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Lift-loss due to the Presence of Anti-icing Fluid on a Falcon 20 Aircraft in Out-of-Ground Effect Conditions

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M. Bastian and K. Hui

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16. Abstract

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The fluids tested in the experiment were undiluted ethylene glycol-based Type I deicing fluid, and both ethylene and propylene glycol-based Type IV anti-icing fluids. Two fluid application combinations were tested on the aircraft: Type IV over Type I, and Type IV only.

Flight test results showed that both fluid combinations produced similar results. At the point of aircraft rotation, most of the fluid had shed from the wings, leaving only a very thin residual film over the entire wing area. The residual anti-icing fluid film caused an average lift loss of 4.1 percent as compared to the clean wing configuration. There was no significant difference in the lift performance penalties associated with either the ethylene or propylene glycol fluids tested.

Two further test series are recommended:

1) Investigation of anti-icing fluids containing varying amounts of frozen precipitation;

2) Anti-icing fluid effects on different aircraft and wing types.

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16. Résumé

La performance au décollage d'un avion, lorsque ses ailes sont revêtues de liquides de dégivrage ou antigivrage, a été déterminée à partir des données recueillies lors d'essais en vol mettant en jeu un avion Falcon 20, réalisés en février 2002 et en février 2003. Ces essais s'inscrivaient dans un programme de recherche mené conjointement par le Centre de développement des transports de Transports Canada et le Laboratoire de recherche en vol du Conseil national de recherches Canada.

Trois liquides ont été utilisés, soit du liquide de dégivrage de type I à base d'éthylène glycol, non dilué, et deux liquides antigivrage de type IV à base, l'un d'éthylène glycol et l'autre, de propylène glycol. Deux modalités d'application des fluides ont été mises à l'essai : type IV sur type I, et type IV seulement.

Les essais en vol ont révélé que les deux modalités d'application des fluides donnent des résultats semblables. Au moment du cabrage de l'avion, la plupart du liquide avait été chassé des ailes. Il n'y restait, de fait, qu'une pellicule très mince, qui couvrait toute l'aile. La présence de cette pellicule résiduelle de liquide antigivrage a entraîné une perte de portance moyenne de 4,1 p. 100, comparativement à la portance d'une aile propre. Aucune différence significative n'a été constatée dans les pertes de portance associées aux liquides à base d'éthylène glycol et de propylène glycol mis à l'essai.

Deux autres séries d'essais sont recommandées :

1) étude de liquides antigivrage présentant divers degrés de contamination par des précipitations gelées;

2) effets des liquides antigivrage sur différents modèles d'avions et types d'ailes.

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Two further test series are recommended:

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2) Anti-icing fluid effects on different aircraft and wing types.

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1.0 Introduction

1.1 Background

For the past number of years, Transport Canada, through its Transportation Development Centre (TDC), and National Research Council Canada (NRC) have together conducted a considerable amount of study in the area of aircraft performance during winter operations. This is a direct outcome from the Commission of Inquiry into the Dryden, Ontario, crash of a Fokker F28 during a winter storm in 1989. One of the areas of study has been that of aircraft performance as it relates to aircraft de/anti-icing fluids.

Wind tunnel studies have been conducted in the past (see reference 1); however, these were done using a scaled wing section, and the airspeeds achieved were below jet aircraft rotation speeds. The difficulty of using de/anti-icing fluids in wind tunnel work is the issue of scalability. While wing sections and airspeeds can be scaled to achieve appropriate Reynolds numbers, the fluid thickness and fluid viscosity cannot be scaled accordingly; hence, the need to conduct full-scale testing on an aircraft.

1.2 Objectives

The primary objective of this program was to measure aircraft lift-loss due to the presence of anti-icing fluids on the wings of an aircraft. Secondary objectives included quantification of fluid levels and thickness distribution across and along the wings after application, fluid loss while taxiing the aircraft prior to takeoff, and determination of the fluid shedding characteristics during the takeoff roll.

1.3 Scope

This report covers those aspects of the program as they relate to determination of the aircraft lift-loss. Other aspects of the program are covered in a report prepared by APS Aviation for TDC (see reference 2 and 3).

This test program is expected to extend over three years, two of which have been completed. In the first two years, baseline conditions were established for the clean aircraft and for the wing covered with undiluted de/anti-icing fluids. For future testing, it is intended to measure lift-loss for different degrees of fluid contamination. This report presents the results for the baseline tests conducted during the February 2002 and February 2003 time frames. A separate report will be published for any future testing done with contaminated de/anti-icing fluids.

2.0 Test Equipment and Support Personnel

The test equipment and support personnel consisted of the Falcon 20 aircraft and crew, Globe Ground deicing facilities and personnel, Transport Canada representatives, and APS Aviation crew.

2.1 Test Aircraft

The test aircraft was a Dassault Falcon 20D, MSN 109, tail number C-FIGD, fitted with two CF700-2D-2 engines. All aircraft tests were performed in the takeoff configuration: flap position of 15°, air brakes not extended, and the landing gear down. The wing has a span of 53.5 ft. and is equipped with a wing fence 9 ft. outboard from the fuselage. Inboard of the wing fence the aircraft has a fixed leading edge, and outboard of the wing fence the leading edge droops forward for all non-zero flap settings. Prior to each intensive test period the aircraft wing was washed.

For the purposes of these tests, a Litton 92 Inertial Reference System (IRS) was installed and integrated into the standard aircraft data acquisition system. The data system collected data at an update rate of 32 Hz. The following is a list of all the critical parameters recorded, followed by a brief description.

Time,	GPS time (seconds)
Pdc,	Dynamic pressure, corrected (mb)
Psc,	Static pressure, corrected (mb)
Alpha,	Angle of attack (degrees)
Beta,	Angle of side slip (degrees)
Balt,	Barometric altimeter (ft)
Mach,	Mach number
Tas,	True airspeed (kn)
Ts,	Static temperature (degrees C)
Epr L,	Left engine pressure ratio
Epr R,	Right engine pressure ratio
Heading,	Heading (degrees, true)
Roll,	Roll angle (degrees)
Pitch,	Pitch angle (degrees)
P,	Roll rate (degrees/sec)
Q,	Pitch rate (degrees/sec)
R,	Yaw rate (degrees/sec)
Ax,	Longitudinal acceleration (g)
Ay,	Lateral acceleration (g)
Az,	Vertical acceleration (g)
Gs,	Ground speed (kn)
Track,	Ground track angle (degrees)

V spd,	Vertical speed (ft/min)
Lat,	Latitude (degrees)
Lon,	Longitude (degrees)
Height,	Earth ellipsoid height (ft)

In addition to parameters recorded on the data acquisition system, the aircraft zero fuel weight, fuel weight, tower winds, and the atmospheric pressure altimeter setting were hand recorded for each test run.

2.2 Ground Equipment

For year 1 of the program, the tests were conducted at the central deicing facilities of the Ottawa Macdonald Cartier International Airport. This required the use of Globe Ground deicing trucks for application of the anti-icing fluids. For year 2 of the program, the tests were conducted at the NRC ramp facilities. APS Aviation Ltd. arranged for the appropriate environmental assessment that allowed this work to be conducted away from the central deicing facilities. For both years, a large diesel generator provided power to run the various pumps and measuring devices.

2.3 Support Personnel

The tests required the coordination of four distinct teams: an aircraft test crew, Transport Canada observers, APS Aviation Ltd. personnel, and a Globe Ground deicing crew. The aircraft test crew consisted of two pilots, a flight test engineer, and an aircraft mechanic. The TDC observers flew on board the aircraft and made overall program decisions. The APS crew consisted of two on-board observers to videotape fluid behaviour and to perform fluid thickness measurements on the wing. Additional APS crew were needed during the application of anti-icing fluids and subsequent testing of them. When operating from the central deicing facility, a standard line crew from Globe Ground was used to apply the deicing fluid. This crew included a foreman, a truck driver, and a spray boom operator. When operating from the NRC ramp, APS personnel applied the fluids from a movable platform.

3.0 Flight Test Program

In this report there are two possible uses of the term contamination that could lead to possible confusion. The use of the term "contaminated wing" refers to any condition of the aircraft wing where the wing is not bare and dry. The contamination could be anything from water or snow, to any combination of de/anti-icing fluids.

A contaminated de/anti-icing fluid is a fluid that is no longer at its concentration of initial application. It is possible for the fluid to be contaminated through deliberate means (dilution with water) or through the absorption of natural precipitation as the fluid protects an aircraft's wing.

3.1 Test Procedures

Two series of tests were conducted over two one-week periods in February 2002 and 2003. During the first year, the tests were conducted at the central deicing facility at the MacDonald Cartier International Airport in Ottawa, Ontario. During the second year, the tests were conducted at the NRC ramp of the same airport. Ideal weather conditions for testing were considered to be overcast with no precipitation and air temperatures of -5 to -10°C. However, these ideal conditions rarely occurred during the two periods of scheduled testing. Hence, most of the tests were conducted in the early morning daylight hours, prior to the sun having any significant daytime heating effects on the aircraft wing surface and the deicing fluid. The decision to conduct testing was based on the long-term weather forecast, with a 24 hour prior "go/no-go" decision. The evening prior to testing, the aircraft was fuelled and parked outside overnight for a thorough cold-soak. This ensured that the wings and the fuel in the wings were at ambient air temperature.

Detailed descriptions of the purpose of each test along with wing conditions before and after each test are contained in references 2 and 3.

The test procedures are best described by outlining a typical timeline of events:

06:30	Briefing to review weather, coordination and the day's objectives.
07:00	Taxi aircraft to the central deicing pad and engine shutdown.
07:15	Application of de/anti-icing fluid (Types I and IV).
07:45	Measurement of: fluid thickness, air temperature, wing temperature.
08:00	Engine startup followed by an alignment of the IRS system.
08:15	Taxi to the button of the runway.
08:20	Repeat measurement of fluid thickness and wing temperatures.
08:25	Takeoff.
08:35	Landing and taxi back to deicing facilities.
08:40	Engine shutdown.

The process was then repeated until sufficient test points were measured or until daytime air or wing surface temperatures rose to above freezing.

3.2 Flight Tests

Prior to the actual anti-icing fluid-covered wing studies, a number of prior test flights were required for instrumentation shakedown and calibration. After initial installation of the Litton 92 IRS, the aircraft was placed on jacks and carefully levelled to the aircraft water line. Using the jacks, the aircraft was then tilted (to a maximum of $\pm$ 4º) in the pitch and roll axis to determine the installation mis-alignment offsets of the Litton 92 IRS axes with respect to the aircraft axis.

The aircraft radome is fitted with a four hole cruciform air data system to measure differential air pressure across the vertical and horizontal axis, from which the angles of attack and side slip are derived. This aircraft air data system required calibration for the takeoff configuration. A test flight was conducted to calibrate the air data system in the takeoff configuration using the Simultaneous Calibration of Air Data Systems (SCADS) data reductions technique (see reference 4). This technique requires the aircraft to be flown in a box pattern while conducting an acceleration/deceleration manoeuvre and a side slip sweep in relatively calm air conditions. Together with the air sensor data, pitot static data, and real-time differential GPS data, the calibration coefficients can be derived for the air data systems. The SCADS technique can only calibrate the air data system for the out of ground effect condition. For determination of the ground effect, a further test flight was performed that consisted of runway flyby manoeuvres at varying heights above the ground.

In total, 27 test flights were flown in support of this program:

- 4 instrumentation shakedown flights,
- 4 calibration flights,
- 19 anti-icing fluid applied flights.

Unfortunately, problems related to cold-soaking of the instrumentation resulted in data loss for two of the data flights, and instrument failure for one additional flight. The heating system on the aircraft operates from bleed air coming from the engines, while airborne only, and because the aircraft spent very little time airborne, the cabin and data instrumentation system became cold-soaked. This made operation of the aircraft difficult and also resulted in the data loss. In year two of the test program the cold soak of the data acquisition system issue was resolved with the use of an external gas heater.

As stated in section 2.1, the aircraft was flown in the takeoff configuration for all of the tests and left in this configuration (gear down, flap position of 15°, and takeoff power) until the aircraft reached 2000 ft. above ground level or approached the maximum flap and landing gear speeds. With the exception of Flight 2002-7, the takeoff procedure was the same for each test and was considered to be as close to "standard operating procedures" as possible. After the aircraft was positioned at the button of the runway with full brakes applied, the takeoff power was set and the brakes were released. At the rotation speed (Vr, roughly 126 kn) the aircraft was rotated to a nose up attitude of roughly 10°. After liftoff and over the roughly 40 s subsequent duration of the steady climb, the pitch attitude of the aircraft decreased slowly from 10° to 5°, and the airspeed was allowed to increase up to a maximum of 190 kn. The takeoff technique for flight 2002-7 differed from the others in that the aircraft was pre-rotated at 80 kn.

4.0 Test Results and Discussion

4.1 Analysis Methods

In this study, C_L-Alpha curves are used as the primary means by which the Falcon 20 aircraft performance is measured and evaluated. These curves are a graphical plot of the coefficient of lift (C_L) versus the angle of attack (Alpha, or α) of the aircraft. The importance of having the very best determination of C_L for the aircraft necessitated the evaluation of two different analysis methods for calculation of the coefficient of lift: a quasi-static state equation and a six degrees of freedom equation. The results from these two methods were compared for overall agreement.

The quasi-static state equation used is as follows;

$$C_L = W / q_{bar} / S * (A_x * \text{Sin}(\alpha) + A_n * \text{Cos}(\alpha) - T/W * \text{Sin}(\alpha)) \qquad (1)$$

Where:

C_L: Coefficient of lift,
W: Aircraft weight (lb),
q_{bar}: Dynamic pressure (psf),
S: Wing surface area (ft^2),
A_x: Longitudinal acceleration (fwd +, g),
A_n: Normal acceleration (up +, g),
T: Installed engine thrust (lb), and
α: Angle of attack (rad).

The six degrees of freedom equation used is a follows (Ref. 6, Eq. 3.4-4a);

$$C_L = (d\alpha/dt + Q - \tan(\beta) * (P * \text{Cos}(\alpha) + R * \text{Sin}(\alpha)) + g / V * (\text{Cos}(\phi) * \text{Cos}(\theta) * \text{Cos}(\alpha) + \text{Sin}(\theta) * \text{Sin}(\alpha)) - T / V / m * \text{Sin}(\alpha)) * m * V / q_{bar} / S \qquad (2)$$

Where:

C_L:	Coefficient of lift,
$d\alpha/dt$:	Time derivative of alpha (alpha-dot, rad/s),
P, Q, R:	Aircraft body rates of roll, pitch, and yaw (rad/s),
α, β:	Angle of attack and side slip (rad),
θ, ϕ:	Aircraft pitch and roll angle (rad),
g:	Gravitational constant (32.174 ft/s^2),
V:	True airspeed (ft/s),
m:	Aircraft mass (w/g, slugs),
q_{bar}:	Dynamic pressure (psf), and
S:	Wing surface area (ft^2).

For both of these equations, the same aircraft engine thrust model was used and consisted of table-look-up data supplied from the engine manufacturer (see reference 7). The table-look-up parameters consisted of barometric height, Mach number, and engine pressure ratio (EPR) setting. A linear interpolation scheme was used to obtain values lying between table entries. The thrust line vector was assumed to be parallel to the aircraft body axis and an installed efficiency of 96 percent was assumed. Both of these assumptions have been shown to be valid over many test programs.

All of the data was carefully analyzed and processed so as to eliminate any data spikes, instrument sensor lags and/or data transportation lags.

The analytical approach used in this report develops the total aircraft C_L versus angle of attack and does not consider the incremental variations of the C_L-α curve due to stabilizer position or elevator position. The procedures used during the tests were fairly uniform, minimizing the variation of the center of gravity position during the tests; however, this could account for some level of data scatter in the results.

4.2 Quasi-Static State Versus Six Degrees of Freedom Equation

The quasi-static state equation results were compared with those derived from the six degrees of freedom equations to ensure overall agreement and to determine which of the two should be used for final data reduction.

A typical takeoff case was selected for comparison of the two equations used. Figure 1 compares the computed C_L results using the equations for the quasi-static determination of C_L and the six degrees of freedom determination of C_L. Figure 2 shows these same two graphs plotted one on top of the other for better comparison.

From these graphs, it is evident that the two equations yield the same average results; however, the data analyzed using the six degrees of freedom equation (6-DOF) contains more scatter. The primary term driving the 6-DOF equation is the $d\alpha/dt$ (Alpha-dot) term and it is this term that introduces the noise shown in the traces of Figures 1 and 2, despite a 2 second boxcar smoothing filter applied to this term. In addition, the flight segment of interest is after the establishment of the takeoff angle of attack, where the $d\alpha/dt$ term is very small. Therefore, it was determined that the quasi-static equation yielded smooth and accurate results and should be used in subsequent data analysis.

4.3 Instrumentation Calibration Results

The instrumentation suite installed in the aircraft for this test program required a number of calibrations to be performed.

The Litton 92 Inertial Reference System was installed on a pallet and strapped down to the seat rails over the centre of gravity of the aircraft. The aircraft was then placed on jacks and levelled to the water line marks. Using the jacks, the aircraft was tilted through a number of pitch and roll angles (± 4 degrees). From these static measurements the installation mis-alignment offsets were determined and found to be:

Pitch axis: 0.14 (deg),
Roll axis: -0.25 (deg), and
Yaw axis: 1.14 (deg).

The air data systems of the aircraft were calibrated using the SCADS technique (see reference 4).

The position error correction for the pitot static system was found to be:

$$P_{ec} = 1.21 - 0.01053 * P_d, \quad (3)$$
$$P_{dc} = P_d + P_{ec}, \text{ and} \quad (4)$$
$$P_{sc} = P_s - P_{ec}. \quad (5)$$

Where:

P_d:	dynamic or total pressure (mb)
P_s:	static pressure (mb)
P_{ec}:	position error correction (mb)
P_{dc}:	dynamic or total pressure, corrected (mb)
P_{sc}:	static pressure, corrected (mb)

The angle of attack and side slip were calculated as follows:

$$Alpha = 13.74 * P_{alpha} / P_d + 5.83 \text{ and} \quad (6)$$

$$\text{Beta} = -16.04 * P_{beta} / P_d + 0.03. \quad (7)$$

Where:

P_d:	dynamic or total pressure (mb)
P_{alpha}:	differential vertical pressure measure across radome (mb)
P_{beta}:	differential horizontal pressure measure across radome (mb)
Alpha:	Angle of attack (deg)
Beta:	Angle of sideslip (deg)

Two ground effect calibrations flights were flown. Due to conflicting aircraft traffic on the first flight, the nonactive runway was used, which led to a high cross wind component during testing. The results from this flight were inconclusive, having a scatter of 0.5° error in Alpha and showing no correlation with aircraft height. A second ground effect calibration flight was flown in calmer wind conditions; however, this flight too showed an inconclusive Alpha correction. The ground effect calibration flights did show a correlation with the coefficient of lift and height above the ground but did not fit well with typical aircraft ground effect results. Hence, it was determined not to apply any ground effect corrections to the data. Furthermore, the ground effect phenomenon was deemed to be sufficiently complex as to merit a separate study in itself and this portion of the flight profile was not used in subsequent data analysis. The selection criteria used to determine the out-of-ground effect portion of the flight profile is shown in Figure 3.

4.4 Clean Wing and De/Anti-icing Fluid-Covered Wing Results

In total, 28 takeoffs were performed in support of the program. All takeoffs were done in the standard takeoff configuration, which consists of a flap setting of 15º and maintaining the landing gear in the extended position. The results from these takeoffs are presented in Figures 4 through 34. Of these, 11 takeoffs were performed with a clean dry wing (Figures 4 to 14), 11 with ethylene glycol applied to the wing (Figures 15 to 25), and 9 with propylene glycol applied to the wings (Figures 26 to 34). For three of the takeoffs the data was lost due to instrument failure (Flights 2002-11, 2002-12, and 2003-13). On each of the graphs a least squares straight line curve was fit to the data, with the resulting coefficients shown in the upper left of the graph. As noted in section 4.3, these graphs do not include that portion of the takeoff profile where the aircraft is in ground effect. The horizontal axis plots the angle of attack (Alpha) of the aircraft and the vertical axis plots the coefficient of lift (C_L). In the time domain the graph reads right to left, where the larger values on the right represent those immediately after liftoff and the lower values on the left represent those at the end of the test run.

A close inspection of the clean wing results (Figures 4 to 14) reveals an anomaly in the data. This becomes very evident when the best straight line fits are compared with each other (shown in Figure 35). Of the 11 takeoffs shown, three of these lie outside the predominant grouping or cluster (Flight 2002-3, 2002-13, and 2003-12). It is unclear as to why these three takeoff results differ from the others. There are a large number of inputs that go into the calculation of both the coefficient of lift and the angle of attack, as presented in section 4.1. Each of the data sources has been carefully investigated with no clear conclusion reached. It is inconceivable that the performance of a clean aircraft actually changed over time as these graphs suggest. Moreover, if these anomalous results were used as the baseline, the contaminated wing lift-losses calculated would be in excess of 10 percent! One must therefore suspect a basic instrumentation misalignment, such as an installation misalignment of the LTN-92 or an Alpha pitot blockage causing a large bias. Unfortunately these possible error sources cannot be investigated post experiment. The three anomalous results lead to an unusually high calculation of the C_L for a given alpha. Therefore, to remain conservative in any conclusions drawn, it was decided not to include these three results from further analysis and comparison. Furthermore, the eight remaining clean wing results were combined together for use as a reference clean wing C_L-Alpha. This result is shown in Figure 36 and is used in all of the subsequent comparisons.

Figures 15 to 34 show the C_L-Alpha plots for all of the contaminated wing tests. A straight line regression was applied to this data to provide the C_L-Alpha relationship. A straight line regression was deemed to be adequate as the data suggests this, and the fluid film thickness on the wing over the test period varies from 1 mm down to almost nil; therefore, its effect on performance could be captured using a simple linear model.

