Learn-To-Fly Project Overview: *In-Flight and Wind Tunnel Global Nonlinear Aerodynamic Modeling*

Jay Brandon

NASA Langley Research Center

Presentation at Boeing Commercial Aircraft Company
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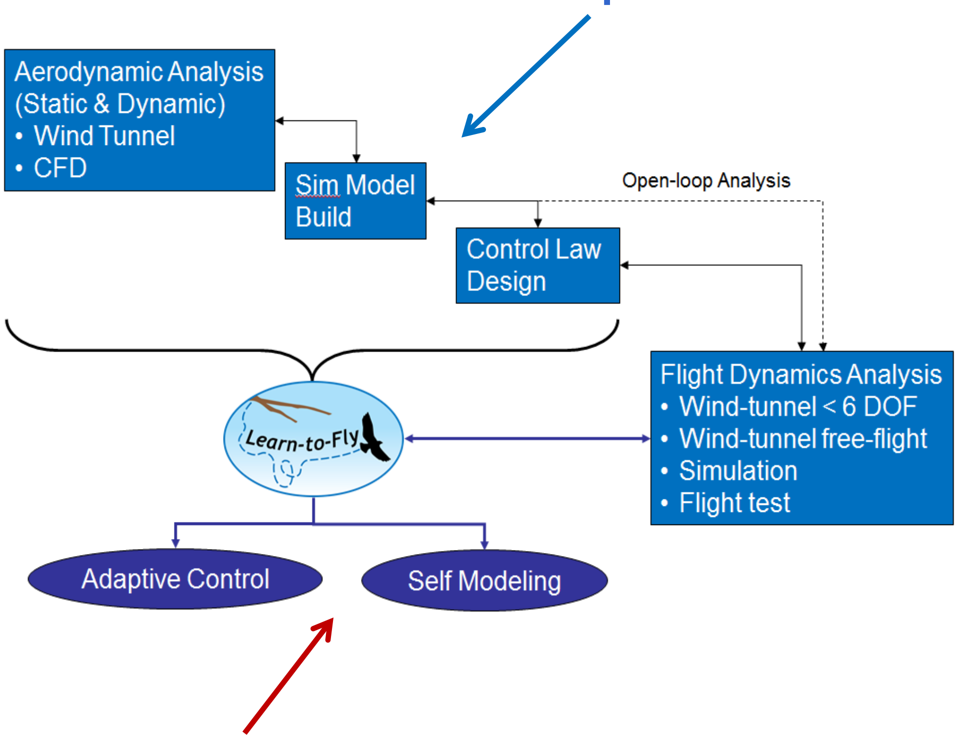
Outline

- L2F Introduction
- Flight Test Overview
  - Test Aircraft
  - Flight Test Maneuvers
  - Aerodynamic Modeling
  - Example Flight Test Results
  - Real-Time Demo
- Wind Tunnel Test Application
- Summary

Learn-To-Fly Attributes

- **Ultimate Goal: Self-Learning and Autonomously-Adapting Vehicles**
- Potential for High Impact In Three Primary Areas:
  - Safety
  - Reliability
  - Design/Development Efficiency

Learn-to-Fly seeks to short-circuit the current process…



…with a new paradigm

Technology Enablers Required:

Computer Processing Capabilities

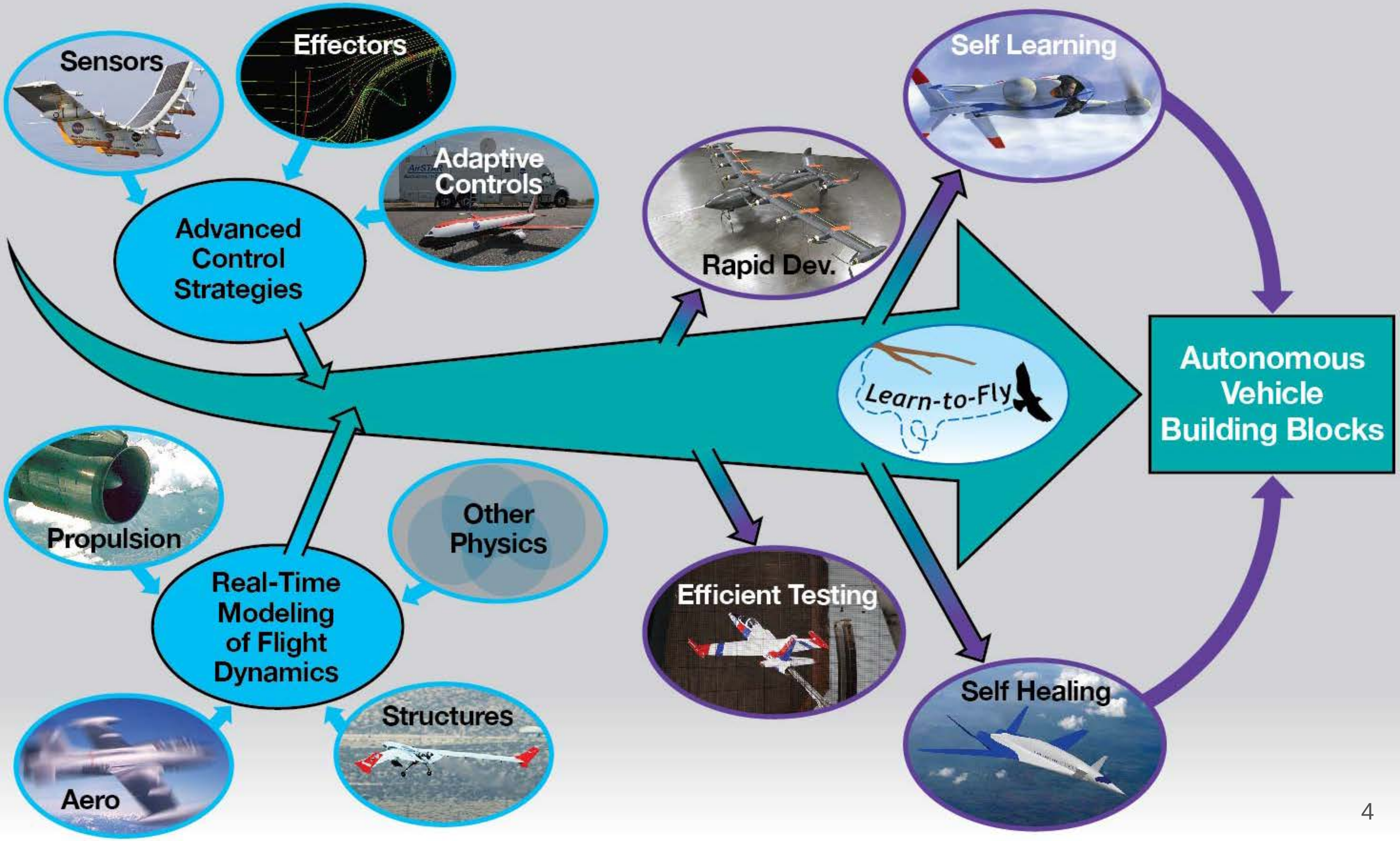
System Identification Advances

- **Non-linear aerodynamic modeling**
- **Real-time system identification**

Flight Control Theory Advances

- Adaptive flight control algorithms

Learn-To-Fly Roadmap



Relevant to NASA and LaRC Goals

- NASA Strategic Vision and Langley Goals
  - Transformative
    - On-demand
      - Assured autonomy
      - “Drawings to flight in 30 days”
      - “Learn-To-Fly”
  - Sustainable
    - Intelligent
      - Innovative technologies
  - Global
    - Safety
      - “Refuse to Crash”
    - Efficiency
      - Distributed electric propulsion
      - “Learn-To-Fly” opens design spaces

Recent L2F Results

- Flight Test
  - Supported by Seedling and the National Test Pilot School
  - Real-time maneuver and modeling analyses
  - Development of near-real-time modeling of 6-DOF nonlinear aero
  - Demonstrated in-flight modeling of large envelope, nonlinear aerodynamics
- Wind Tunnel Based Nonlinear Modeling
  - Supported by the Aeronautical Sciences Project - Advanced Aircraft Flight Controls
  - Developmental study using wind tunnel testing
  - R/C L-59 model tested in 12-Foot Low-Speed Tunnel
  - Development of technology and modeling techniques
  - Inexpensive & quick

