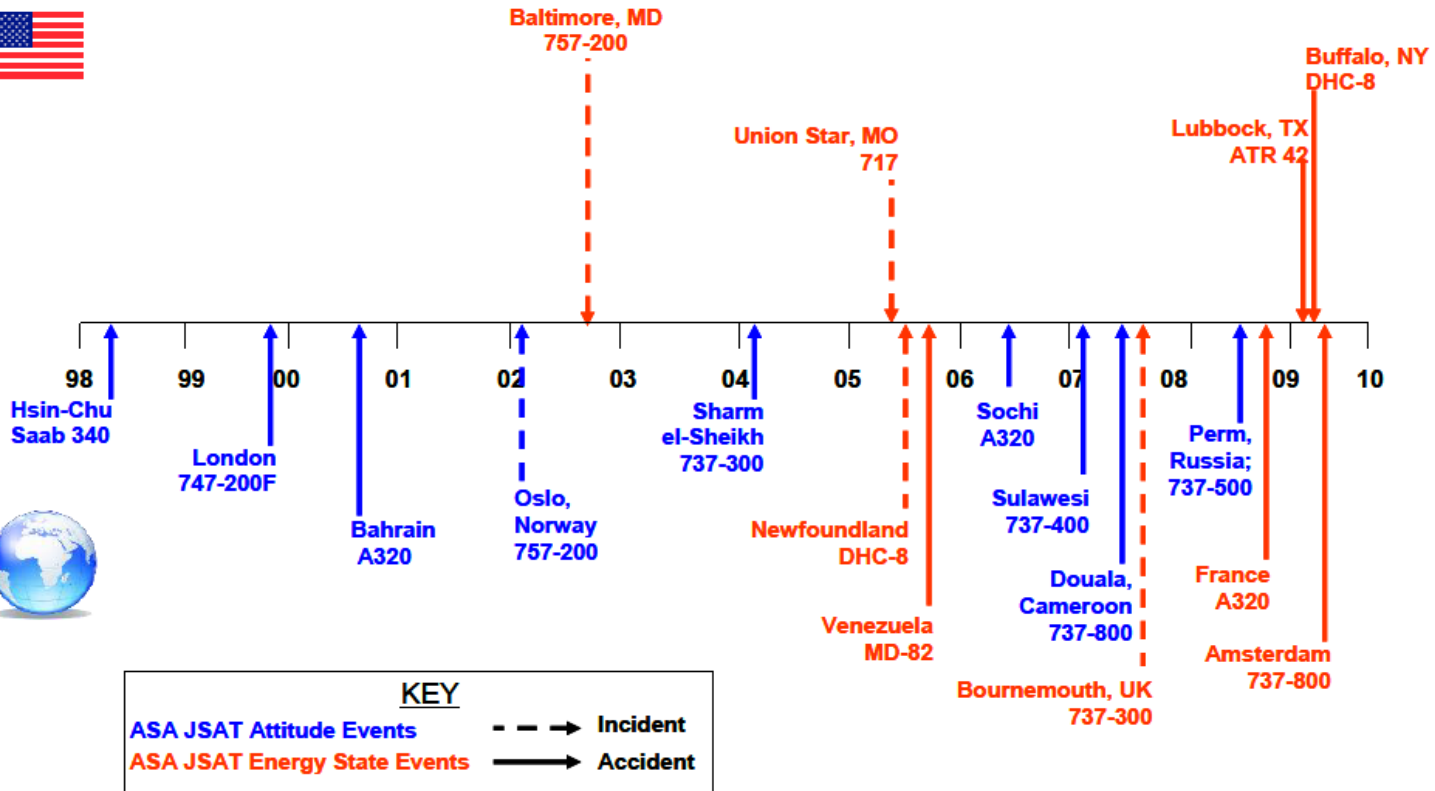
Loss of Control – Inflight (LOC-I)

Boeing Statistical Summary of Commercial Worldwide Jet Transport Accidents, 2011

ASA JSAT Team Analysis

Industry and government experts studied 18 LOC-I accident/incident scenarios, with focus on cases where flight crew lost awareness of attitude or energy state
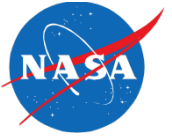
Significant Themes

Energy Awareness Cases	Lack of External Visual References	Flight Crew Impairment	Training	Airplane Maintenance	Safety Culture	Invalid Source Data	Distraction	Systems Knowledge	Crew Resource Management	Automation Confusion / Awareness	Ineffective Alerting	Inappropriate Control Actions	Total
Icelandair 757-200 (Baltimore)	x				x	x	x	x	x	x	x	x	9
Midwest Express 717	x				x	x	x		x		x	x	7
Colgan Air DHC-8-Q400	x	x	x		x		x	x	x	x	x	x	10
Provincial Airlines DHC-8	x		x				x			x	x	x	6
Thomsonfly 737-300	x		x	x	x		x			x	x		7
West Caribbean MD-82	x	x			x		x	x	x	x	x	x	9
XL Airways A320		x	x	x	x	x	x	x	x	x	x		10
Turkish Airlines 737-800	x			x	x	x	x		x	x	x		8
Empire Air ATR-42	x	x			x		x		x	x	x		7

No single technology will solve the LOC-I problem.

http://goo.gl/NAZ7MD

CAST Recommendations

- ASA JSAT Suggested 274 intervention strategies, and categorized them:
  - Aircraft Design
  - Flightcrew Training
  - Airline Operations and Maintenance
  - Safety Data
  - **Research**
    - **NASA/ARMD/AOSP/ATD/TASA Subprojects**
    - **This work focused on outputs of Safety Enhancements (SE) 207 and 208**

SE207 Output Focus

- **Output 3**: Develop and refine systems that predict the future aircraft energy state and/or auto-flight configuration if the current course of action is continued and provide appropriate alerting.

- **Output 2**: Develop and refine algorithms and display strategies to provide control guidance for recovery from approach-to-stall or stall.

SE208 Output Focus

- **Output 1a**: Displays that present the current and future expected state of automated systems in an intuitive manner.

- **Output 1b**: Displays that show, in a simple, integrated manner (e.g, a synoptic), the aircraft flight-critical data systems in use by automated systems and primary flight instruments

- Should do so for both the mode currently selected and any impending mode transitions expected per design of these systems.

http://goo.gl/CBqsnD

SE207/SE208 Themes

- **Automation Confusion/Awareness.**
  - Trajectory prediction, synoptic displays
- **Inappropriate Control Input.**
  - Safe flight envelope estimation, and stall recovery guidance
- **Ineffective Alerting.**
  - Predictive alerting, Synoptic displays, Multiple-hypothesis prediction
- **Systems Knowledge.**
  - Synoptic displays

- Other SE207/208 outputs and additional themes are addressed by other subprojects and external work.

TECHNOLOGIES

Trajectory Prediction
Safe Flight Envelope Estimation
Predictive Alerting
Synoptic Displays
Stall Recovery Guidance

Trajectory Prediction

- Fast-time simulation of simplified aircraft dynamics

- Models behavior of FMS, APS, ATS

- Bank, flight path angle, thrust commands (1st order system with rate limits)