A number of the takeoffs exhibited significantly less scatter in the data than other flights. For example, see Figures 26 and 30 for two extremes. Figure 39 shows a plot of the wind speed versus the root mean square (rms) of the C_L-Alpha correlations. This graph shows that there is a strong correlation between the wind speed and the scatter in the data. In and of itself, the wind speed is not causing the scatter in the data but rather the atmospheric turbulence, which in itself is directly proportional to the wind speed. This emphasizes the importance of performing flight testing in the calmest wind conditions possible.

In the strict sense the C_L calculated in this paper is the total C_L and contains a number of second order terms, most notably: horizontal stabilizer position and elevator position. Unfortunately, at the time of the experiment the aircraft was not yet fitted with the instrumentation required to measure these control surface positions. Reference 5 shows that movable horizontal stabilizers (such as the Falcon 20 elevator trim) can have significant effect on the coefficient of lift and can take on the appearance of apparent data noise. For any future testing it is important to determine these effects and remove them from the results.

There are a number of interesting results when the clean wing results are compared with the contaminated results. It is important to note that for all of the takeoffs presented, the correlations between the coefficient of lift and angle of attack are all 95 percent and above. The combined plot of all the best straight line fits, for all wing conditions, are shown in Figure 37. Looking at the general trends one can see that there is a fairly large scatter in the data at the higher angles of attack (or just after takeoff) and that the scatter diminishes significantly toward the lower angles of attack (approximately 40 seconds after takeoff). This follows intuition, where one would expect that just after takeoff varying amounts of residual anti-icing fluid would be present on the wings and therefore larger differences in the lift being generated by the wings. As airspeed increases and alpha decreases, more and more of the residual fluid on the wings sheds, and the performance of the wings starts to approach that of the clean wing. Figure 37 clearly shows this result. This result is further corroborated by Flights 2003-8 (Figures 28 and 29) and 2003-11 (Figures 32 and 33). In both of these tests the aircraft performed two consecutive takeoffs. The first takeoff did not differ from any of the other contaminated wing takeoffs. The second takeoff was performed immediately following the first, without any reapplication of anti-icing fluid (thus, with only residual fluid on the wings, left on from the first test circuit flown). In both of these cases the second takeoff result showed performance results approaching the clean wing configuration. Table 1 shows the degradation in C_L for the contaminated wing as compared to the clean wing.

Table 1: Degradation in the Coefficient of Lift

Test #	*Date*	*Flight #*	*Alpha-0*	*C_L @ 8.4°*	*Delta C_L (%)*	*Temp.*	*Comment*
		Reference *	-1.21	0.8478	0.0%		Clean wing
1	06 Mar.'02	2002-4	-1.03	0.8111	-4.3%	-8°c	Type IV - EG over Type 1 EG
2	06 Mar.'02	2002-5	-1.30	0.8086	-4.6%	-7°c	Type IV - EG over Type 1 EG
3	06 Mar.'02	2002-6	-1.23	0.8165	-3.7%	-4°c	Type IV - EG over Type 1 EG
4	06 Mar.'02	2002-7	-1.00	0.8459	-0.2%	-3°c	Type IV - EG no precipitation
5	06 Mar.'02	2002-8	-1.12	0.8155	-3.8%	-3°c	Type IV - EG no precipitation
6	11 Mar.'02	2002-9	-0.75	0.8203	-3.2%	-11°c	Type IV - EG no precipitation
7	11 Mar.'02	2002-10	-1.27	0.8150	-3.9%	-8°c	Type IV - EG light freezing rain
10	24 Feb.'03	2003-2	-1.44	0.8037	-5.2%	-13°c	Inboard - EG no precipitation
11	24 Feb.'03	2003-3	-1.14	0.8057	-5.0%	-13°c	Type IV - EG
12	24 Feb.'03	2003-4	-1.09	0.8071	-4.8%	-13°c	Type IV - EG
13	24 Feb.'03	2003-5	-1.05	0.8246	-2.7%	-13°c	Outboard - EG
14	25 Feb.'03	2003-6	-1.14	0.8160	-3.7%	-20°c	Type IV - PG
15	25 Feb.'03	2003-7	-1.10	0.8089	-4.6%	-20°c	Type IV - PG
16	25 Feb.'03	2003-8.1	-0.92	0.8153	-3.8%	-18°c	Type IV - PG
17	25 Feb.'03	2003-8.2	-0.98	0.8411	-0.8%	-18°c	Residual - PG
18	26 Feb.'03	2003-9	-1.31	0.7662	-9.6%	-23°c	Type IV - PG
19	26 Feb.'03	2003-10	-1.17	0.7902	-6.8%	-23°c	Type IV - PG
20	26 Feb.'03	2003-11.1	-1.03	0.8227	-3.0%	-19°c	Type IV - EG
21	26 Feb.'03	2003-11.2	-0.89	0.8420	-0.7%	-15°c	Residual - EG
23	27 Feb.'03	2003-14	-0.83	0.8393	-1.0%	-23°c	Type IV – EG, Pre-diluted

* Average of all clean wing cases
** Tests 8,9, and 22 were not for flight data collection

In Table 1, the columns are labeled as follows:

Test #:	Test sequence number,
Data:	Flight test date,
Flight #:	NRC flight number designator,
Alpha-0:	angle of attack for which the wing generates zero lift,
C_L @ 8.4°:	coefficient of lift at 8.4 degree angle of attack,
Delta C_L:	percent change in C_L from the reference case, and
Comment:	wing contamination state.

The degradation in the coefficient of lift of the aircraft due to the presence of anti-icing fluid was determined by taking the difference between the clean wing coefficient of lift (C_L) condition and a contaminated wing C_L condition at a given angle of attack. To make a fair comparison between the coefficients of lift, a reference or typical takeoff angle of attack (Alpha) was chosen. The reference Alpha was calculated by taking a typical takeoff weight (25,000 lb.) and takeoff speed (Vr, 126 kn) and calculating the C_L required for liftoff; then, from the reference clean wing C_L-Alpha curve, the reference angle of attack was calculated and determined to be 8.4°. Figure 38 shows graphically how the reference Alpha and delta C_L are determined. Table 1 presents these tabular results for the degradation in the coefficient of lift for each of the test points.

Alpha-0 is the angle of attack for which the wing generates zero lift. Table 1 shows that the contaminated wing cases vary from -1.59° to -0.75° and evenly span the reference case, which is at -1.21°. From the SCADS analysis, the accuracy of the angle of attack was found to be ±0.5°. This shows that the anti-icing fluid does not change the basic airfoil shape or lift-generating characteristics of the wing. This is not surprising in that well before liftoff the majority of the anti-icing fluid has been shed and only a very thin layer is left on the wing.

The average lift-loss for all of the contaminated wing cases (with the exception of the two residual cases, Flights 2003-8.2 and 2003-11.2) is 4.1 percent. The maximum lift-loss measured was 9.6 percent (Flight 2003-9, Figure 30) and the smallest was 0.2 percent (Flight 2002-7, Figure 18). There is a large scatter in the lift-loss, which spans 9.4 percent; however, it is important to note that all of these lie below the reference case. Only for the two residual fluid test cases does the wing performance match that of the clean wing. As noted, Flight 2002-7 (Figure 18) used an unusual pre-rotation takeoff technique and had the least amount of relative lift-loss: only 0.2 percent. Figure 18 shows that for this test, the angle of attack ranged from only 3° to 6° and does not span the reference angle of attack used in the calculations, which is 8.4°. Therefore, because this point represents an extreme value and has been interpolated outside its measured range, it is of questionable validity. If Flight 2002-7 is omitted, the lift-loss would range from 9.6 percent to 3.0 percent with an average lift-loss of 4.3 percent.

It is important to make a note of caution at this point. The composite clean wing reference data, shown in Figure 36, has an rms value of 0.0188, which represents 2.2

percent of the takeoff C_L. Compared to the average lift-loss of 4.3 percent an rms error of 2.2 percent on the reference case represents a significant level. Despite this large uncertainty error in the comparison of the results, it is important to reiterate that every one of the contaminated wing conditions tested fell below the reference case results.

The ethylene glycol and the propylene glycol exhibited the similar performance penalties. Also, there was no performance difference between a Type I fluid application followed by a Type IV fluid or that of a Type IV fluid only application.

Two flights were flown with the anti-icing fluid applied to only partial wing coverage, Flights 2003-2 and 2003-5. One was done with the fluid applied inboard of the wing fence section, and the other outboard of the wing fence section. For both of these tests the fluid was applied to a freshly washed clean wing with no prior fluid applications. These tests were performed to examine whether one particular span of the wing had a greater contribution to the overall lift generated. Table 1 shows that the lift-loss for the inboard wing section was 5.2 percent and that of the outboard wing section was 2.7 percent. Taken in isolation, this result may suggest that the inboard section was more affected than the outboard section. However, the average lift-loss for all the test cases was 4.1 percent and the sum of both inboard and outboard sections was 7.9 percent, which is still within the data scatter but approaching an extreme. Therefore, given the single test result that falls withing the data scatter, no conclusion can be drawn at this time.

It is important to note that the degradation in lift due to the presence of the anti-icing fluid is transient. The average lift-loss reported of 4.1 percent is valid for the point in time of liftoff. This then diminishes to negligible amounts over a period of roughly 40 to 60 seconds after liftoff.

The Falcon 20 aircraft operates at a typical takeoff weight of 25,000 lb. A 4.1 percent lift-loss due the presence of anti-icing fluids translates into 1000 lb. of reduced lifting capacity. To compensate for the lift-loss, and still maintain the same safety margin at takeoff rotation, the aircraft rotation speed would have to be increased by 2 to 3 kn, which would increase the runway length required for both normal takeoff and single engine continued takeoff operations.

Without increasing the calculated rotation speed, a rotation of an additional 0.4^o could be used to achieve the same lift at rotation as with the clean wing aircraft. However, the margin of safety in this case would be reduced due to the increased liftoff angle of attack and the probability that the aircraft angle of angle of attack for $C_{L\text{-max}}$ would also be reduced due to the presence of anti-icing fluids.

Another important aircraft performance issue that must be considered is the reduction in the single engine climb gradient due to reduced lift generated by the wing. For the Falcon 20 at maximum takeoff weight limited by climb gradient, a 4.1 percent lift-loss would result in a 20 percent reduction of the single engine climb gradient.

5.0 Conclusions

From the testing conducted a number of conclusions were drawn and can be summarized as follows:

A) Aircraft lift-loss was successfully measured due to the presence of anti-icing fluids applied to the wings.

B) The average lift-loss following takeoff due to the presence of de/anti-icing fluid on the wings was 4.1 percent. This is equivalent to 1000 lb. of lift-loss and required an increase in the takeoff angle of attack of 0.4° to compensate for this lift-loss.

C) No distinction could be made between the ethylene glycol and propylene glycol effects on the aircraft performance penalties.

D) There was insufficient data to draw any conclusions regarding the effects of applying fluid to either the inboard or outboard sections of the wing.

E) On two occasions where a second takeoff was performed without a reapplication of any anti-icing fluid, the wing performance matched that of the clean wing, suggesting the analytical approach used in the work has validity.

6.0 Recommendations

A) Further testing is required to determine the effects of differing levels of contamination applied to the anti-icing fluids.

B) Safety and regulatory issues prevent the aircraft from taking off with fluids contaminated beyond their capacity to absorb precipitation. Hence, there is a need to tie the aircraft data to wind tunnel and computational fluid dynamics work.

C) Further testing should be done with different aircraft: specifically, aircraft with high-efficiency wings that may exhibit significantly different performance penalties.

D) A detailed study of the in-ground effect portion of the flight profile should be made. Also, the effect of elevator and horizontal stabilizer position on C_L should be determined and removed from the C_L calculation.

Comparison of Quasi-Static State and 6 Degrees of Freedom Coefficient of Lift Equation (Separate)

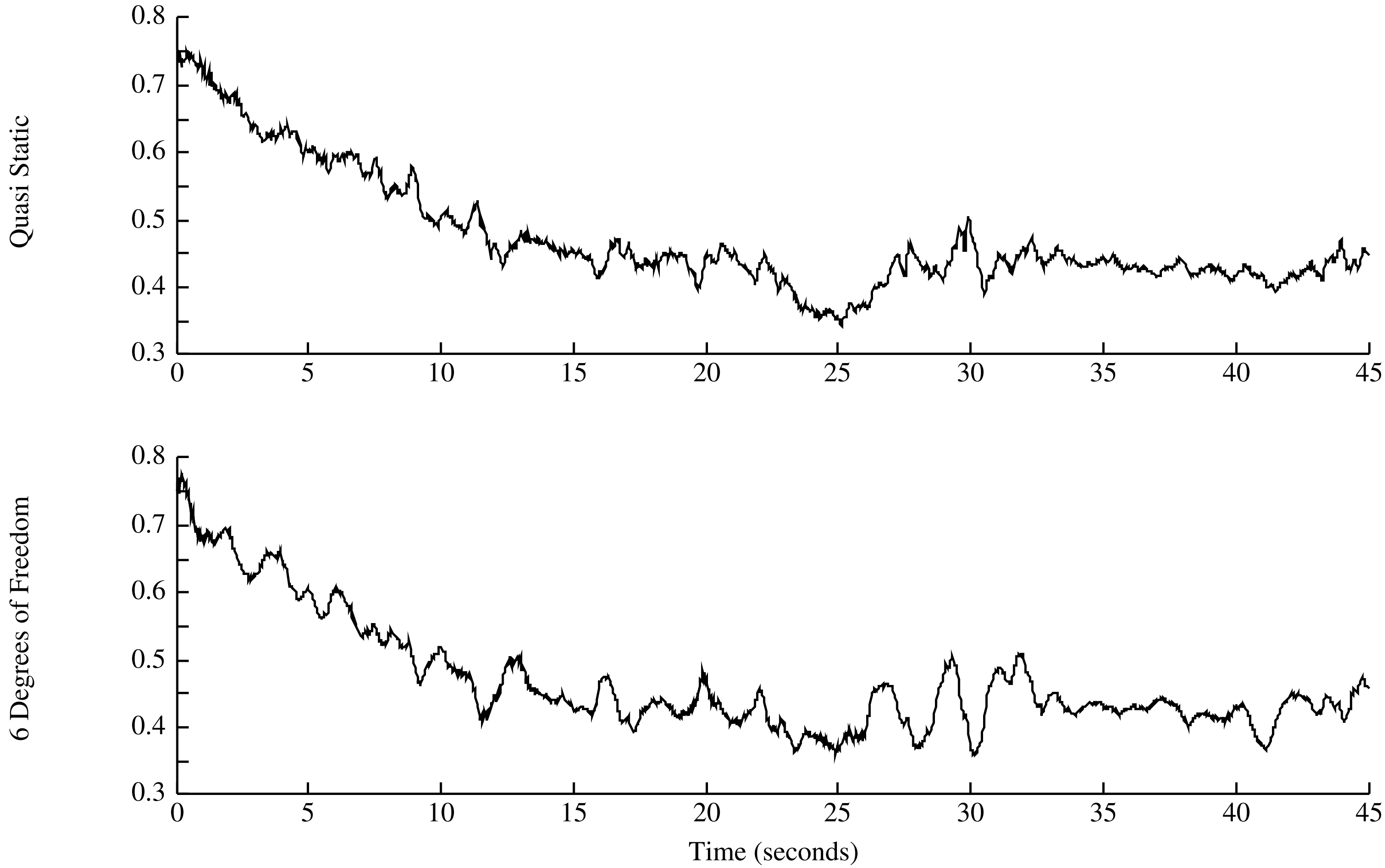


Figure 1

Figure 2

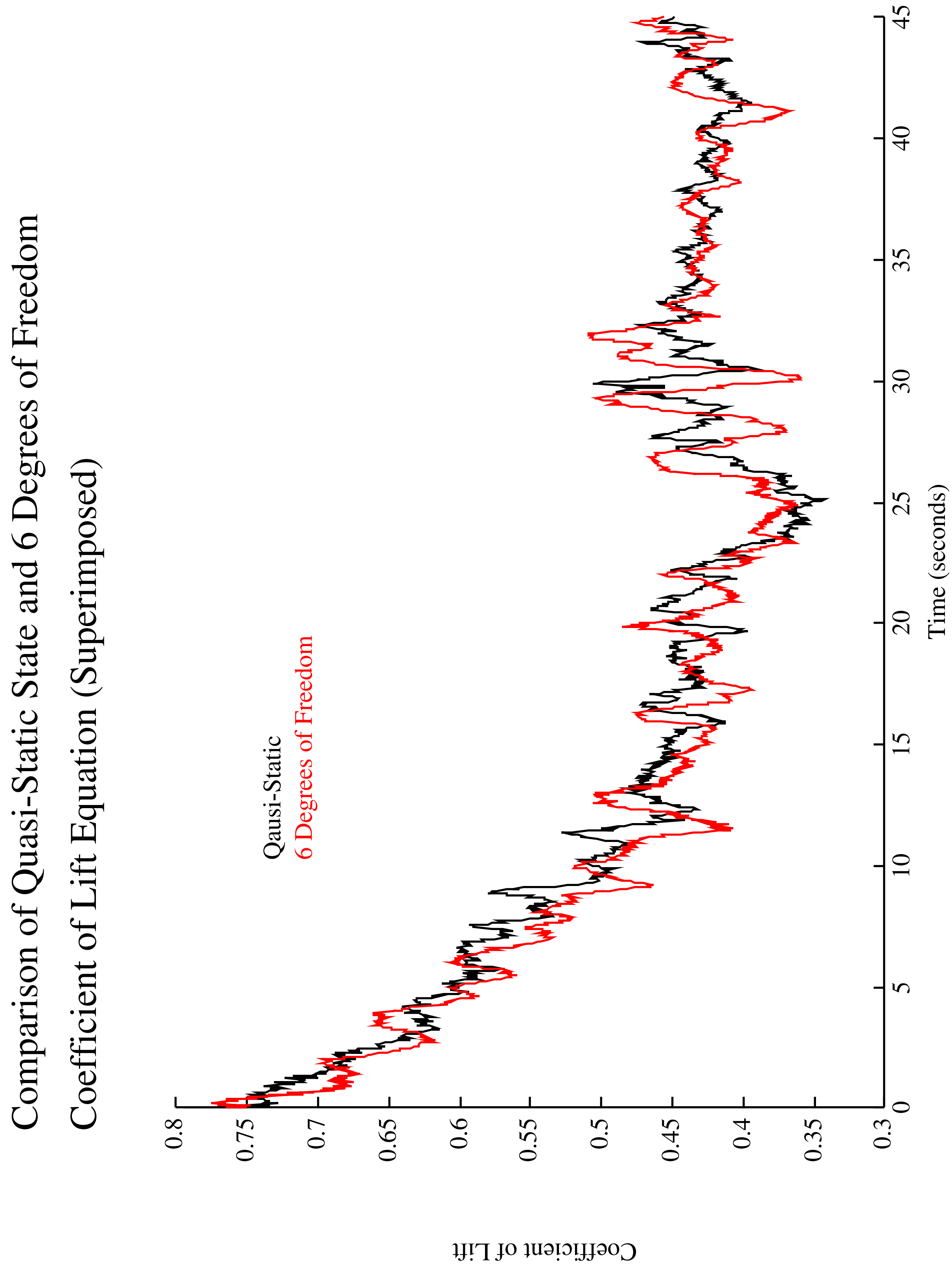

Comparison of Quasi-State State and 6 Degrees of Freedom
Coefficient of Lift Equation (Superimposed)
Qausi-Static
6 Degrees of Freedom
Coefficient of Lift
Time (seconds)
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0
5
10
15
20
25
30
35
40
45

Figure 3

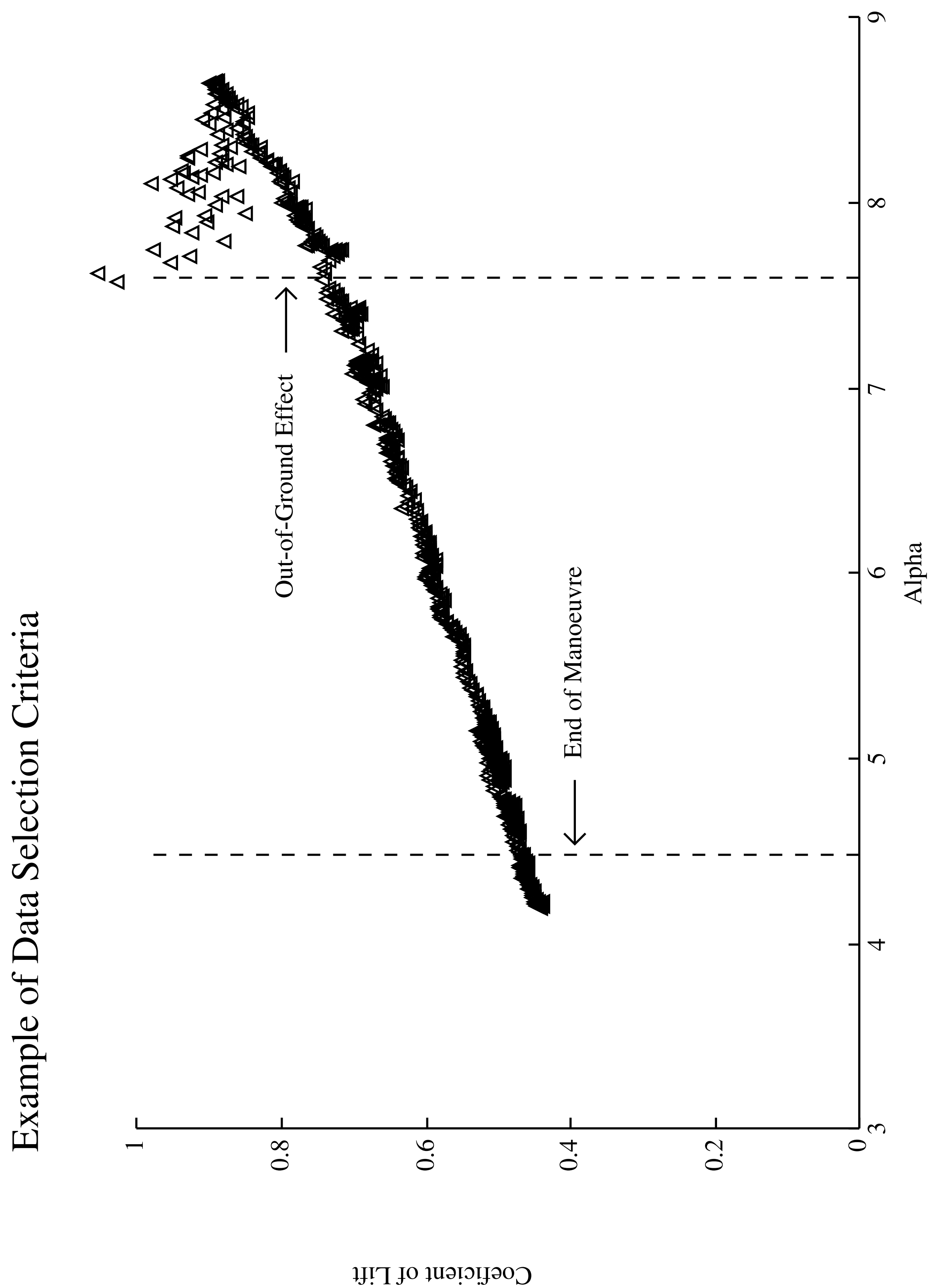

Example of Data Selection Criteria
Out-of-Ground Effect
End of Manoeuvre
Alpha
Coeficient of Lift
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 4

