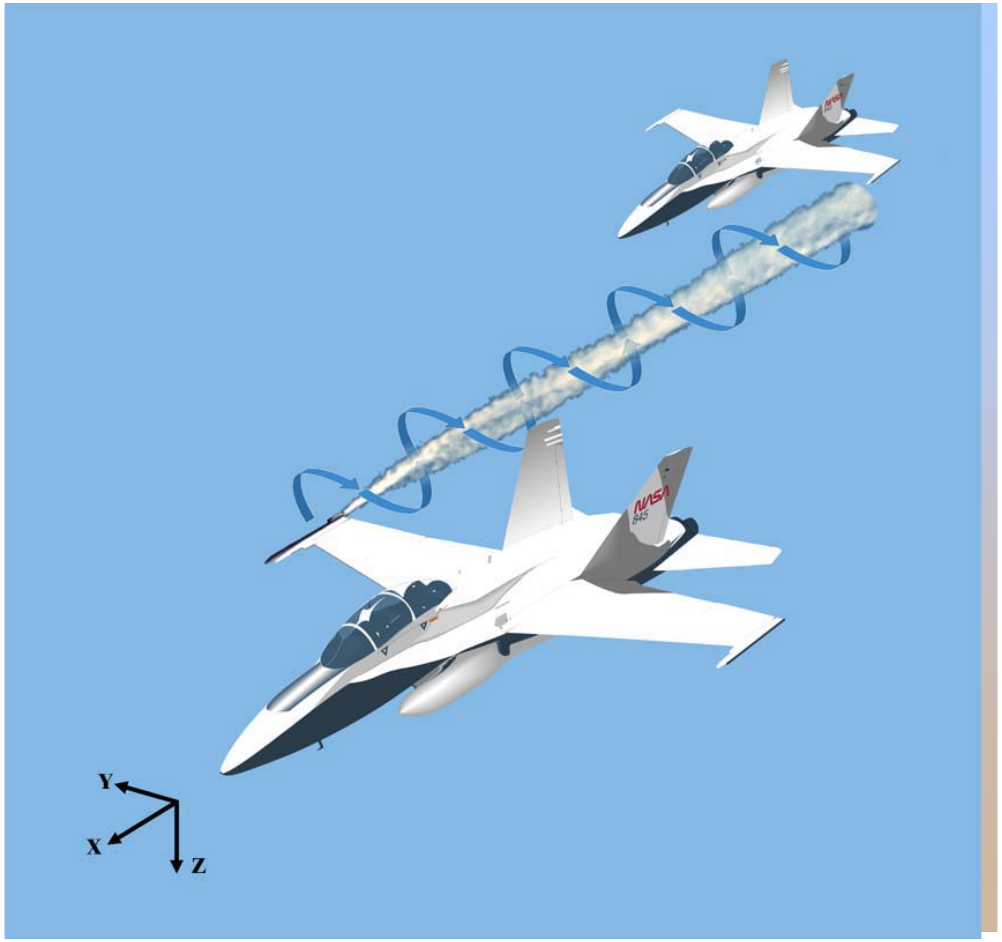
Overview of Experiment

- Flight Conditions
  - M = 0.56, 25000 feet (Subsonic condition)
  - M = 0.86, 36000 feet (Transonic condition)
- Nose-To-Tail (N2T) Distances
  - 20, **55**, 110 and 190 feet
- Nomenclature
  - X-direction (longitudinal)
  - Y-direction (lateral)
  - Z-direction (vertical)

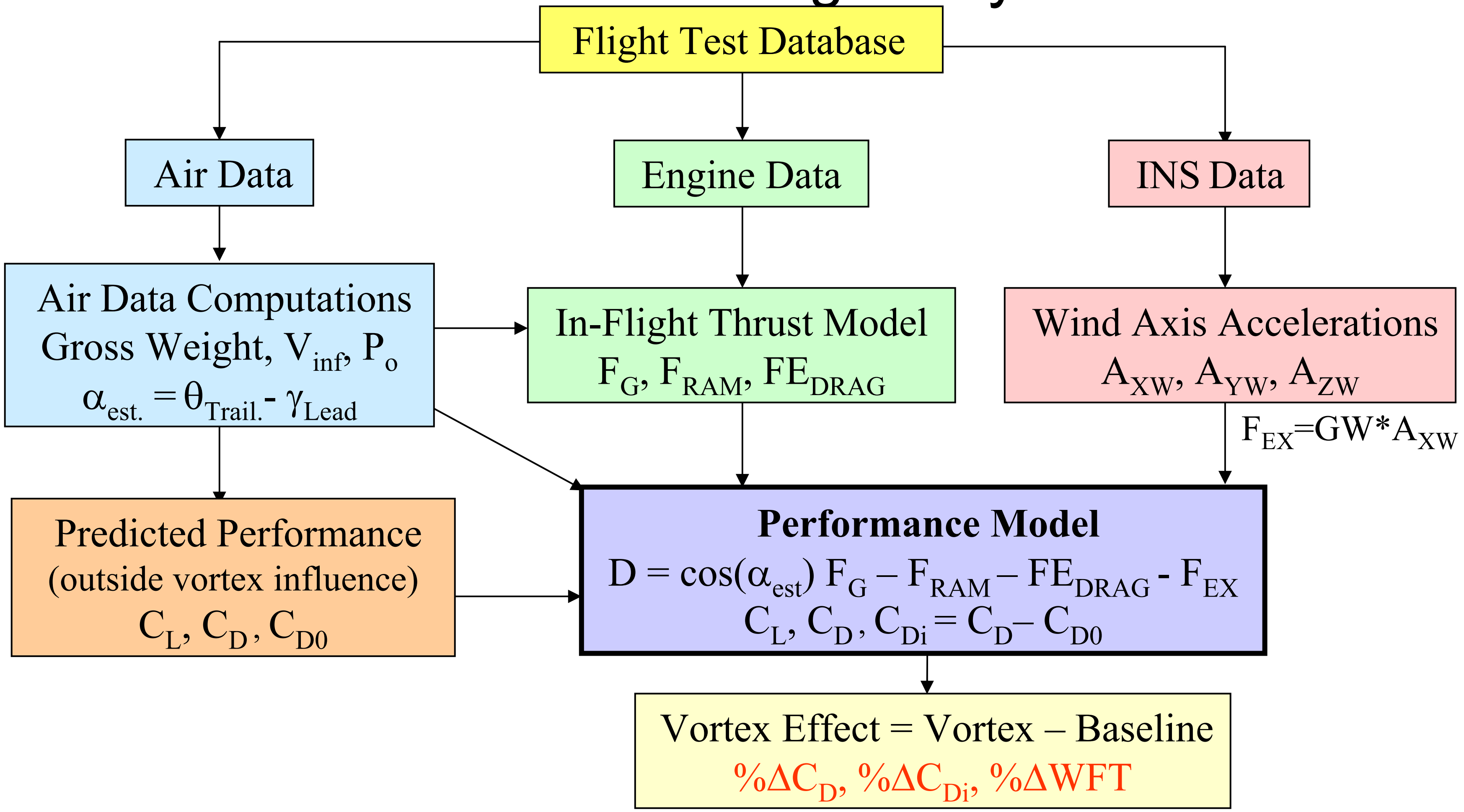


The *subsonic* flight condition (M=0.56, h=25000 feet) was selected to match pre-existing data from vortex-effect prediction codes. These codes needed to be validated to determine their utility on future applications of AFF. Since a possible future application of AFF is for transport airplane, flight data were also acquired at M=0.86 and h =36000 feet. This *transonic* flight condition is representative for that class of vehicle.

The vortex effects were also mapped at different longitudinal distances behind the leader airplane. These Nose-To-Tail (N2T) distances were monitored by the control room and maintained by the pilots through periodic radio calls. Only the results from the subsonic condition, 55' N2T will be presented here. **55' is equal to the length of the F/A-18.**

The reference axis system was as shown above. It should be noted that although Z is positive down, this presentation will refer to positions above the lead airplane (or *high*) as positive and positions below the lead airplane (or *low*) as negative.

Lift and Drag Analysis



Flight Test Database

Air Data

Engine Data

INS Data

Air Data Computations
Gross Weight, V_{inf}, P_o
$\alpha_{est.} = \theta_{Trail.} - \gamma_{Lead}$

In-Flight Thrust Model
F_G, F_{RAM}, FE_{DRAG}

Wind Axis Accelerations
A_{XW}, A_{YW}, A_{ZW}

$F_{EX}=GW*A_{XW}$

Predicted Performance
(outside vortex influence)
C_L, C_D, C_{D0}

Performance Model
$D = \cos(\alpha_{est}) F_G - F_{RAM} - FE_{DRAG} - F_{EX}$
C_L, C_D, $C_{Di} = C_D - C_{D0}$

Vortex Effect = Vortex – Baseline
$\%\Delta C_D$, $\%\Delta C_{Di}$, $\%\Delta WFT$

Performance data was determined using classical techniques. A force balance along the flight path was used to determine drag while a force balance perpendicular to that was used to determine lift: **D = cos(αest) FG – FRAM – FEDRAG-(GW*AXW); L = sin(αest) FG + (GW*NXW).** Three primary data reduction areas feed the performance mode; 1) Air Data, 2) IFT, and 3) Accelerations.

The Air Data model computes gross weight (GW) using empty weight and the remaining total fuel accounting for crew weight. It also includes a calculation of an estimated alpha, αest, which is based on the trailing aircraft's pitch angle and the lead aircraft's flight path angle (αest = qtrail-γlead). **This was required because the trailing aircraft's alpha probes are unusable during formation flight due to localized upwash influences of the lead aircraft.** Because the lead aircraft flew at steady-state conditions (constant speed and altitude), the flight path angle, γlead, was always close to zero.