Flight Project Overview

- **Competitively Selected Project**
  - Sponsor: NASA Aeronautics Research Institute
  - 320 proposals from 8 NASA Centers, 20 selected for Phase I
  - Phase II awarded
  - Final set of flights conducted in February 2014
- **Cooperative Project With NTPS**
  - Co-PI Gene Morelli

Flight Test Aircraft

Aermacchi Impala MB-326M

- **Large flight envelope, aerobatic capability**
- **Well instrumented:**
  - α / β **on nose boom, dynamic pressure, engine rpm, fuel flow**
  - **accelerations, angular rates, and controls**
  - **real-time data in aft cockpit and telemetered to the ground**

Flight Test Setup

- Standard Front Cockpit
- Onboard Instrumentation
- Real-time Analysis Computer mounted in Aft Cockpit

Data Input Maneuvers

- Conventional Approaches
  - Trimmed flight – time consuming single point conditions
  - Normal flight regime
  - Single axis at a time
  - Stitched together model

Correlation Coefficient

$$\rho_{u_1 u_2} = \frac{\sum_{i=1}^{N}\left[u_1(i)-\bar{u}_1\right]\left[u_2(i)-\bar{u}_2\right]}{\sqrt{\sum_{i=1}^{N}\left[u_1(i)-\bar{u}_1\right]^2}\sqrt{\sum_{i=1}^{N}\left[u_2(i)-\bar{u}_2\right]^2}}$$

- Global Modeling Maneuvers
  - Optimized multi-axis automated inputs
  - Fuzzy piloted inputs
  - Fuzzy inputs with changing flight conditions
    - Decel
    - WUT/WDT
    - SPAZ
    - Spin / departures
  - Single global model