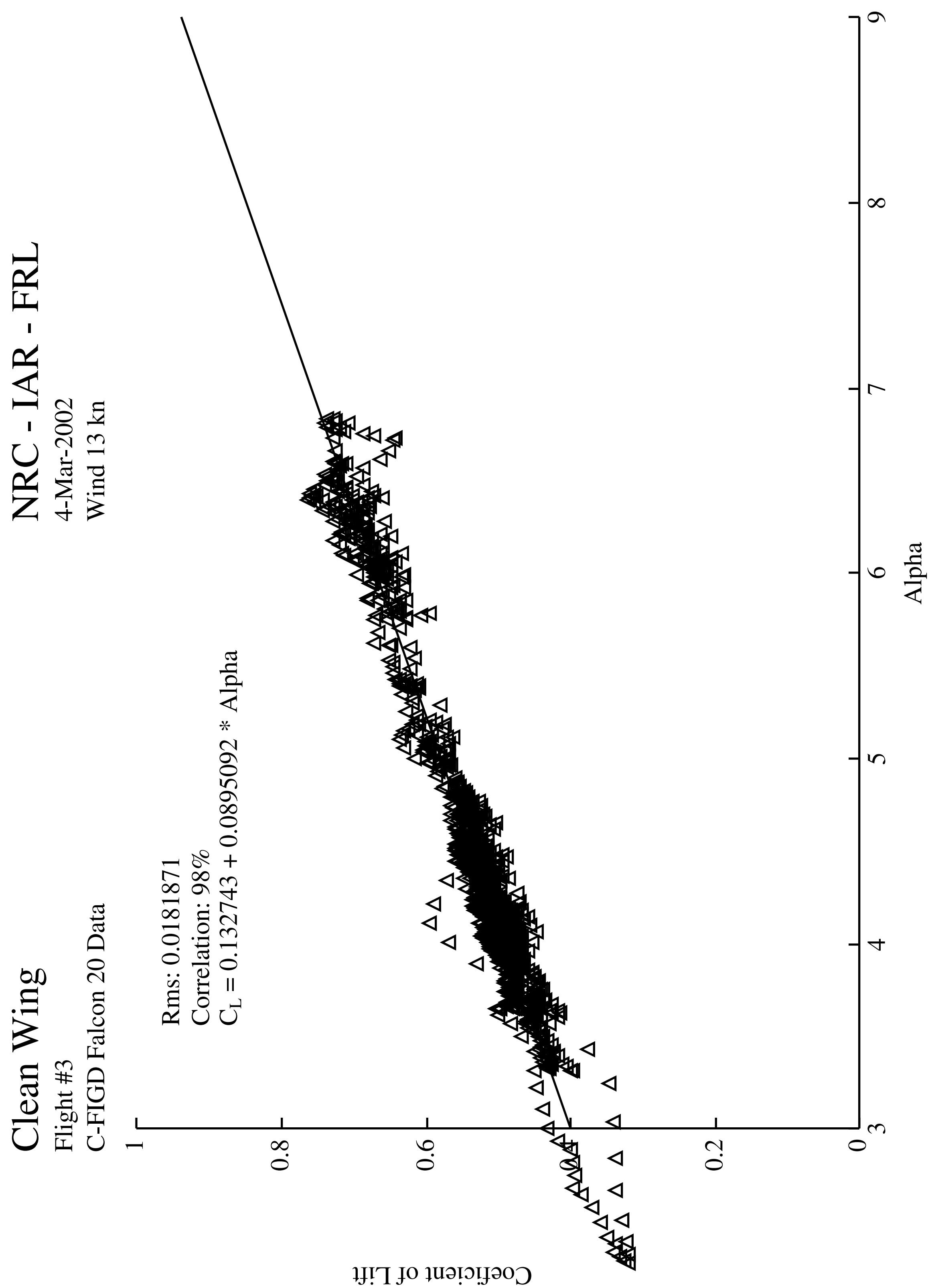

Clean Wing
Flight #3
C-FIGD Falcon 20 Data
NRC - IAR - FRL
4-Mar-2002
Wind 13 kn
Rms: 0.0181871
Correlation: 98%
C_L = 0.132743 + 0.0895092 * Alpha
Coeficient of Lift
Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 5

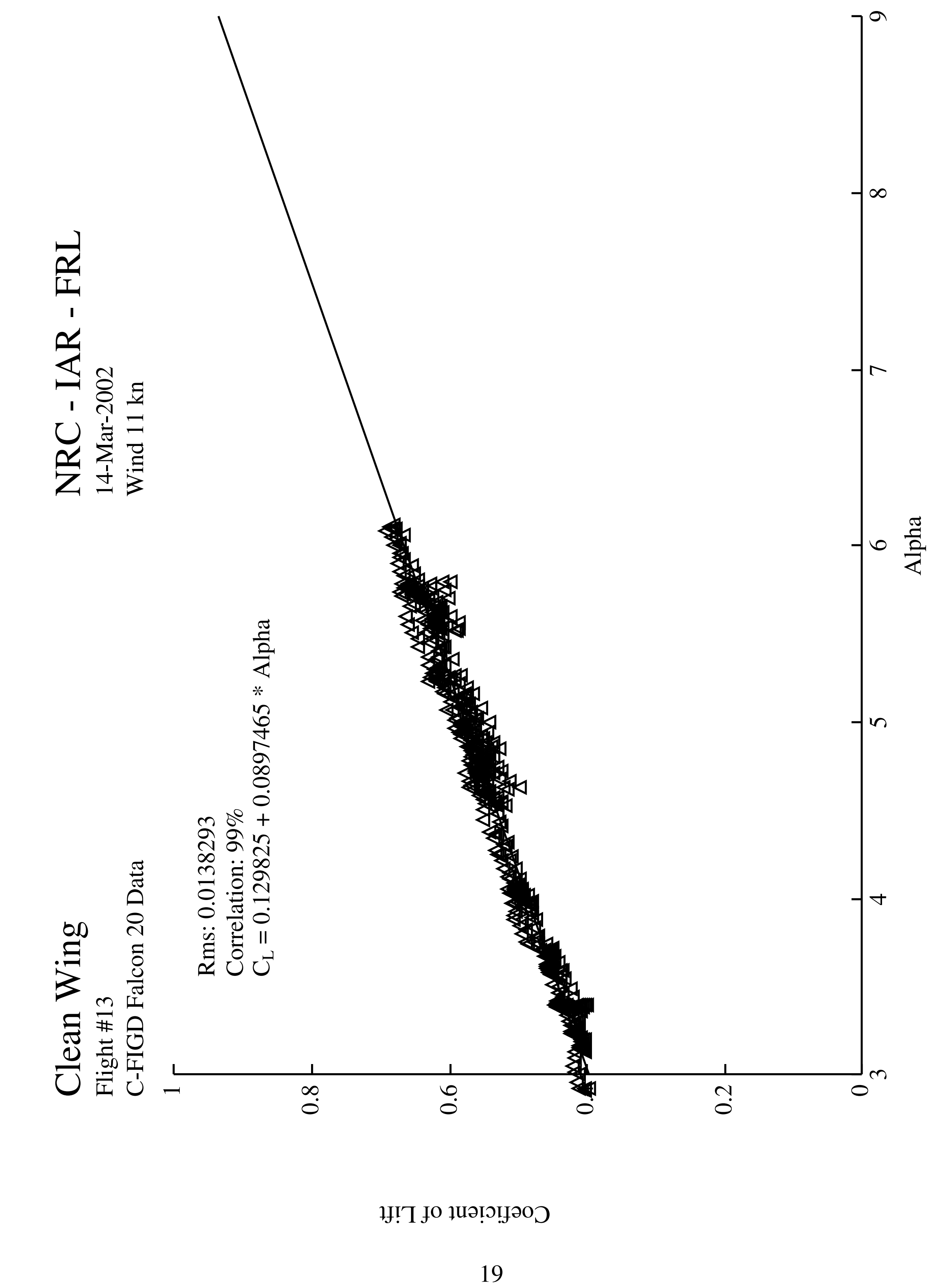
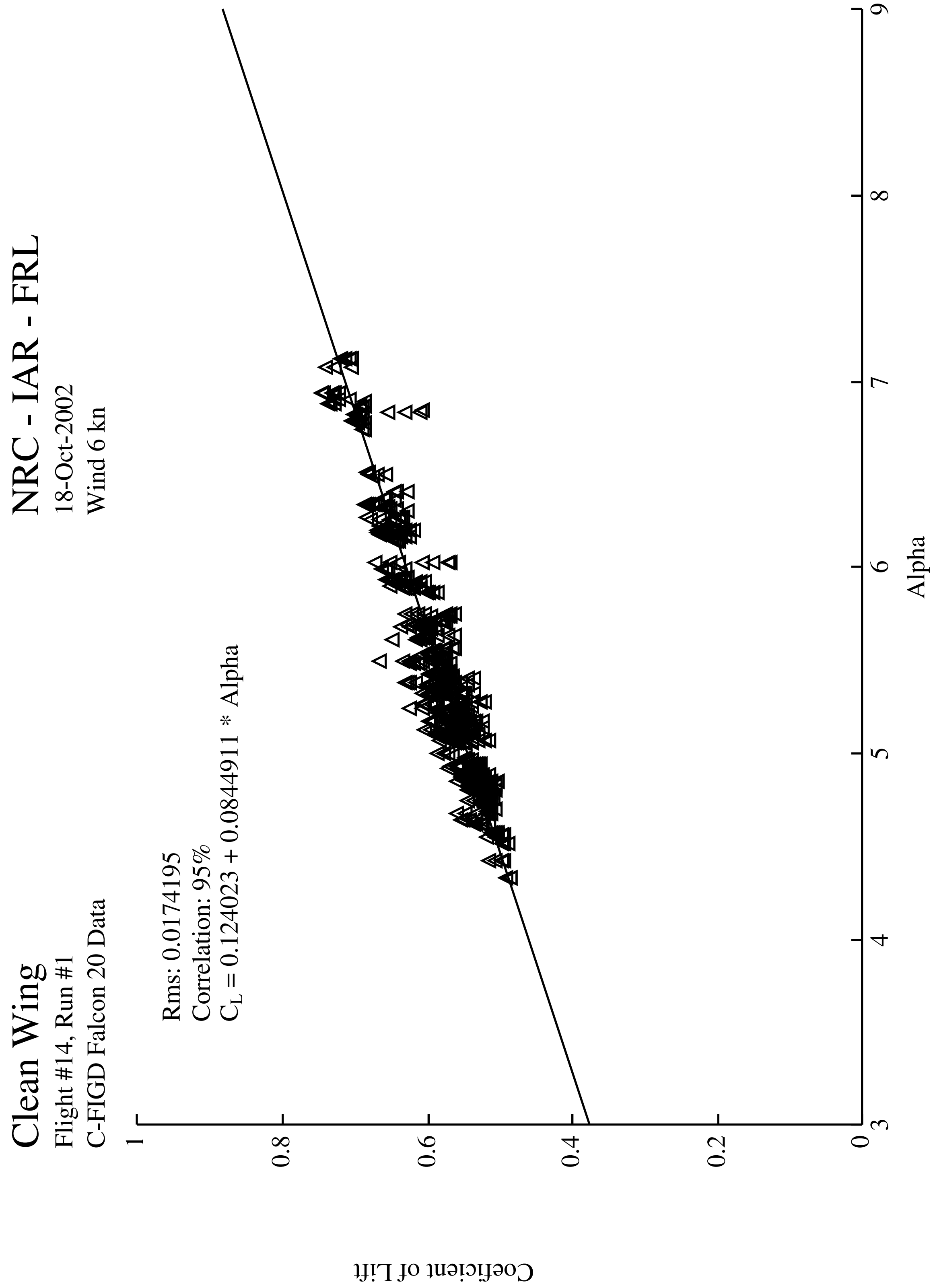

Clean Wing
Flight #13
C-FIGD Falcon 20 Data
NRC - IAR - FRL
14-Mar-2002
Wind 11 kn
Rms: 0.0138293
Correlation: 99%
C_L = 0.129825 + 0.0897465 * Alpha
Coeficient of Lift
Alpha
0
0.2
0.6
0.8
1
3
4
5
6
7
8
9

Figure 6



Clean Wing
Flight #14, Run #1
C-FIGD Falcon 20 Data
NRC - IAR - FRL
18-Oct-2002
Wind 6 kn
Rms: 0.0174195
Correlation: 95%
C_L = 0.124023 + 0.0844911 * Alpha
Coeficient of Lift
Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 7

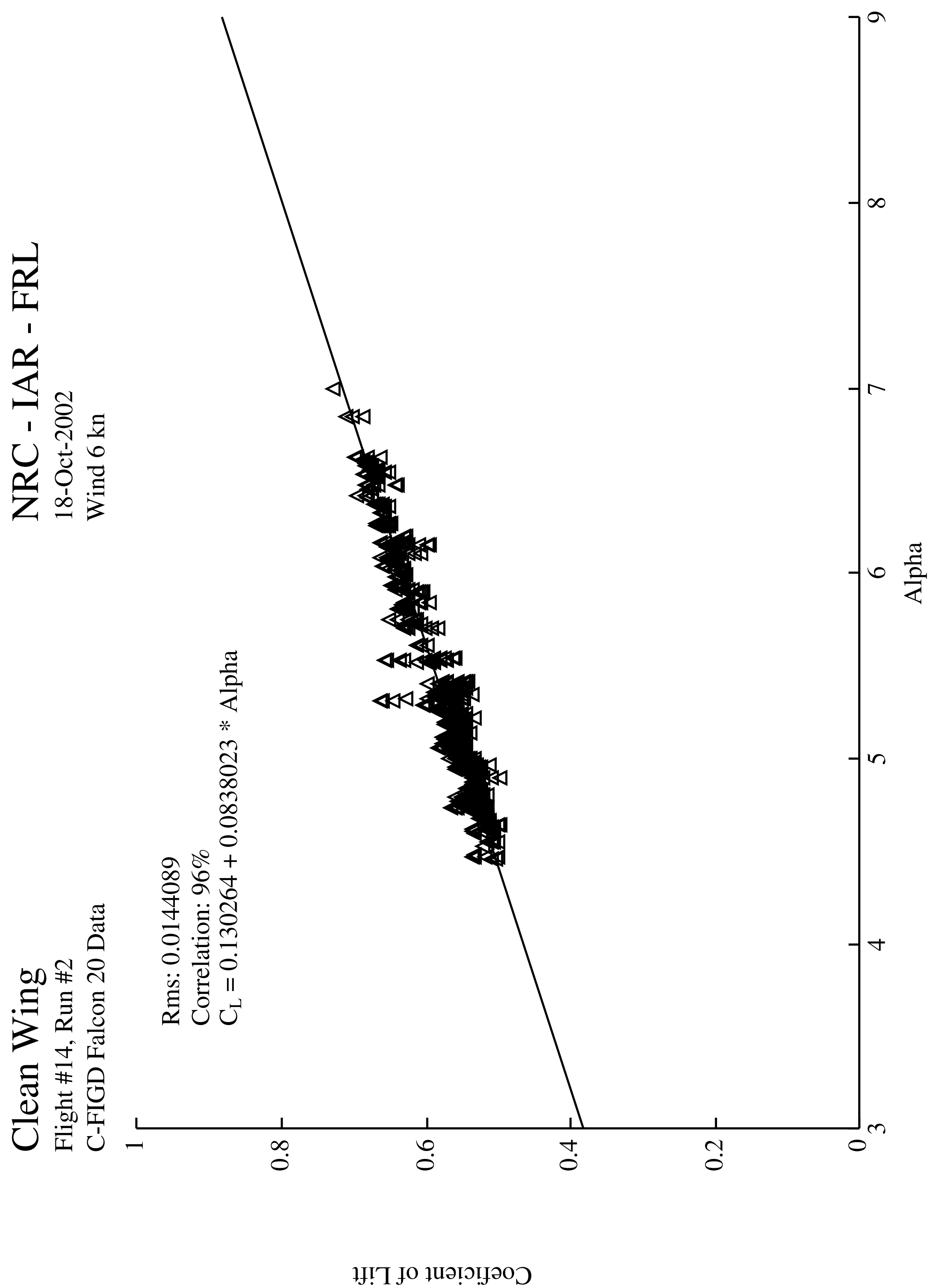

Clean Wing
Flight #14, Run #2
C-FIGD Falcon 20 Data
NRC - IAR - FRL
18-Oct-2002
Wind 6 kn
Rms: 0.0144089
Correlation: 96%
C_L = 0.130264 + 0.0838023 * Alpha
Coeficient of Lift
Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 8

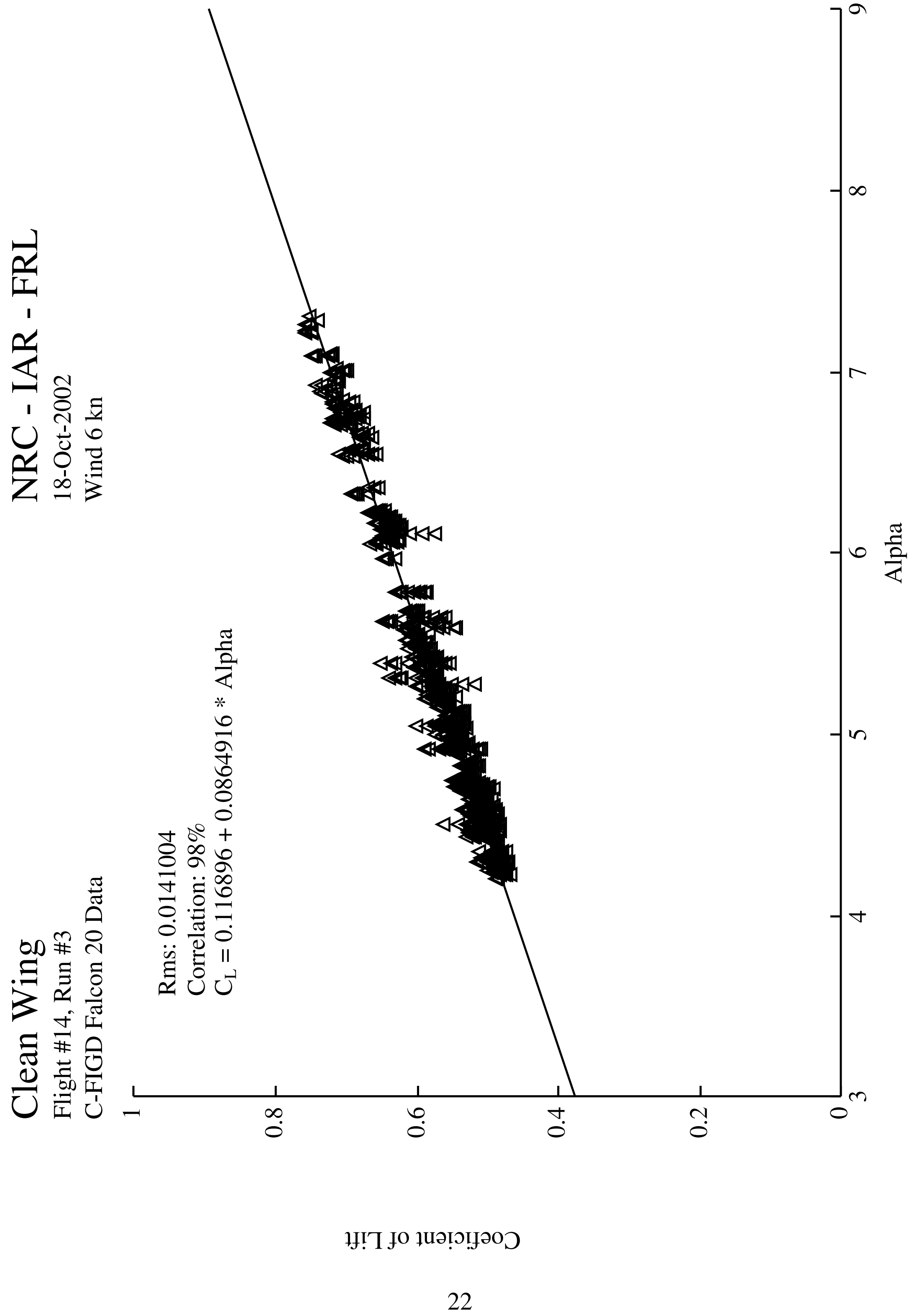
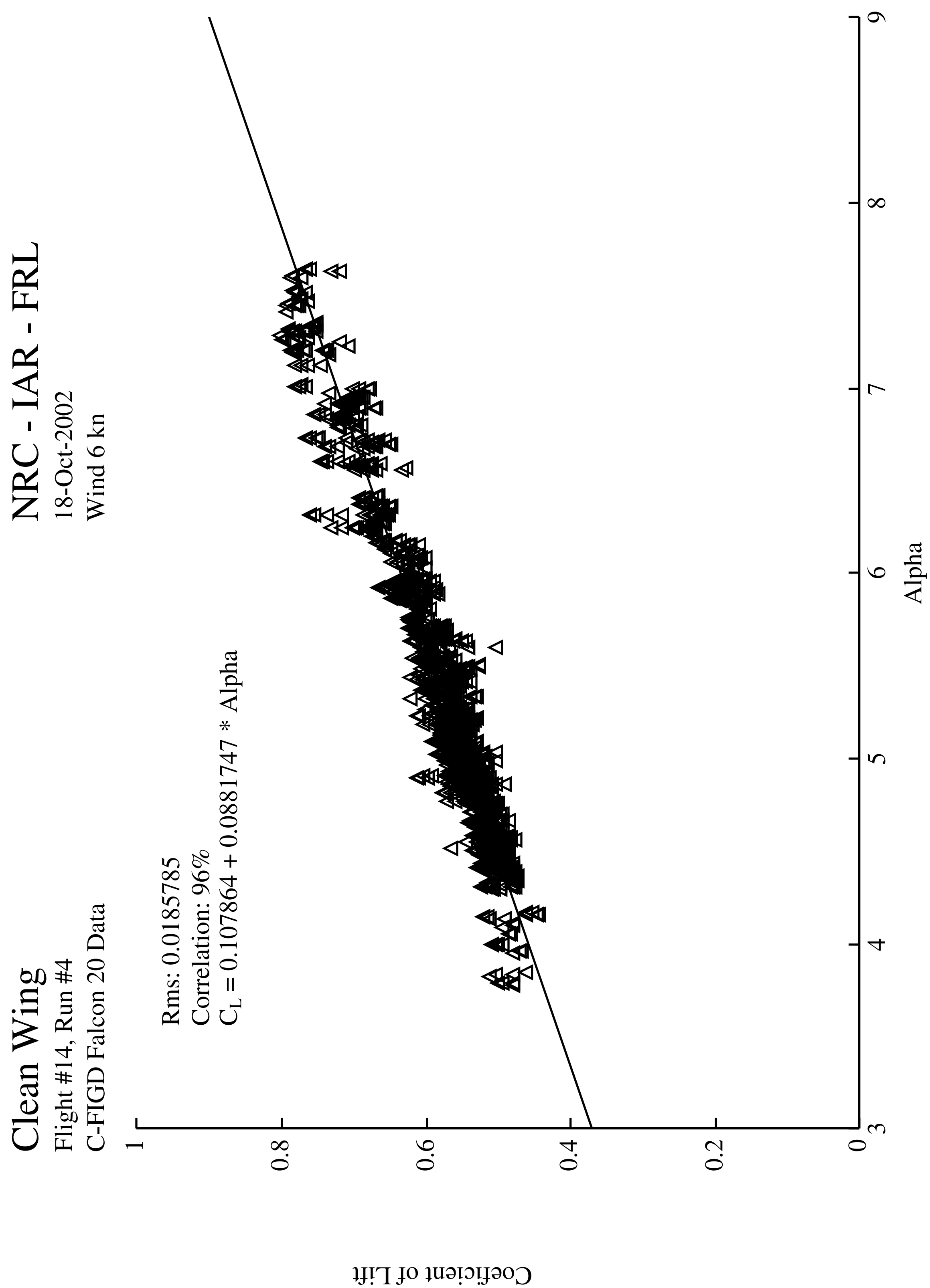