The engine manufacturer's IFT model was used to calculate thrust on the F404-GE-400 engines installed in the trailing F/A-18 Aircraft. The next chart describes the measurements used to run this model. The model calculated gross thrust (FG), ram drag (FRAM) and engine throttle dependent drag, (FEDRAG). Gross thrust is the primary force the engine produces out the tail pipe, FRAM represents the force loss due to the momentum of air, W1, entering the inlet, and FEDRAG accounts for the external drag forces associated with the engine nozzle and inlet spillage flow.

The INS was used to obtain vehicle acceleration data. This data was corrected for rotation effects due to not being mounted exactly on the center of gravity. It then was translated into the flight path (wind axis) coordinate system. Axial acceleration was used to compute vehicle excess thrust: FEX = GW*AXW

The performance model used the information from the three paths described above to obtain lift, drag and respective coefficients. To obtain drag reduction values, data obtained during formation flight (vortex) was compared to baseline (non-vortex) points completed in a back-to-back fashion. Some formation flight test points did not include a slide-out maneuver to obtain baseline conditions. For these few points, baseline data were estimated based on data trends in drag related to gross weight. A simple prediction model was used to calculate baseline lift and drag values to evaluate the reasonableness of the baseline data.

Test Point Procedure

- Pilot Procedure
  - Acquire and hold position within the influence of the vortex for 30 seconds of stable data
  - Engage auto-throttle velocity-hold and maintain position for 20 seconds of stable data
  - Laterally slide out of position (away from lead a/c), engage altitude-hold and stabilize outside of vortex for 20 seconds
- Technique provides direct comparison of performance data in and out of vortex
- Use of auto-pilot and auto-throttle significantly improved maneuver and data quality

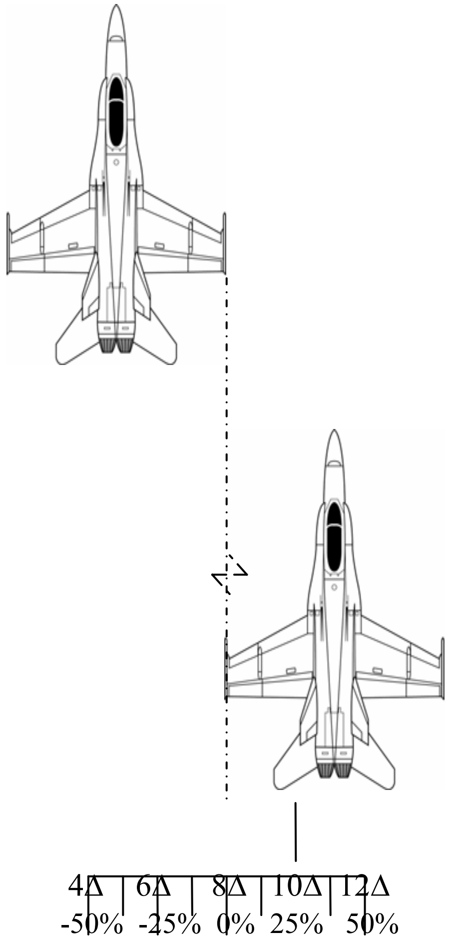
Each test point was conducted in the same way. Once both aircraft were on condition, the trail aircraft maintained its position behind the lead aircraft for 30 sec. During this time, the pilot of the trail aircraft was controlling every aspect of his aircraft, including throttles. Because of the transient nature of the vortex effects, especially with significant wing overlap, the pilot's throttle movements were, in some cases, coarse and over-corrective. This problem was exacerbated when combined with a significant longitudinal distance like 190' N2T, because maintaining longitudinal separation became especially difficult when the pilots did not have a good visual (close) reference.

After 30 sec of stable data, the pilot engaged the auto-throttle (ATC) velocity hold and held position for another 20 sec. More often than not, the ATC would have to be set a few times before the N2T closure rate was small enough to call stable. After 20 sec of stable, ATC-engaged data, the control room gave the call for 'slide out', at which time the pilot of the trail aircraft maneuvered laterally out of position to the right, engaged altitude-hold, and stabilized for another 20 sec outside of the vortex. The control room then gave a 'test point complete' call at the appropriate time.

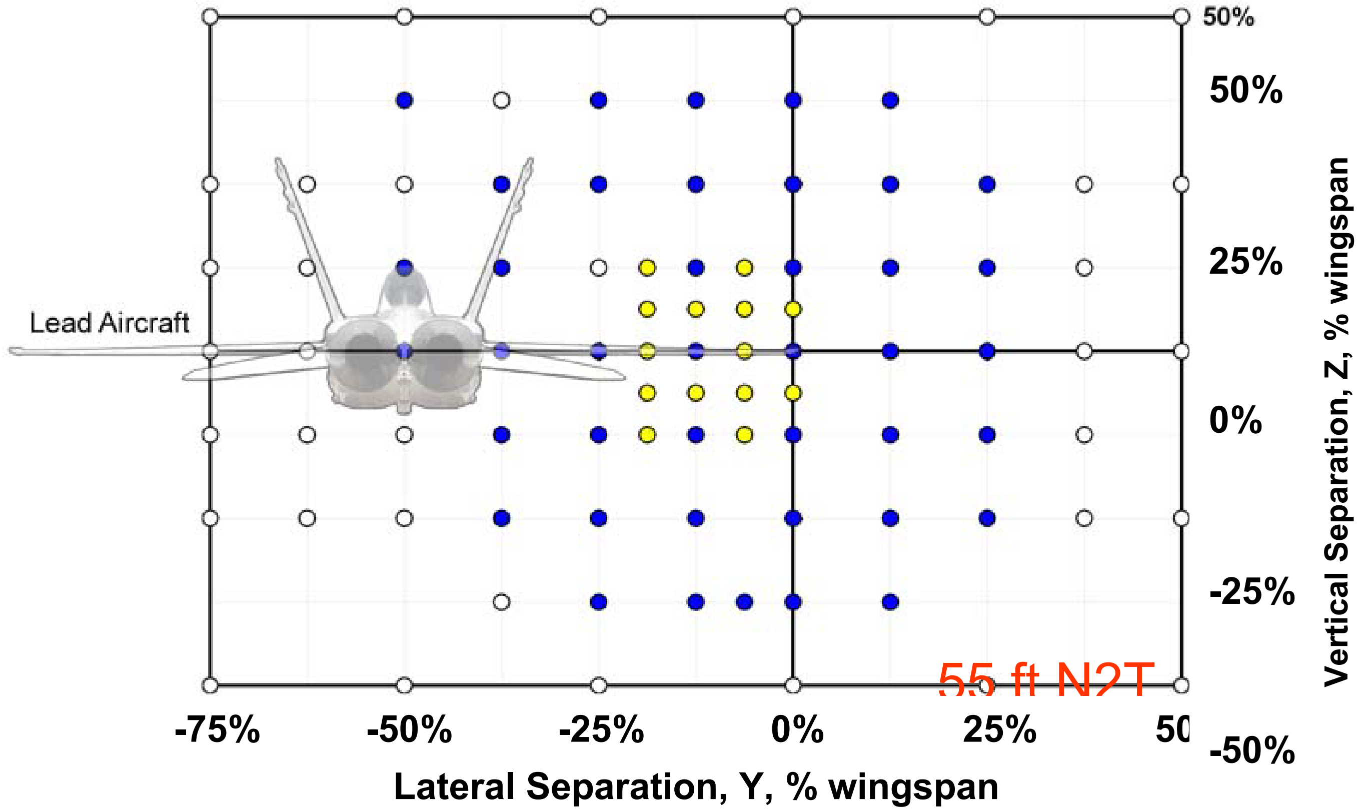
Following a video of an example test point, an explanation as to why the test point procedure was set up in this way will be given.

Flight Test Point Matrix

Condition 2	Condition 1
Mach 0.86	Mach 0.56
36,000 ft	25,000 ft



(% Wingtip Separation)



Real-time feedback in cockpit using ILS needles

N2T (X) position monitored through control room calls (no direct feedback in cockpit)

To fully map the vortex, a grid of test points, or test matrix, was created.
Several factors constrained this matrix, including:

Limited test flights available
The guidance (needle) display was limited to 60 target files.

To maximize the resolution of the vortex mapping in the most efficient manner, the matrix was based on 1/8 of an F/A-18 wingspan, or just under 5 feet.

To fully map the vortex, a grid of test points, or test matrix, was created. Because flight test time was limited, the number of matrix points had to be kept to a minimum without sacrificing the resolution of the vortex mapping. In addition, **the guidance (needle) display** used by the trailing pilot to fly each test point was **limited to 60 target files**. Designed within these boundaries, the test **matrix was based on 1/8 of an F/A-18 wingspan** (*b*F/A-18=37.5 ft), or about 4.7 ft. A grid of equally-spaced points in the Y- and Z- axis was then set up using this parameter. An example of such a grid is shown above.