- 5 minute prediction horizon
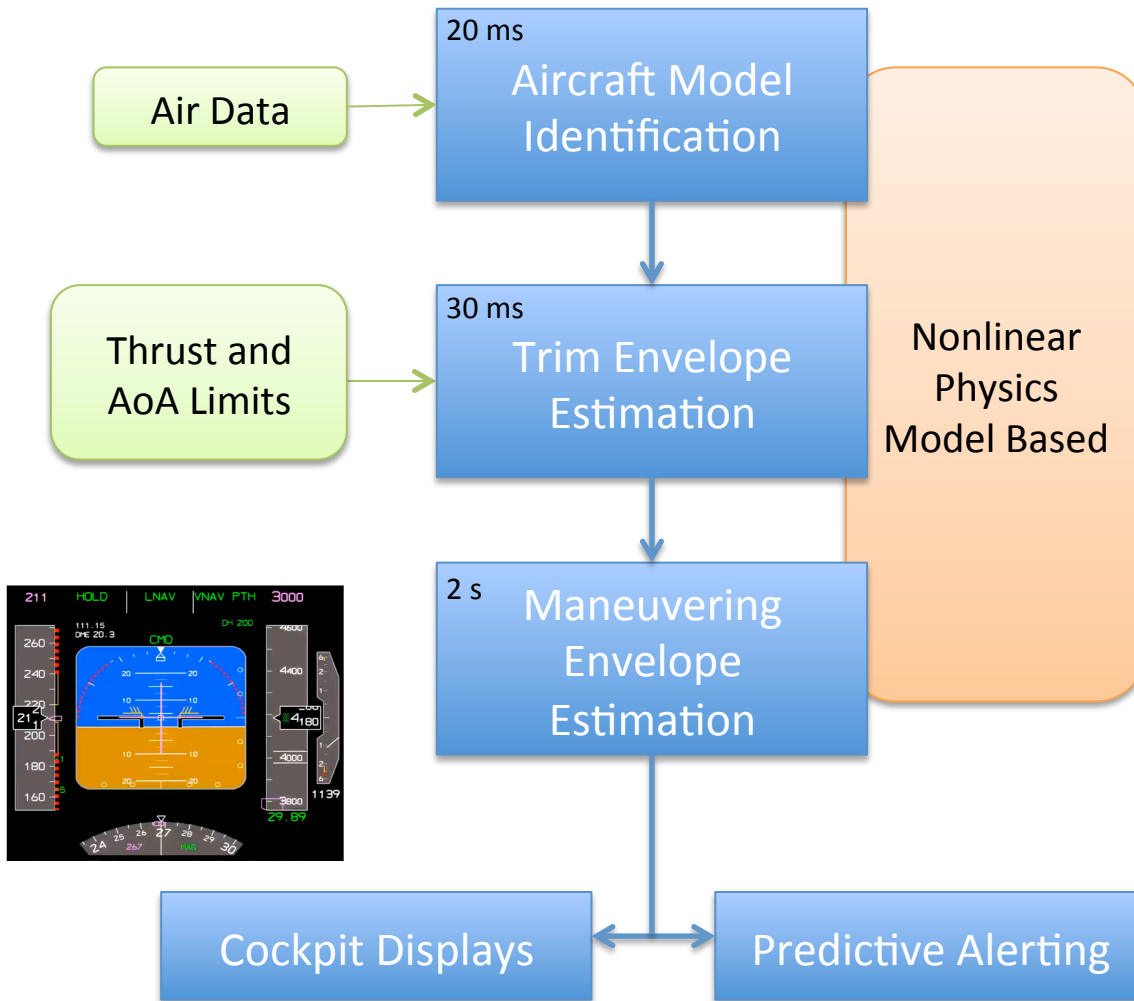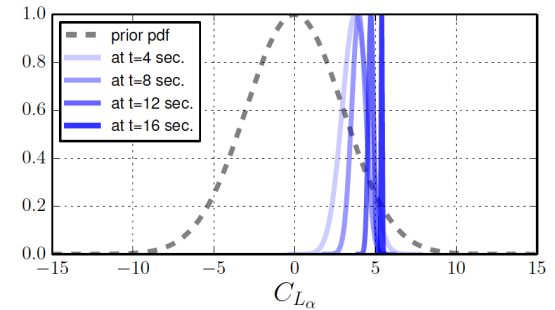

https://goo.gl/5FYhvv
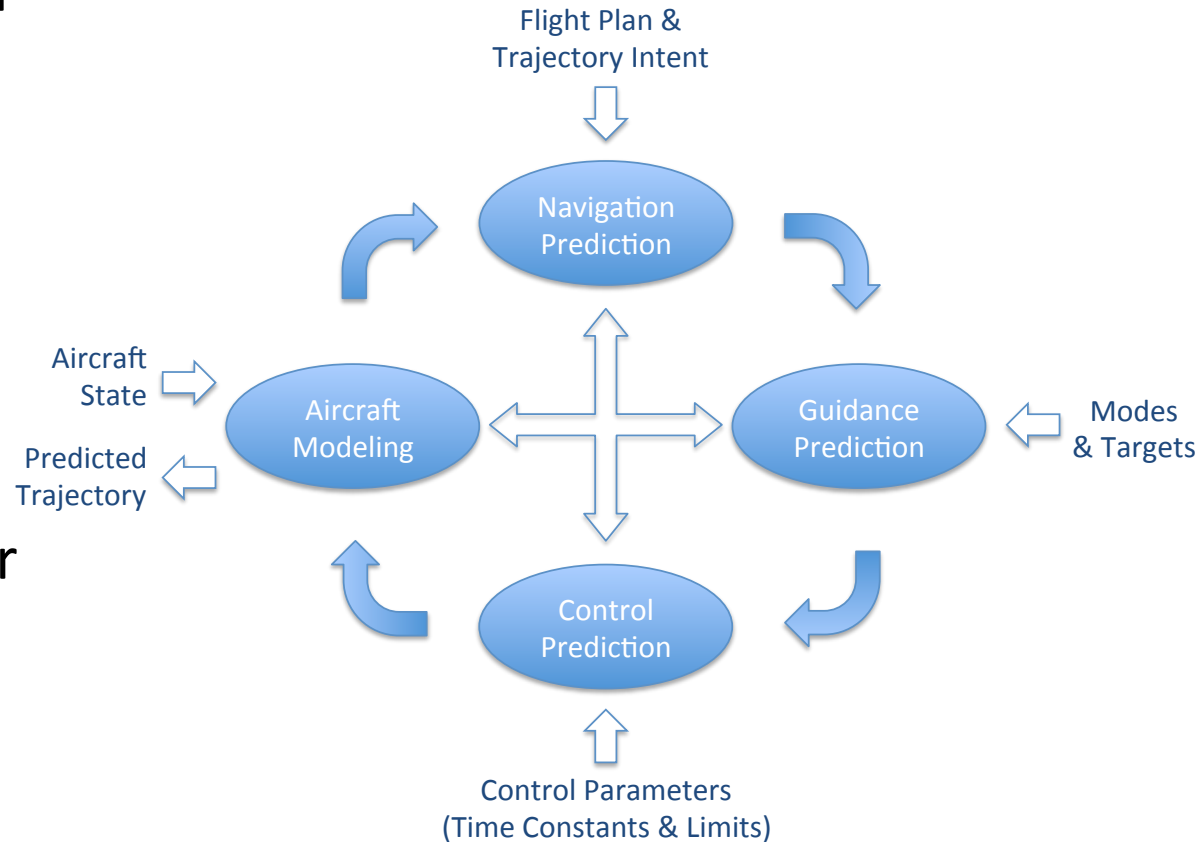
Trajectory Prediction
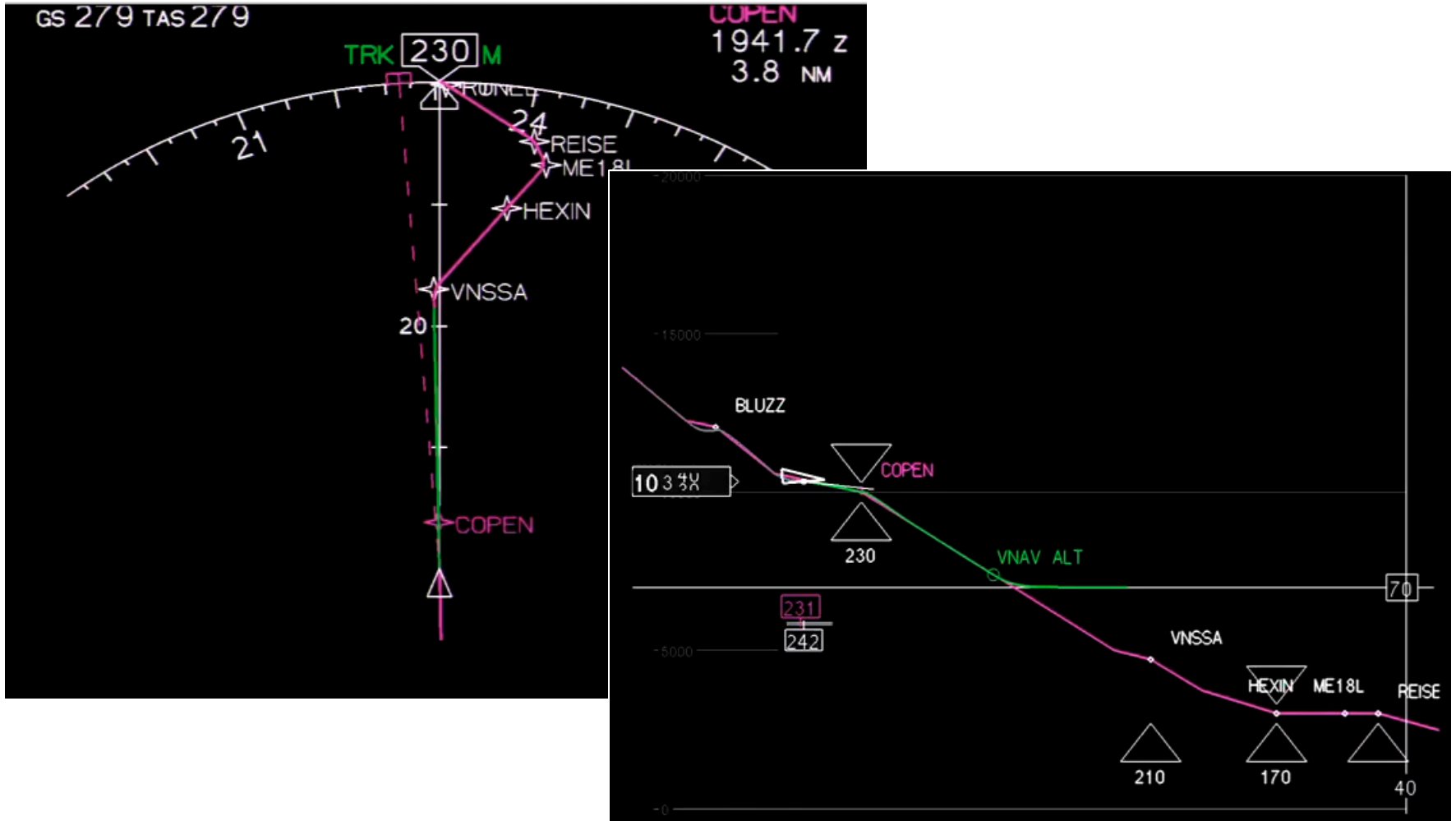
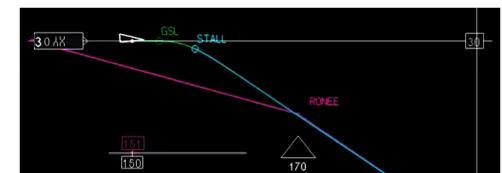Trajectory prediction on the Navigation Display (ND) and Vertical Situation Display (VSD)