Comparison of Input Type

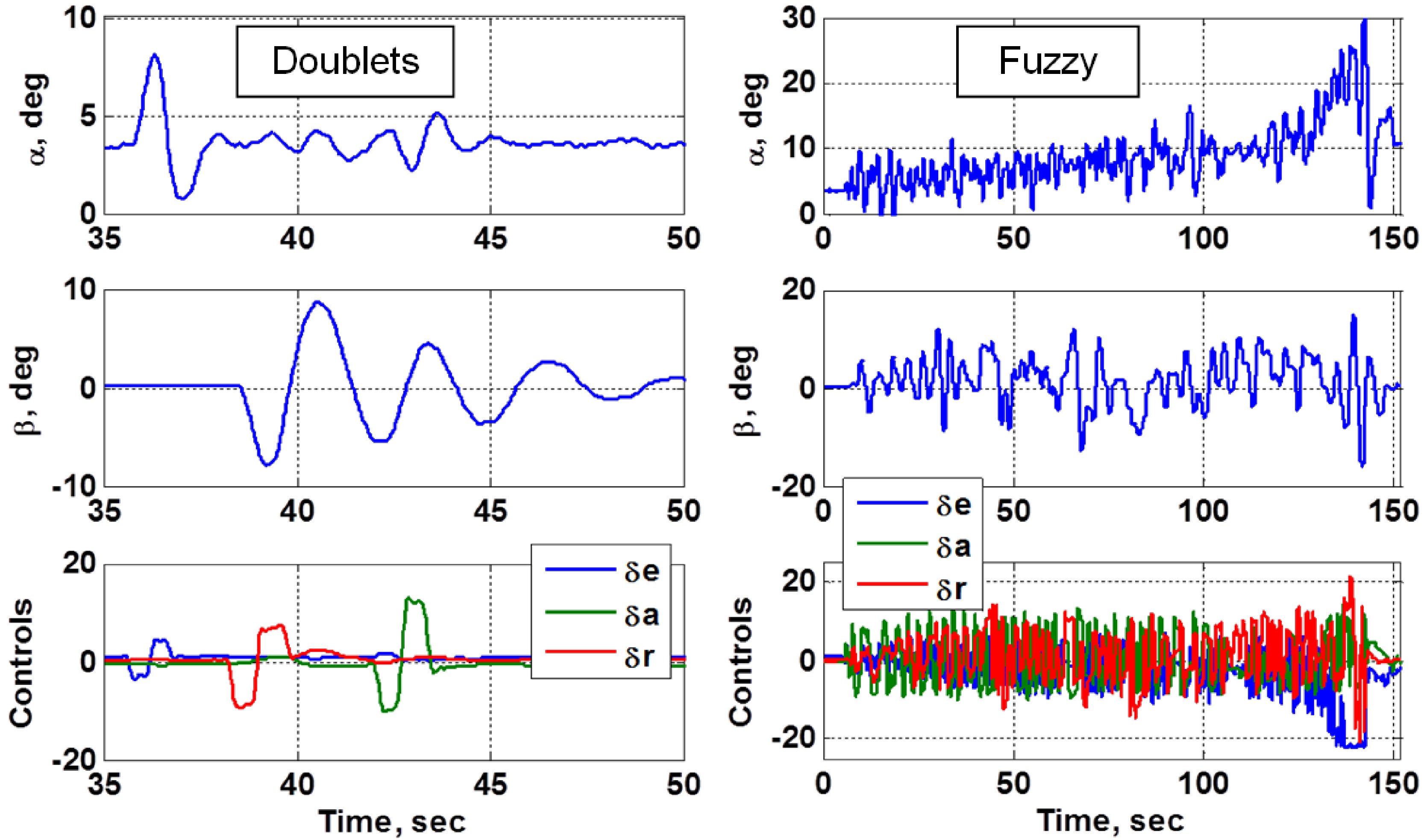
Conventional Doublets

- Trim
- Sequential inputs

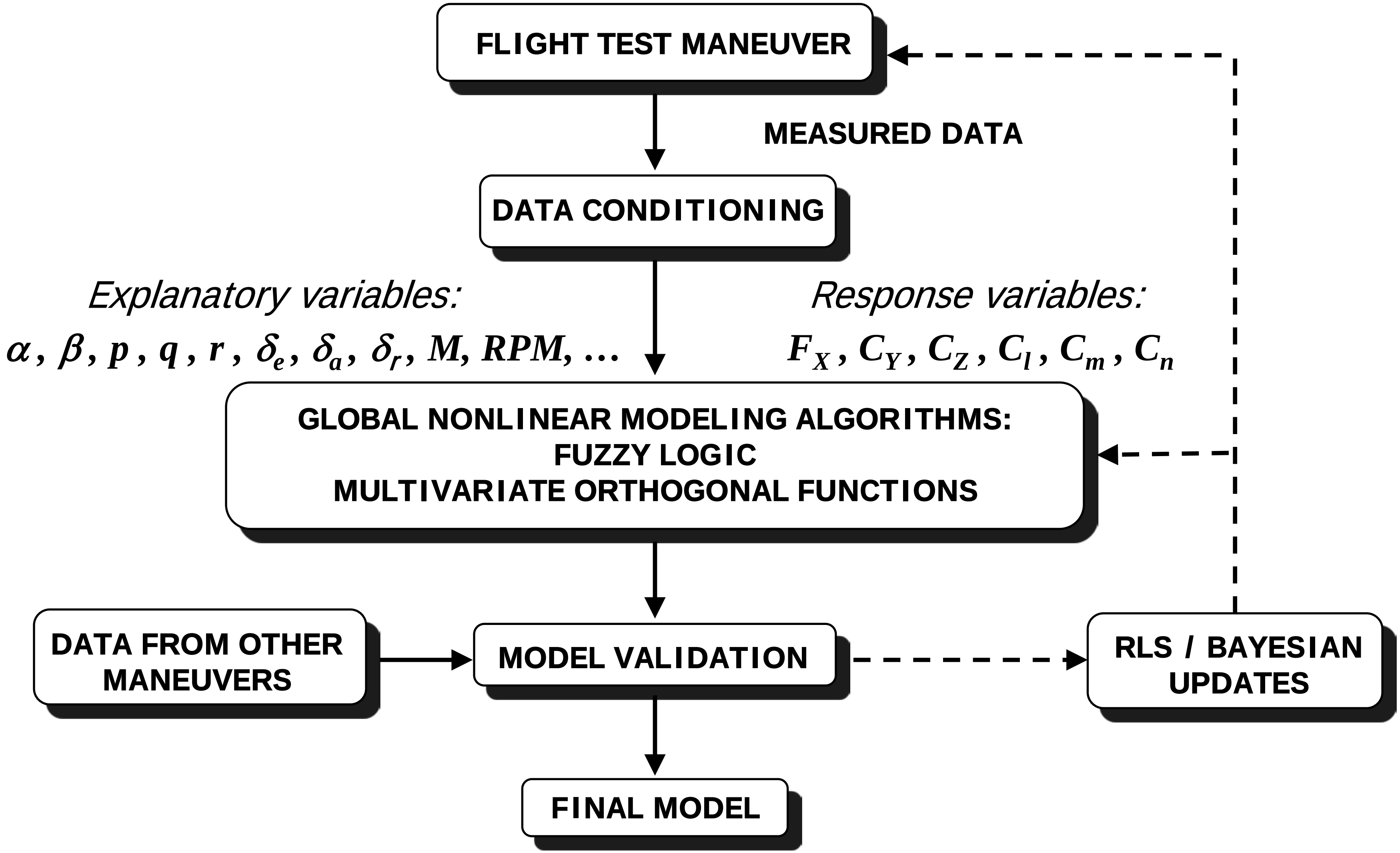
Fuzzy Inputs

- Trim
- Simultaneous uncorrelated inputs

Flight Test Maneuvers

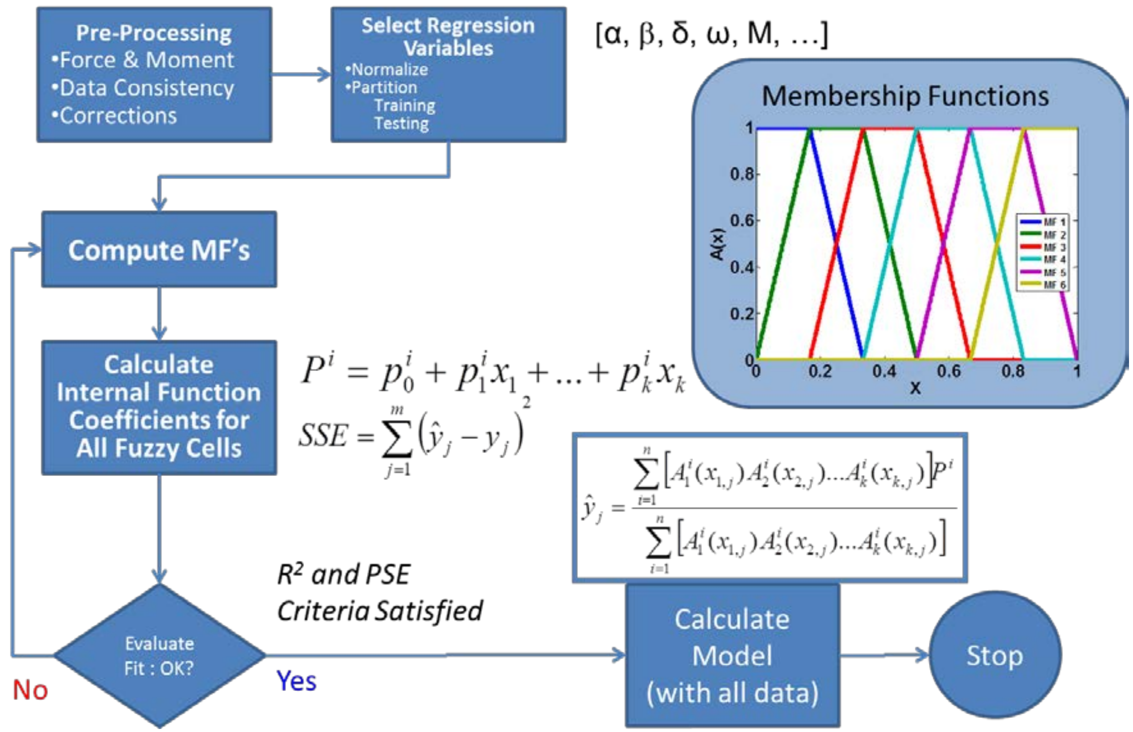


In-Flight Aerodynamic Modeling



Fuzzy Logic Modeling

- No a priori aero model construct
- Fuzzy cells constructed to identify relationships between input and output data
- Multiple internal functions create the "fuzziness"
- Single model across wide range of state variables
- Predicted outputs are smooth