Autonomous Formation Flight Test Results

Summary Of Phase 0 -February 2001

Summary Of Phase 1 -August 2001

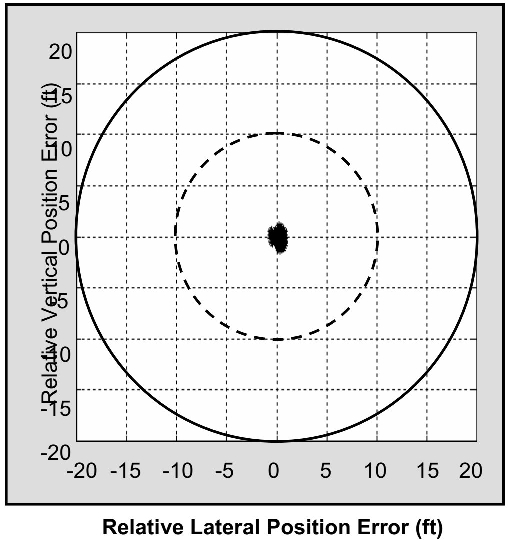
NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC01-0050-9 Date: February 21, 2001 Photo by: Jim Ross

wo F/A-18B aircraft involved in the AFF program return to base in close formation with the autonomou function disengaged.

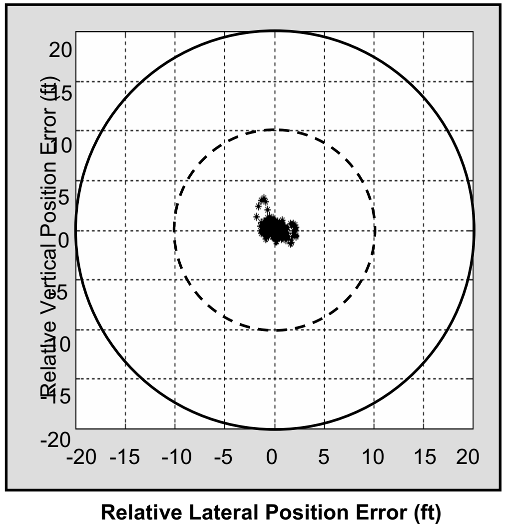
Phase 0 Control Experiment #1
Steady-State Tracking

Extremely Accurate Position Outside The Vortex Demonstrated (Winter 2001).

(Experiment: Dial In –75/-75 ft Translations)



AFF Flight 715 - February 21, 2001
2-Minute Tracking Task
High Performance Gainset



AFF Flight 714 - February 21, 2001
2-Minute Tracking Task
Integral Gainset

The additional feedback of the integral of the position error in the INTEGRAL gainset was very successful at eliminating any steady-state offsets in position error. An undesired side-effect of the integrator was larger overshoots for this gainset than for the others. However, performance and stability were still well within the acceptable region for these gains.

The HIGH PERFORMANCE gainset exhibited extremely good disturbance rejection capability. Position errors during steady-state tracking with these gains were approximately 1 foot both laterally and vertically.

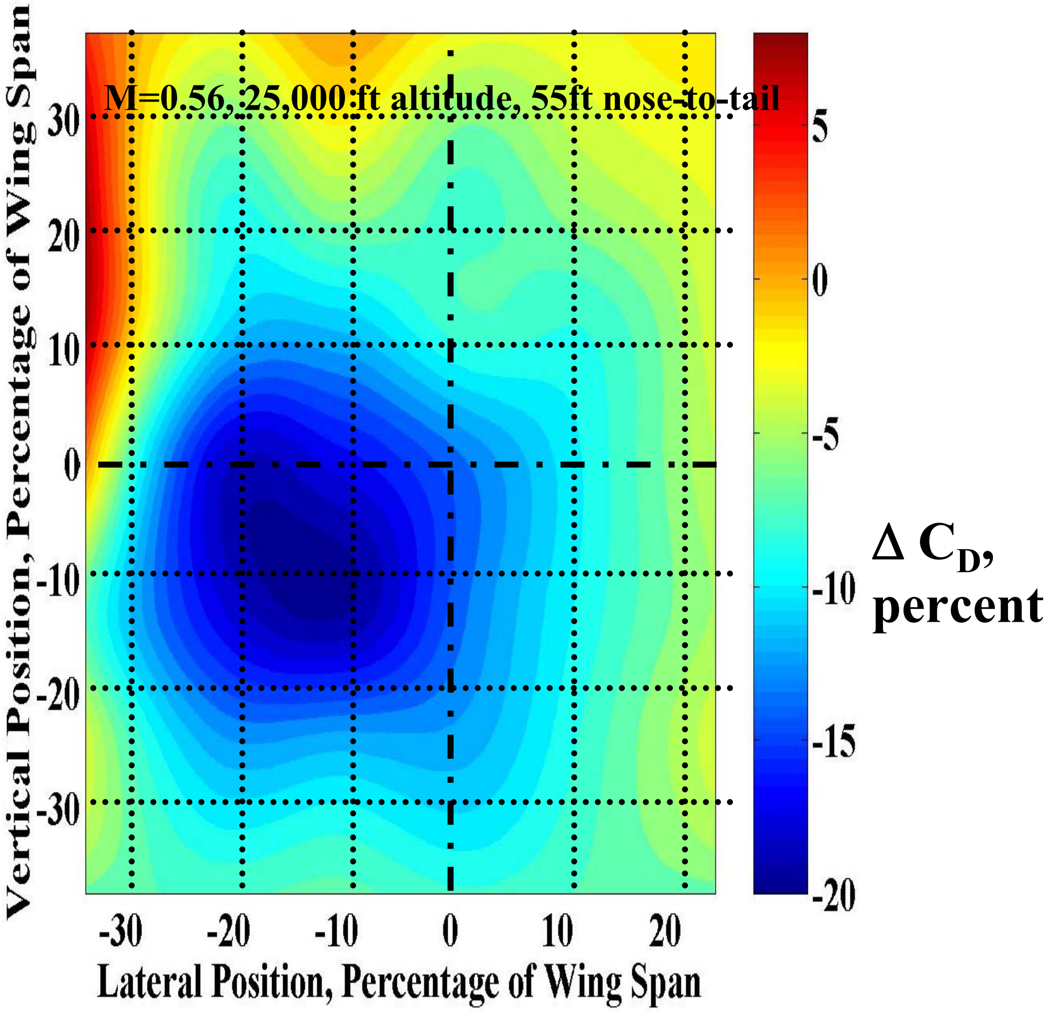
Drag Change Contour Plot

Contour plots:

- Provides a true perspective of the vortex's influence on vehicle performance

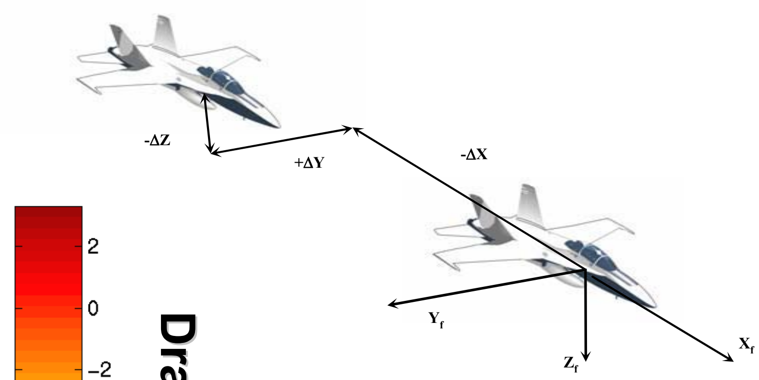
Factors:

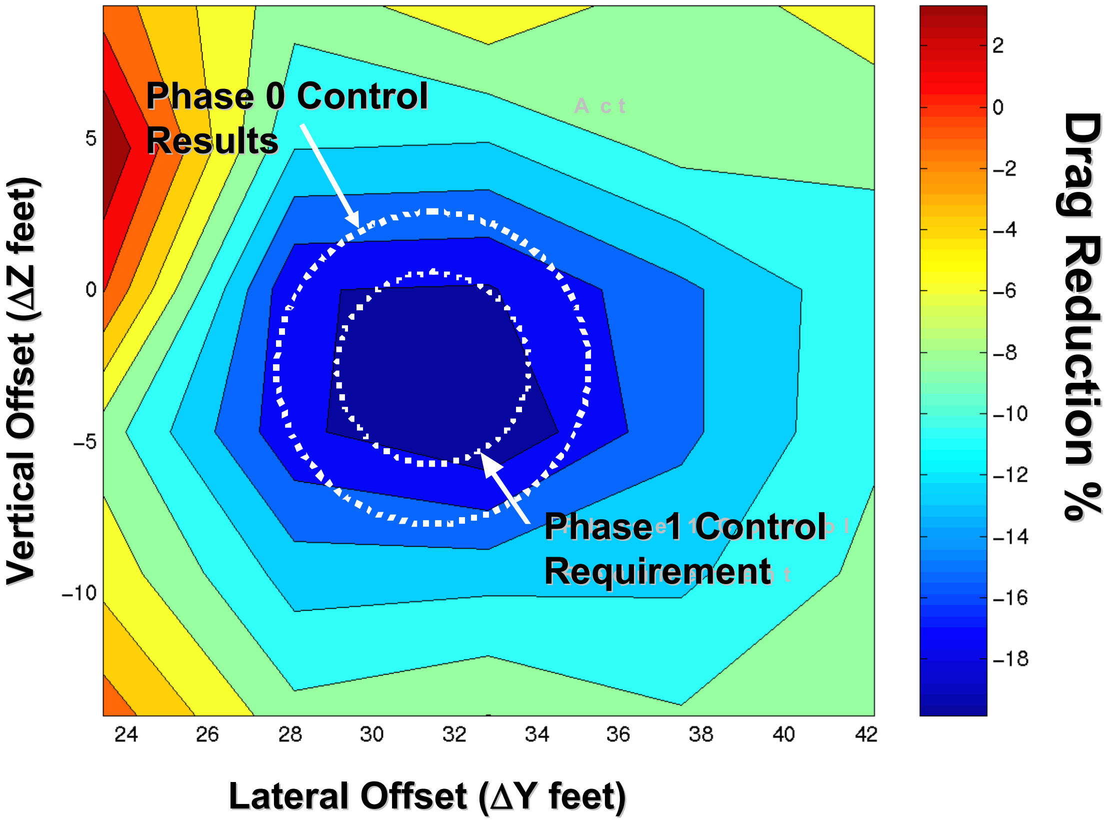
- Number of test points
- Data smoothing
  - – bicubic spline
- Extrapolation
  - – missing data points