https://goo.gl/5FYhvv

14

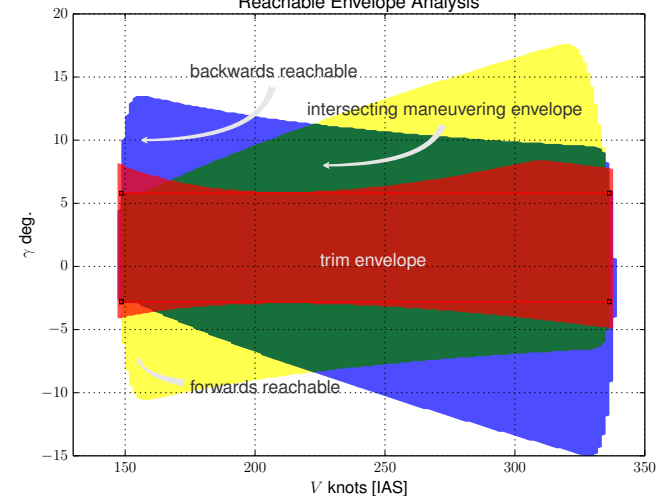# Safe Flight Envelope Estimation

Air Data → **Aircraft Model Identification** (20 ms)

Thrust and AoA Limits → **Trim Envelope Estimation** (30 ms)

Maneuvering Envelope Estimation (2 s)

Nonlinear Physics Model Based

Cockpit Displays ↔ **Predictive Alerting**

Aero derivative estimation with UQ

- prior pdf
- at t=4 sec.
- at t=8 sec.
- at t=12 sec.
- at t=16 sec.

C_{L_α}

Reachable Envelope Analysis

backwards reachable

intersecting maneuvering envelope

trim envelope

forwards reachable

γ deg.

V knots [IAS]

https://goo.gl/5FYhvv

Trim Envelopes

Clean Config at 6096.0 m.