Clean Wing
Flight #14, Run #3
C-FIGD Falcon 20 Data
NRC - IAR - FRL
18-Oct-2002
Wind 6 kn
Rms: 0.0141004
Correlation: 98%
C_L = 0.116896 + 0.0864916 * Alpha
Coeficient of Lift
Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 9



Clean Wing
Flight #14, Run #4
C-FIGD Falcon 20 Data
NRC - IAR - FRL
18-Oct-2002
Wind 6 kn
Rms: 0.0185785
Correlation: 96%
C_L = 0.107864 + 0.0881747 * Alpha
Alpha
Coeficient of Lift
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 10

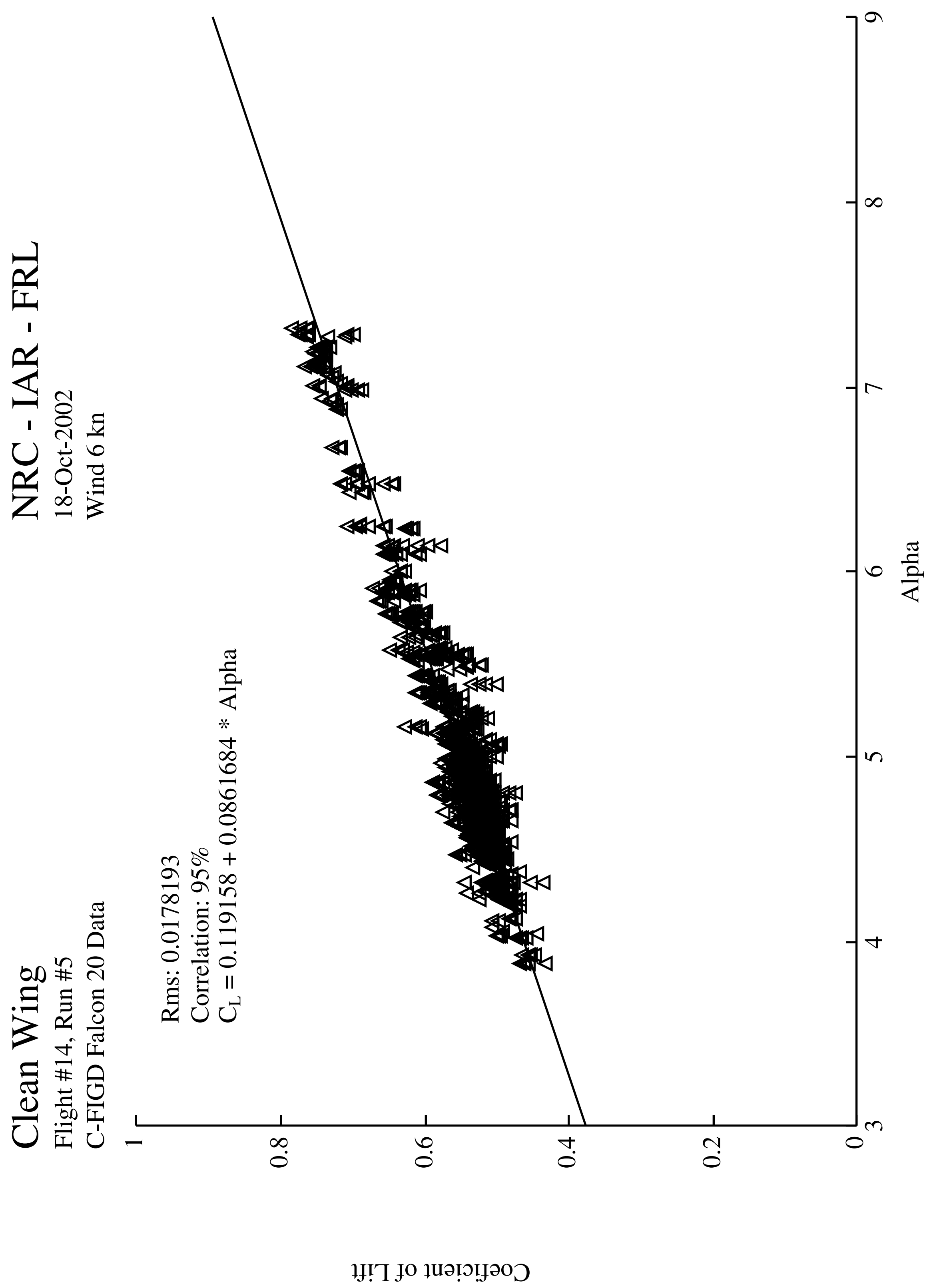
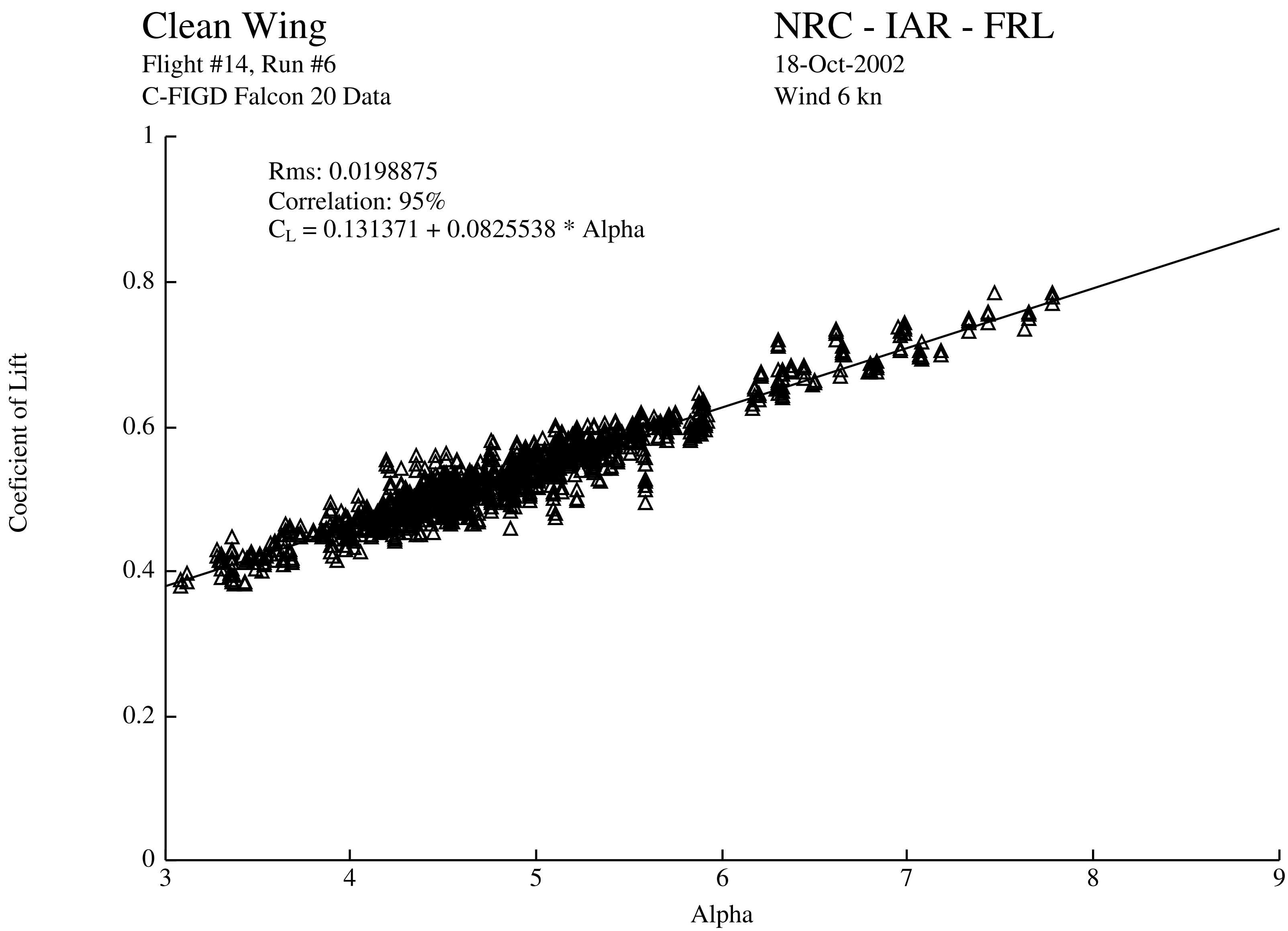

Clean Wing
Flight #14, Run #5
C-FIGD Falcon 20 Data
NRC - IAR - FRL
18-Oct-2002
Wind 6 kn
Rms: 0.0178193
Correlation: 95%
C_L = 0.119158 + 0.0861684 * Alpha
Coeficient of Lift
Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 11



Clean Wing
Flight #14, Run #6
C-FIGD Falcon 20 Data
NRC - IAR - FRL
18-Oct-2002
Wind 6 kn
Rms: 0.0198875
Correlation: 95%
C_L = 0.131371 + 0.0825538 * Alpha
Coeficient of Lift
Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 12

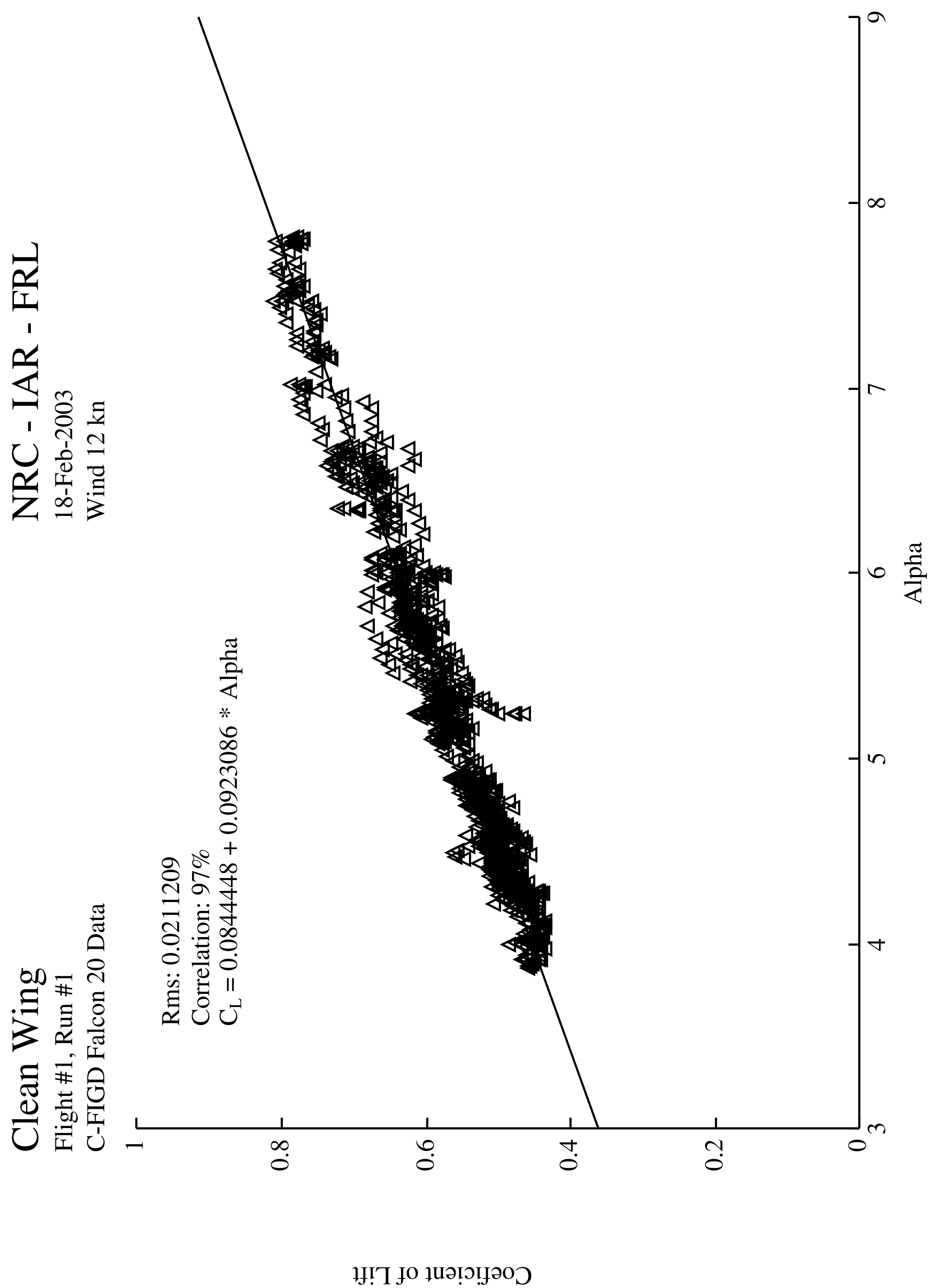

Clean Wing
Flight #1, Run #1
C-FIGD Falcon 20 Data
NRC - IAR - FRL
18-Feb-2003
Wind 12 kn
Rms: 0.0211209
Correlation: 97%
C_L = 0.0844448 + 0.0923086 * Alpha
Coeficient of Lift
0
0.2
0.4
0.6
0.8
1
Alpha
3
4
5
6
7
8
9

Figure 13

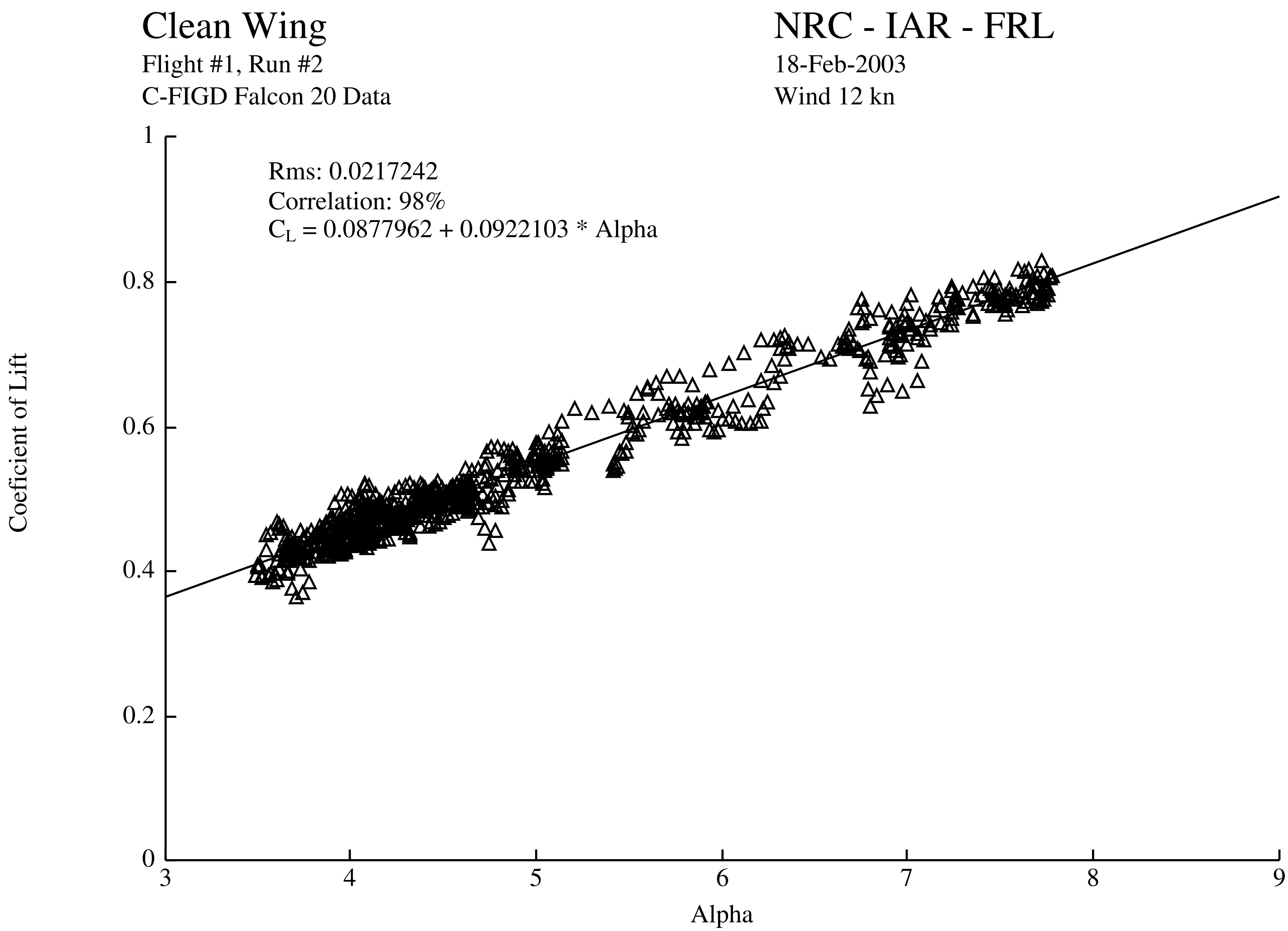

Clean Wing
Flight #1, Run #2
C-FIGD Falcon 20 Data
NRC - IAR - FRL
18-Feb-2003
Wind 12 kn
Rms: 0.0217242
Correlation: 98%
C_L = 0.0877962 + 0.0922103 * Alpha
Coeficient of Lift
Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 14