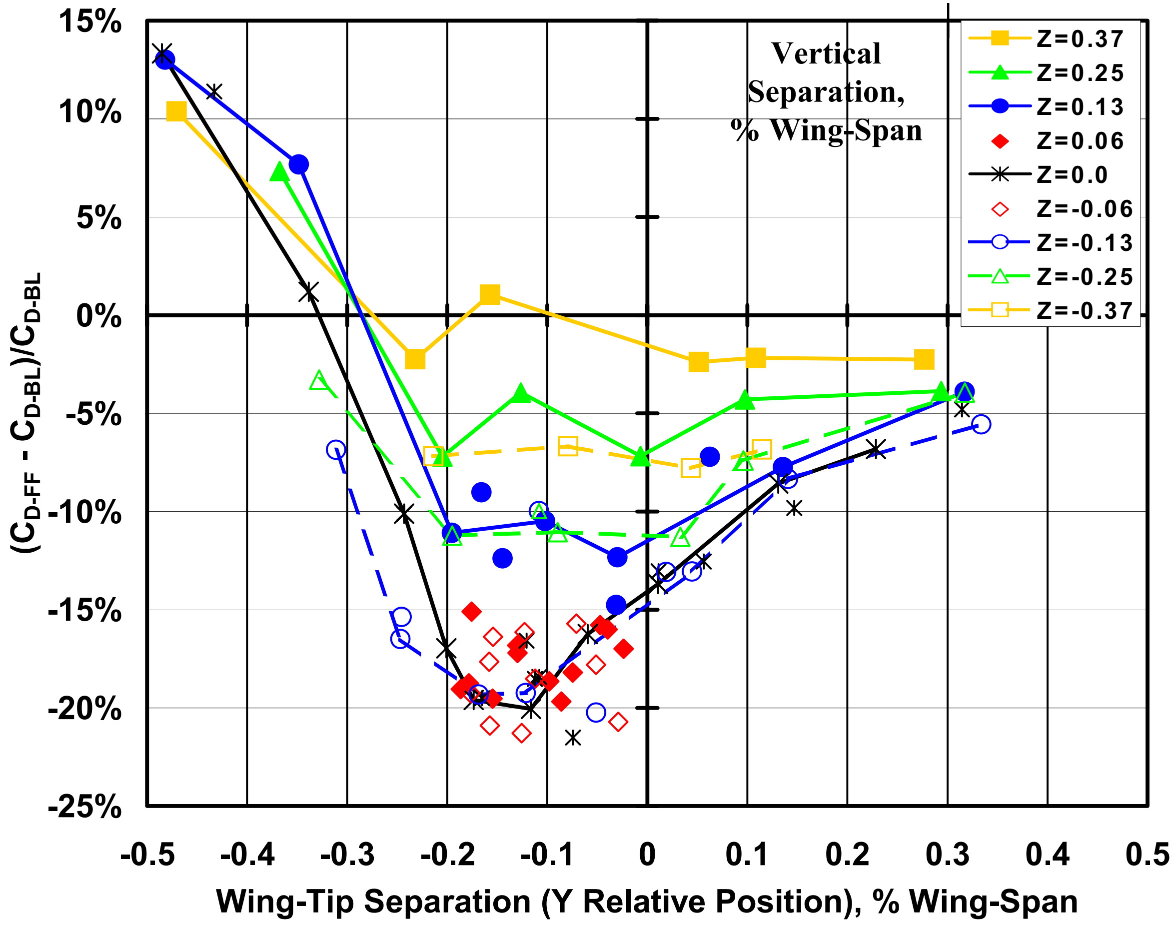
This particular contour plot (Mach 0.56, 25,000ft) contains **92 test points.**

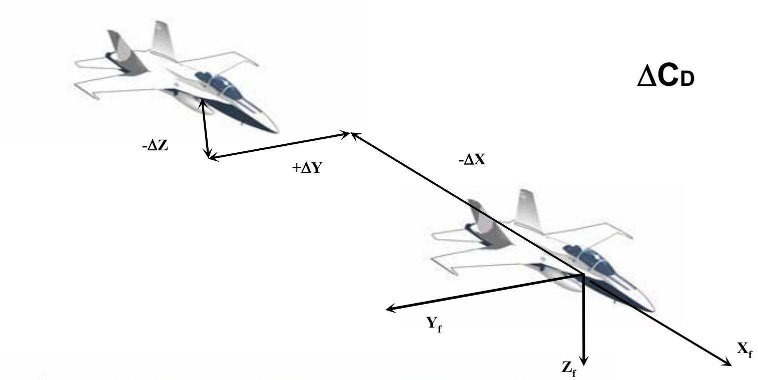
Actual Flight Test Results Validate “Drag Bucket” Theory

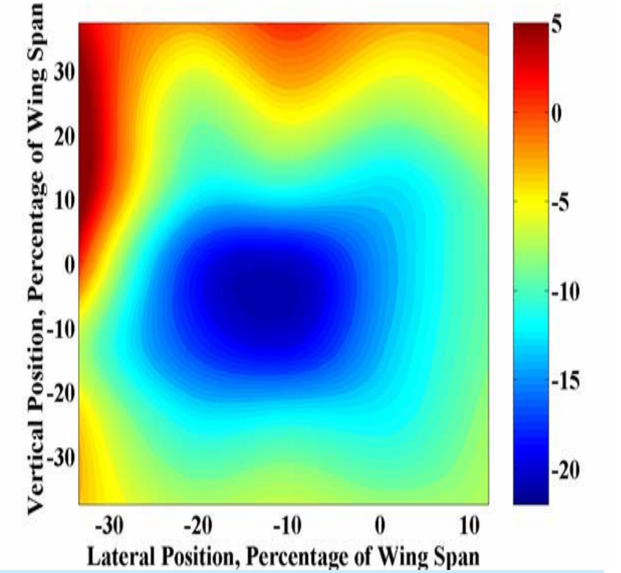




Contour Plot of Multiple Data Points







Percent change in drag versus position at M=0.56, 25,000ft, 55’ N2T

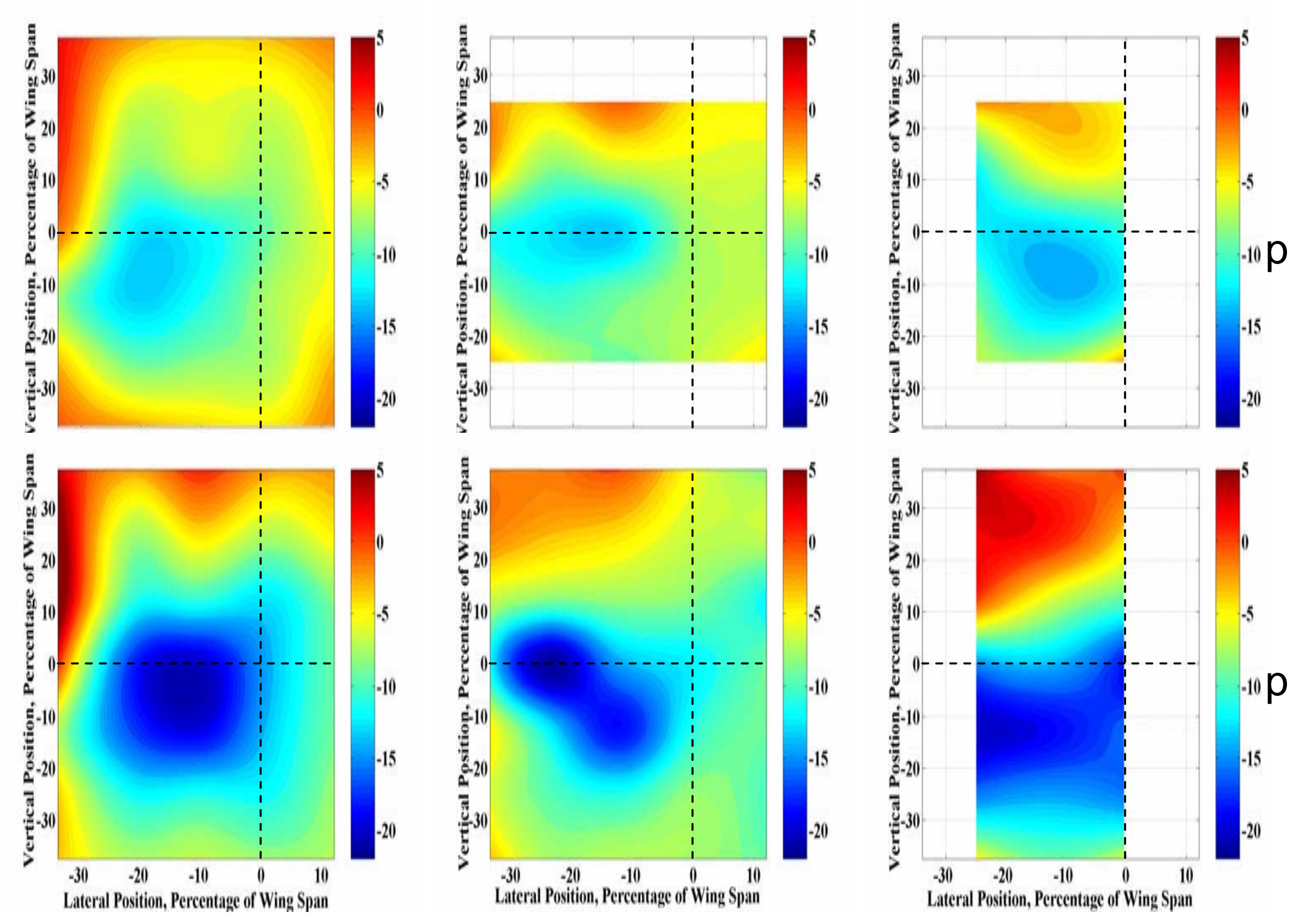
The change in lift and drag coefficient were evaluated for each maneuver by comparing drag while in the vortex to baseline values. In general very small changes (variations of less than 2%) in calculated lift coefficient were found for all conditions **as predicted**.