http://goo.gl/ko1ycZ
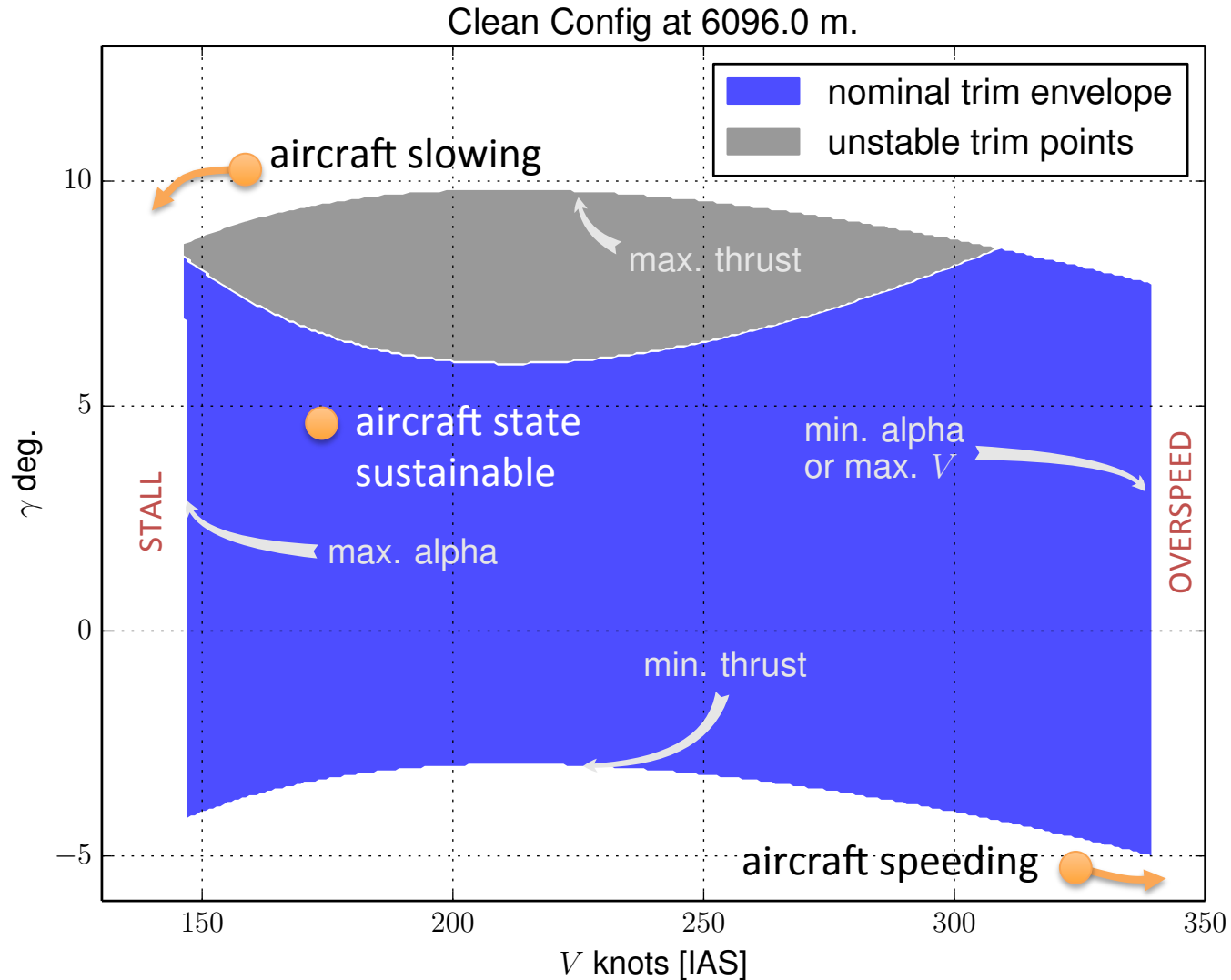
Dynamic Effects
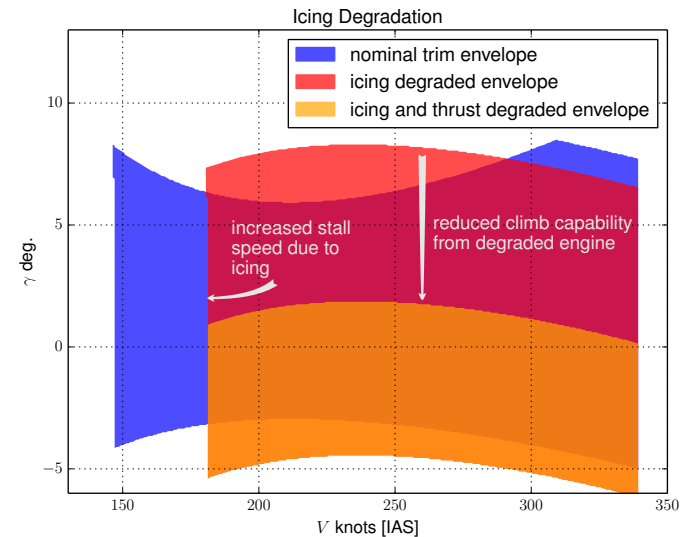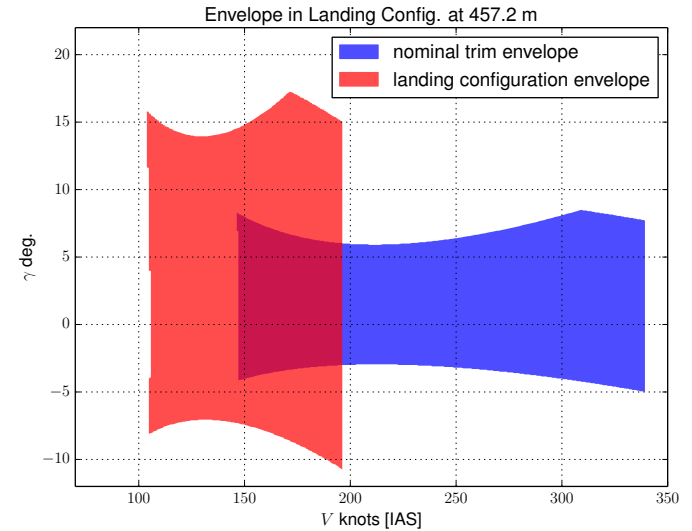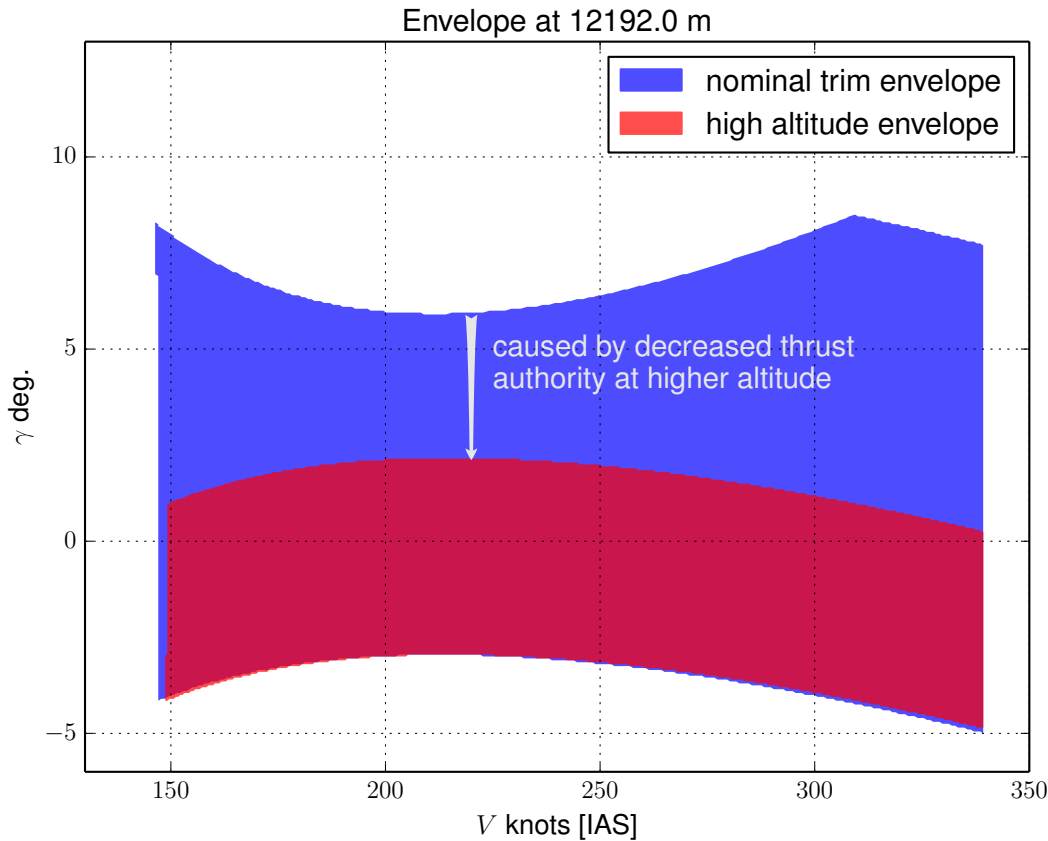
Flight Envelope Driven PFD
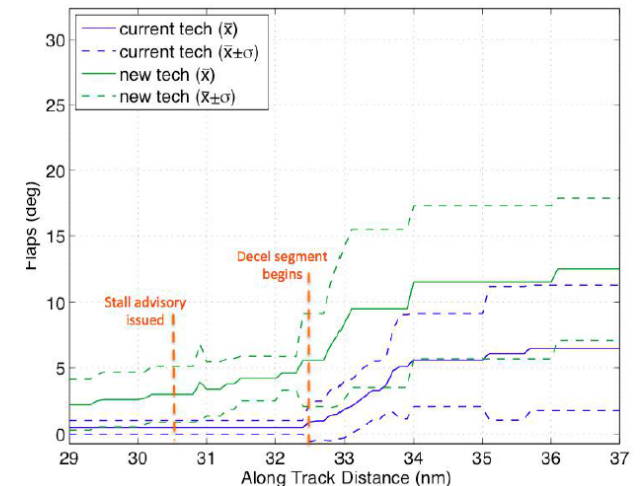
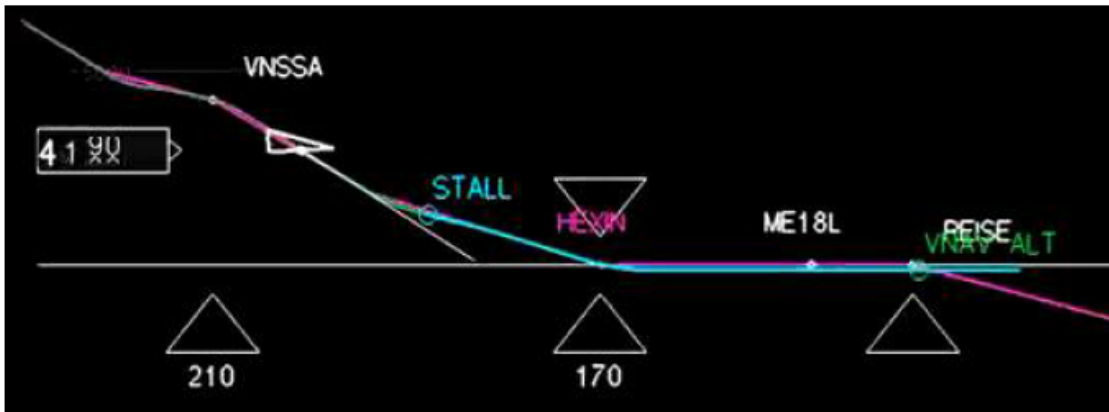# Example Icing Scenario

