Autonomous Formation Flight

MIT Course 16.886, Spring 2004
Air Transportation Systems Architecting

Greg Larson
Program Manager
Boeing Phantom Works

Gerard Schkolnik
Program Manager
NASA DFRC

Overview

Autonomous Formation Flight: NASA RevCo Program

Boeing is currently engaged with NASA Dryden Flight Research Center on a technically ambitious project, Autonomous Formation Flight (AFF). The project's primary goal is to investigate potential benefits of flying aircraft in the aerodynamic wake vortex emanating from a lead aircraft's wing tip. Initial analytic studies predict that a trailing aircraft may experience drag reductions of 10% or more by gaining additional lift in the updraft portion of the lead's wake vortex. The technical challenge is to be able to find the optimal position within the vortex to fly, then hold that position consistently in what is an extremely turbulent flow field. We know that pilots have been able to do this in the past, but the task involves a very high workload.

The Autonomous Formation Flight system marries an extremely robust flight control and guidance system with a close-coupled GPS/IMU placed on two F-18s. Inter-ship communication allows the multiple GPS/IMU systems to share state data and through and extended Kalman filter technique, they yield a differential carrier phase solution. They resolve the relative position accuracy between the aircraft in formation to less than 10 cm. Through shared state data, the guidance systems aboard both F-18s resolve coordinated trajectories that permit the aircraft to maintain formation. The trailing aircraft is thus capable of maintaining its position within the lead aircraft's wing tip vortex with extremely high accuracy.

The implications and applications of this technology are far reaching, not just for fuel economy but for other future applications such as aerial refueling, aircraft logistics, air traffic control, and carrier landing systems.

Special Acknowledgements & References To Technical Papers

Jake Vachon (NASA TM 2003-2107341)

Ronald Ray (NASA TM 2003-2107341)

Kevin Walsh (NASA TM 2003-2107341)

Kimberly Ennix (NASA TM 2003-2107341)

Ron Ray (NASA TM 2002 210723)

Brent Cobleigh (NASA TM 2002 210723)

Jake Vachon (NASA TM 2002 210723)

Clint St. John (NASA TM 2002 210723)

Eugene Lavretsky (AIAA-2002-4757)

Glenn Beaver (NASA TM-2002-210728)

Peter Urschel (NASA TM-2002-210728)

Curtis E. Hanson (NASA TM-2002-210728, NASA TM-2002-210729)

Jennifer Hanson (AIAA-2002-3432)

Jack Ryan (NASA TM-2002-210729)

Michael J. Allen (NASA TM-2002-210729)

Steven R. Jacobson (NASA TM-2002-210729)

Presentation Outline

- Project Summary
- Objectives
- Theory
- Experiment Design
- Phase 0 Flight Test
- Phase 1 Flight Test
- Cruise Mission Demonstration
- Performance Seeking Control
- Aerial Refueling
- Concluding Remarks

Test flights began in August and culminated with a drag-reduction demonstration flight in the beginning of December 2001.
A total of 28 flights were accomplished, and the full test point matrix was accomplished at both M=0.56, 25000 feet, and M=0.86, 36000 feet.
415 test points were flown
5 Project Pilots were involved in AFF Phase One Risk Reduction

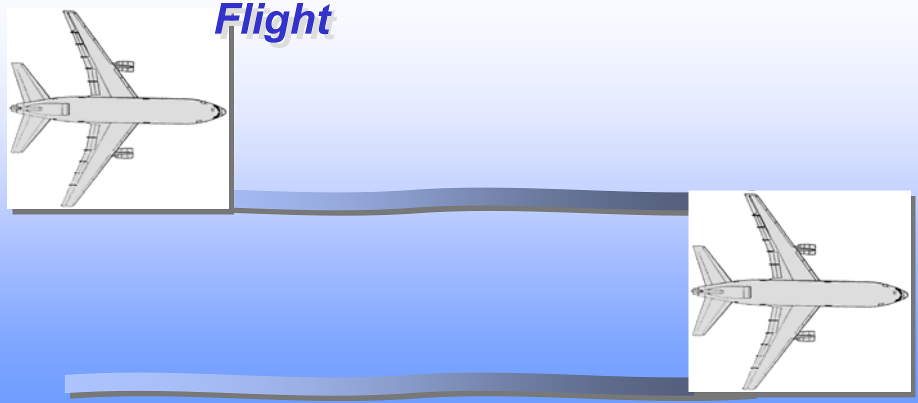
Autonomous Formation Flight

- **Background**
  - Many bird species fly in “V” formation to take advantage of the up-wash field generated by adjacent birds, resulting in less energy expended.
  - Analytical studies and recent AFF flight tests validate these observations.
- **AFF Objectives**
  - Validate drag reduction concept and prediction tools of a system of aircraft in formation in the flight environment
  - Develop and evaluate sensor and control methodologies for autonomous close formation flight
- **Approach**
  - Flight test autonomous station keeping control laws of pair of F-18 aircraft.
  - Validate drag benefits and wing tip vortex behavior using piloted flight tests.
  - Develop and validate advanced relative GPS system capable of 10 cm relative position accuracy.
  - Integrate updated sensors and advanced formation control laws to perform autonomous station keeping within the vortex wake of a lead aircraft.
- **Benefits**
  - Potential commercial fuel savings of $0.5 to 1 million per year per trailing aircraft.
  - Application to UAV Swarming, & Aerial Refueling.