For the 55 feet N2T condition shown,up to 19% drag reduction was calculated with peak values between level and -13% vertical position and a lateral position of 10-20% wingtip overlap. Overall the data indicates a **large** region of significant gains. The data is not symmetric about the the peek position and shows **increased sensitivity as the trailing aircraft moved inboard of the peak position as opposed to outboard of this position.** In fact, drag increases were measured at some high wing overlap positions, verifying the importance of proper station-keeping to obtain the best results. Data quality varied for each test point with the outboard data tending to have better quality than the inboard data, primarily due to the pilots ability to maintain stable conditions. Some inboard test points were very difficult to fly due to the lead aircraft’s vortex impacting the tail or fuselage. Fortunately the region of best drag benefits was fairly stable and good data quality was obtained on most points. Atmospheric conditions also affected the data on some test points due to turbulence and vertical winds. The back-to-back comparison of vortex and baseline data helped to minimize these effects.

Total Drag

Condition 2
Mach 0.86
36,000 ft

Condition 1
Mach 0.56
25,000 ft



ΔC_D, percent

ΔC_D, percent

55 ft N2T

110 ft N2T

190 ft N2T

Compare / Contrast

- Max drag reduction 30-40% greater at Condition 1 than Condition 2
- Optimal location is relatively constant at all flight conditions and longitudinal positions
  - Optimum Position
    - $-0.20 < Y < -0.10$
    - $-0.10 < Z < 0.0$
- Drag *increases* calculated with high wing overlap
- 190 ft: Broadly distributed cross-section, poorly-defined peak
- Demonstrated that only a relatively low-precision for Y-Z positioning is required to stay within beneficial region
- More complete picture can be developed with more exhaustive study

Condition 2	Condition 1
Mach 0.86	Mach 0.56
36,000 ft	25,000 ft

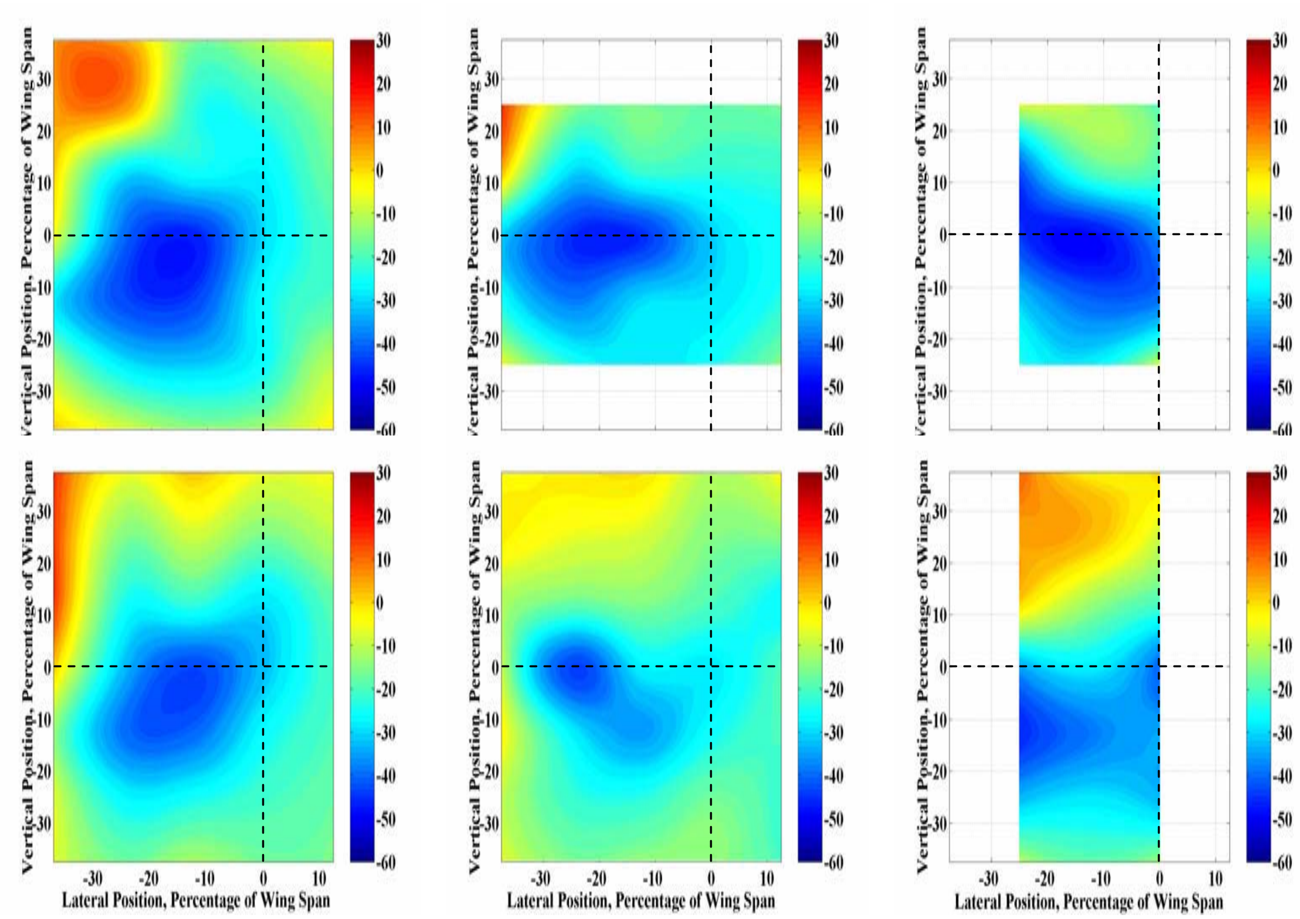
Discussion of Induced Drag

- Induced drag, $C_{Di} = C_D - C_{Do}$
  - C_{Do} obtained from wind tunnel data
- Theory predicts C_{Di} will not change with flight condition
  - Simplest form, $C_{Di} = C_L^2 / (\pi eAR)$
  - AFF data indicates *slightly* greater improvement at higher / faster flight condition with larger regions of benefit
  - Difference between flight conditions is small percentage of overall reduction -- May be a function of data quality, technique, or noise?
- Optimum position
  - Similar to C_D results
- Hoerner predicted C_{Di} reduction of 40%
  - AFF results show improvement between 40 - 50% at both flight conditions and all longitudinal positions

Induced Drag Effects More Significant at Higher Mach But Remarkably Consistent as N2T Length Increases

Condition 2
Mach 0.86
36,000 ft

Condition 1
Mach 0.56
25,000 ft



ΔC_D, percent

ΔC_D, percent

55 ft N2T

110 ft N2T

190 ft N2T

Discussion of Fuel Flow

- Results sensitive to time slice chosen
  - Throttle movement (lessened using Auto-Throttle)
    - Complete throttle cycles used
  - Atmospheric upsets
    - Changes in the lead airplane fuel flow data during a test point were used to adjust trailing airplane data
- Turbulent day - demonstrated improved C_D in the vortex, but increased fuel flow
- No data gathered at 20’ nose-to-tail separation
  - Auto-throttle technique deemed too risky at this position
- Fuel flow data tracks drag data well
  - Comparison of drag/fuel flow results adds confidence to overall data set