Current technology

New technology

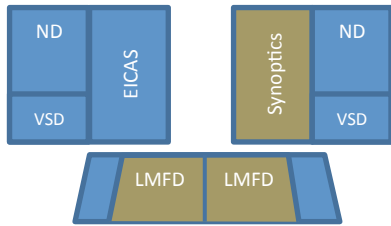Flap usage across experiments

Predicted Stall Advisory on VSD

System Interaction Synoptic

Normal

Available on any of these display spaces
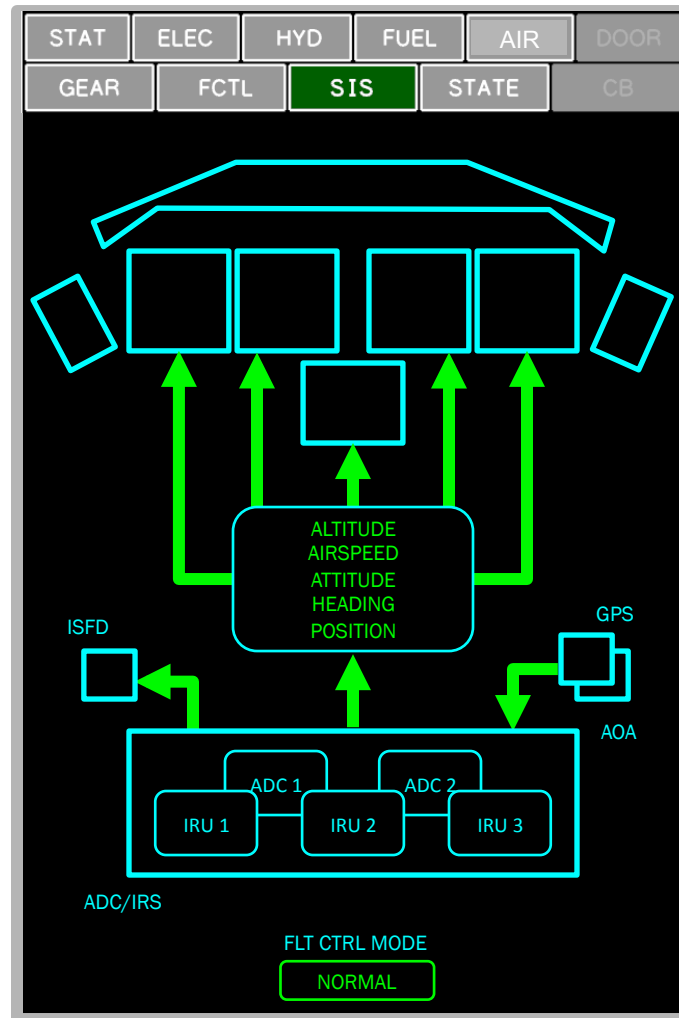
Mode control panel

Display panels

Flight-critical information

Flight-critical data systems

:ISFD – standby instrument :Flight control mode

http://goo.gl/Jl7tJE

System Interaction Synoptic

Available on any of these display spaces
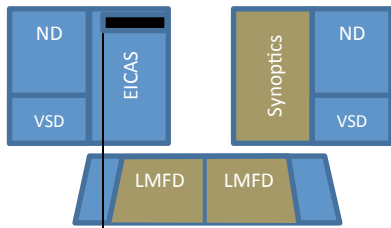
EICAS Msg:

☐ NAV AIR DATA SYS

http://goo.gl/Jl7tJE
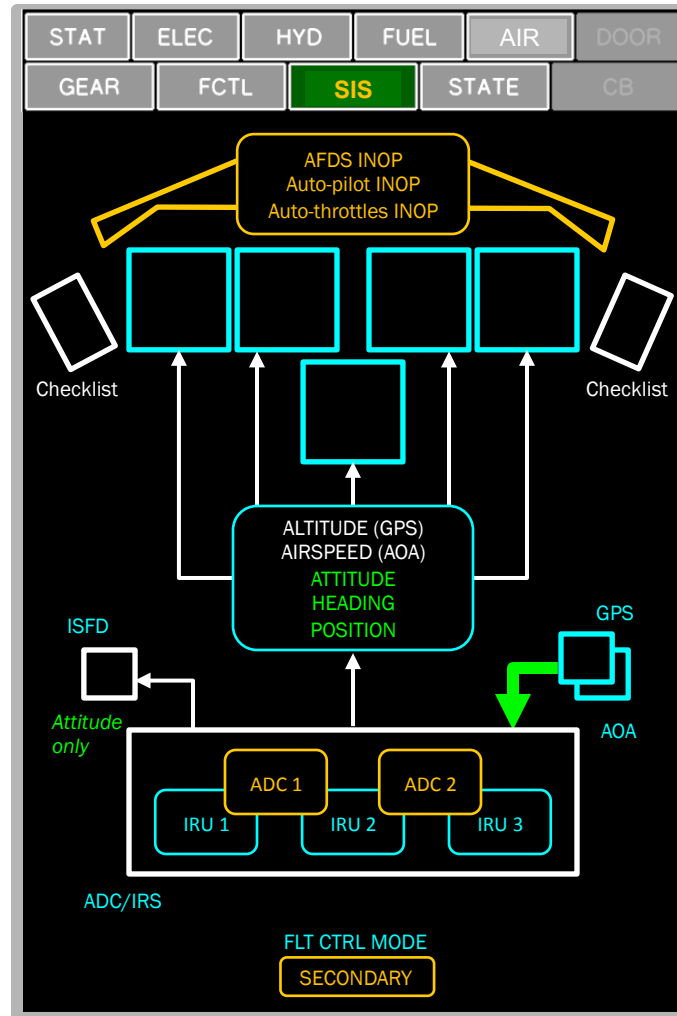
Non-normal

(example)

Associated checklist(s) available on both Electronic Flight Bags (EFBs)

Checklist(s) will be simplified:

1. Removes information now provided on this display

2. Context-relevant data provided rather than lists, or needs to look in reference documents

Simplified Check List

Stall Recovery Guidance (SRG)

FAA Stall Recovery Template AC120-109A[*], 2015

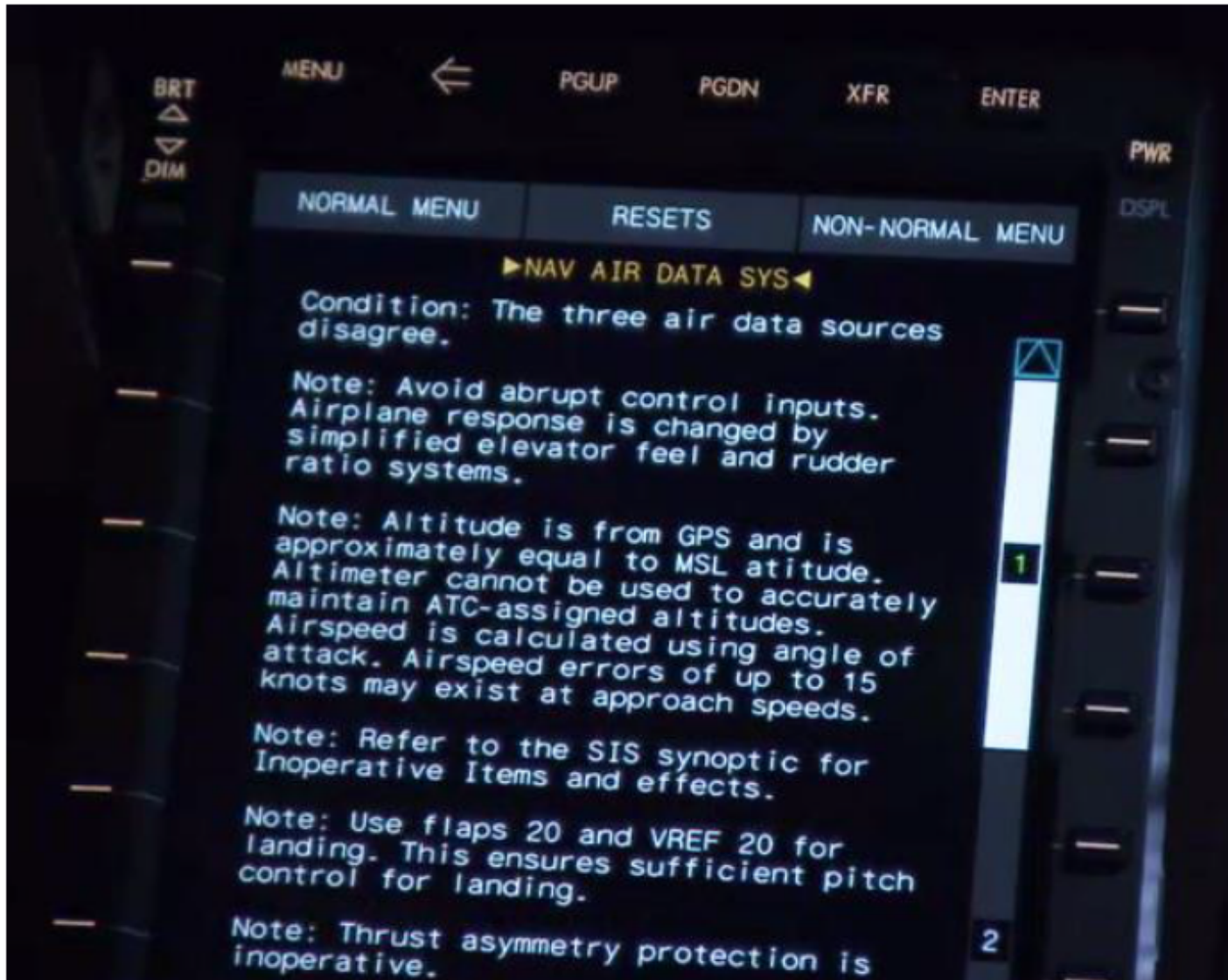|	
1	**Disconnect autopilot and autothrottle/autothrust**
	Rational: Leaving the autopilot or autothrottle/autothrust connected may result in inadvertent changes or adjustments that may not be easily recognized or appropriate, especially during high workload situations.
2	**(a) Nose down pitch control until impending stall indications are eliminated.** **(b) Nose down pitch trim as needed.**
	Rational: Reducing the angle of attack is crucial for recovery. This will also address autopilot-induced excessive nose up trim. If the control column does not provide sufficient response, pitch trim may be necessary.
3	**Bank wings level.**
	Rational: This orients the lift vector for recovery.
4	**Apply thrust as needed.**
	Rational: Amount of thrust depends on aircraft configuration and in some cases applying maximum thrust may create a strong nose-up pitching moment if airspeed is low.
5	**Retract speed brakes/spoilers.**
	Rational: This will improve lift and stall margin.
6	**Return to the desired flightpath.**
	Rational: Apply gentle action for recovery to avoid secondary stalls then return to desired flightpath.