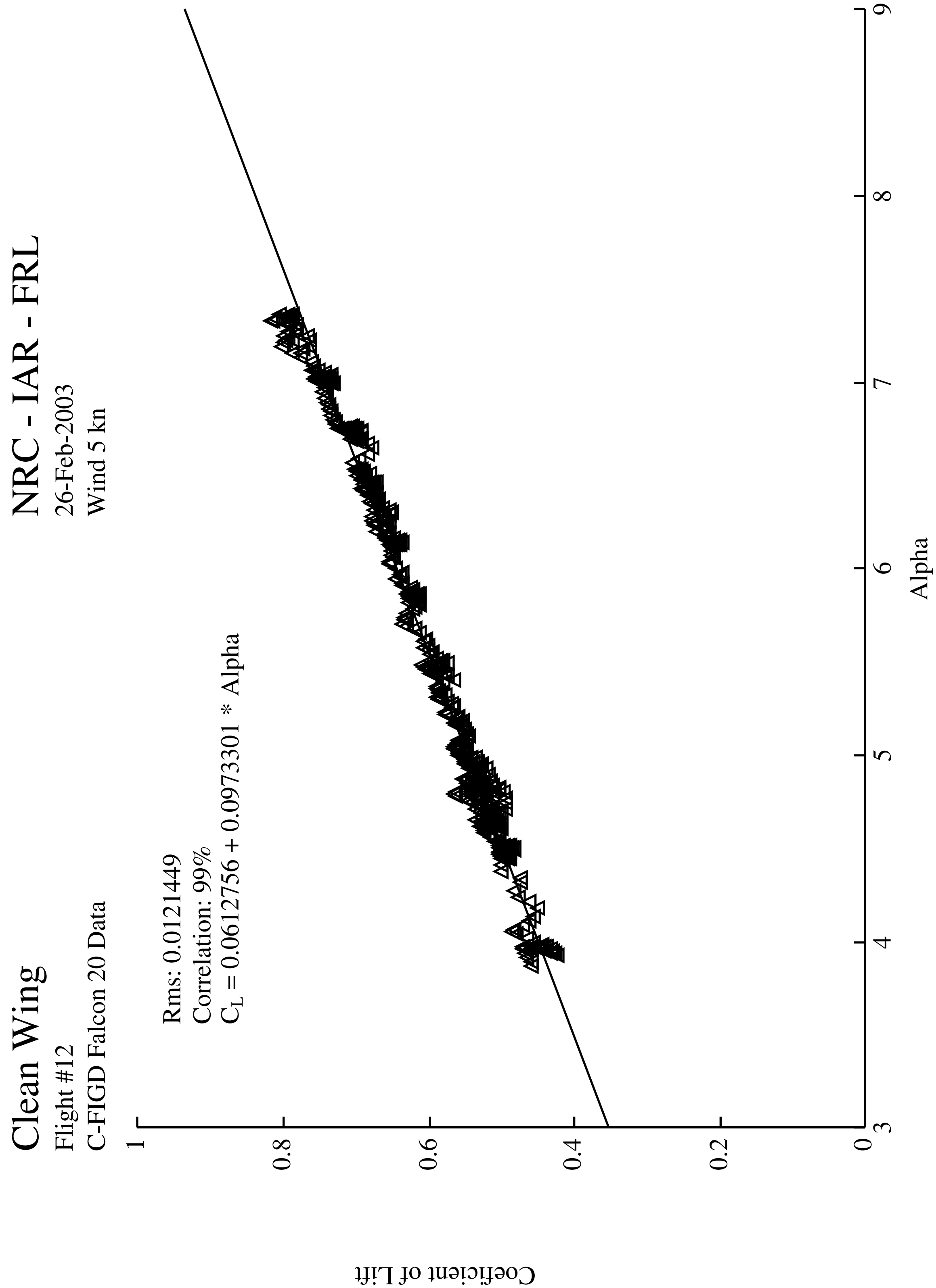

Clean Wing
Flight #12
C-FIGD Falcon 20 Data
NRC - IAR - FRL
26-Feb-2003
Wind 5 kn
Rms: 0.0121449
Correlation: 99%
C_L = 0.0612756 + 0.0973301 * Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9
Alpha
Coeficient of Lift

Figure 15

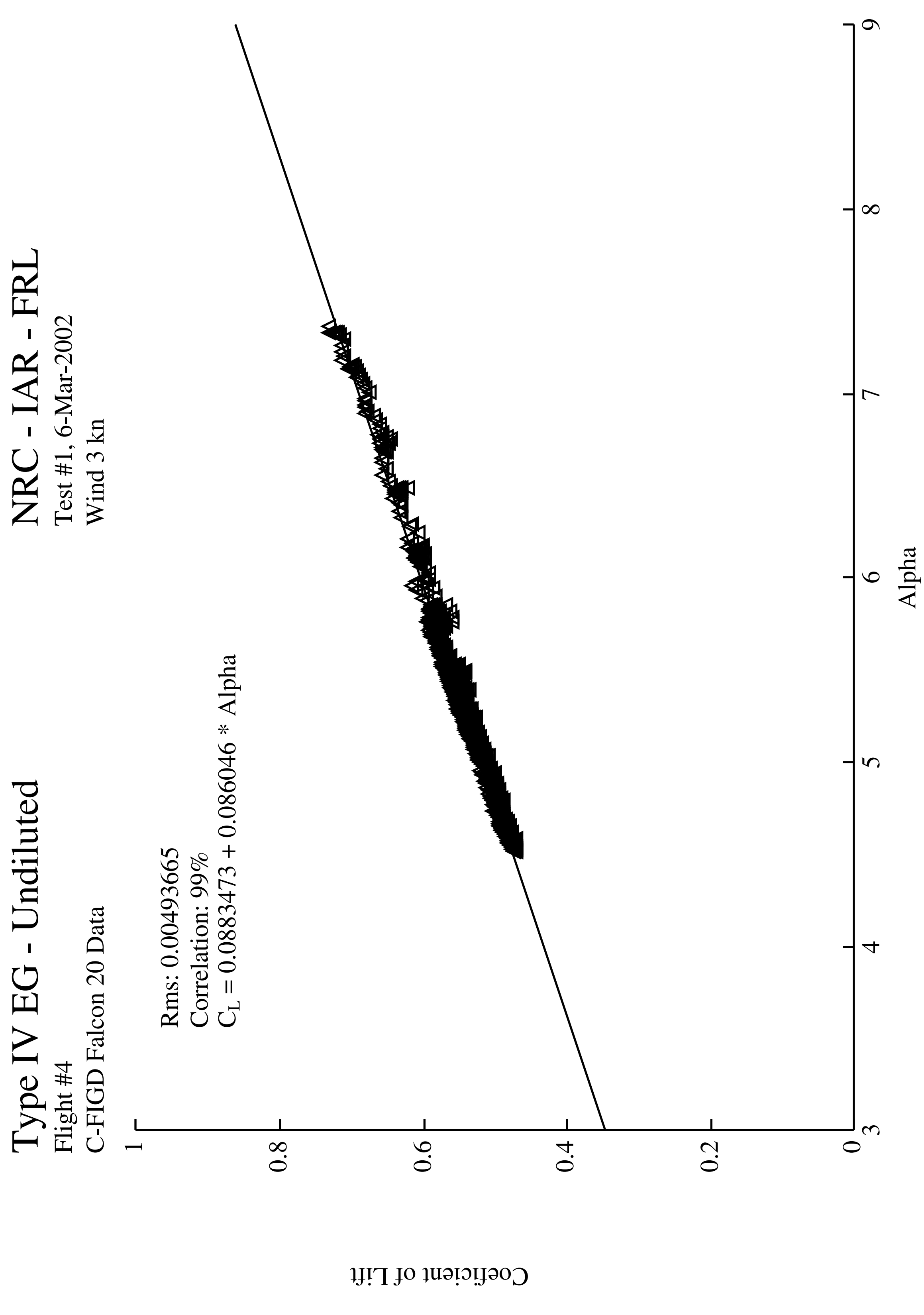
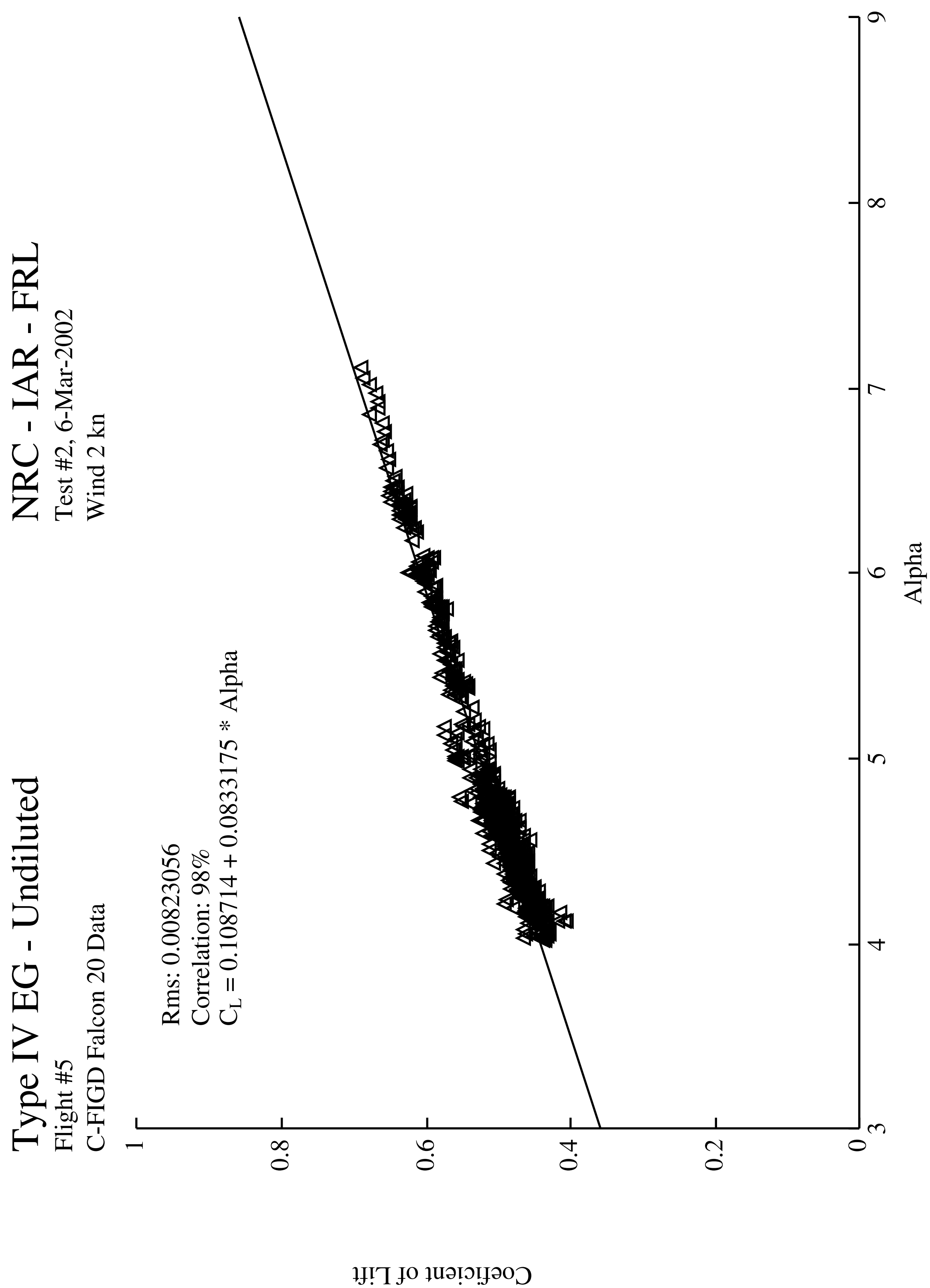

Type IV EG - Undiluted
Flight #4
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Test #1, 6-Mar-2002
Wind 3 kn
Rms: 0.00493665
Correlation: 99%
C_L = 0.0883473 + 0.086046 * Alpha
Alpha
Coeficient of Lift
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 16



Type IV EG - Undiluted
Flight #5
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Test #2, 6-Mar-2002
Wind 2 kn
Rms: 0.00823056
Correlation: 98%
C_L = 0.108714 + 0.0833175 * Alpha
Alpha
Coeficient of Lift
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 17

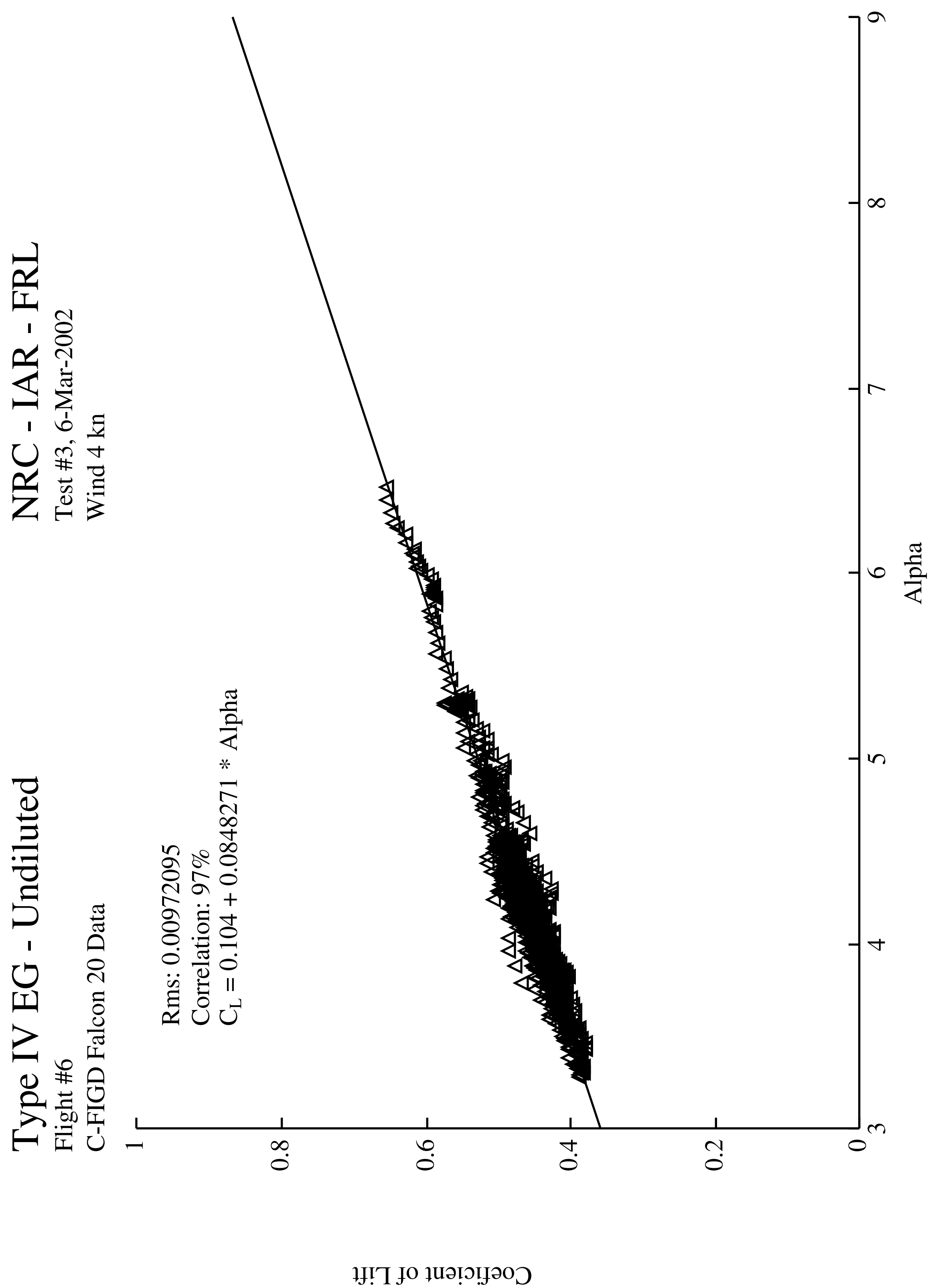

Type IV EG - Undiluted
Flight #6
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Test #3, 6-Mar-2002
Wind 4 kn
Rms: 0.00972095
Correlation: 97%
C_L = 0.104 + 0.0848271 * Alpha
Coeficient of Lift
Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 18

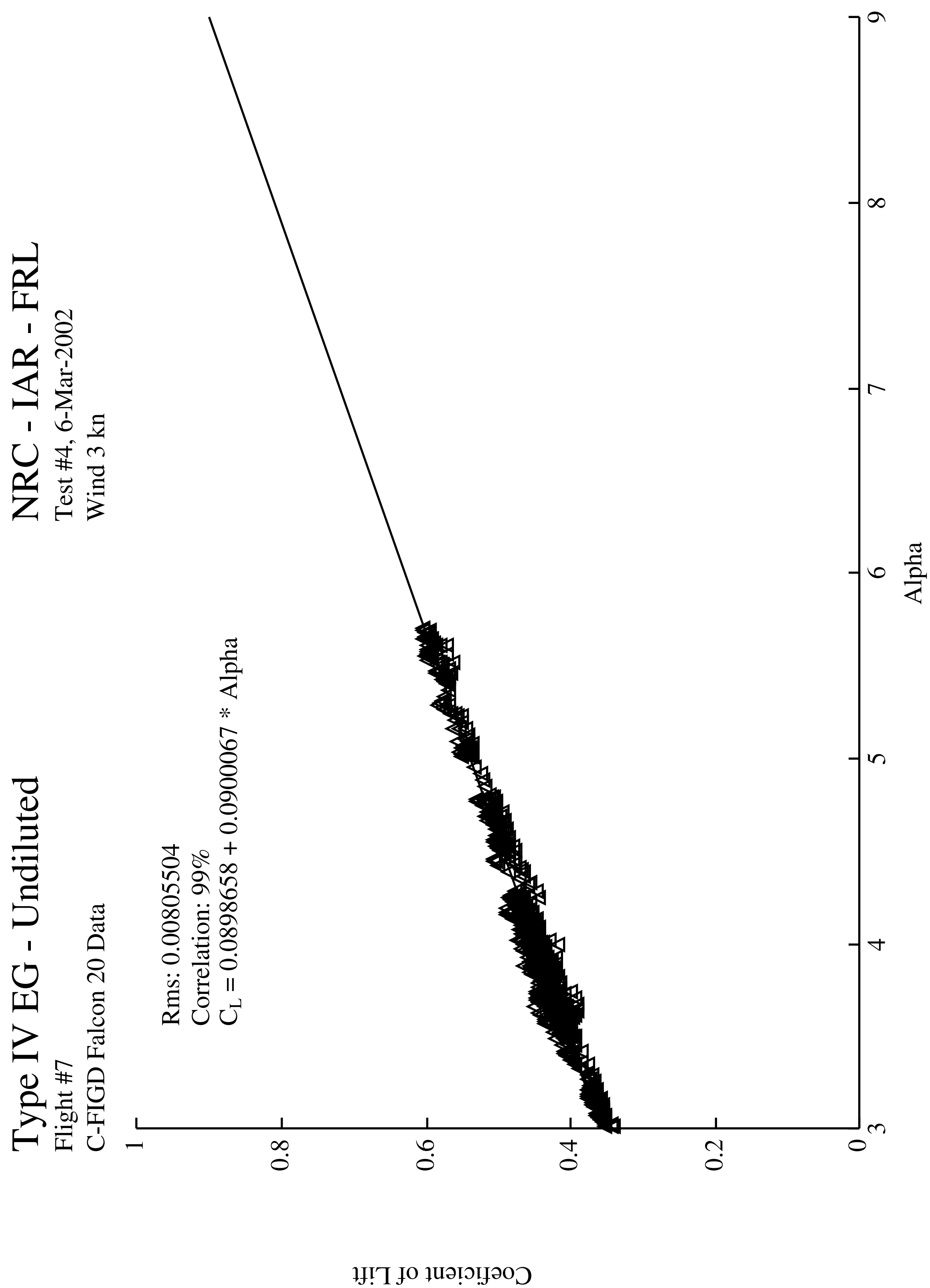
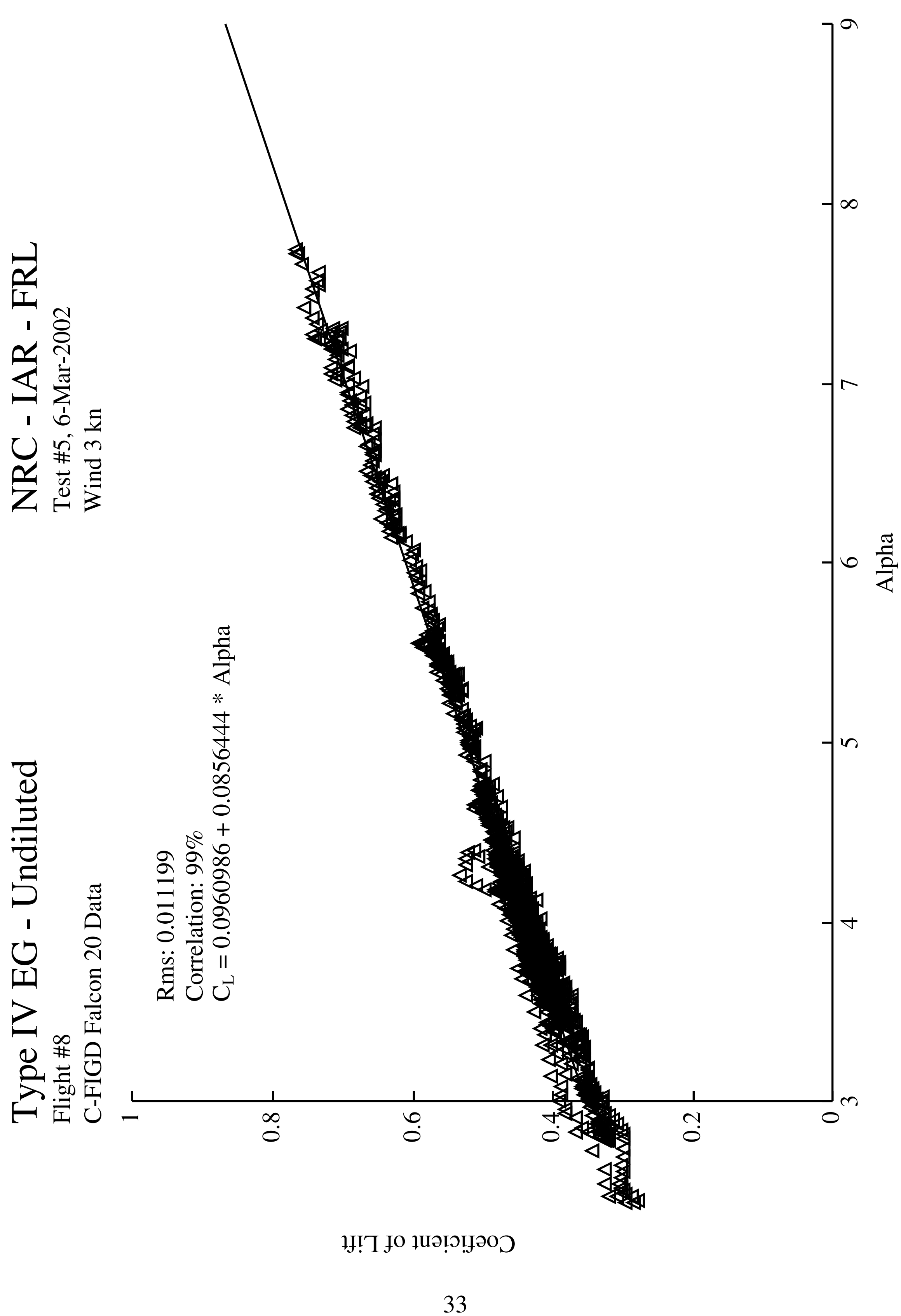
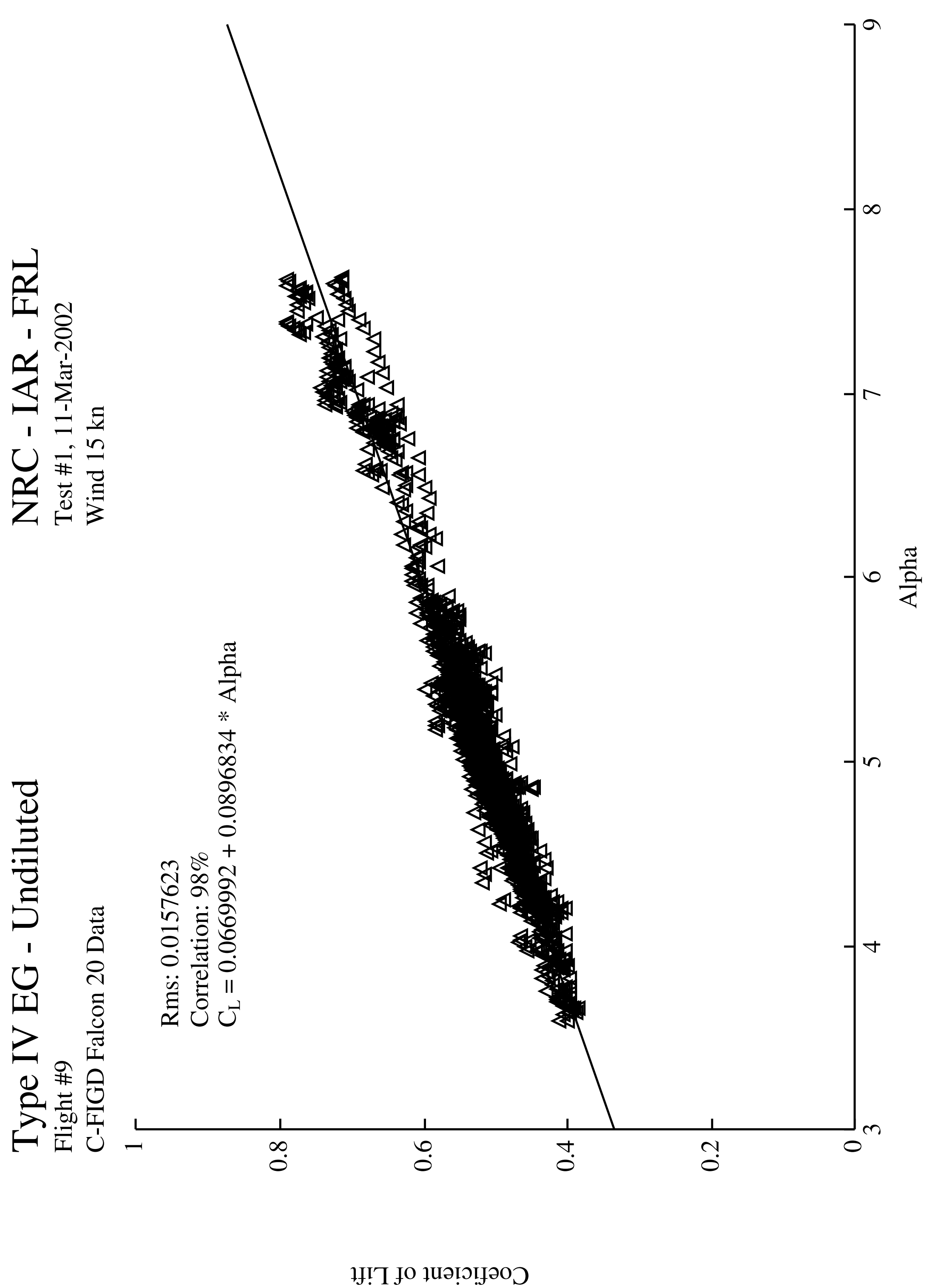