- Max measured reduction, over 18% from baseline

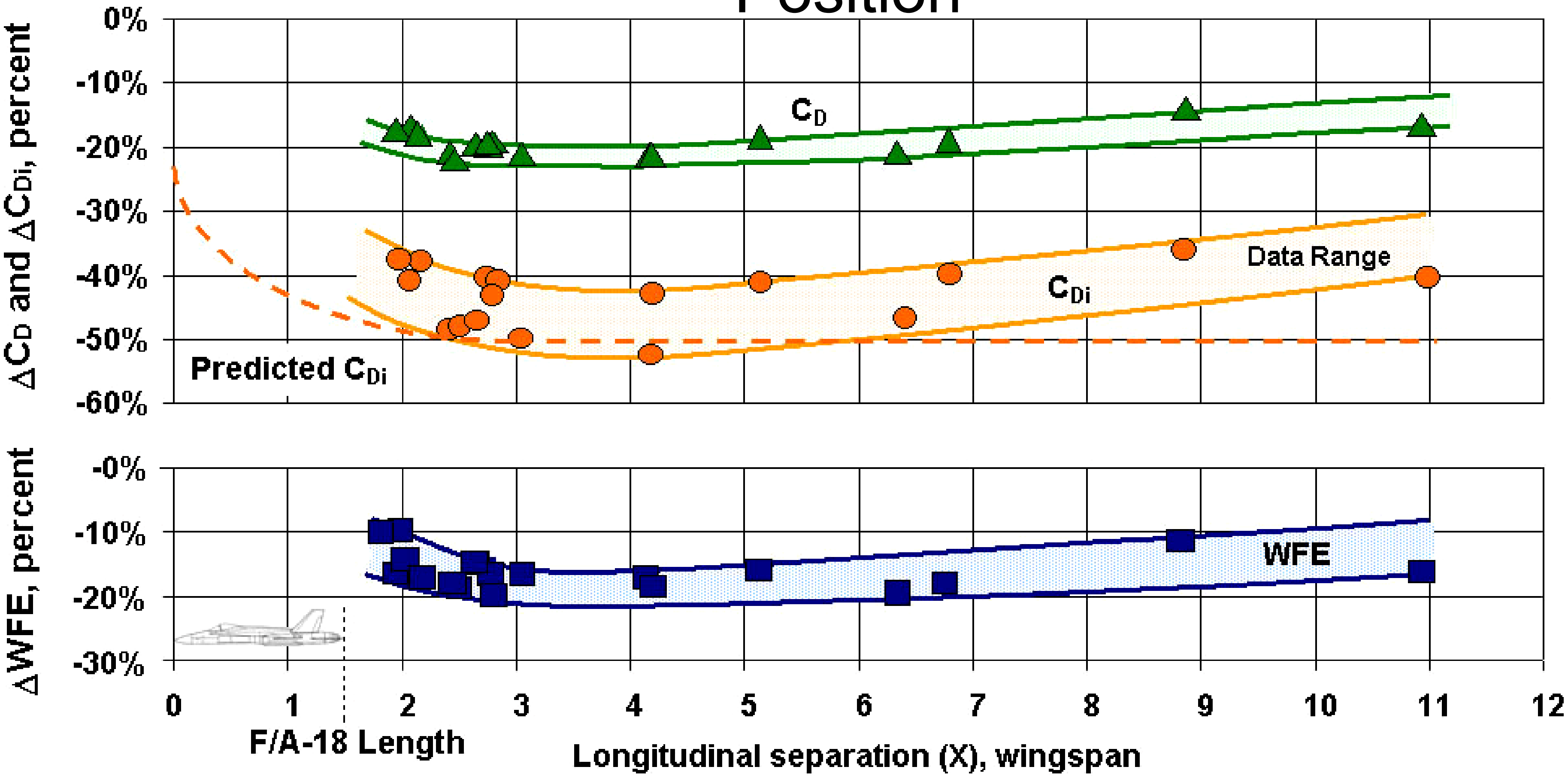
Effects of Longitudinal Separation

- Several longitudinal stations flown consecutively at the perceived “optimal” location
  - Y = -0.19 *b*
  - Z = -0.06 *b*

- Best benefits found at approximately X = 4.2 *b*, or 100 feet nose-to-tail
  - Close to predictions using horseshoe vortex model*
  - Afterwards, benefits slowly diminish, but are still significant

* *Ray, R., et. al, Flight Test Techniques Used to Evaluate Performance Benefits During Formation Flight   AIAA-2002-4492*

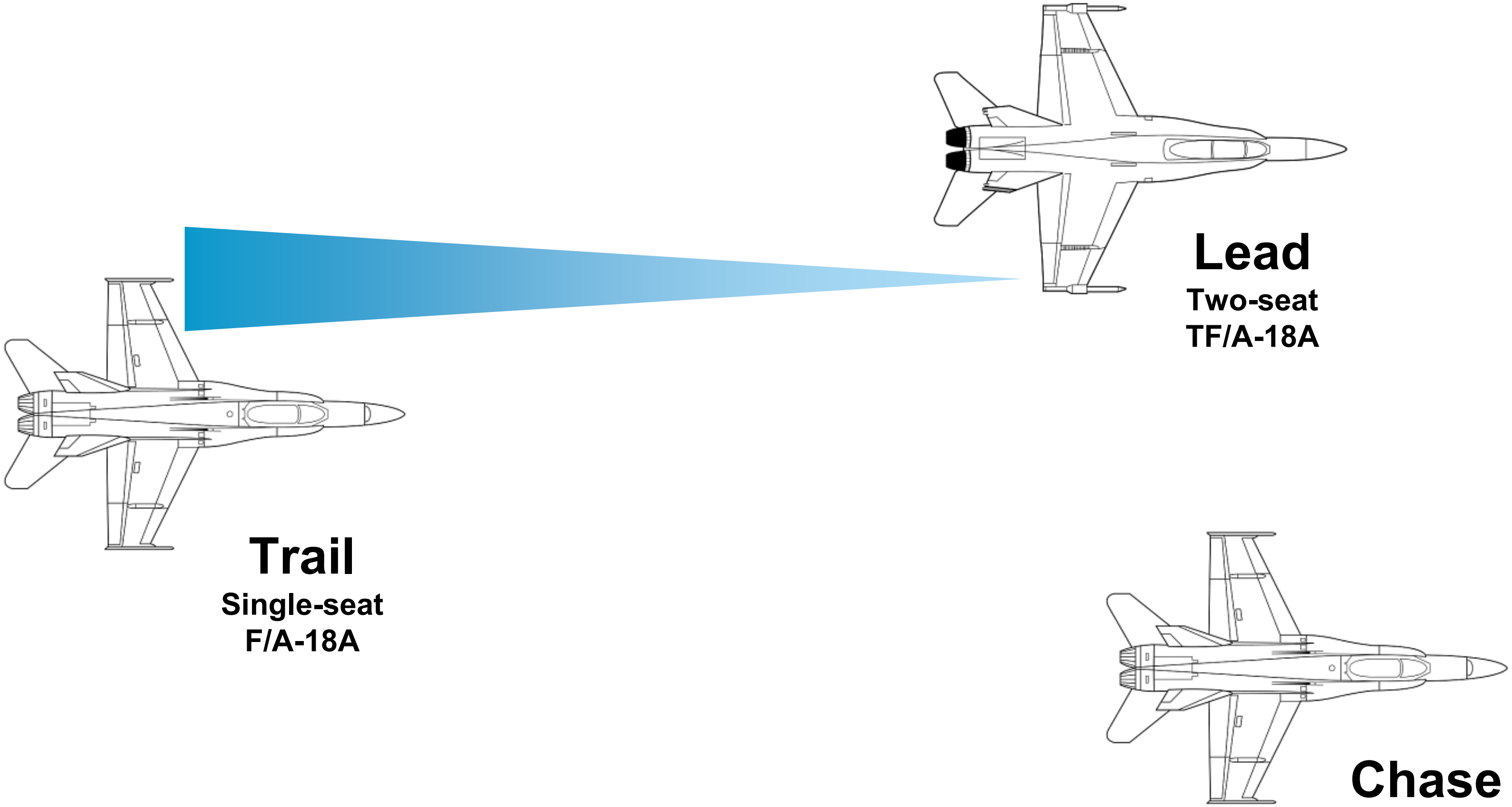
Performance as a Function of Longitudinal Position*



All data obtained at $Y = -0.19b$, $Z = -0.06b$

Data was gathered to evaluate the effect **of** longitudinal spacing on drag and fuel-flow benefits. The "optimum" lateral and vertical position (Y=-19%, Z=-6%) was flow at a series of trailing positions to obtain this data. Additional data from the matrix of data points flow previously was also used to help fill in the chart. The results show the best benefits were found at a distance of 2.7 wingspans aft (270%). This is close to the prediction shown by Blake, W., and Dieter Multhopp (AIAA-98-4343, August 1998), **which** uses the horseshoe vortex model **for a generic wing shape**. Further aft the benefits begin to diminish, but are still significant. It was also found **that** the vortex position was not as stable further aft and **seemed** to **wander** around somewhat, based on pilot **comments.** The scatter in the data seems to confirm this. The open symbols represents a test point of very poor quality. The reduction in induced drag, forward of the maximum value, is predicted by the simple model. These results show a large region of benefit as a function of downstream separation. This is good news for designers developing autonomous controllers where the engine must control longitudinal spacing. Rapid throttle movements to hold precise position could use excessive amounts of fuel. A low gain controller on the engine throttle should improve its ability to minimize fuel usage.

Last Experiment Performed On Program
X-Country Cruise Mission Formation Experiment