* Abbreviated table for brevity

http://goo.gl/q0y74v

How to achieve a stall recovery?

- In a high-stress/workload environment, recalling the template is difficult

- FAA template does not specify:
  - Pitch down target
  - Airspeed to begin pitching up
  - Pitch up rate, without causing secondary stall

- Issues can be solved by guidance algorithms
  - Model predictive control, energy based, pseudo-control hedging.

SRG Guidance Display

- Pilot only sees the resulting guidance signal
  - Provides only the immediate control action
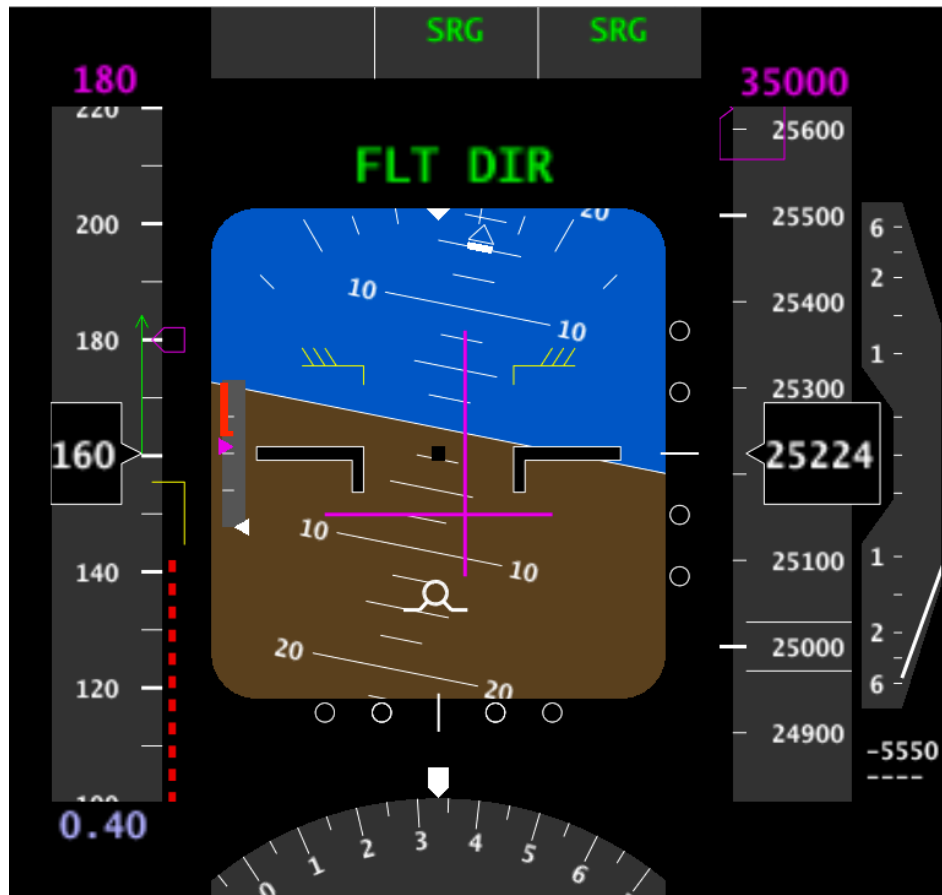
Flight-director with augmented, pitch limited, thrust guidance

SRG Evaluation Plan

- Vertical Motion Simulator
- Integrate stall dynamics modeling
- Evaluate recovery algorithms
  - optimal control based, energy based, and pseudo-control hedging based.
- Across three scenarios:
  - High altitude, climb out, pitch trim issue on approach. Based on AC120-109A
- Dependent variables:
  - Cooper-Harper ratings
  - stick activity, number of secondary stalls, inappropriate inputs
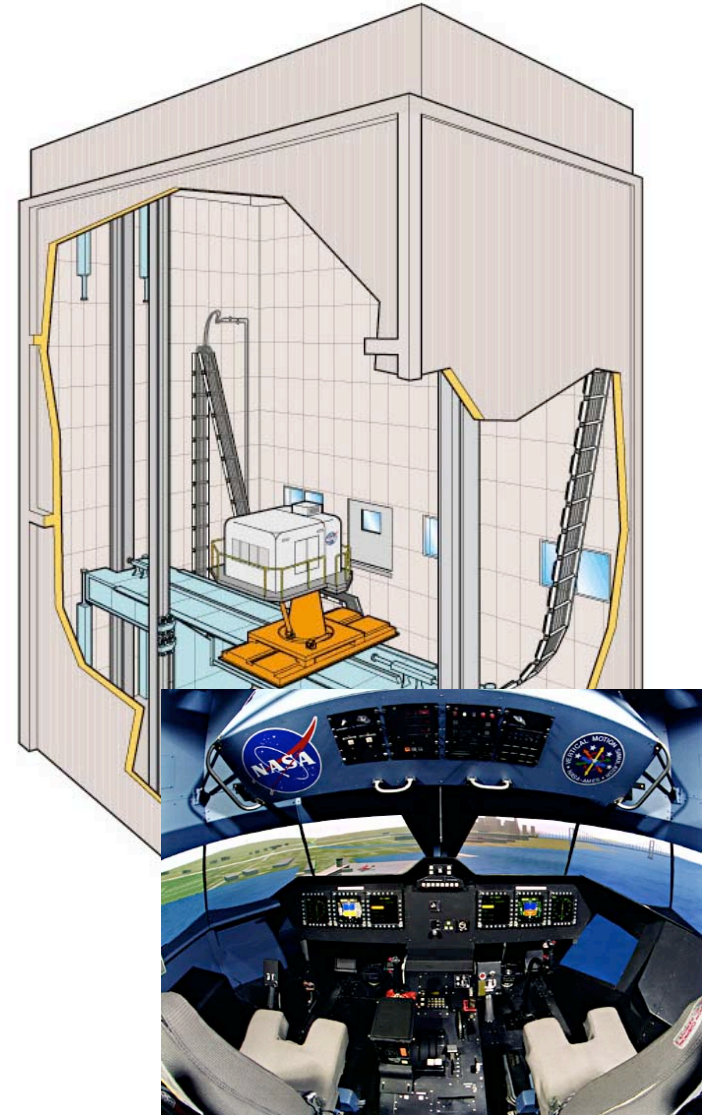
Evaluation Roadmap