Multivariate Orthogonal Function Modeling with Splines

Time History Data

$F_X, C_Y, C_Z, C_l, C_m, C_n$

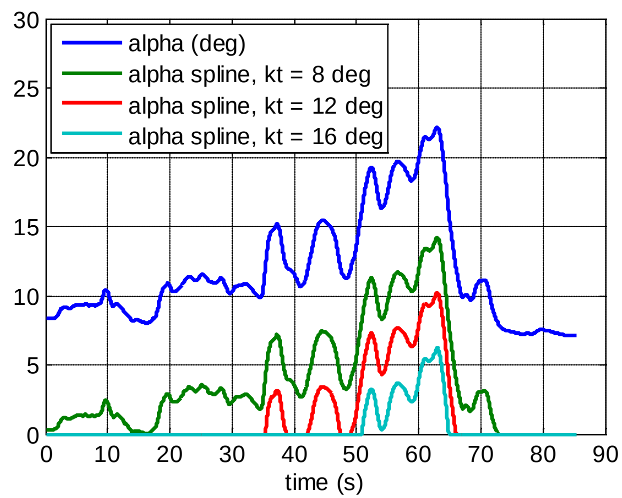
$\alpha, \beta, q, \delta_e, \ \ldots$

Polynomial Generation up to Selected Maximum Order

Orthogonalization and Model Term Selection

Decomposition into Ordinary Polynomial Terms

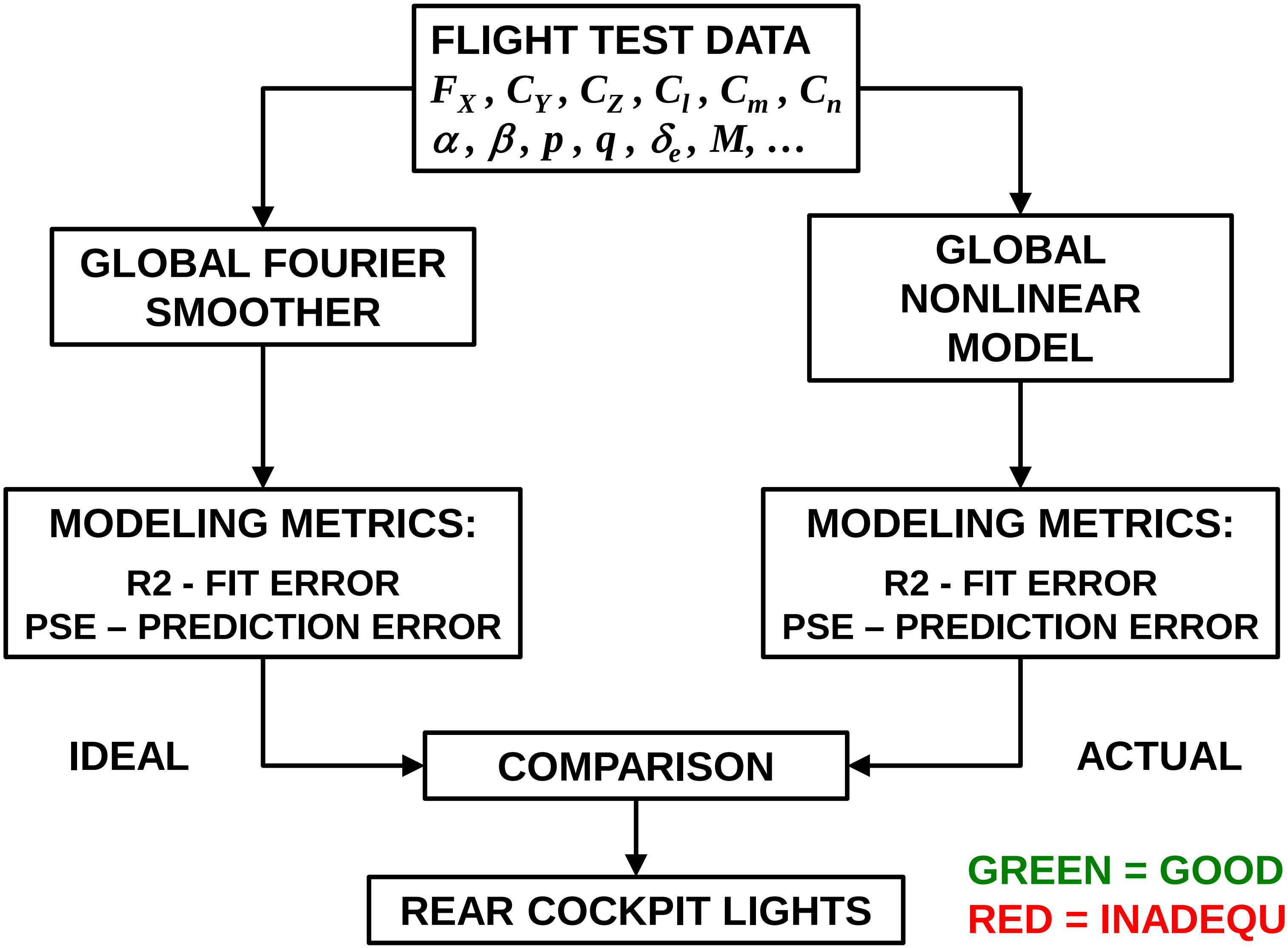
First-Order Splines



$$C_m = C_{m_o} + C_{m_\alpha}\alpha + C_{m_q}\frac{q\bar{c}}{2V} + C_{m_{\delta_e}}\delta_e + C_{m_{\alpha^2}}\alpha^2 + C_{m_{\delta_e \alpha_{12}^1}}\delta_e\left(\alpha - 12\right)_+^1$$