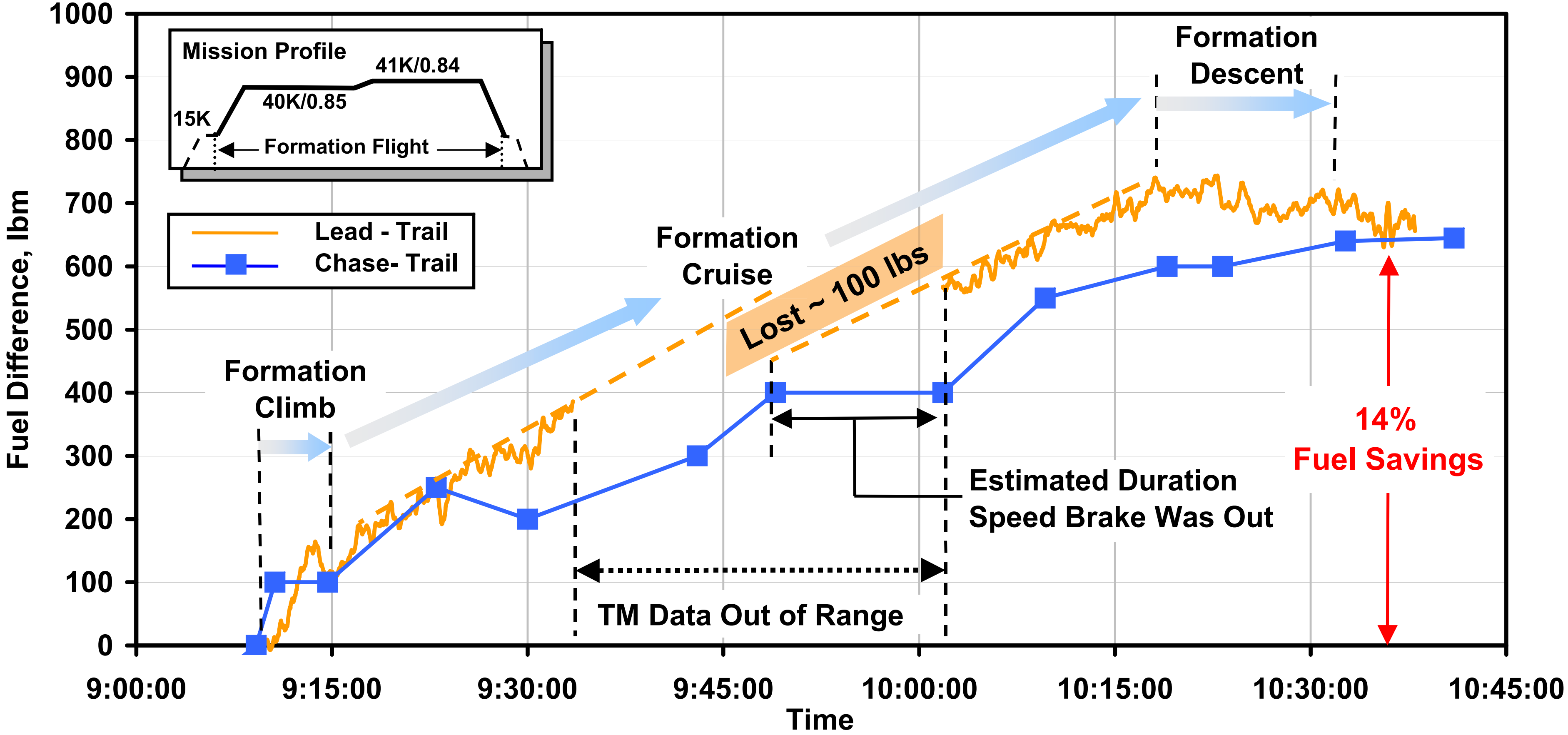
Lead
Two-seat
TF/A-18A

Trail
Single-seat
F/A-18A

Chase (Control)
Single-seat
F/A-18A

Summarize everything, then ask if there are any questions...

Cruise Mission Demonstration

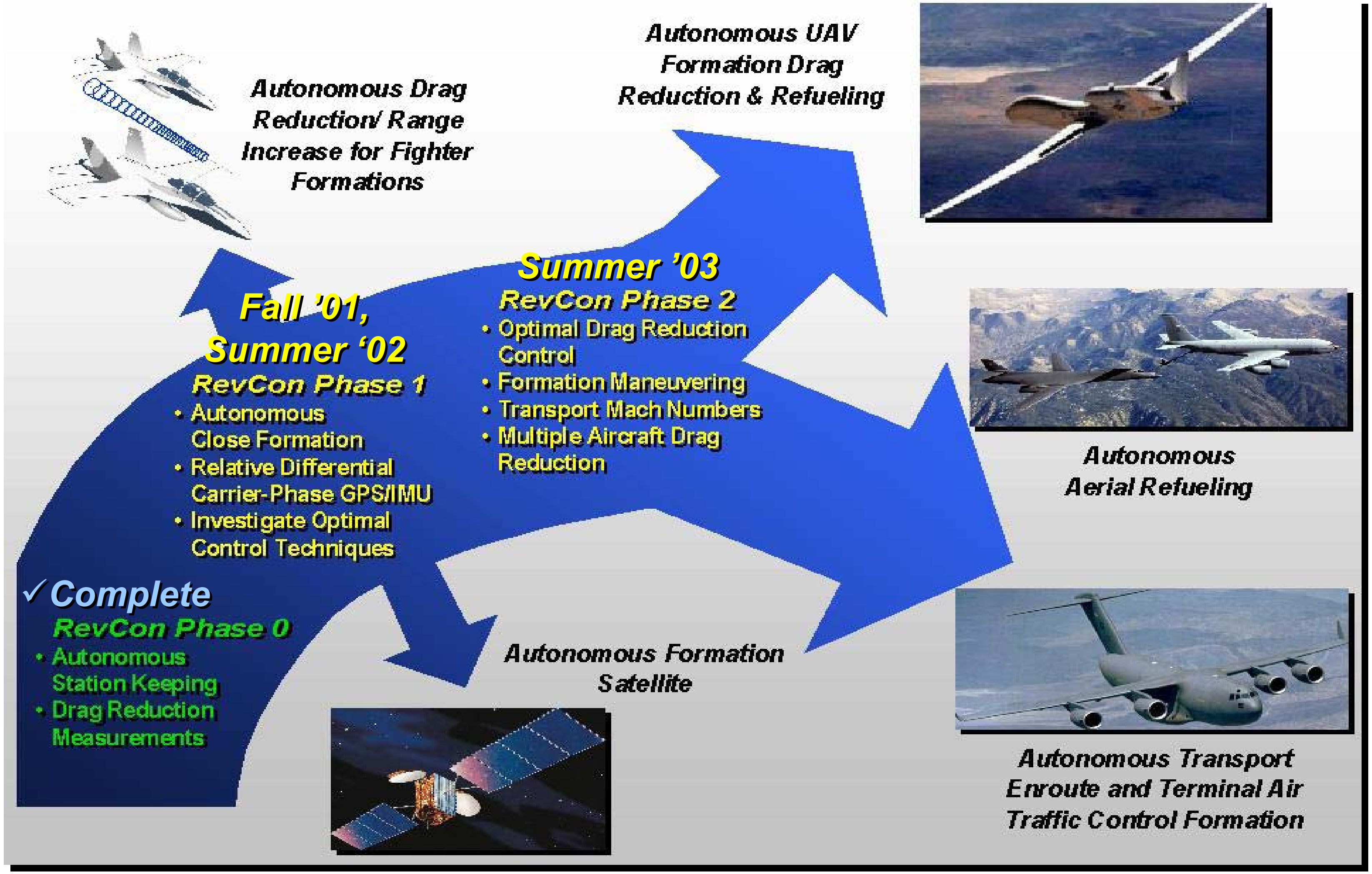


- Summary of cruise demonstration data
  - Simulated mission profile with independent chase of similar configuration
  - Estimated 110 N mi of range improvement if formation cruise continued

A simulated F/A-18 cruise mission was performed to demonstrate the potential benefits of flying in the optimum formation position during extended periods. An independent chase aircraft was also deployed during this flight to obtain fuel burn data of a F/A-18 of similar configuration and weight. Both the trailing and chase aircraft were single-seaters while the lead aircraft was a two-seater. The independent chase had no data acquisition system installed. Fuel tank readings for all aircraft were recorded periodically during the mission as plotted above with the telemetry data from the two formation aircraft.

The results show significant fuel savings were recorded for the trail aircraft despite problems with the mission. Telemetry data was lost during the mission (as expected) because the aircraft flew out of telemetry range to accomplish the mission. When TM was reestablished it was discovered the speed brake was partially deployed on the trailing aircraft. That was corrected for the remainder of the mission, however it is estimated approximately 100 lbs of fuel savings were not realized due to this problem. Also, the pilot in formation began to realize the guidance needles were not reading accurately as the aircraft flew further away from Edwards AFB. He continued the mission by flying by the “seat of his pants”, using the experience he had gained during the flight test program. Even with these problems, a 640lbm(14%) fuel savings was realized over the chase aircraft and over 700lbm of saving was measured compared to the lead aircraft over the duration of the formation. Independent checks of the fuel required to fill-up each aircraft verified these readings to within 50lbs.

AFF Roadmap



Autonomous Drag Reduction/ Range Increase for Fighter Formations

Autonomous UAV Formation Drag Reduction & Refueling

Fall '01, Summer '02

RevCon Phase 1

- Autonomous Close Formation
- Relative Differential Carrier-Phase GPS/IMU
- Investigate Optimal Control Techniques

Summer '03

RevCon Phase 2

- Optimal Drag Reduction Control
- Formation Maneuvering
- Transport Mach Numbers
- Multiple Aircraft Drag Reduction

✓***Complete***

RevCon Phase 0

- Autonomous Station Keeping
- Drag Reduction Measurements

Autonomous Formation Satellite

Autonomous Aerial Refueling

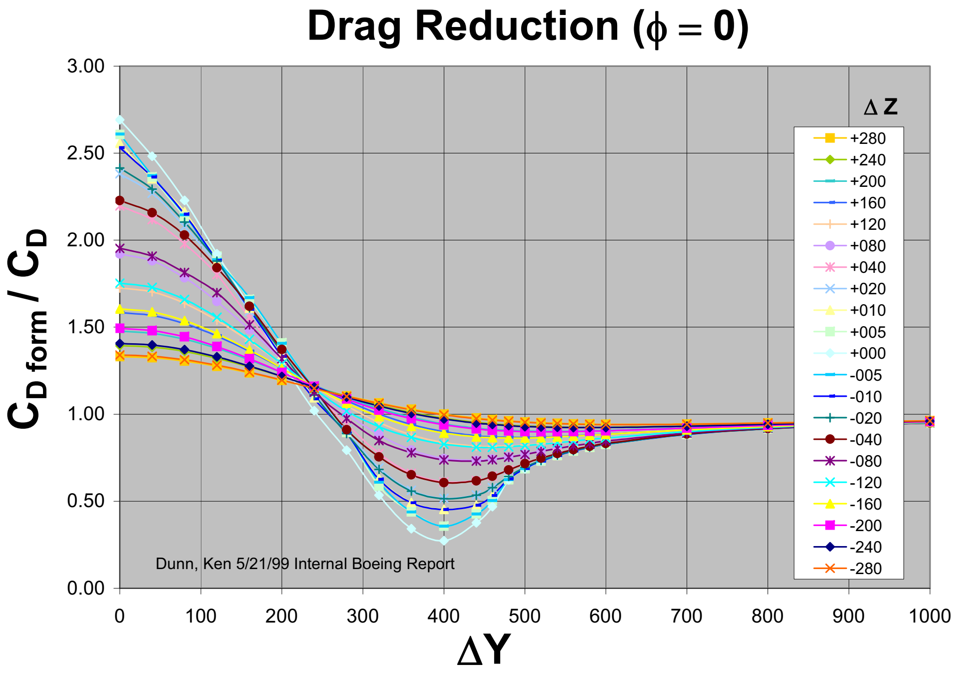
Autonomous Transport Enroute and Terminal Air Traffic Control Formation