Type IV EG - Undiluted
Flight #7
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Test #4, 6-Mar-2002
Wind 3 kn
Rms: 0.00805504
Correlation: 99%
C_L = 0.0898658 + 0.0900067 * Alpha
1
0.8
0.6
0.4
0.2
0
3
4
5
6
7
8
9
Alpha
Coeficient of Lift

Figure 19



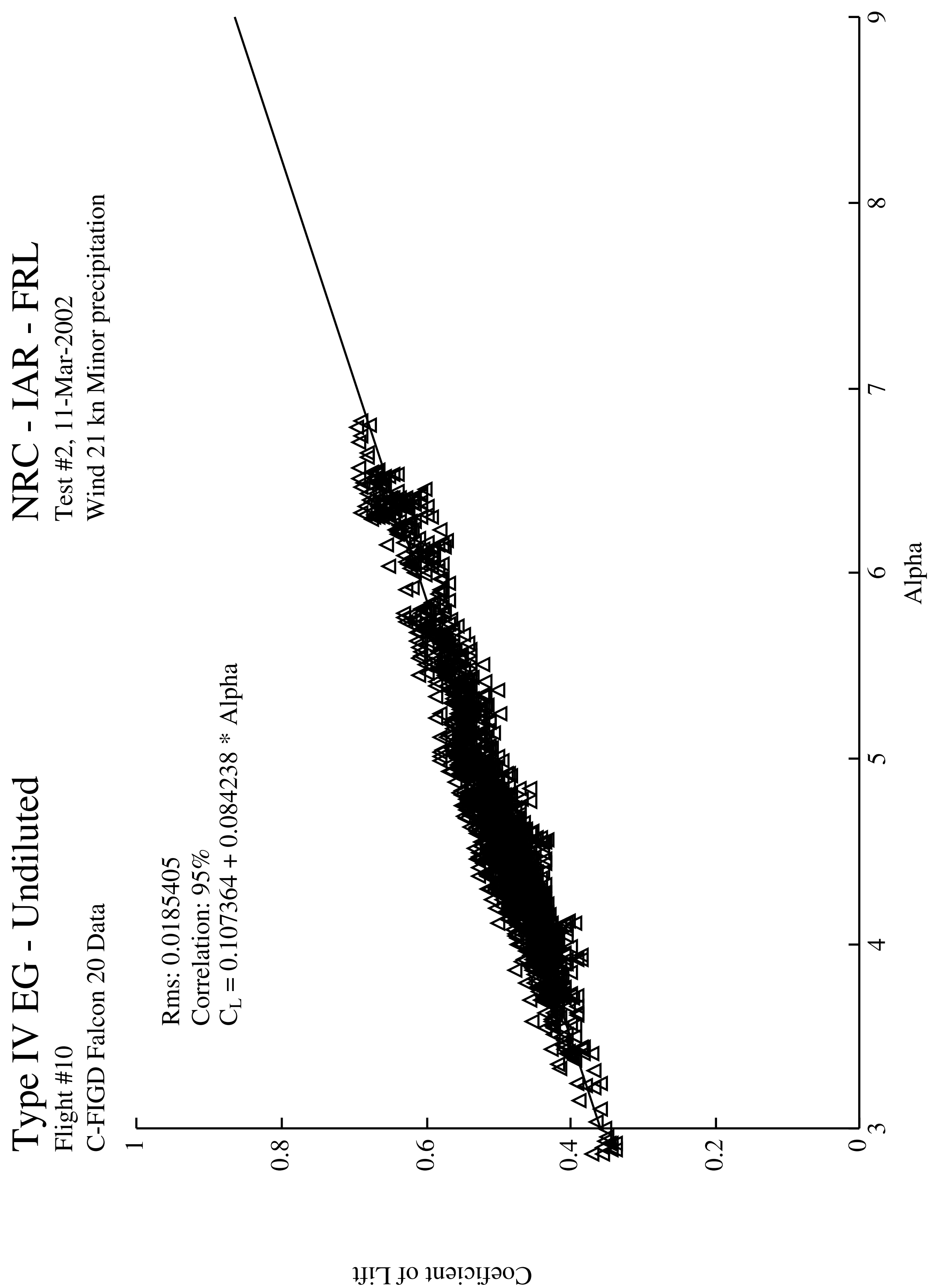
Type IV EG - Undiluted
Flight #8
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Test #5, 6-Mar-2002
Wind 3 kn
Rms: 0.011199
Correlation: 99%
C_L = 0.0960986 + 0.0856444 * Alpha
Coeficient of Lift
Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 20



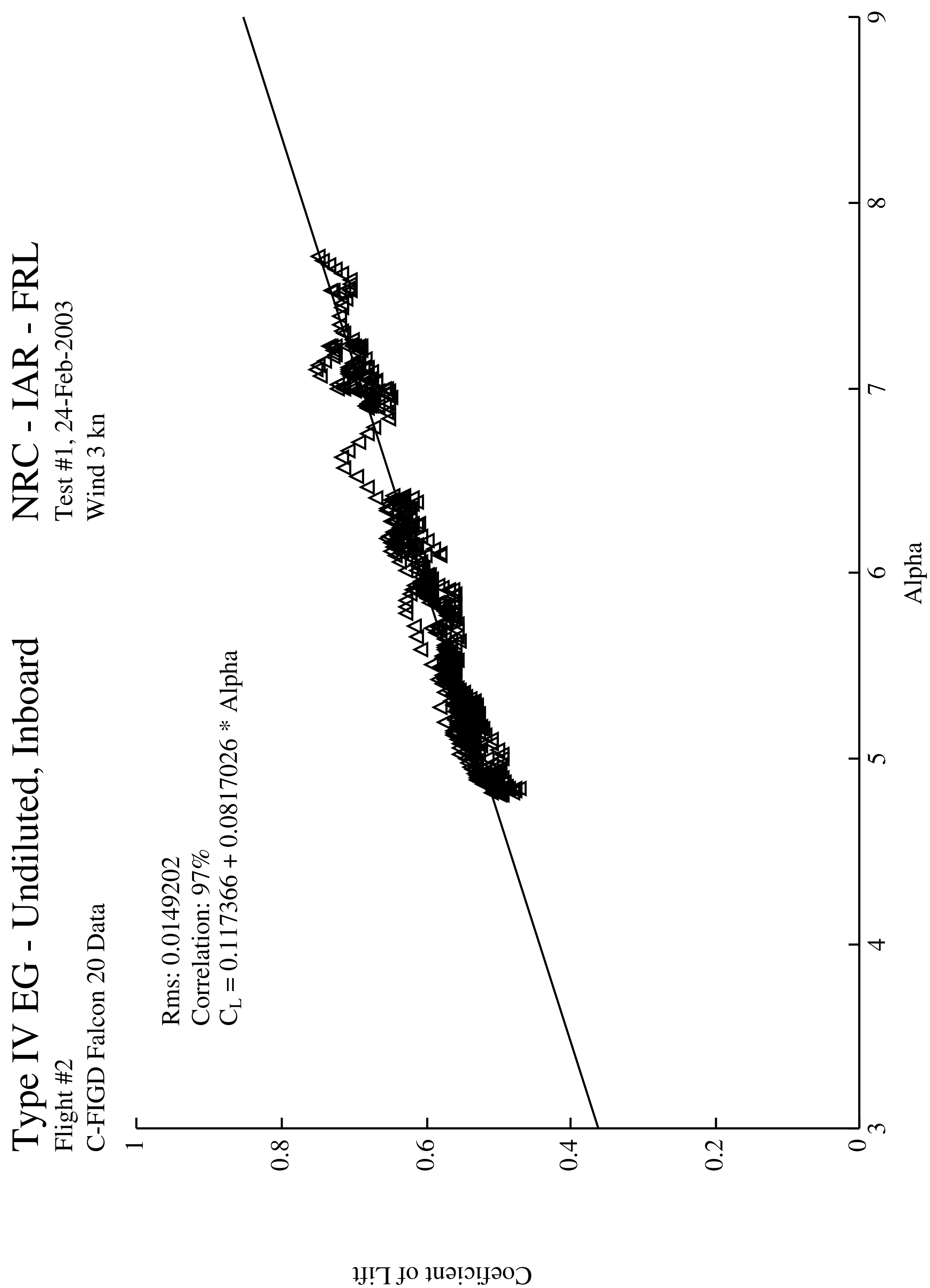
Type IV EG - Undiluted
Flight #9
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Test #1, 11-Mar-2002
Wind 15 kn
Rms: 0.0157623
Correlation: 98%
$C_L = 0.0669992 + 0.0896834 * Alpha$
Coeficient of Lift
Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 21



Type IV EG - Undiluted
Flight #10
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Test #2, 11-Mar-2002
Wind 21 kn Minor precipitation
Rms: 0.0185405
Correlation: 95%
C_L = 0.107364 + 0.084238 * Alpha
Coeficient of Lift
Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 22



Type IV EG - Undiluted, Inboard
Flight #2
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Test #1, 24-Feb-2003
Wind 3 kn
Rms: 0.0149202
Correlation: 97%
C_L = 0.1117366 + 0.0817026 * Alpha
1
0.8
0.6
0.4
0.2
0
3
4
5
6
7
8
9
Alpha
Coeficient of Lift

Figure 23

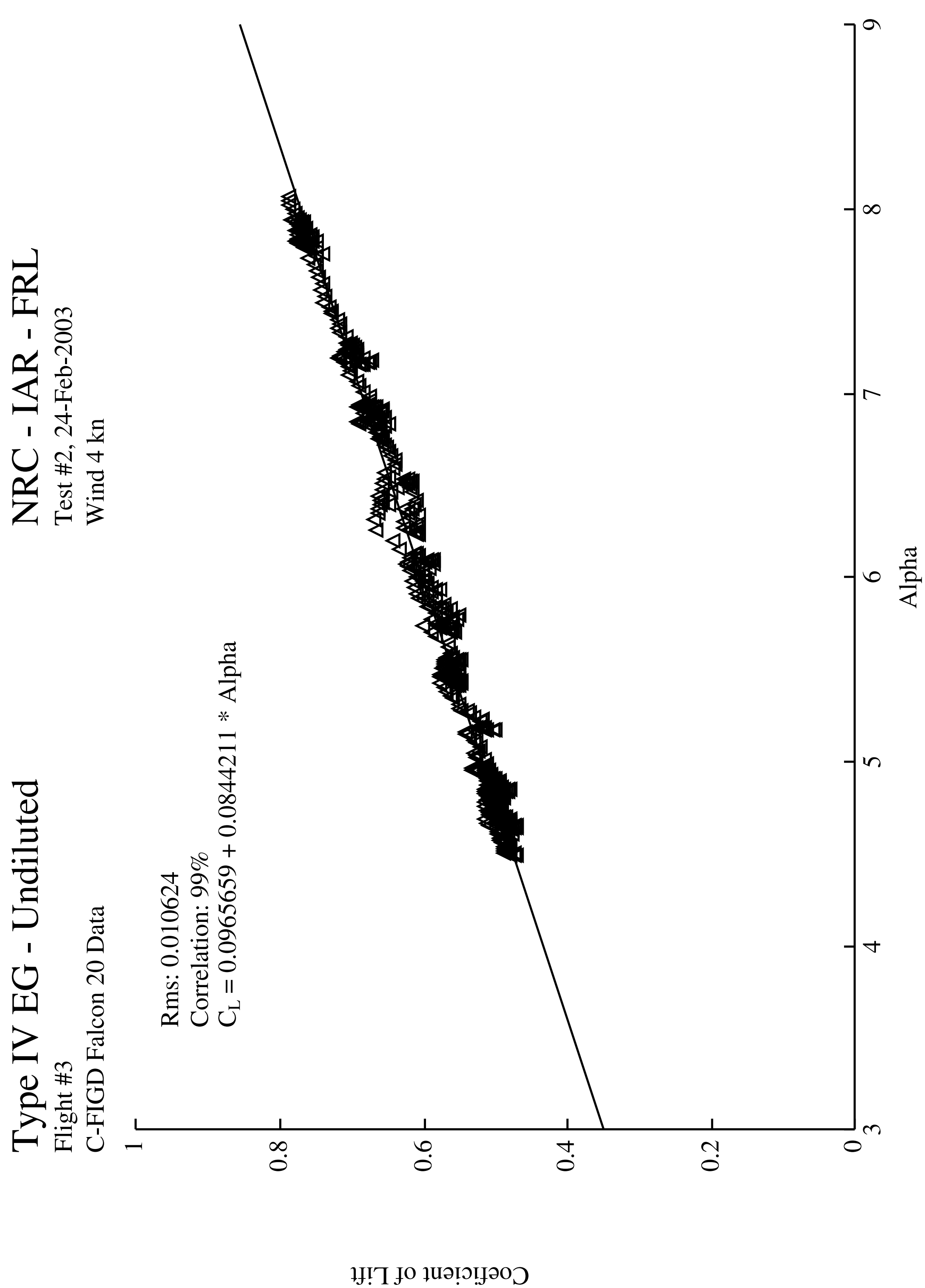
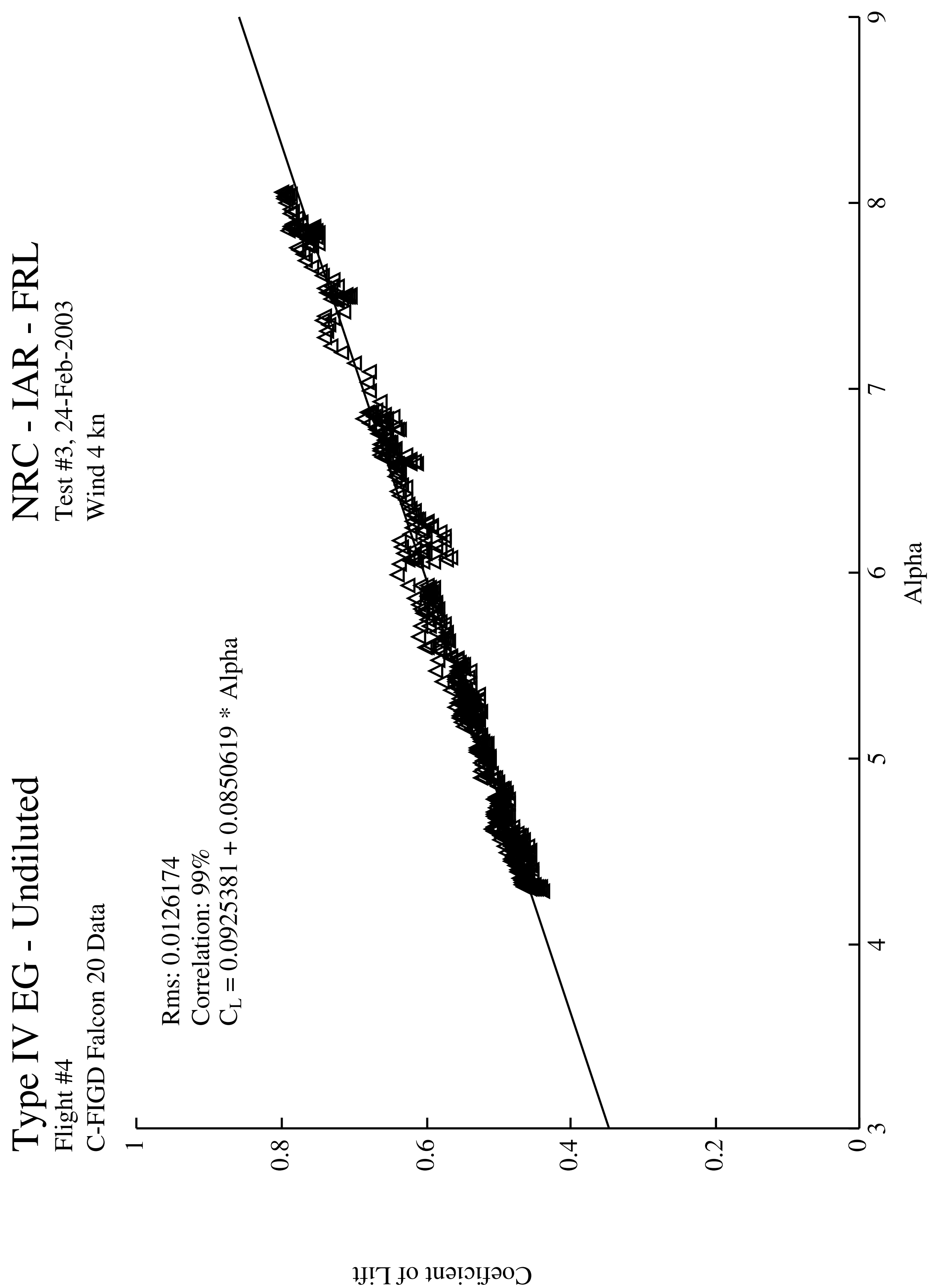
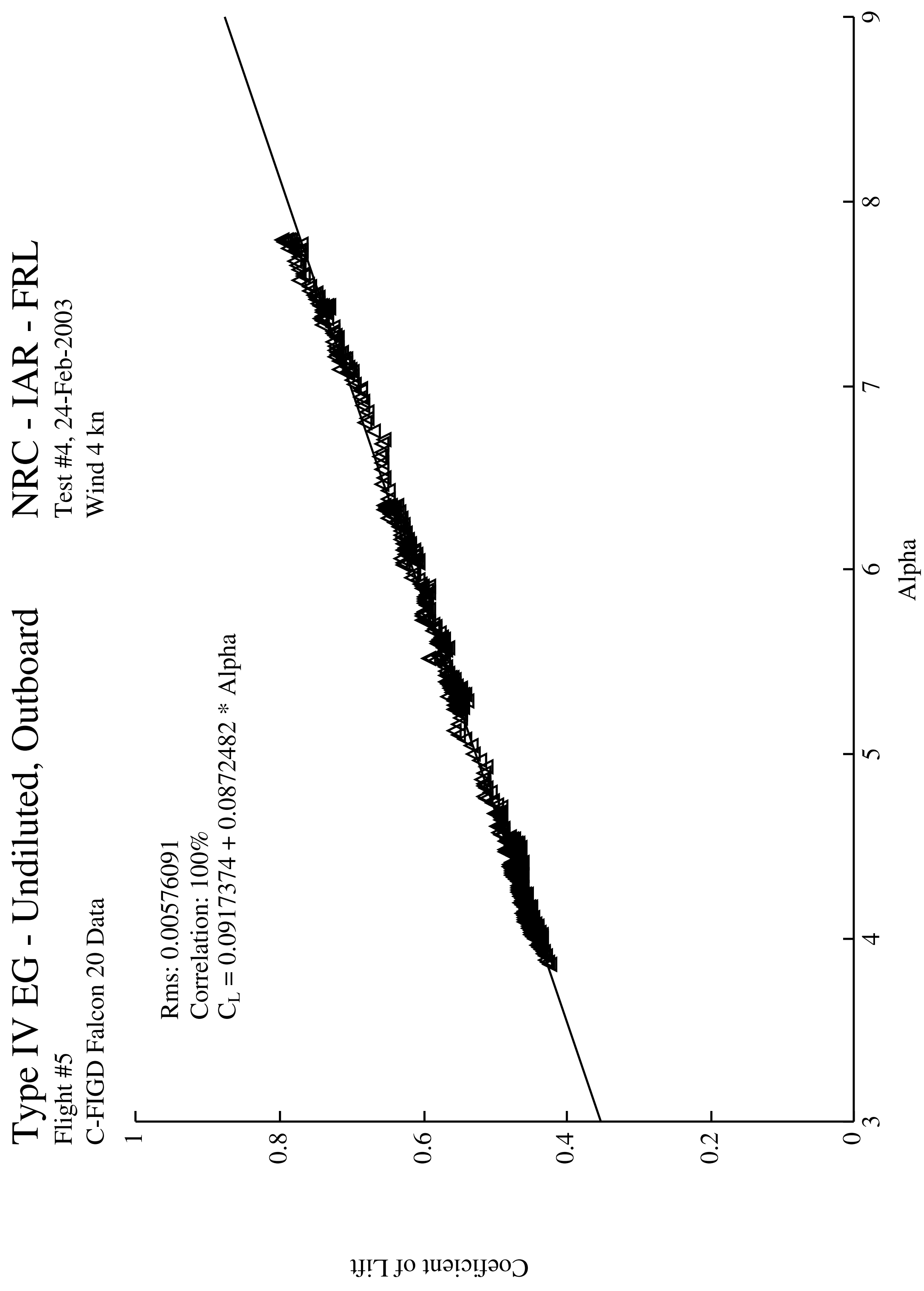