BOEING

Primary Project Objective:
Demonstrate Drag Reduction

Drag Reduction Through Formation Flight



TRL LEVEL 3

Theory -
50% Reduction in Induced Drag

Experimental -
Early F-18 Data Shows 10-15% Total Drag Loss

TRL LEVEL 7

Safety
Reliability
Feasibility

Ready for Commercial Application

For a transcontinental route, per trailing aircraft per year

$\Delta C_{D_i} = 35\%$

$\Delta C_D = 10 – 15\%$

$\Delta w_f = 10 – 15\%$

$\Delta\$ = 0.5M$

$\Delta CO_2 = 10M\ lbs$

$\Delta NO_x = 0.1M\ lbs$

Autonomous Formation Flight
Partners and Responsibilities

NASA DFRC
- Overall Project Management
- Flight Safety and Mission Assurance
- GN&C Design and Analysis
- Verification and Validation Testing
- Flight Vehicle Integration
- Flight Test Operations

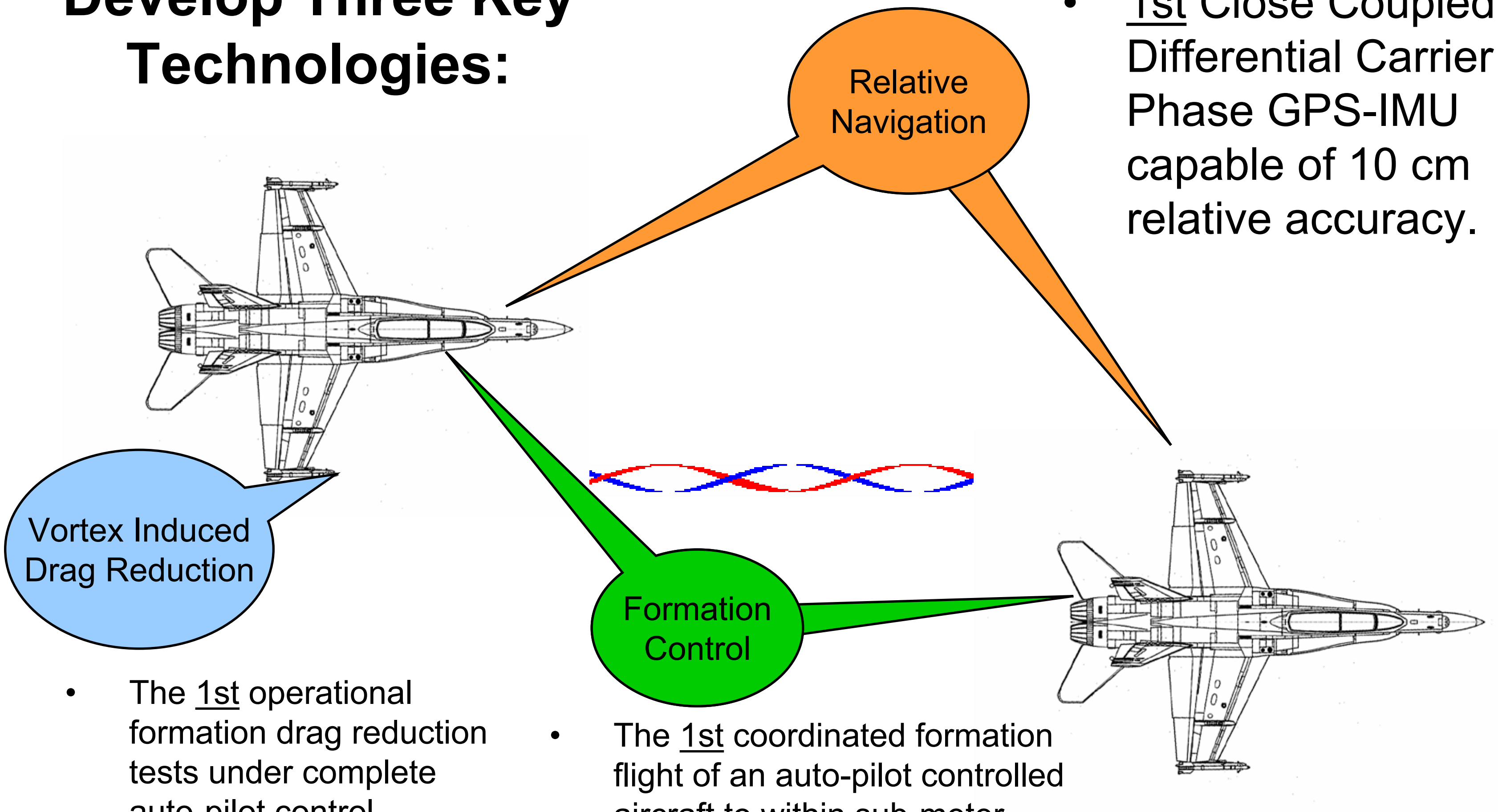
Project Has NASA RevCon Status And Is Reported At The Congressional Sub-Committee Level

UCLA
Theoretical Research
- GN&C Design Methodologies
- GPS Algorithm Development
- Advanced System Concepts

The Boeing Company
- Operational Concept
- GN&C Design and Analysis
- Aerodynamic Models and Simulations
- Formation Flight Information System (FFIS) (Integrated GPS & IMU).
- Formation Flight Computer System (FFCS).
- Formation Flight Control System Software.
- Integration with F-18 Flight Control Computer (PSFCC) Systems.

Revolutionary Technologies

Develop Three Key Technologies:

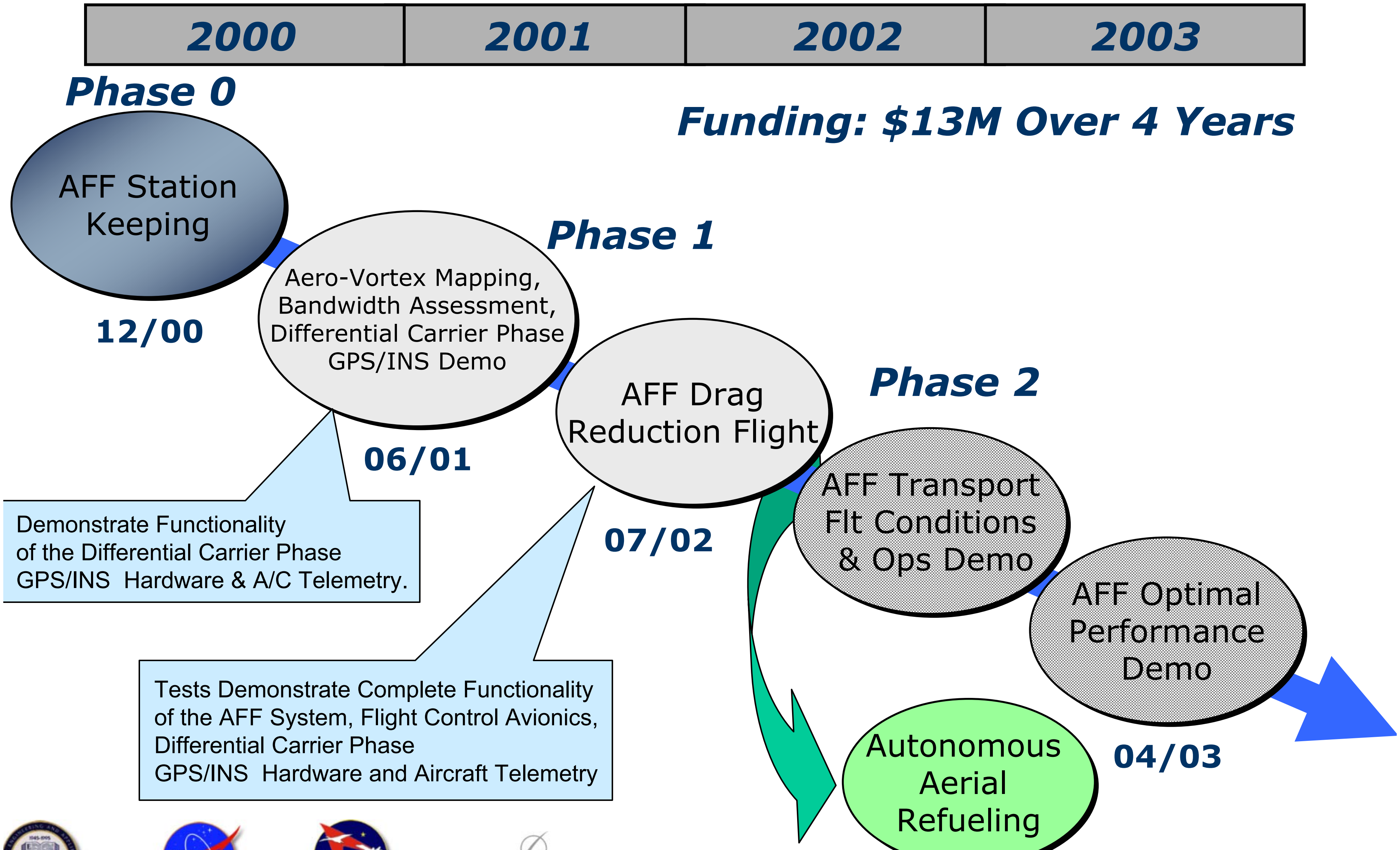


- 1st Close Coupled Differential Carrier Phase GPS-IMU capable of 10 cm relative accuracy.

- The 1st operational formation drag reduction tests under complete auto-pilot control.

- The 1st coordinated formation flight of an auto-pilot controlled aircraft to within sub-meter accuracy.

AFF Development Roadmap

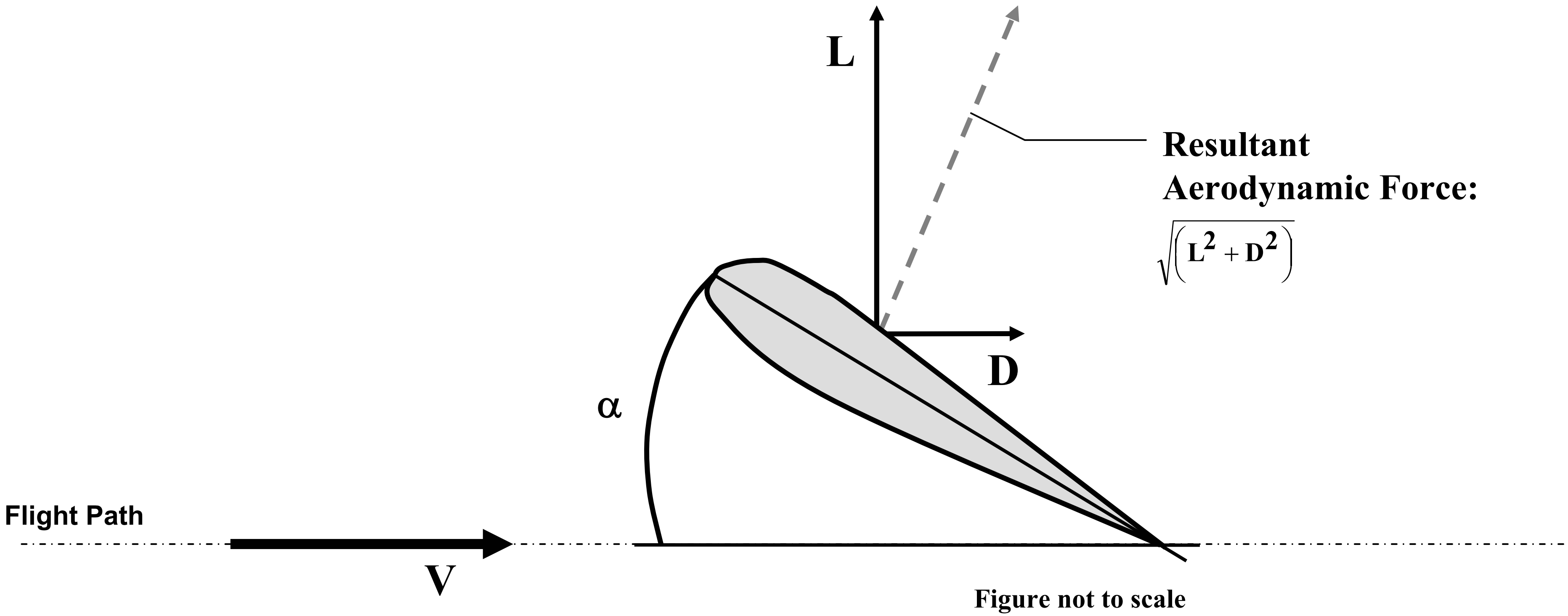


Program Approach

Create the Autonomous Formation Flight Project (AFF) Using two NASA F/A-18 airplanes