The objectives of the initial phase (Phase 0) of AFF research were to reduce the programmatic risks for achieving automated drag reduction. Four potential risk areas were identified, the primary of which was guidance, navigation and control. Information was sought regarding the feasibility of using the Global Positioning System (GPS) for formation navigation and the achievable control precision of an outer-loop autopilot. In addition, flight data was collected to be used to validate and improve the project's design tools. Other areas of concern were aerodynamics, flight systems and flight operations. Measurements of the effects of the vortex were collected during piloted drag reduction tests to compare with simulation vortex models. Much of the systems integration effort required for the autonomous drag reduction tests was accomplished and tested during the Phase 0 program. In addition, experience was gained by the entire project that will aid in the flight test planning of future experiments.

Roadmap Charts –1
Performance Seeking Control

“Drag Bucket” Hypothesis Is An Ideal Application For Performance Seeking Control

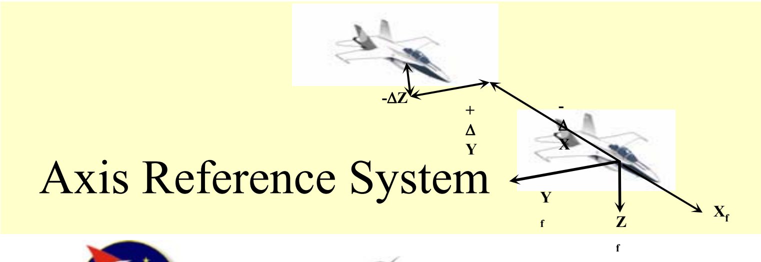
Peak-seeking control uses nonlinear and adaptive techniques to estimate and optimize a performance measure.



- Hypothesis validated by CFD results, linear theory

- Incremental force and moment coefficients function of
  - -lateral separation
  - -vertical separation
  - -relative bank
  - -lead A/C lift coefficient

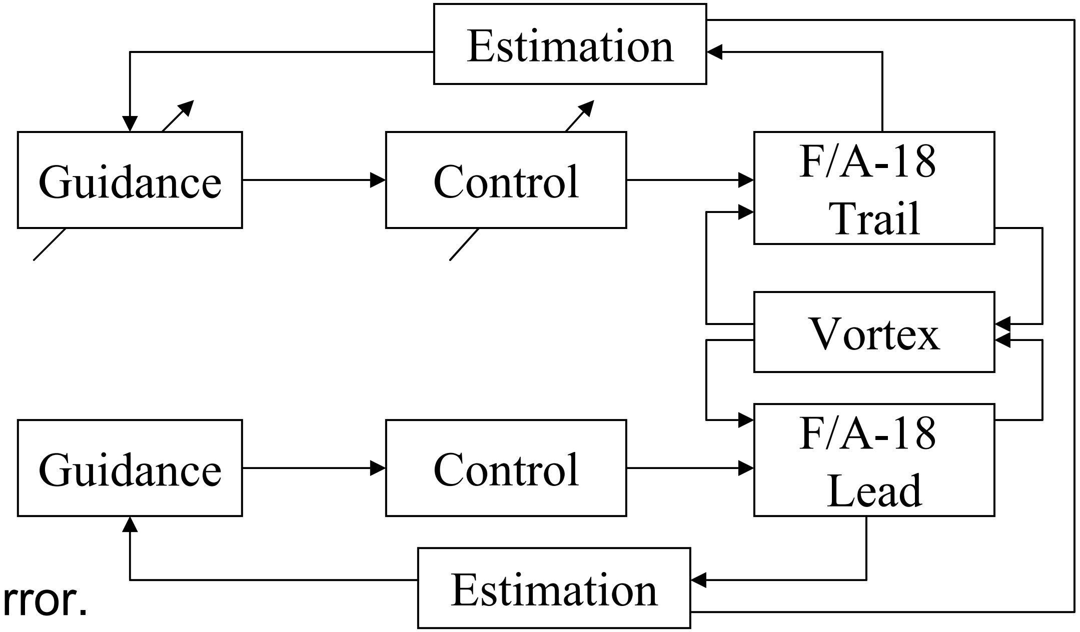
- Peak drag reduction near “sweet spot”
  - •400 in laterally
  - •level flight
  - •same altitude


Axis Reference System

Formation Flight Control

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC01-0050-17 Date: February 21, 2001 Photo by: Lori Losey
Two F/A-18B aircraft involved in the AFF program return to base in close formation with the autonomous function disengaged.

- Peak-Seeking control adjusts control commands adaptively to minimize drag and reduce throttle usage.



- Vortex is unknown nonlinear coupling.
- Theory is still limited.
- Key design trade off is ‘persistent excitation’ vs. tracking error.
- Adaptive leader commands allow cooperation.

Roadmap Charts –2
Autonomous Aerial Refueling Concepts

Leader-Follower Guidance Can Be Directly Applied To Aerial Refueling Tasks

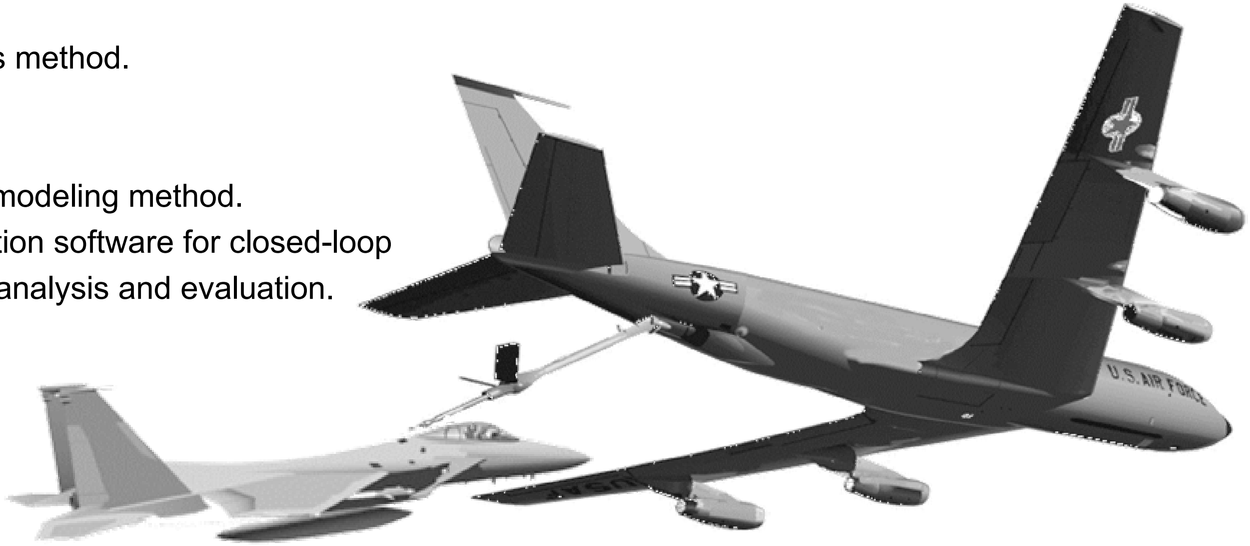
Concept Analogous To Piloted Formation Flight.

GPS/IMU Located Onboard Leader (tanker) and follower.

Boom dynamics & position translated onboard leader and transmitted to follower

Follower Aircraft Tracks Position of Refueling Boom And Tanker

- **Guidance**
  - leverage AFF guidance SW / HW.
  - fuse differential GPS with optical/radar based sensors.
- **Control**
  - leverage AFF controls method.
  - improvements.
- **Simulation**
  - leverage AFF vortex modeling method.
  - develop batch simulation software for closed-loop system performance analysis and evaluation.



Conclusions

- Dramatic Demonstration of Relative Positioning/Control
- Accurate In-Flight Wake Field Vortex Mapping
- Maximum Reductions
  - Drag, up to 22%, calculated at Condition 1 for longitudinal separations of X=3.0 and 4.4
  - Total fuel flow, over 18%

- Optimum Positioning
  - $X = 4.2$ b (nose-to-nose)
  - $-0.20 < Y < -0.10$ b
  - $-0.13 < Z < 0.0$ b
  - ‘Sweet Spot’ is larger than predicted (18 ft^2)
    - Region with > 25% C_{Di} or >10% C_D reduction
  - Optimum Position matches location of max rolling moment
  - Favorable effects degrade gradually with increased N2T distances after peaking at 3 span lengths aft