Type IV EG - Undiluted
Flight #3
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Test #2, 24-Feb-2003
Wind 4 kn
Rms: 0.010624
Correlation: 99%
C_L = 0.0965659 + 0.0844211 * Alpha
Alpha
Coeficient of Lift
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 24



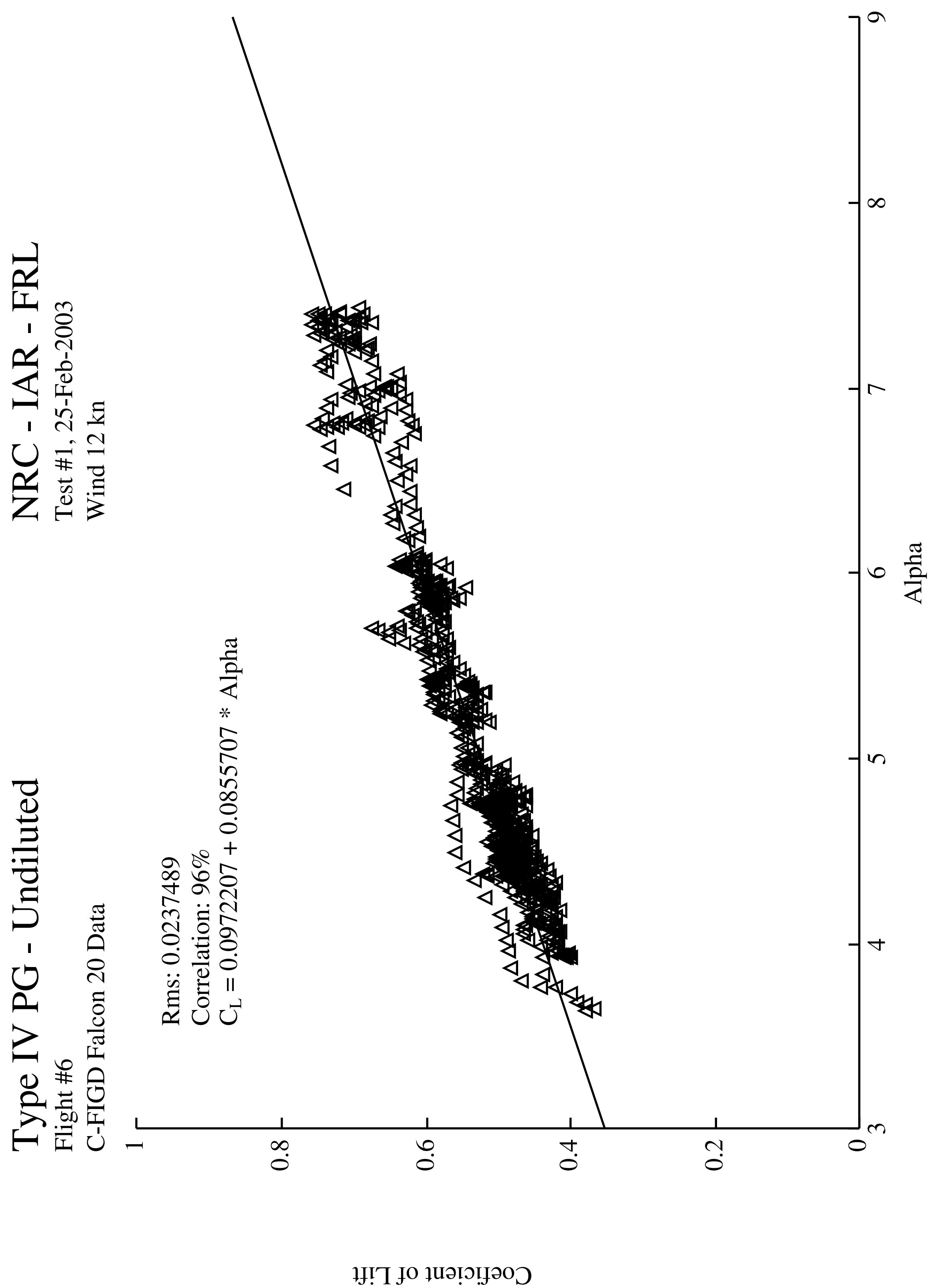
Type IV EG - Undiluted
Flight #4
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Test #3, 24-Feb-2003
Wind 4 kn
Rms: 0.0126174
Correlation: 99%
C$_L$ = 0.0925381 + 0.0850619 * Alpha
Coeficient of Lift
Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 25



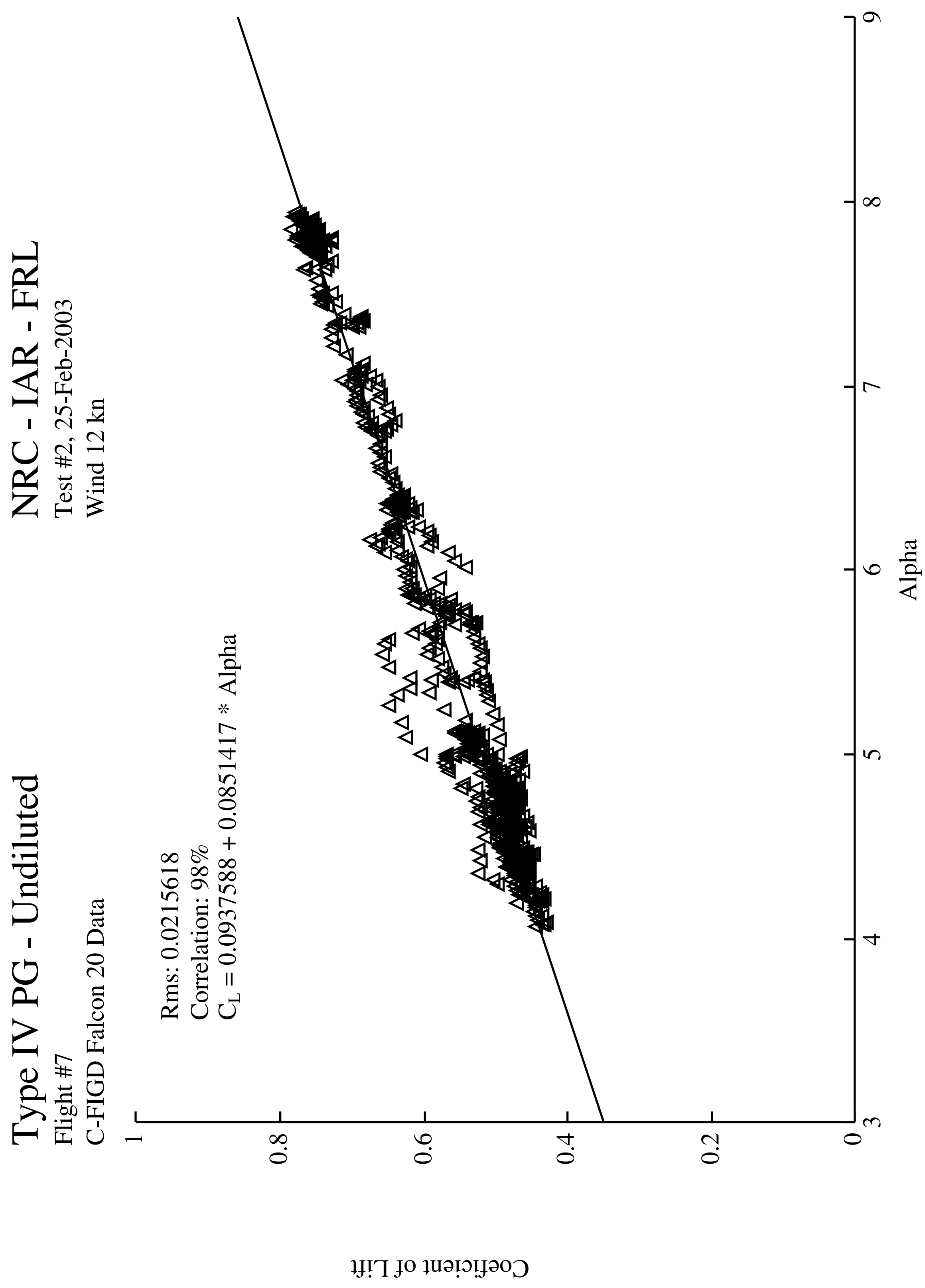
Type IV EG - Undiluted, Outboard
Flight #5
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Test #4, 24-Feb-2003
Wind 4 kn
Rms: 0.00576091
Correlation: 100%
C_L = 0.0917374 + 0.0872482 * Alpha
Coeficient of Lift
Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 26



Type IV PG - Undiluted
Flight #6
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Test #1, 25-Feb-2003
Wind 12 kn
Rms: 0.0237489
Correlation: 96%
C_L = 0.0972207 + 0.0855707 * Alpha
Alpha
Coeficient of Lift
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 27



Type IV PG - Undiluted
Flight #7
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Test #2, 25-Feb-2003
Wind 12 kn
Rms: 0.0215618
Correlation: 98%
C_L = 0.0937588 + 0.0851417 * Alpha
Coeficient of Lift
Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 28

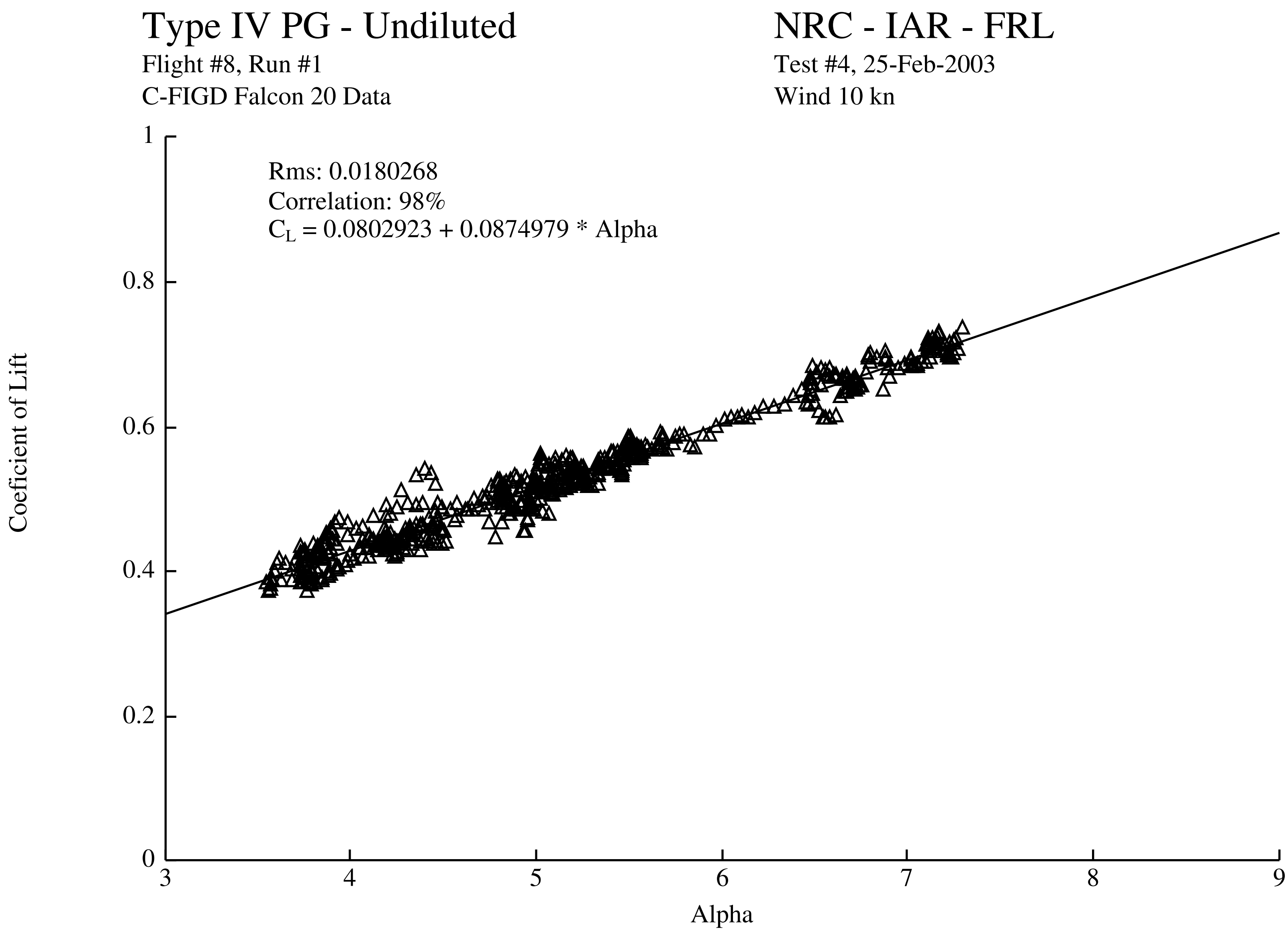

Type IV PG - Undiluted
Flight #8, Run #1
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Test #4, 25-Feb-2003
Wind 10 kn
Rms: 0.0180268
Correlation: 98%
C_L = 0.0802923 + 0.0874979 * Alpha
Coeficient of Lift
Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 29

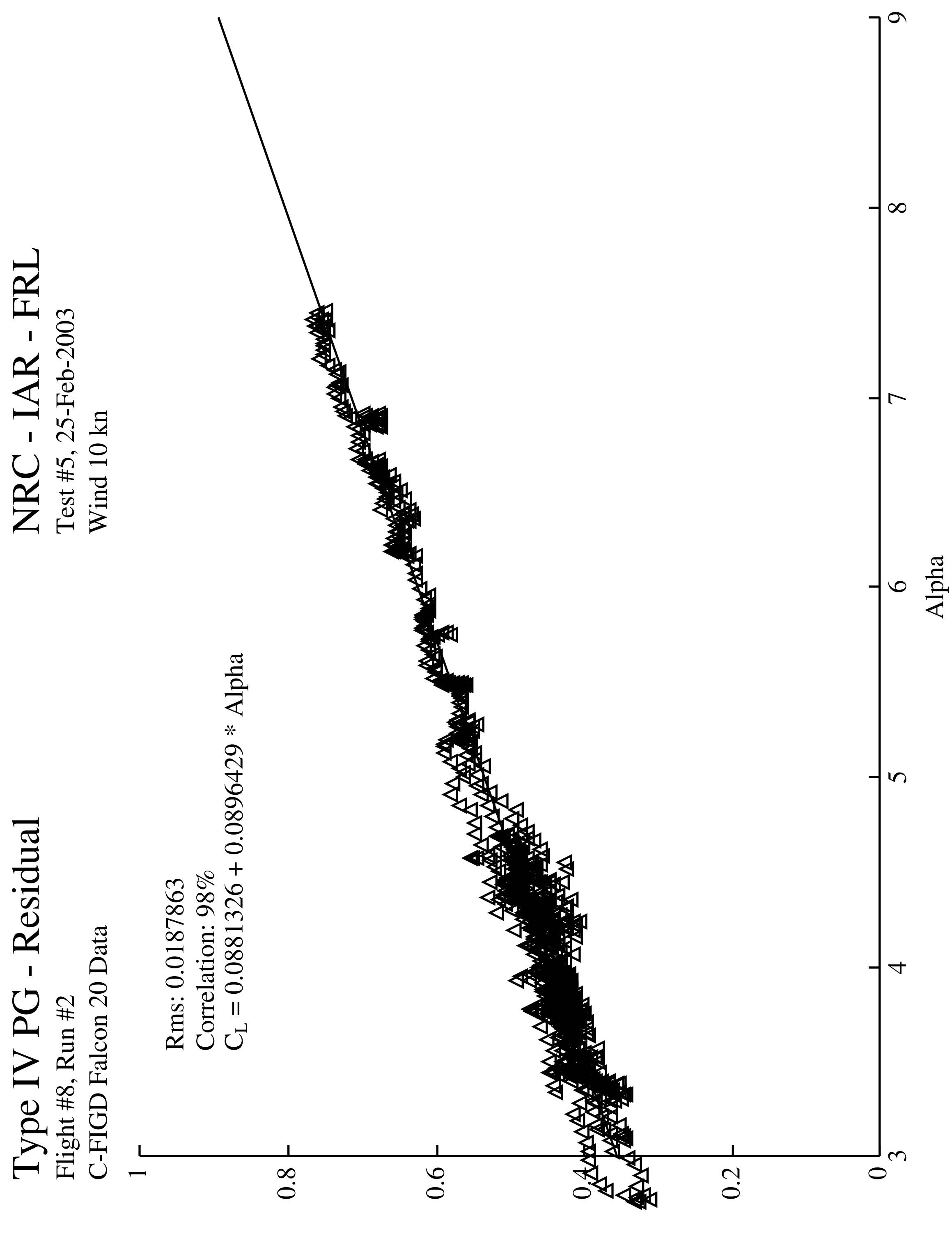

Type IV PG - Residual
Flight #8, Run #2
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Test #5, 25-Feb-2003
Wind 10 kn
Rms: 0.0187863
Correlation: 98%
C_L = 0.0881326 + 0.0896429 * Alpha
Coeficient of Lift
Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 30