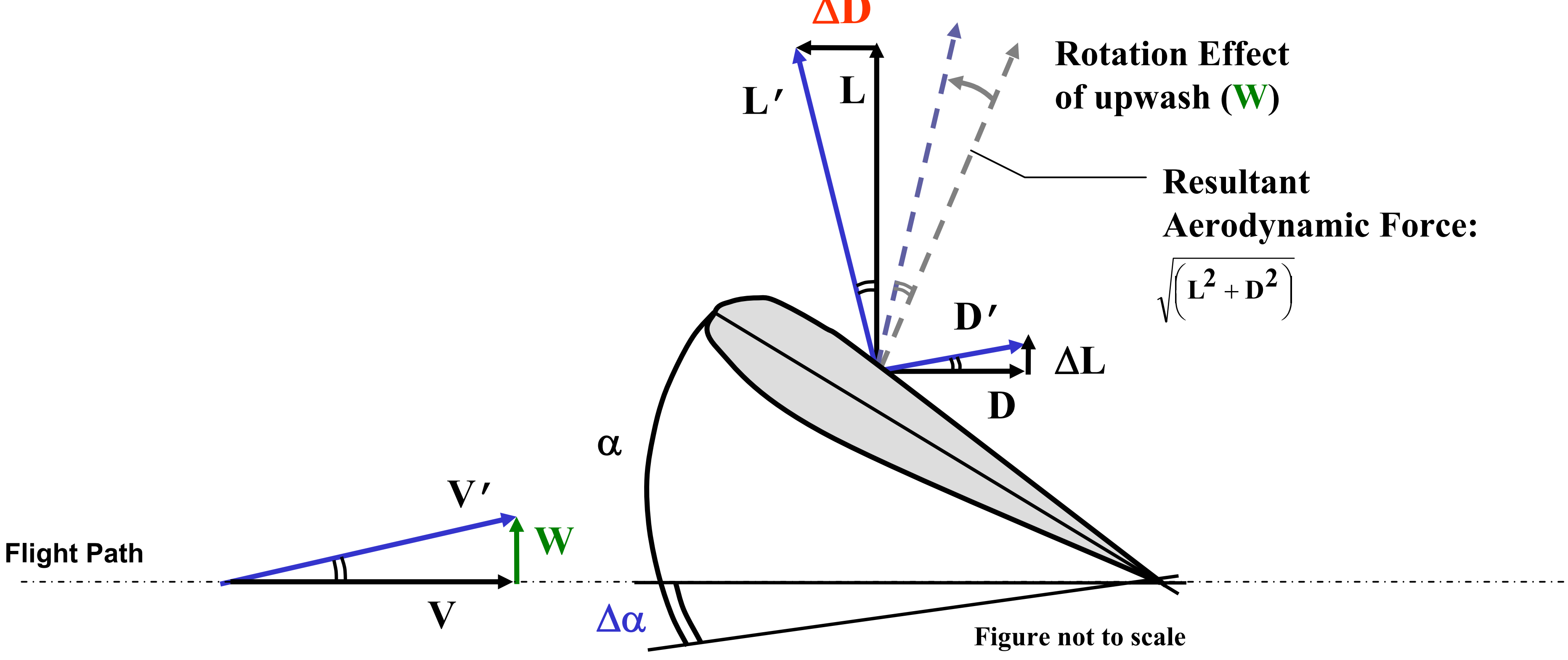
- Phase 0 - Demonstrate Autonomous Station-Keeping
  - Fall of 2000
- Phase 1 Risk Reduction - Map the Vortex Effects
  - Fall of 2001
- Phase 1 - Autonomous Formation Flight
  - Incomplete

Lift and Drag Force Basics



- **Aerodynamic forces on an aircraft**
  - Drag is parallel to flight path
  - Lift is perpendicular to flight path
  - Lift is an order of magnitude greater than drag

Vortex Influence on Lift and Drag



- **Basic theory states drag reduction, ΔD, is caused by the rotation of the original lift vector due to the upwash effect of the vortex**
  - The associated lift increase is very small because D<<L
  - Only the induced drag is affected by vortex, **ΔD = sin(Δα) L**

The most common theory on Formation Flight states that "drag reduction" is actually obtained due to a rotation of the lift vector that occurs while a trailing aircraft is in the upwash field of the lead aircraft. The figure above illustrates this concept showing how the baseline (non-formation flight) lift and drag values, L and D, rotate by the change in angle of attack, Δα, due to the upwash effect while in the vortex flowfield.

Because of traditional bookkeeping methodology, the actual lift and drag values are maintained relative to the vehicle's global, rather than local, flight path during formation flight. The term, ΔD, is used to represent the drag change due to the rotation of the lift force from L to L'. The drag during formation flight, DFF, is obtained by:

DFF = D' cos(Δα) -ΔD where: ΔD = sin(Δα) L

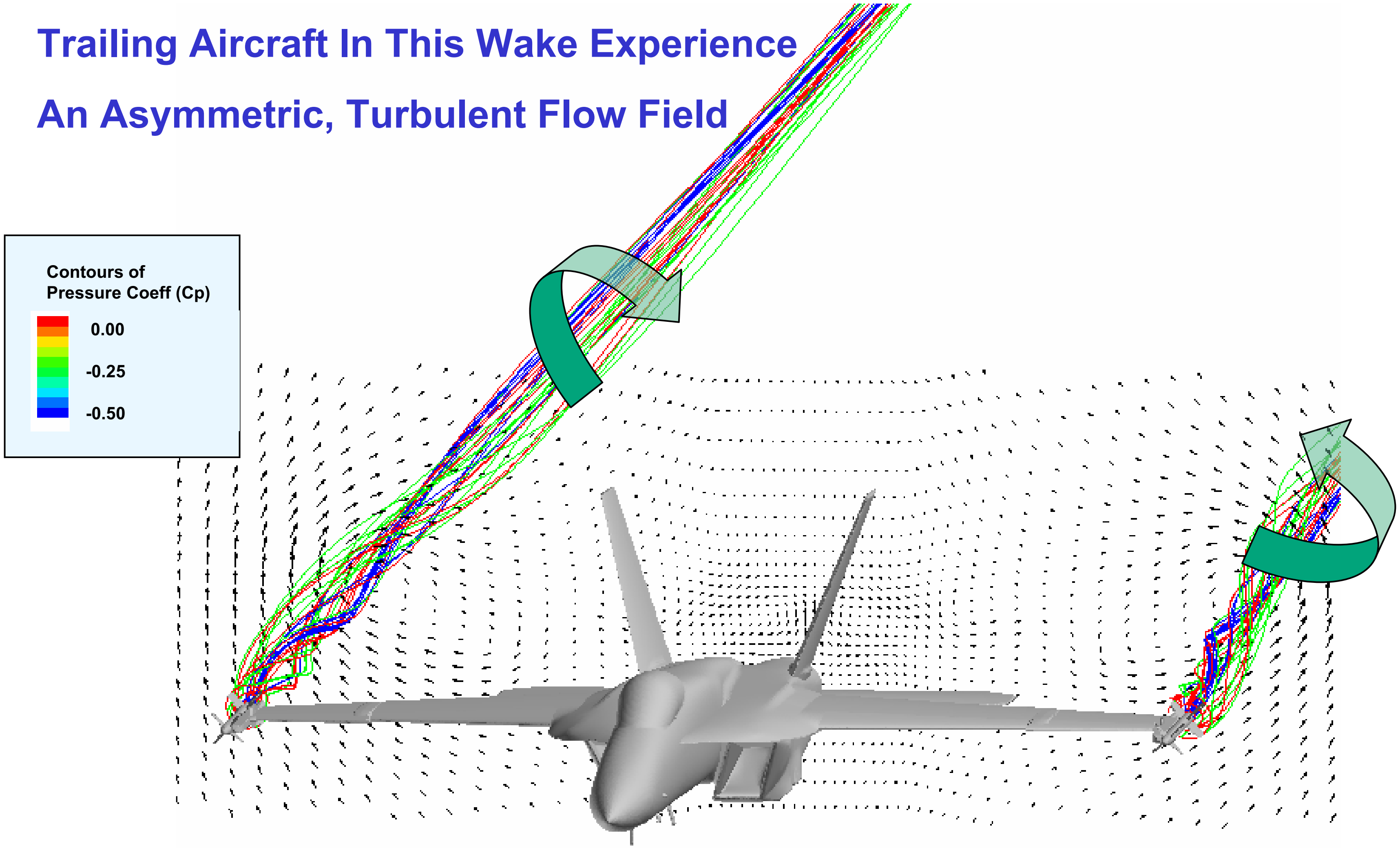
In a similar manner the term ΔL, is used to represent the lift change due to the rotation of the drag force from D to D'. The lift during formation flight, DFF, is obtained by:

LFF = L' cos(Δα) + ΔL where:ΔL = sin(Δα) D

Because lift tends to be an order of magnitude greater than drag (L>>D), drag is influenced significantly more by the rotation effect than lift is. A considerable reduction in drag can be realized by a small upwash angle, while an insignificant increase in lift occurs.