Sept. 2019 — Technology transition demo

Jan. 2018 — AIME 2

Apr. 2017 — SRG

Jan. 2016 — Automation and Information Management Experiment (AIME) – 12 crews, 250 flights
http://goo.gl/Jl7tJE, and analysis at DASC 2016, and SciTech 2017
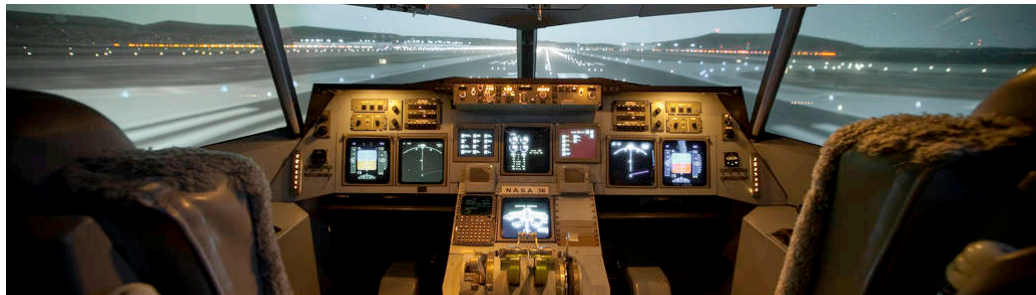
Aug. 2014 — Tactical Flight Management System with Maneuvering Envelope (TFMS-ME) Experiment – 10 crews, 80 flights
https://goo.gl/5FYhvv

NASA LaRC RFD

NASA ARC ACFS

AIME Usability Outcome

System Usability Scale (SUS) Scores
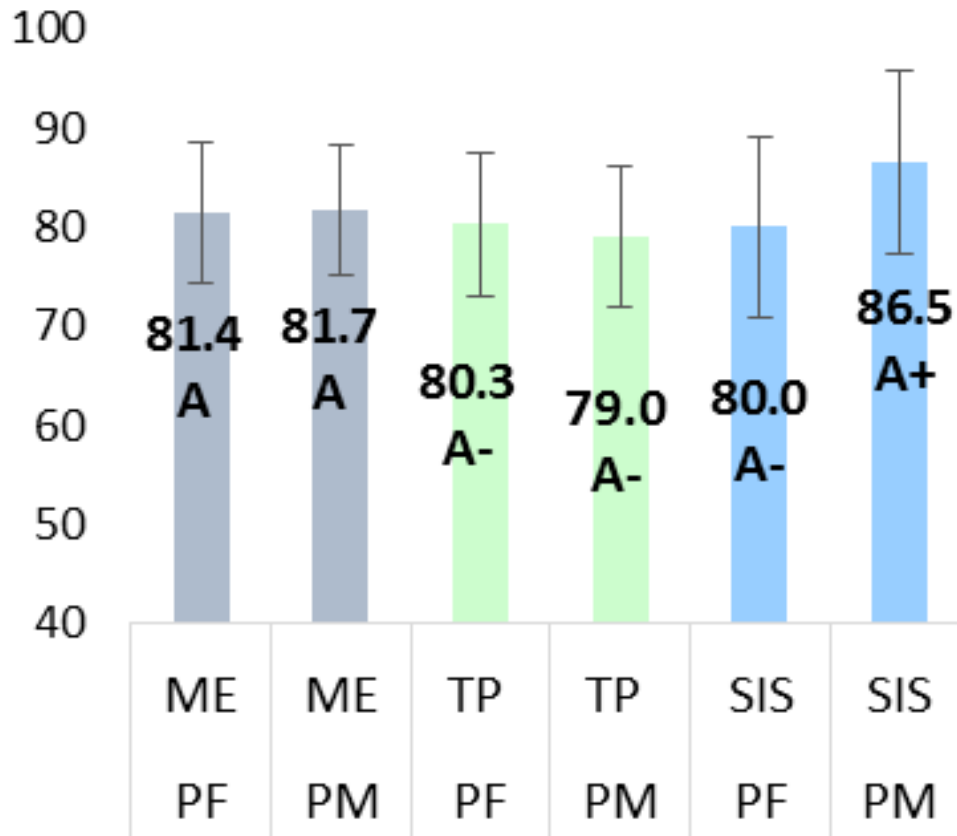
Standardized scale based on questionnaire filled out by pilots.

ME = Maneuvering Envelope
TP = Trajectory Prediction
SIS = System Interaction Synoptic
PF = Pilot Flying
PM = Pilot Monitoring

Formal results to be presented at the 2016 Digital Avionics Systems Conference

Evaluation Objectives

- Development and Demonstration
  - Raise the TRL for new technology via testing and demo in a high-fidelity flight sim environment (e.g. confirm performance across span of targeted conditions)
  - **Study the effects of growing automation and information complexity**
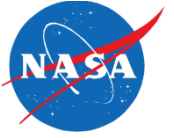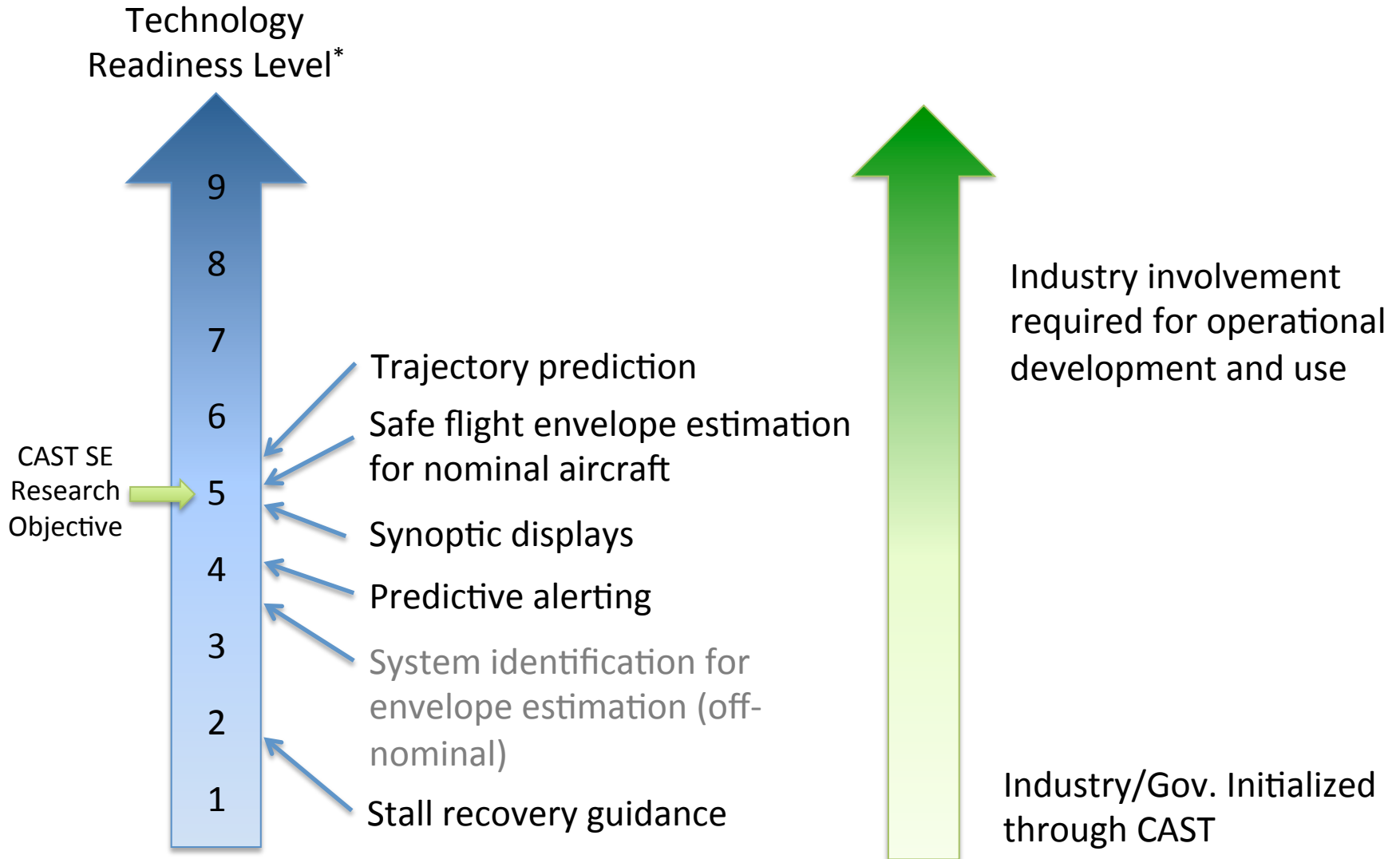
- Evaluate the usability and acceptability of new technology concepts
  - Is project on correct path, or need a change of direction?