Final Model

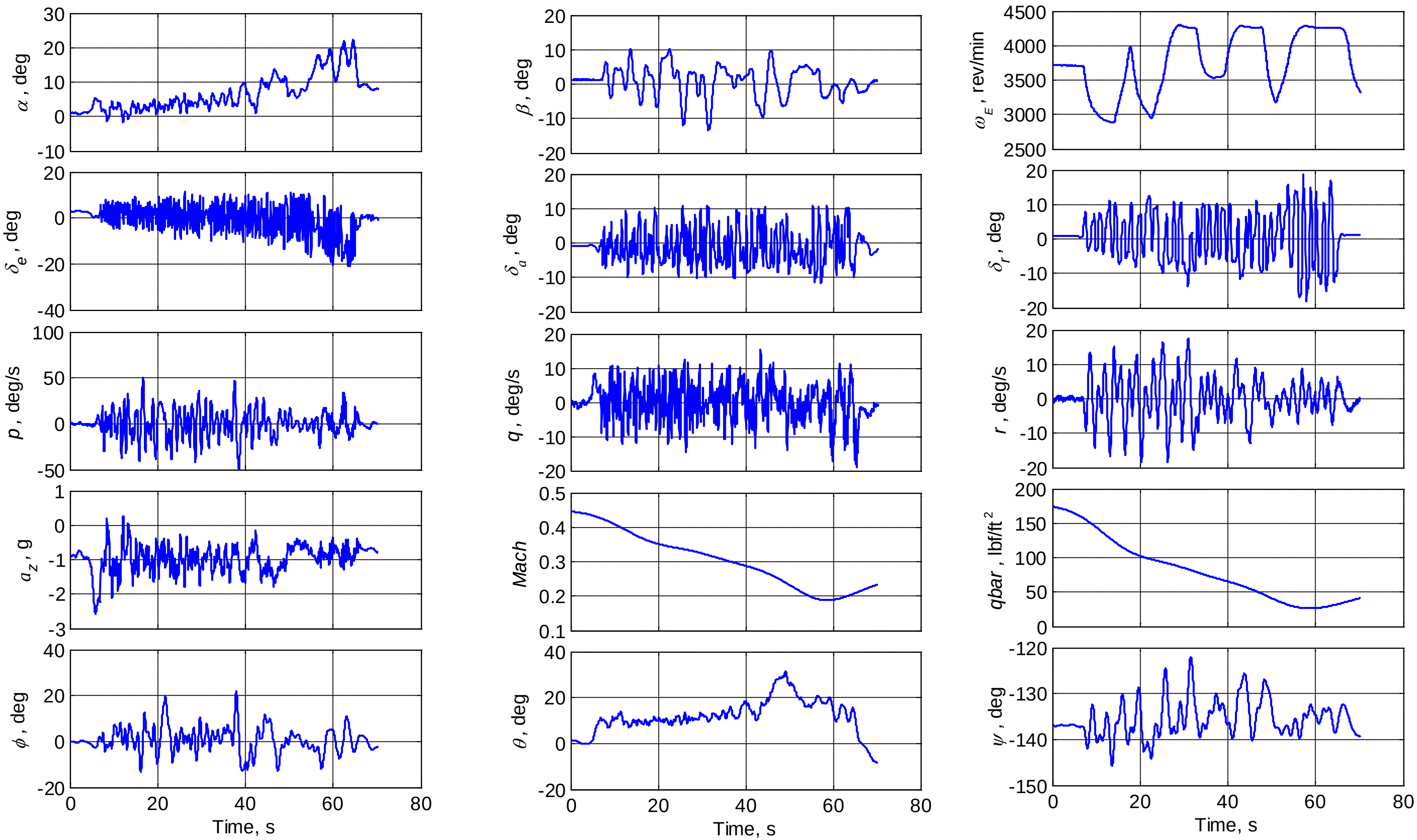
In-Flight Model Evaluation



GREEN = GOOD
RED = INADEQUATE

Powered Fuzzy Deceleration

P2F8C15



Explanatory Variable Coverage

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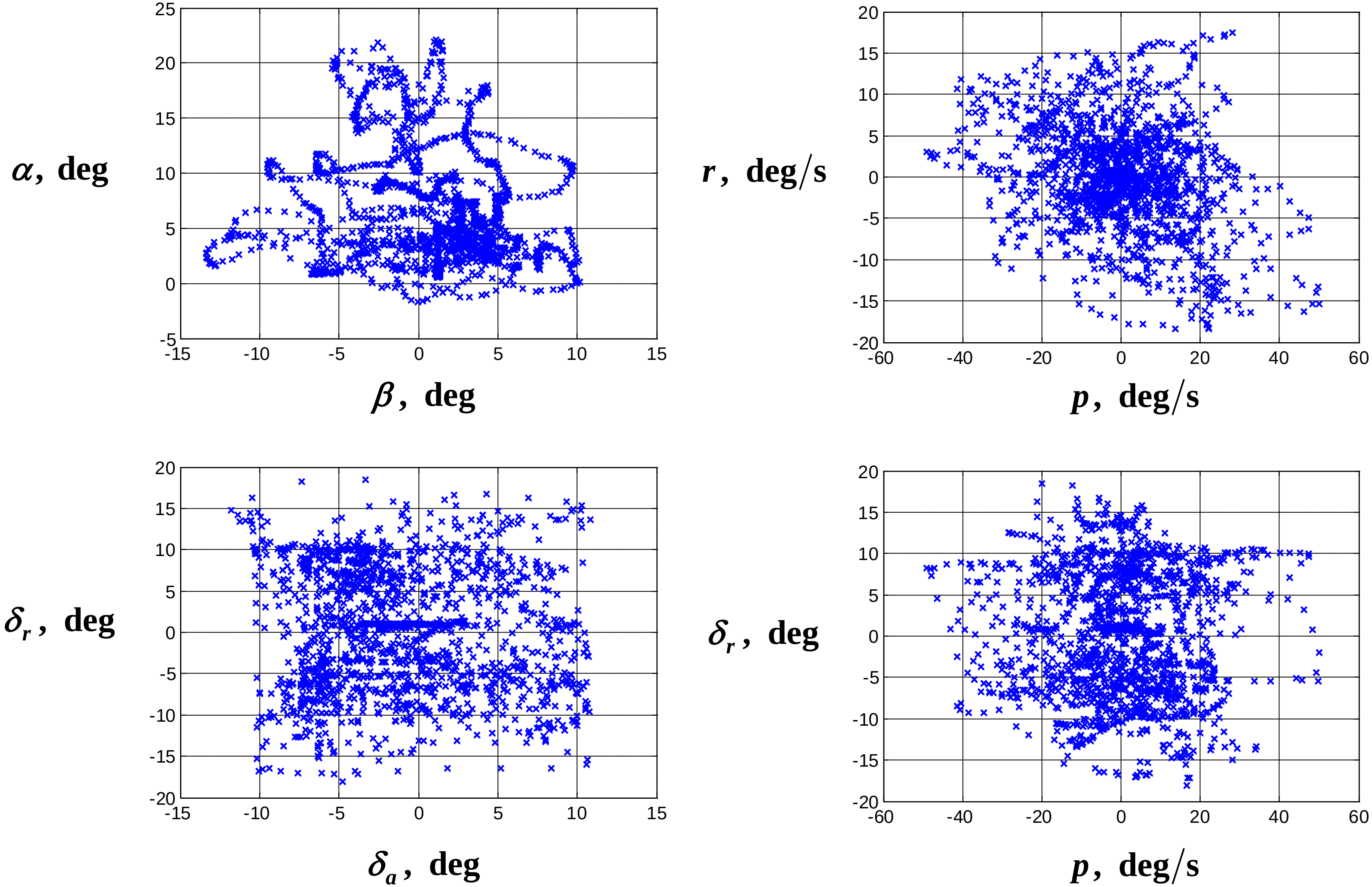

Video of SPAZ Maneuver

SPAZ Maneuver

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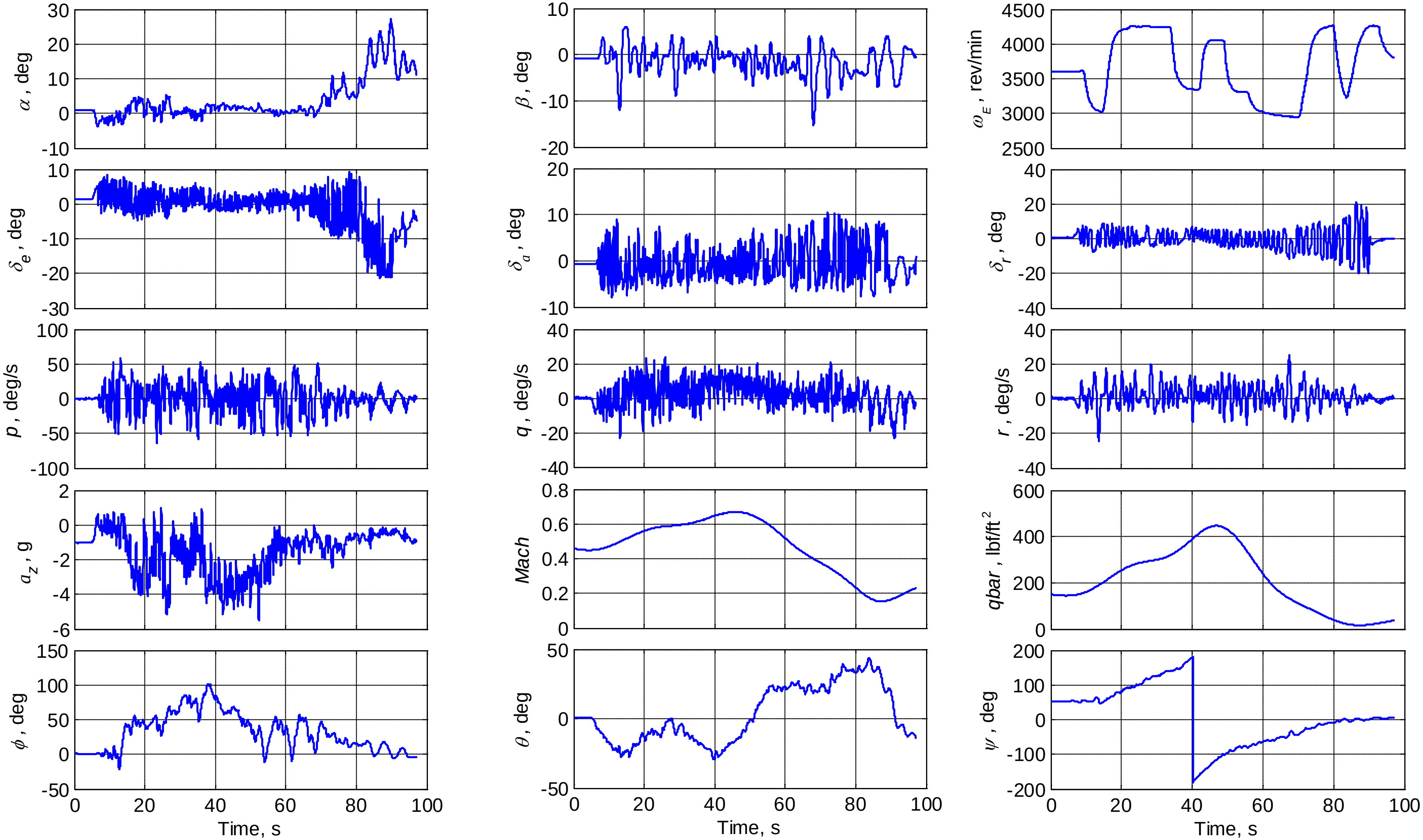

Explanatory Variable Coverage

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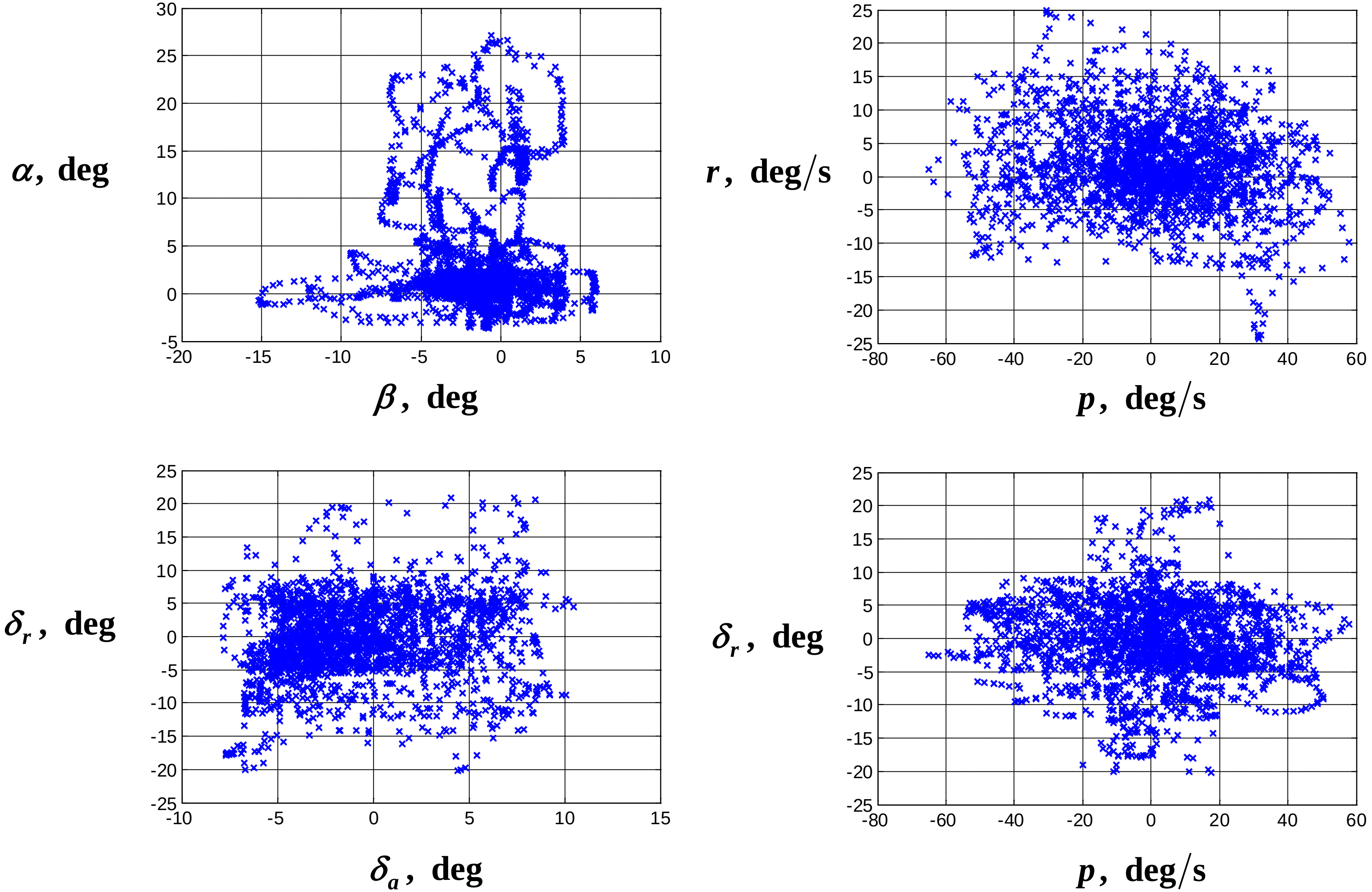