F-18 Wing Vortices & Cross Flow Gradient

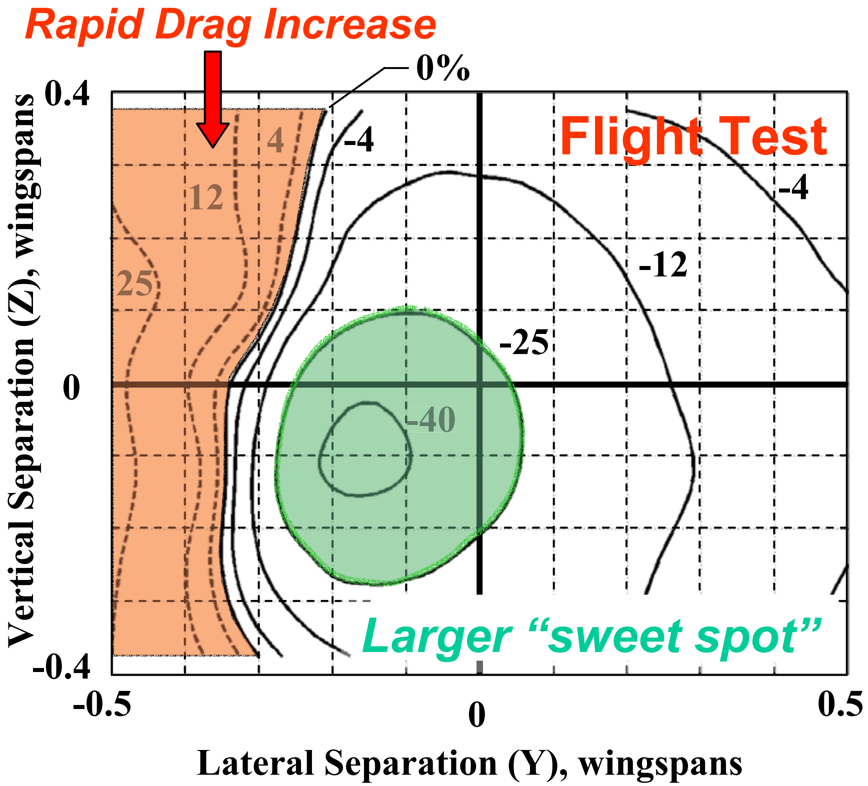
3-View, F/A-18E: Mach 0.85, AOA 3deg



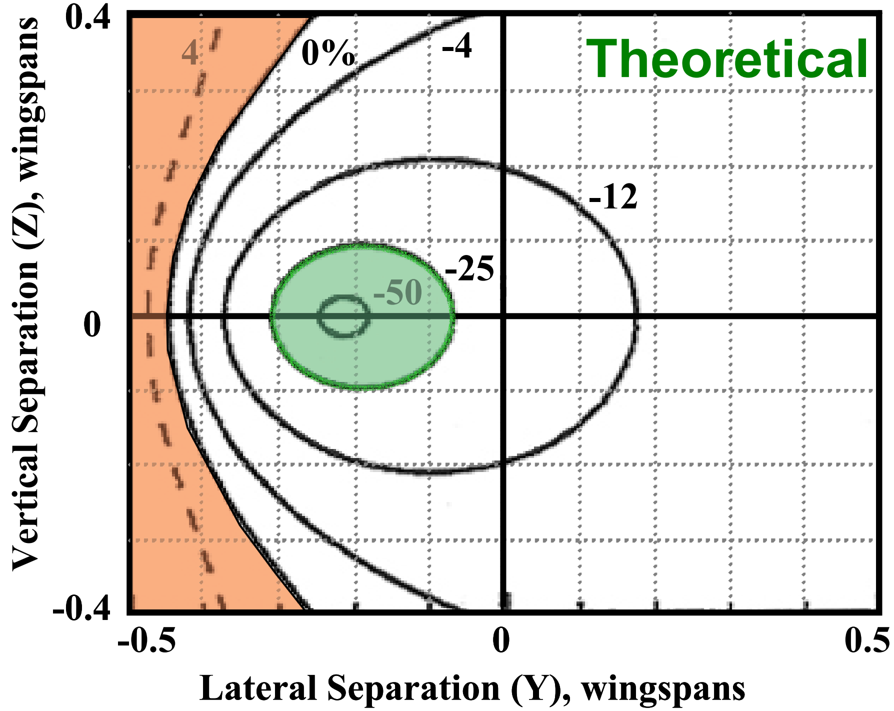
CFD Results: Courtesy of Dave Stookesberry, Boeing STL.

Vortex Influence on Induced Drag

Percent Induced drag change, M=0.56, 25,000 ft, 55 ft N2T



Calculated induced drag change obtained from flight data, with similar results at ALL flight conditions!



Predicted induced drag change using generic horseshoe vortex model*

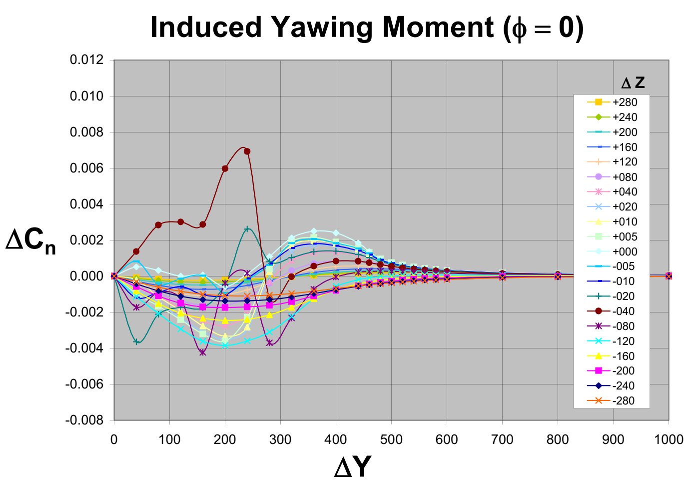
*Adapted from: Blake and Multhopp, AIAA-98-4343, August 1998

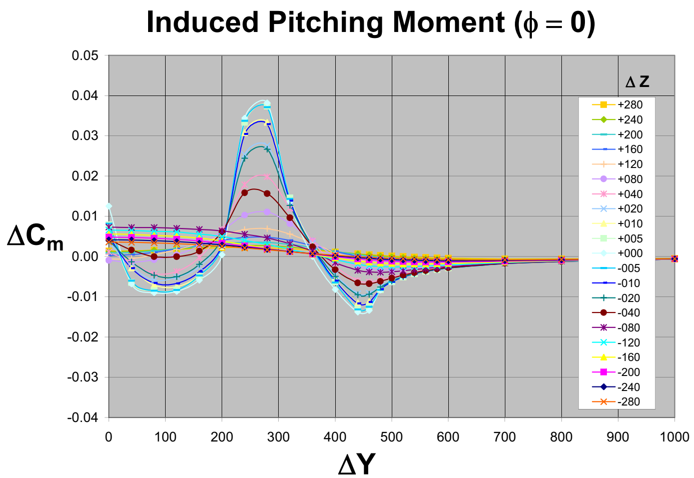
Hammer home that this is **INDUCED** drag!

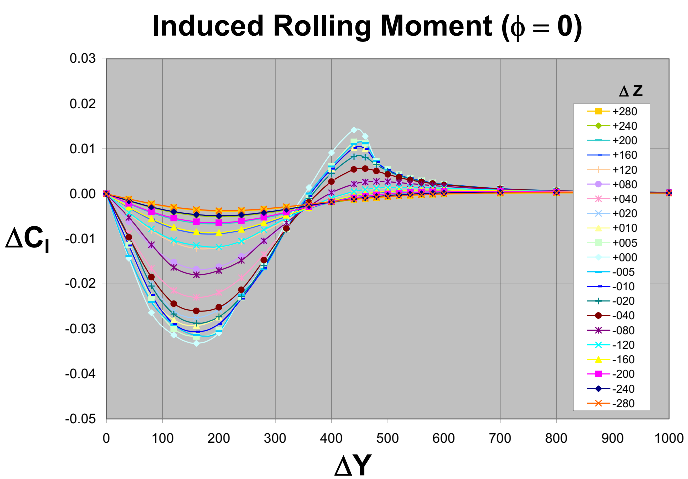
The flight results also measure higher drag increases inboard than predicted, but this is also the region where data quality is worse because the points are more difficult to fly. Some of these points were very unstable as the vortex seemed to impinge on the tail or other surfaces causing the trailing aircraft to continually wander from the target position. Higher trim drag effects could also contribute to the large drag increases. The line of zero benefit is also located further outboard than predicted. These results indicate substantially higher sensitivity to lateral positioning inboard of the sweet spot than predicted. **Small changes in lateral positioning in this region can result in large changes in benefits (drag increase!). The overall vertical sensitivity is less than predicted; the overall shape of the region of most benefit is more round than oval as predicted for a generic wing. Induced drag results are similar at all flight conditions and separation distances:**

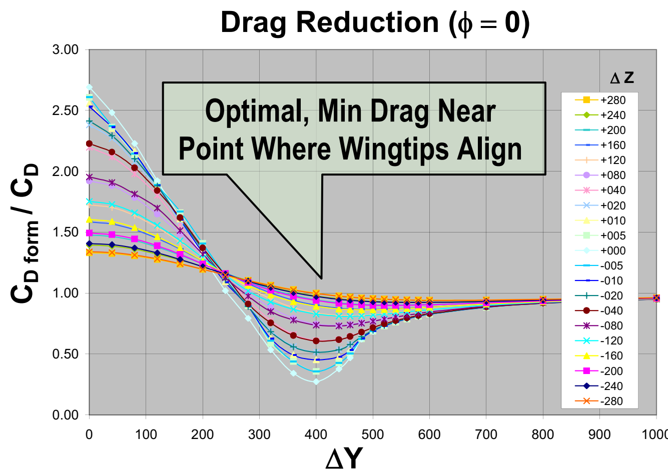
The induced drag change measured at the transport flight condition (not presented) correlated very well to those obtained at the reference condition shown above in both shape and magnitude. This is a significant result indicating an accurate model of induced drag change could potentially be used to model drag benefits at other conditions.