- Discovery ("learn by doing")
  - Design characteristics requiring refinement for future studies
  - Unknown unknowns related to state awareness and prediction

- Advance test infrastructure capability for future experiments
  - Evaluate the use of the eye-tracking system and physio measurement system for potential to validate design effectiveness, and to detect attention issues
  - Establish confidence in test platform performance given new modifications
  - Identify gaps and capabilities to be improved for subsequent studies

http://goo.gl/Jl7tJE

CONCLUSION

Current Tech. Readiness Levels

Technology
Readiness Level*

9

8

7

6

CAST SE
Research
Objective → 5 ← Trajectory prediction

← Safe flight envelope estimation
for nominal aircraft

4 ← Synoptic displays

← Predictive alerting

3

System identification for
envelope estimation (off-
nominal)

2

1 ← Stall recovery guidance

Industry involvement
required for operational
development and use

Industry/Gov. Initialized
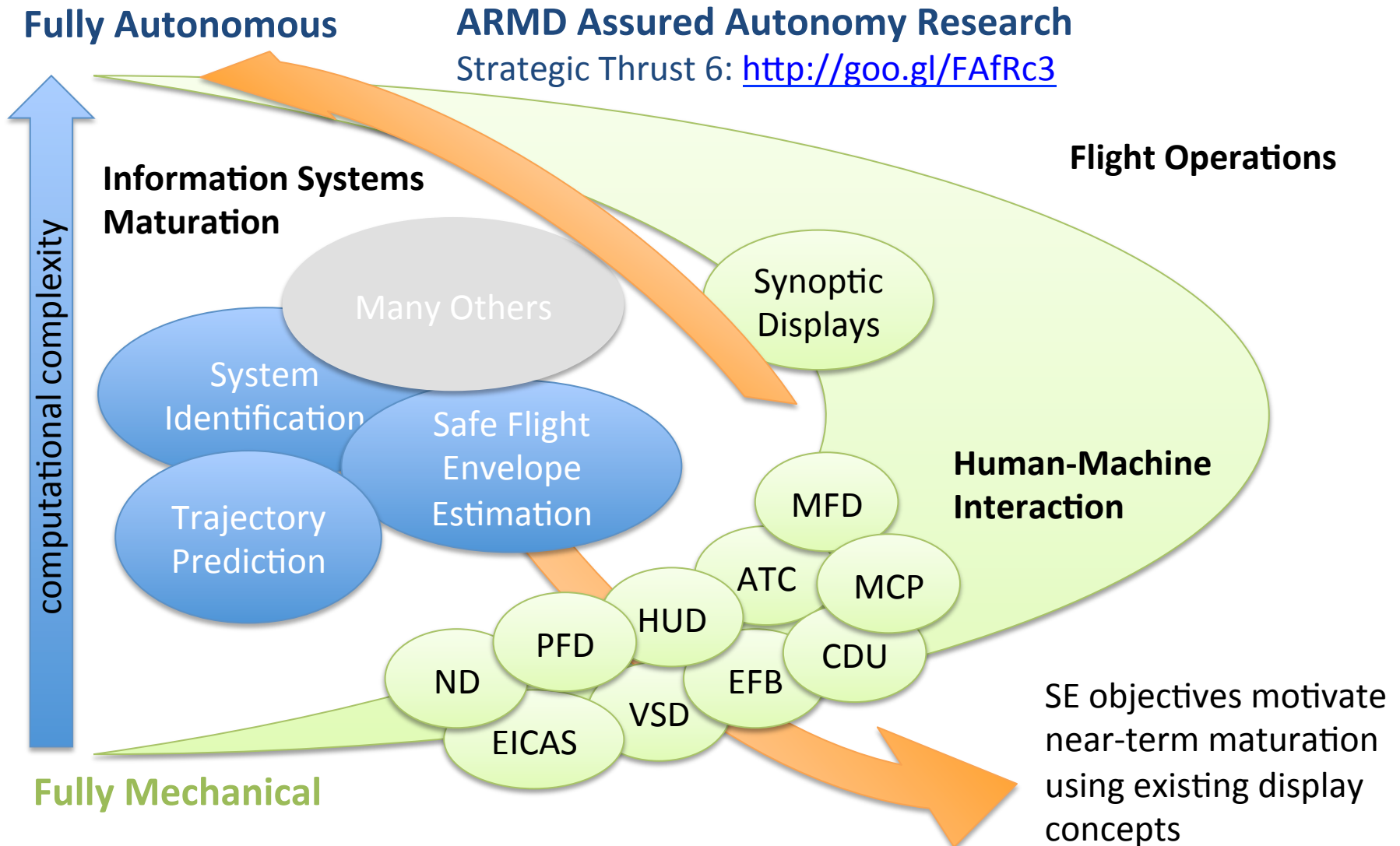through CAST

* not including operational readiness

The Autonomy Long Game

Conclusion

- Presented CAST motivated research objectives

- Looked at some of the resulting technologies
  - Now at various readiness levels

- Looking for increased industry feedback and interaction as technologies are matured
  - Email: stefan.r.schuet@nasa.gov
  - Software licensing
  - Space Act Agreements
  - NASA Research Announcements

- More info:
  - https://ti.arc.nasa.gov/tech/asr/aces/tfmsme/

References

Slides 5-10

Airplane State Awareness Joint Safety Analysis Team, "Final Report Analysis and Results," provided to the Commercial Aviation Safety Team, June 17, 1014.

Safety Enhancement SE207, "ASA – Research – Attitude and Energy State Awareness Technologies," Detailed Implementation Plan, December 4, 2014.

Safety Enhancement SE208, "ASA – Research – Airplane Systems Awareness," Detailed Implementation Plan, December 4, 2014.

Slides 13-19

K. H. Shish, J. Kaneshige, D. M. Acosta, S. Schuet, T. Lombaerts, L. Martin, and A. N. Madavan. Trajectory prediction and alerting for aircraft mode and energy state awareness. In AIAA Infotech @ Aerospace. American Institute of Aeronautics and Astronautics, January 2015.

T. Lombaerts, S. Schuet, D. M. Acosta, J. Kaneshige, K. H. Shish, L. Martin. Piloted simulator evaluation of maneuvering envelope information for flight crew awareness. In AIAA Guidance, Navigation, and Control Conference. American Institute of Aeronautics and Astronautics, January 2015.

S. Schuet, T. Lombaerts, D. Acosta, K. Wheeler, J. Kaneshige. An Adaptive Nonlinear Aircraft Maneuvering Envelope Estimation Approach for Online Applications (AIAA 2014-0268). In AIAA Guidance, Navigation, and Control Conference, January 2014.

Slide 23

Federal Aviation Administration, "Stall Prevention and Recovery Training," Advisory Circular 120-109A, November 24, 2015.

Slides 20-22, and 27-29

S. D. Young, M. U. D. Haag, T. Daniels, E. Evans, K. H. Shish, S. Schuet, T. Etherington, and D. Kiggins. Evaluating technologies for improved airplane state awareness and prediction. In AIAA Infotech @ Aerospace, number AIAA 2016-2043. American Institute of Aeronautics and Astronautics, January 2016.

Young, S.; et. al.; "Flight Simulation Study of Airplane State Awareness and Prediction Technologies," to be presented at the 35th AIAA/IEEE Digitial Avionics Systems Conference, Sacramento, CA, September 25-29, 2016.

Evans, E.; Young, S.; Daniels, T.; Santiago-Espada, Y.; and Etherington, T.; "Analysis of Pilot Feedback Regarding the Use of State Awareness Technologies During Complex Situations," to be presented at the 35th AIAA/IEEE Digitial Avionics Systems Conference, Sacramento, CA, September 25-29, 2016.