Flight Test Maneuver Information

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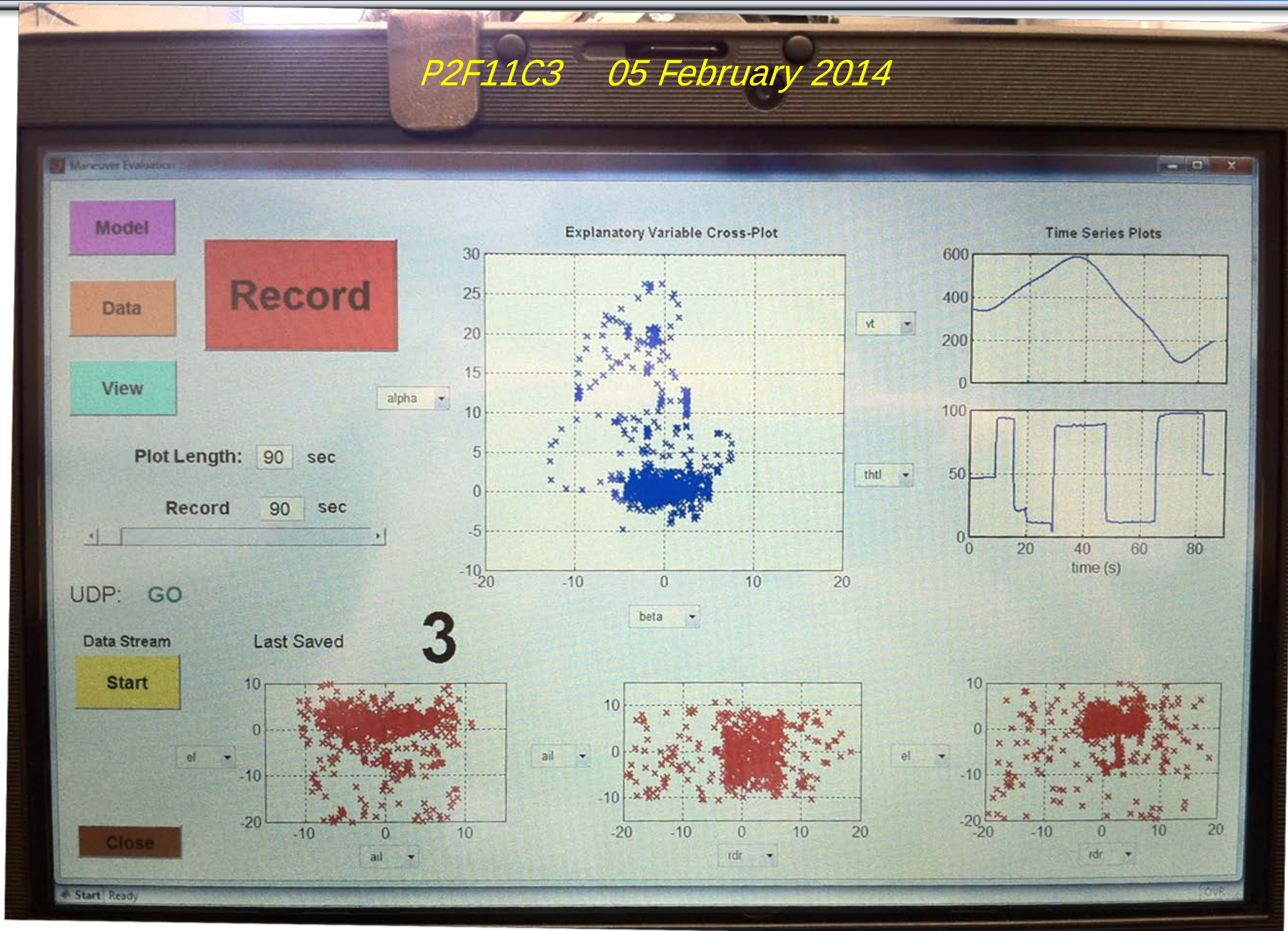
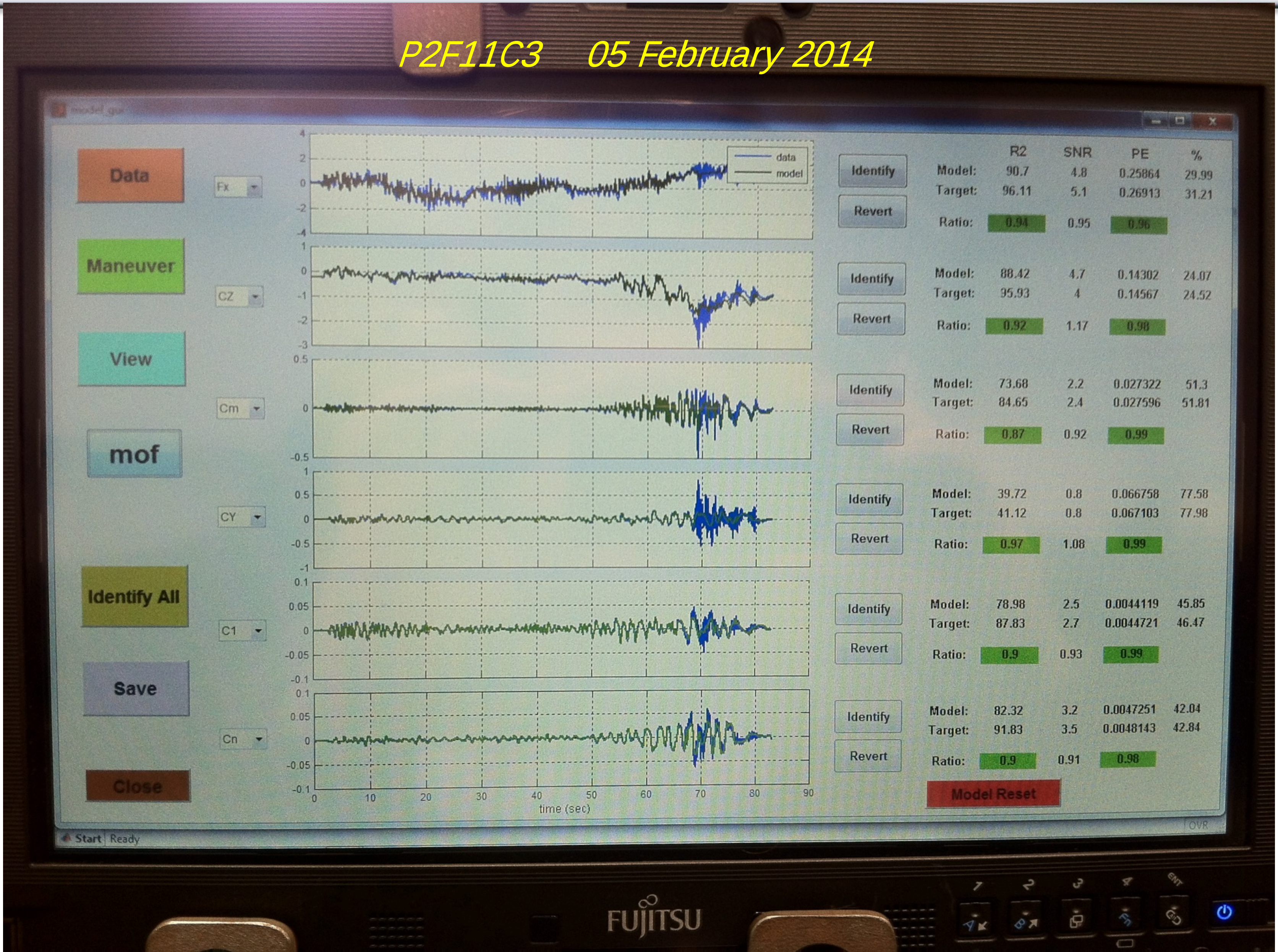