F-18A Wake Vortex Characteristic Aero-Increments Vary Greatly With Offset Distance ΔY Between A/C









Linear Panel Method Results

AFF Research Aircraft

NASA 845 Systems Research Aircraft (SRA)

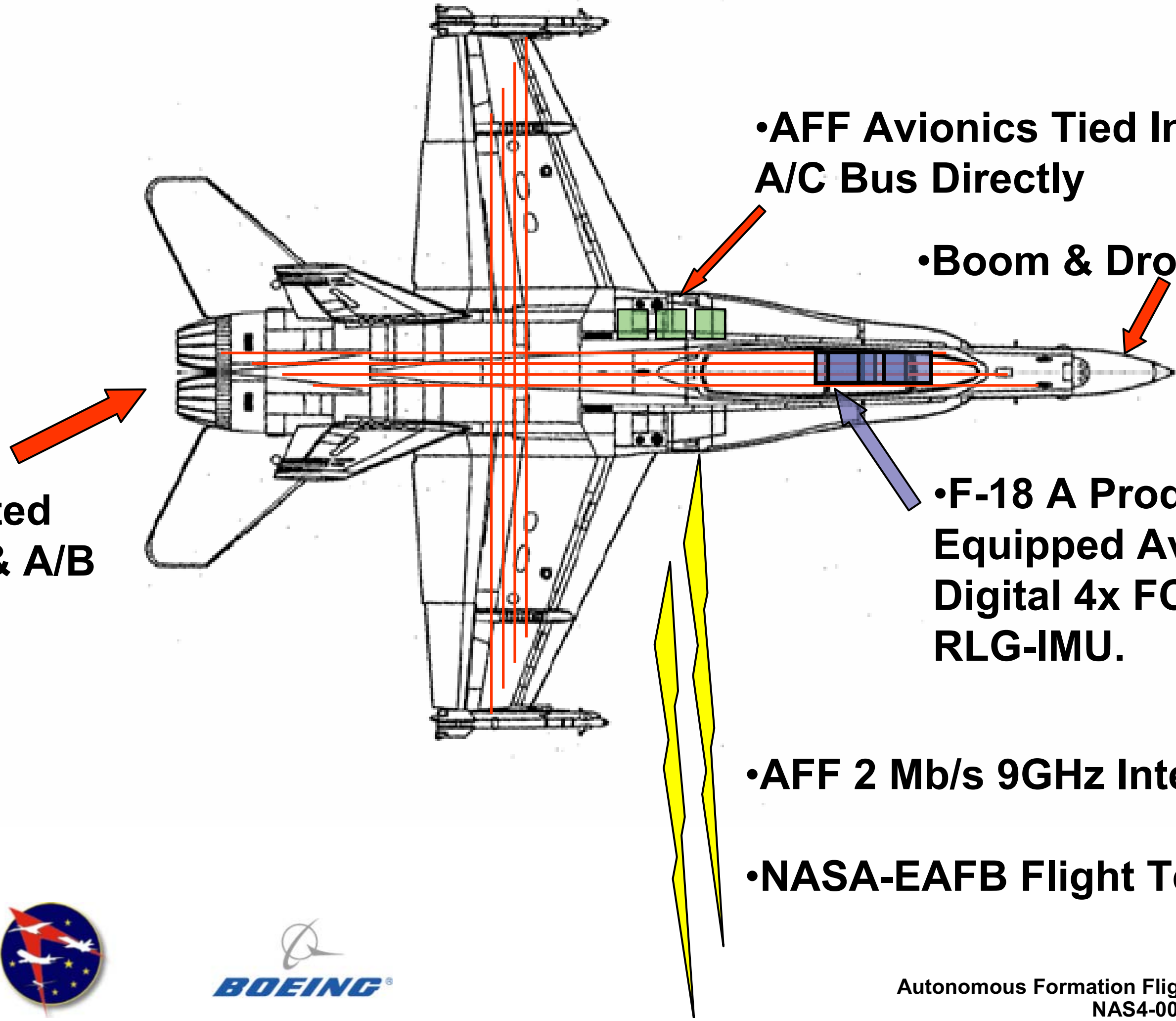
- **Pre-Production TF-18A (2 Seater)**
- **Research Modifications**
  - **Instrumentation/Telemetry System**
  - **Independent Separation Measurement System**
  - **Formation Flight Control System & Instrumentation System**
  - **Production Support Flight Control Computers**
  - **Engines Modified with Flight Test Instrumentation Package for Thrust Measurement**
  - **Cockpit Highly Adaptable Research Monitor System**
  - **HUD Video & Hot Microphone System**