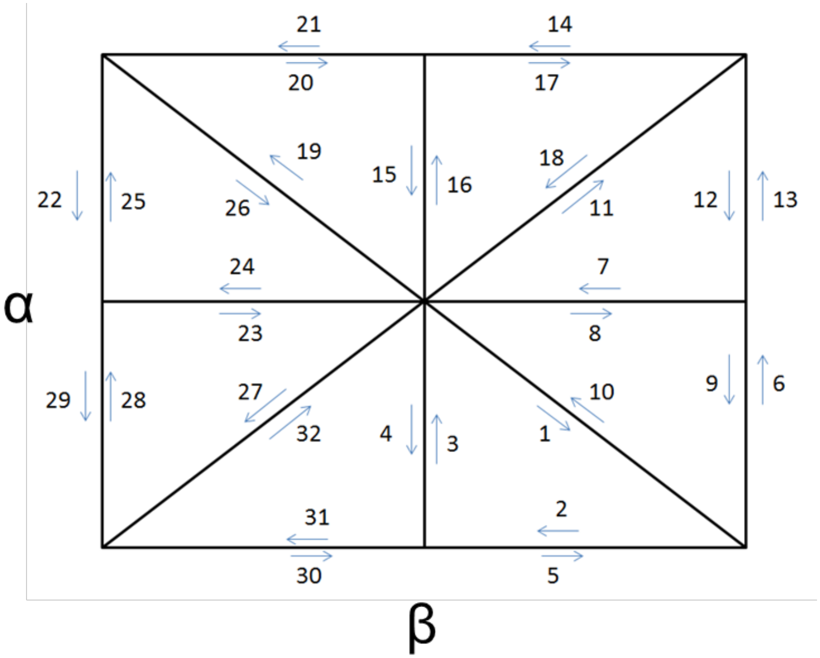
Modeling Results



Real-Time Demonstration

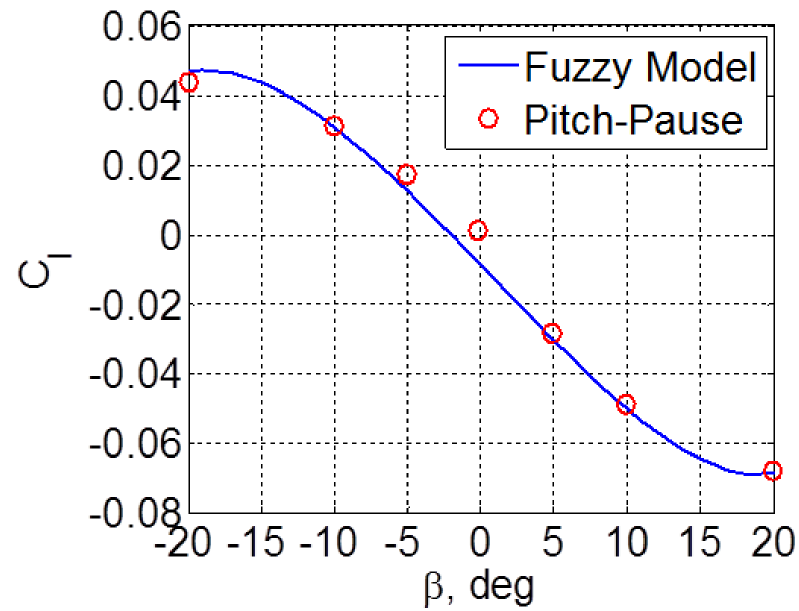
L2F Aerodynamics Modeling / L-59 Model Testing

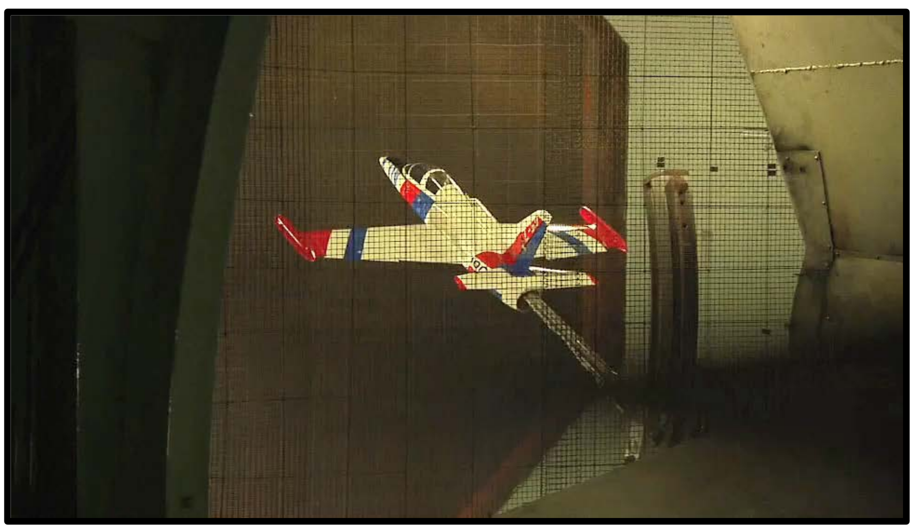
- Objective: Rapid, high-fidelity, nonlinear aerodynamics model generation
  - Large envelope
  - Control effectiveness
- Proof of concept using face-centered “crossbox” test pattern
- R/C L-59 model tested in 12-Foot Low-Speed Tunnel
  - Development of technology and modeling techniques
  - Cheap/expedient model

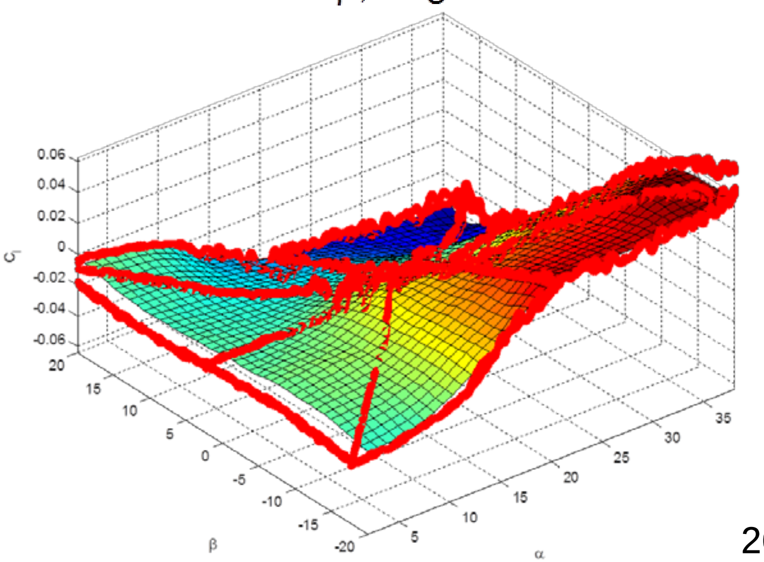


L2F Wind Tunnel Test

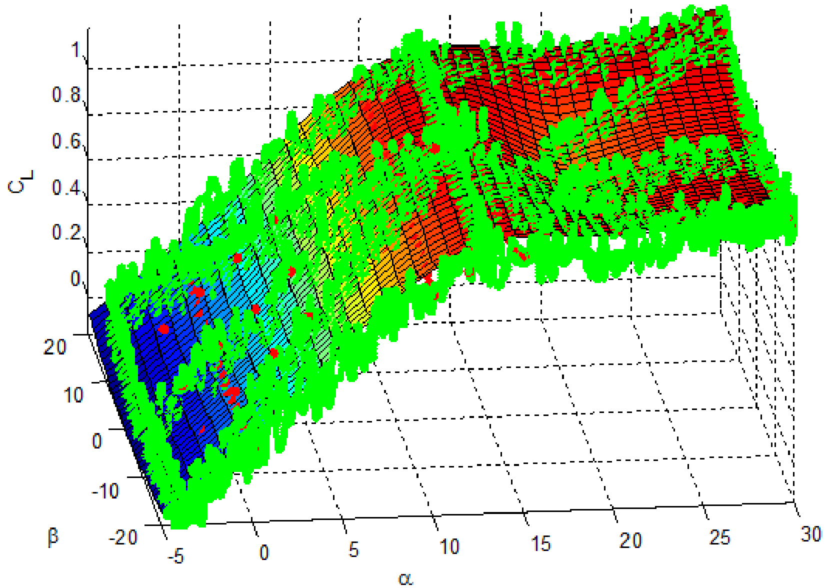
- Continuous Motions
  - α and β
  - Control deflections
- Modeling with Fuzzy Logic and Orthogonal Polynomials
- Comparisons with Conventional Data Approach

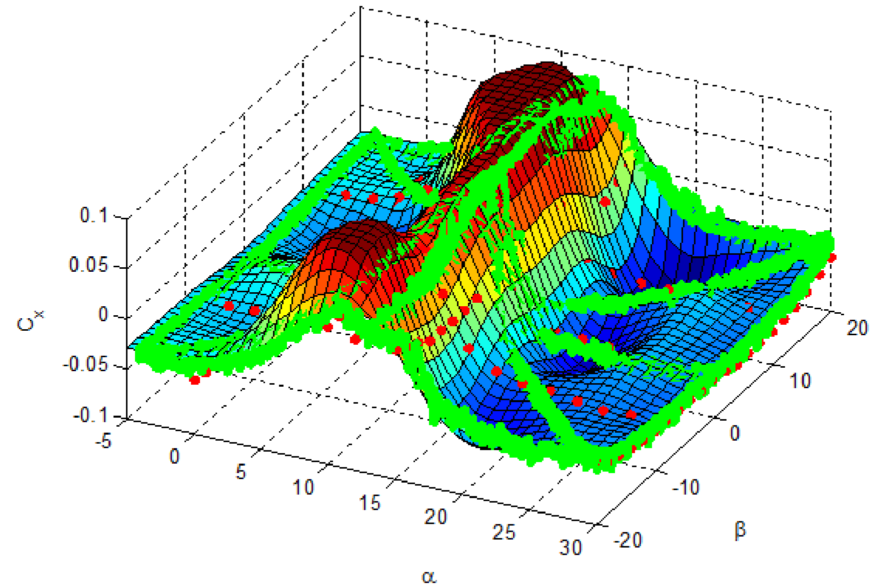


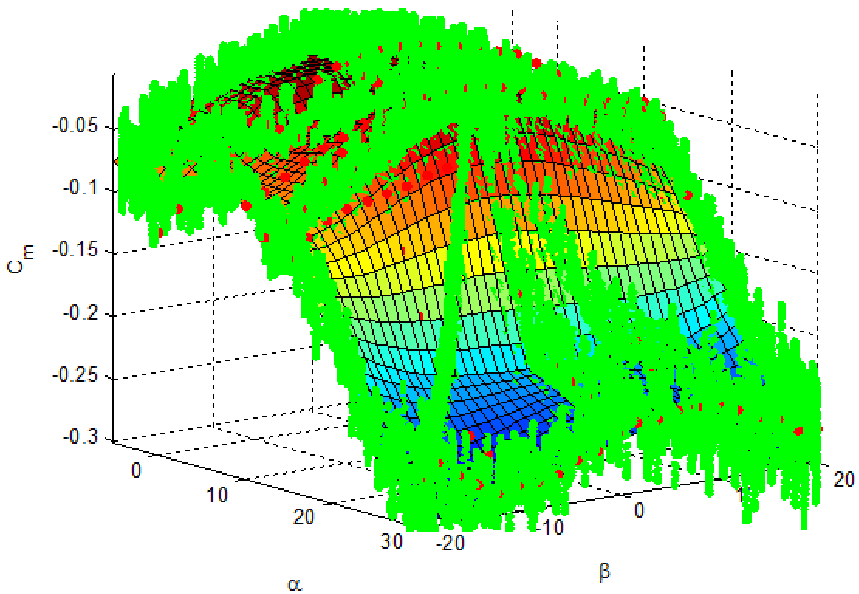


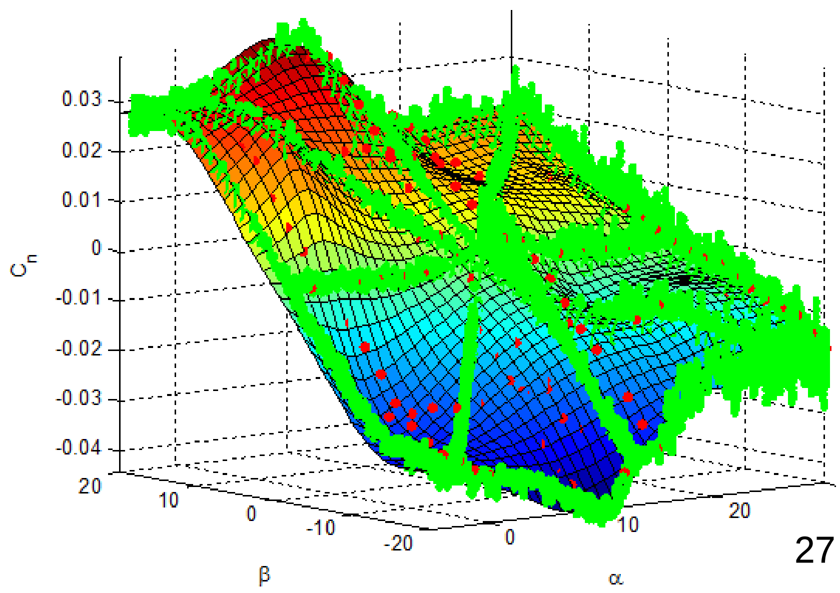


Other Model Examples









Wind Tunnel Application Plans

- Plans
  - Develop autonomous model assessments
  - Develop autonomous decisions on where more data is needed
  - Develop/demonstrate autonomous database generation
  - Extend to dynamic testing (roll motions) combined with static and controls

Summary

- New testing and modeling approaches shown can achieve high-quality results with significant reductions in cost and time:
  - Automated onboard modeling, real-time flight maneuver guidance
  - Improved flight crew awareness during flight tests
  - Reduced number of flights and maneuvers required
  - Rapid simulation development or updates for modified aircraft
  - Efficient, automated high-fidelity nonlinear aerodynamic modeling throughout normal and extended flight envelopes – flight or ground testing applications
- A step toward developing self-learning and adaptive aerospace vehicles – airplanes, helicopters, UAVs, spacecraft
  - High fidelity nonlinear models of current aerodynamic characteristics provide a tool for effective control design or adaptations in flight
  - Tool for identifying changes for safety or performance improvements
- More work still to be done to refine and validate the approach, but key aspects can be incorporated into flight test projects now

Questions?

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