NASA 847

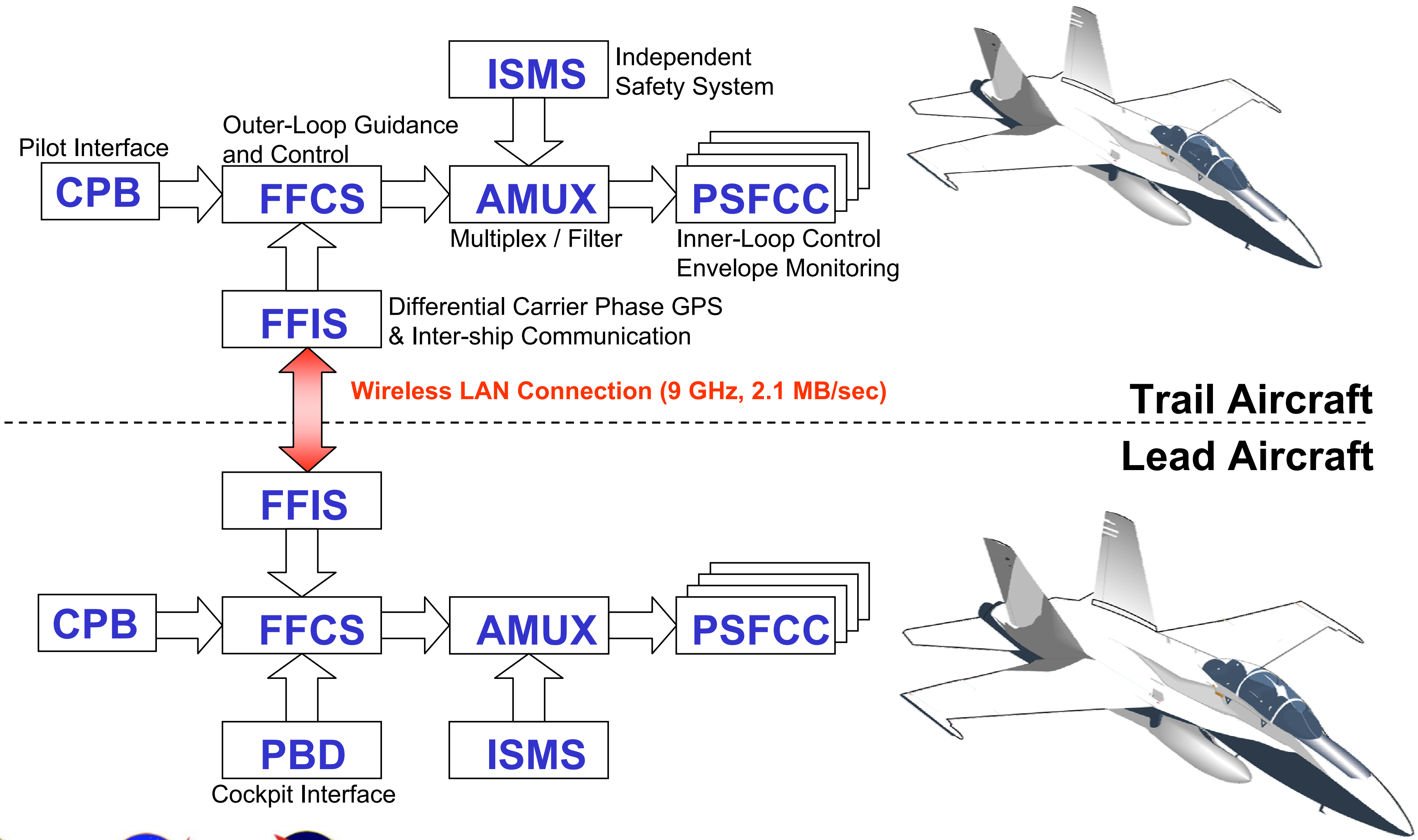
- **Production F-18A (1 Seater)**
- **Research Modifications**
  - Instrumentation/Telemetry System
  - Independent Separation Measurement System
  - Formation Flight Control System & Instrumentation System
  - Production Support Flight Control Computers
  - HUD Video & Hot Microphone System

Two NASA F-18 aircraft were used for this research. Both aircraft were equipped with instrumentation and telemetry systems as well as identical GPS receiver units. The Systems Research Aircraft (SRA) was designated as the follower and outfitted with the formation autopilot, consisting of a research computer and specially modified flight control computers. A NASA chase aircraft acted as the formation lead. A third NASA chase aircraft was occasionally used for photographic documentation of the experiment.

NASA's F-18s Are Uniquely Modified Production Versions



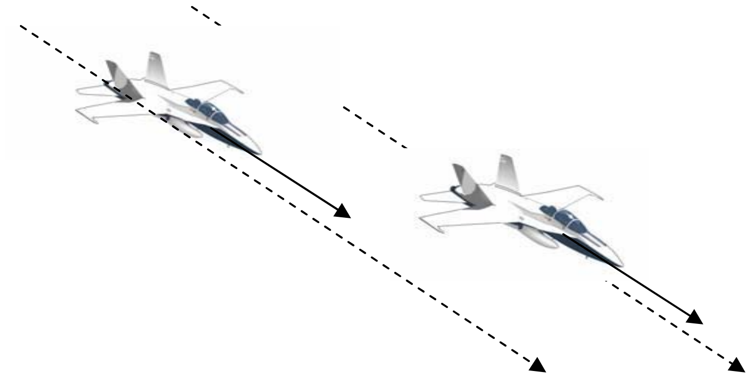
AFF System H/W Couple The Aircraft Through A Wireless LAN



AFF Guidance Overview

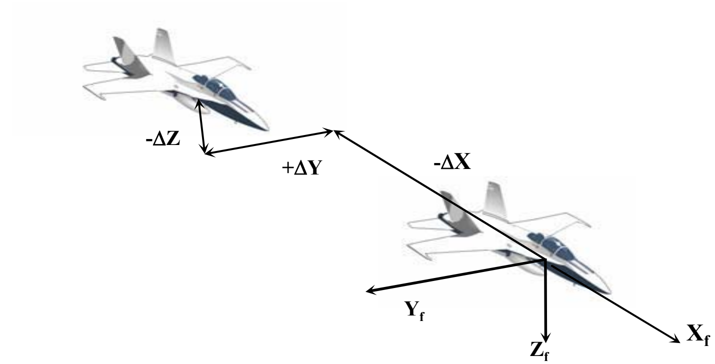
Two Guidance Approaches

Trajectory Tracking



- Trajectories defined by great circle path. IC = lead aircraft initial heading, velocity and alt.
- Position errors are calculated between AC and prescribed trajectory.
- Appropriate for small and large formations with prescribed maneuvering.

Leader-Follower



- Reference frame defined by lead aircraft's current velocity vector.
- Position errors are based on aircraft relative position.
- Appropriate for tracking arbitrary maneuvering. Potential Application To Aerial Refueling & Auto-Carrier Landing Systems.