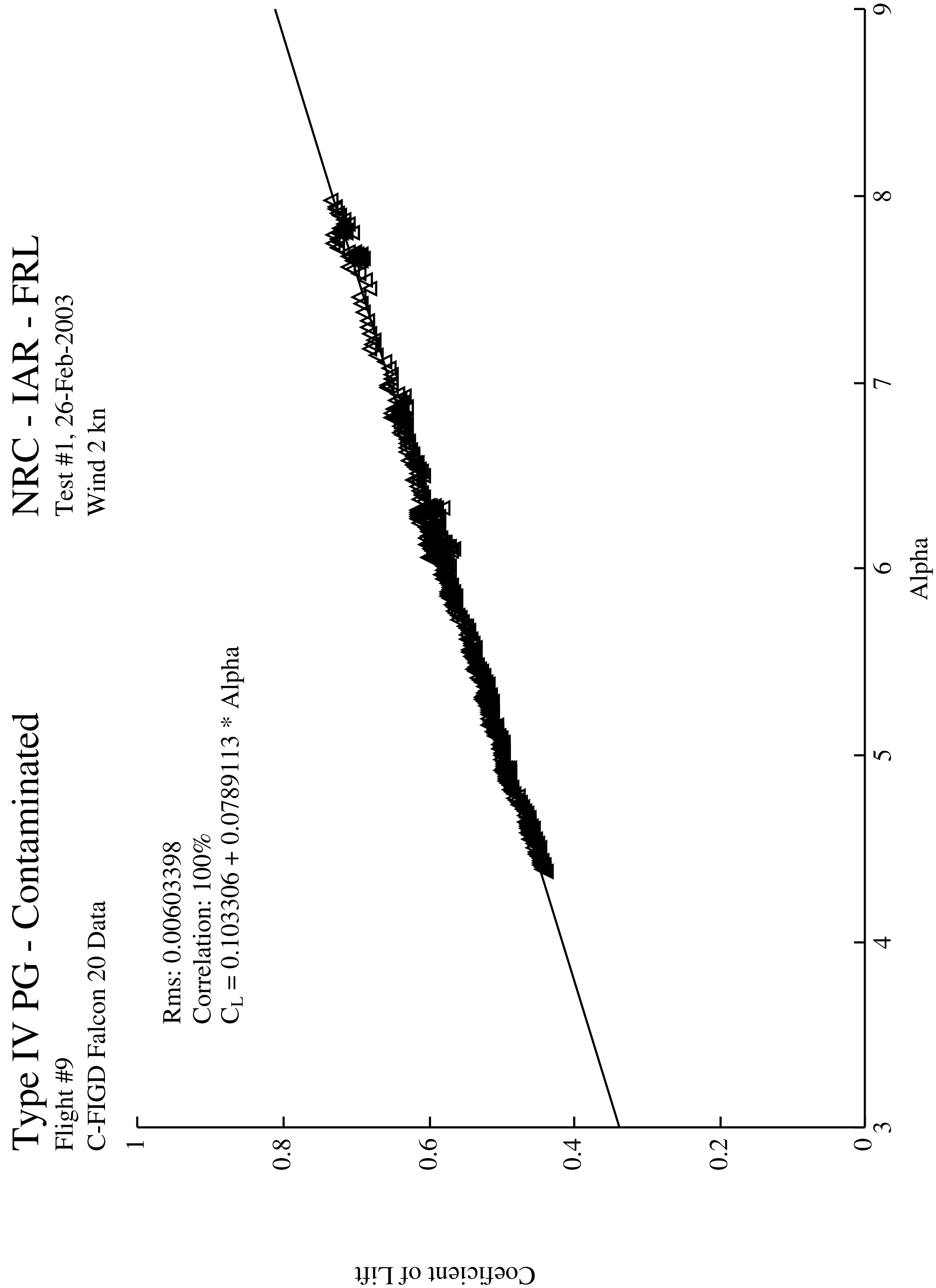
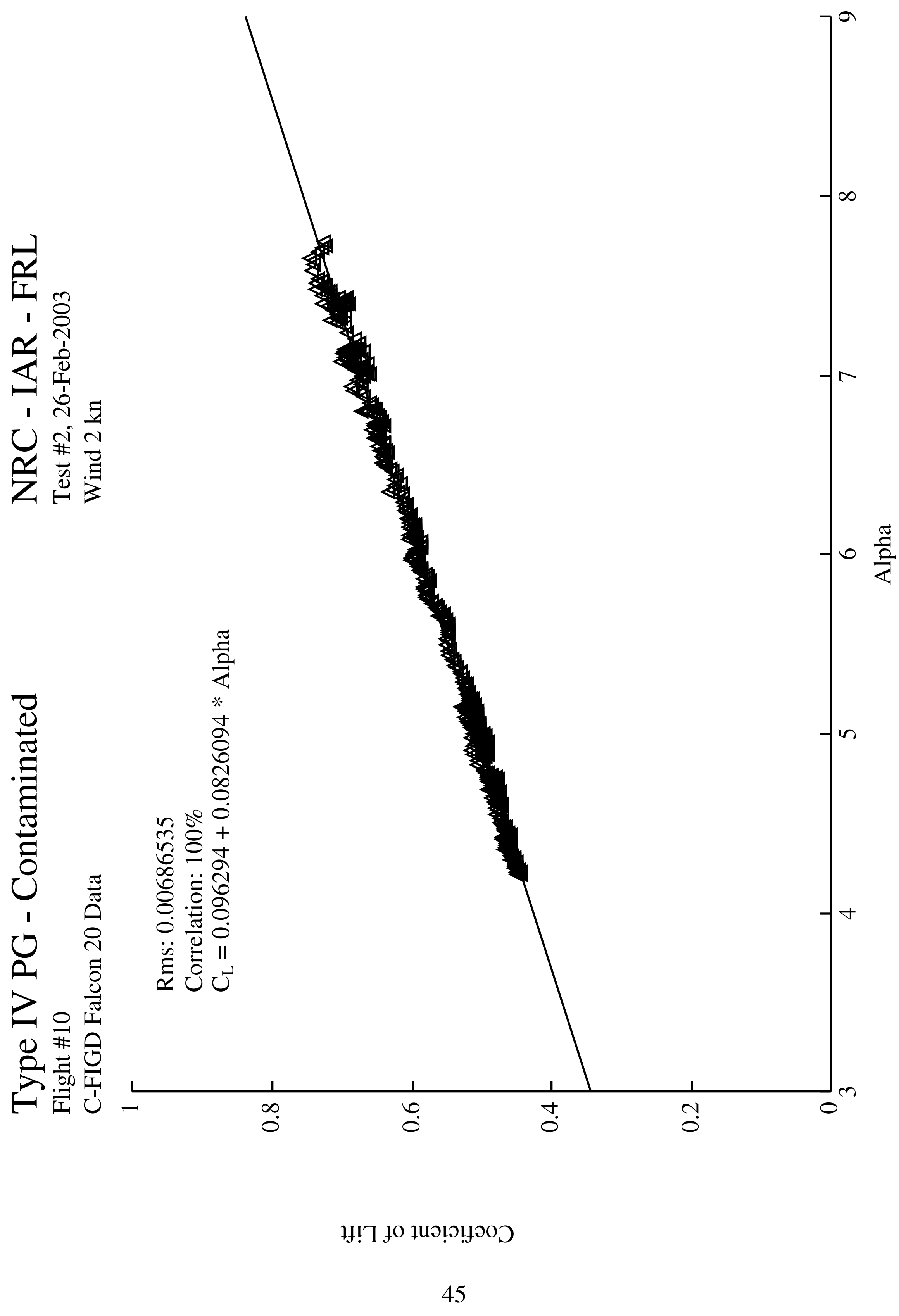
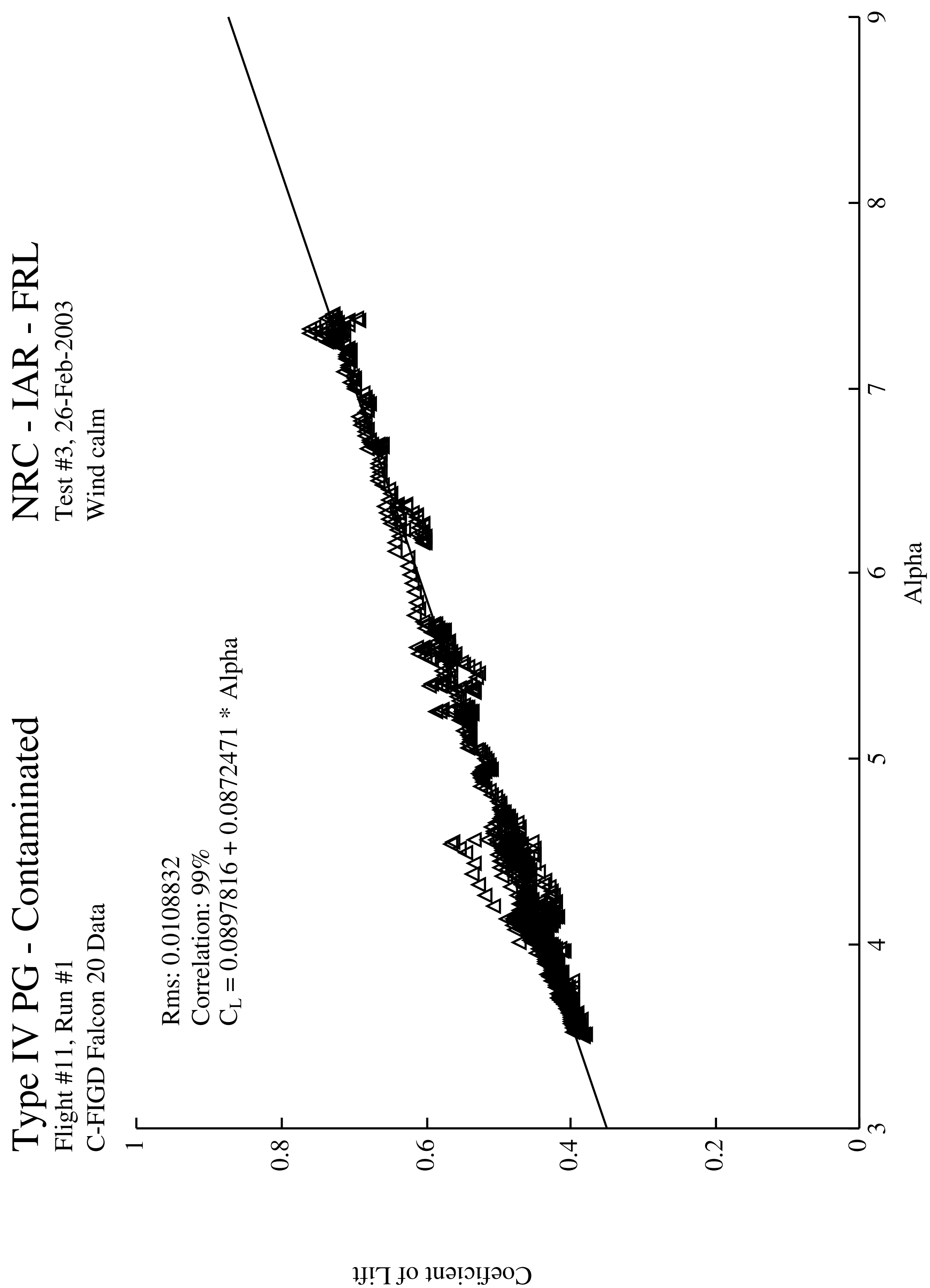

Type IV PG - Contaminated
Flight #9
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Test #1, 26-Feb-2003
Wind 2 kn
Rms: 0.00603398
Correlation: 100%
C_L = 0.103306 + 0.0789113 * Alpha
Alpha
Coeficient of Lift
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 31



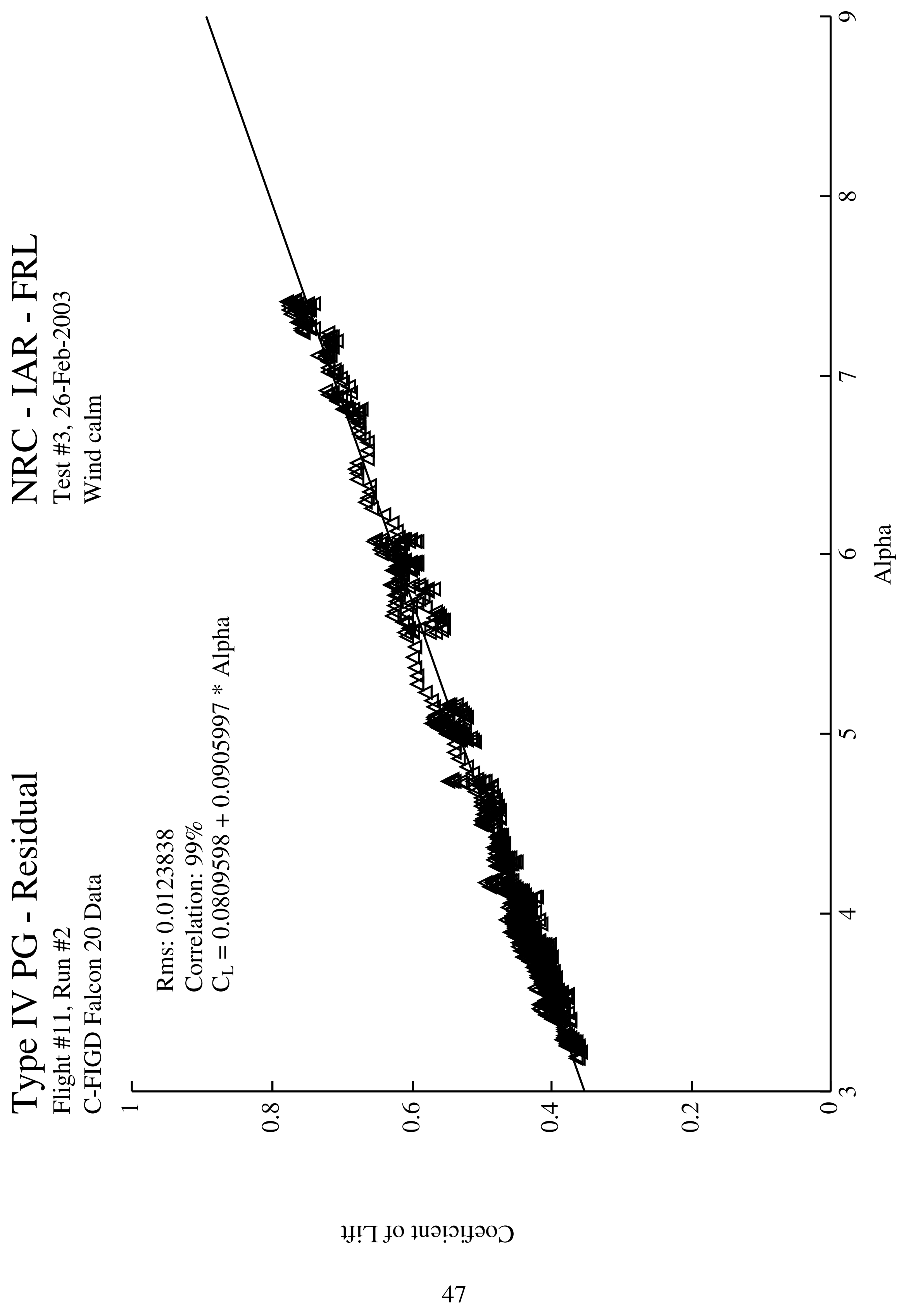
Type IV PG - Contaminated
Flight #10
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Test #2, 26-Feb-2003
Wind 2 kn
Rms: 0.00686535
Correlation: 100%
C_L = 0.096294 + 0.0826094 * Alpha
Alpha
Coeficient of Lift
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 32



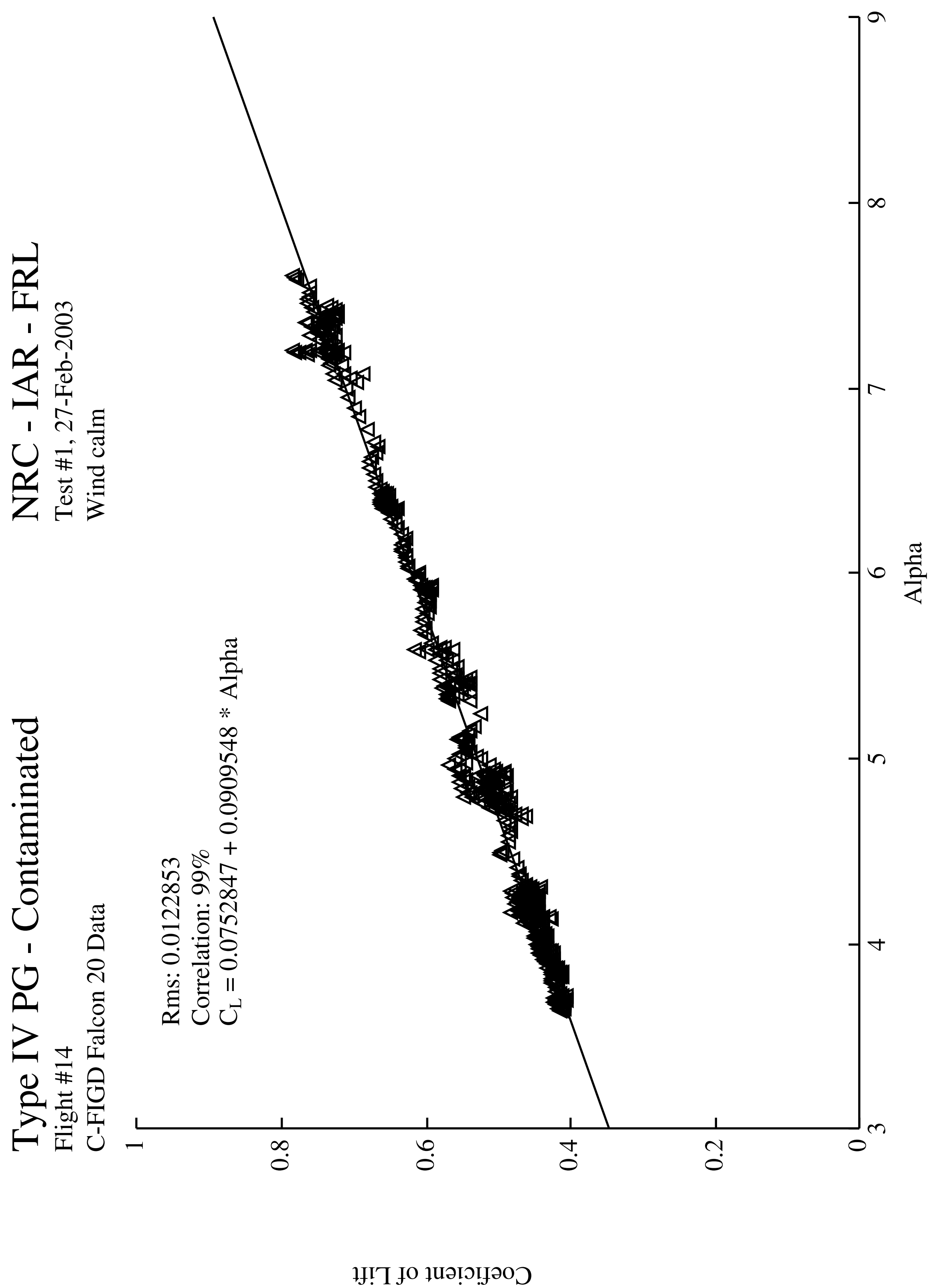
Type IV PG - Contaminated
Flight #11, Run #1
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Test #3, 26-Feb-2003
Wind calm
Rms: 0.0108832
Correlation: 99%
C_L = 0.0897816 + 0.0872471 * Alpha
Coeficient of Lift
Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 33



Type IV PG - Residual
Flight #11, Run #2
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Test #3, 26-Feb-2003
Wind calm
Rms: 0.0123838
Correlation: 99%
C_L = 0.0809598 + 0.0905997 * Alpha
Coeficient of Lift
Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 34


Type IV PG - Contaminated
Flight #14
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Test #1, 27-Feb-2003
Wind calm
Rms: 0.0122853
Correlation: 99%
C_L = 0.0752847 + 0.0909548 * Alpha
Coeficient of Lift
Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

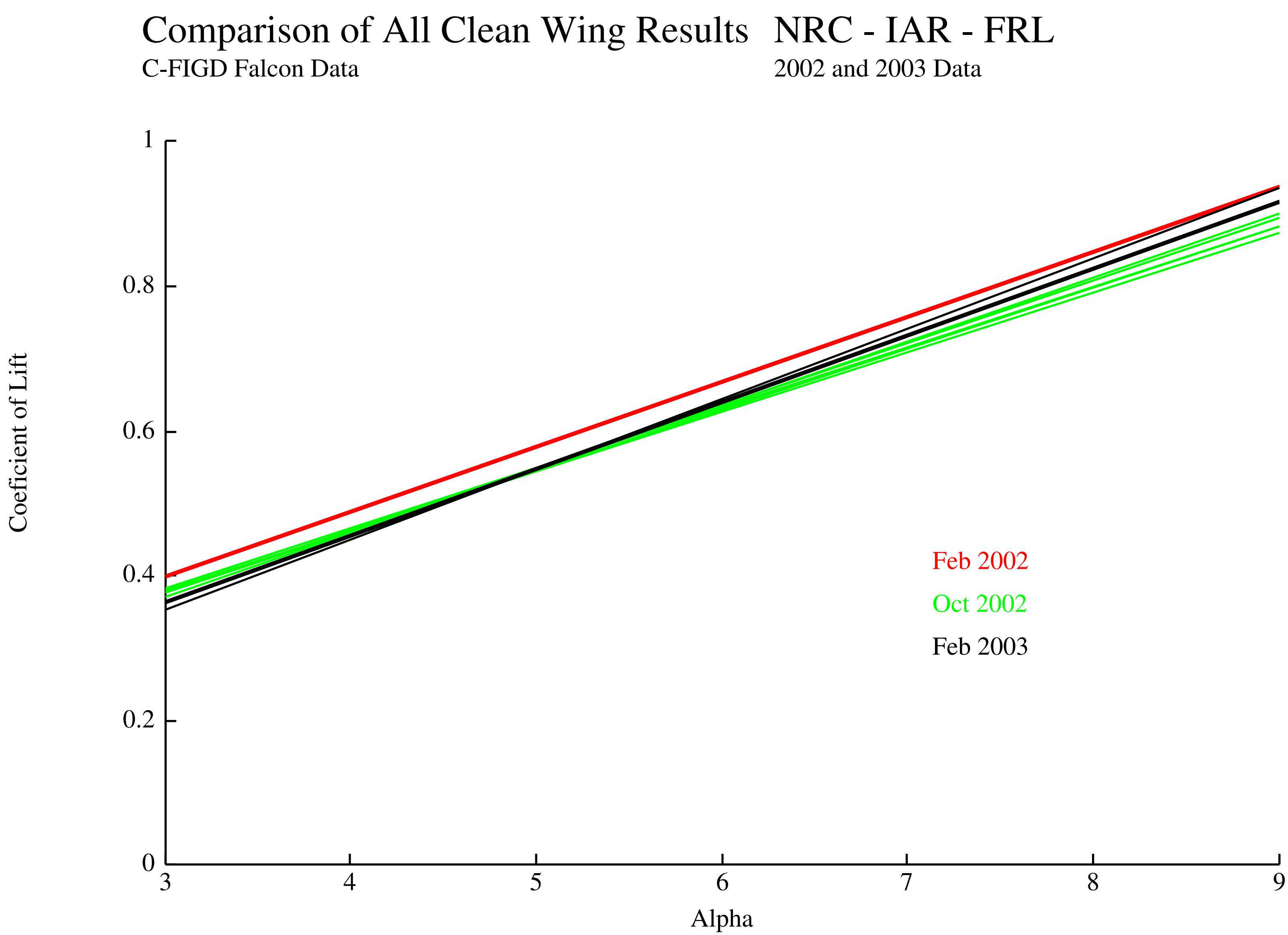

Comparison of All Clean Wing Results NRC - IAR - FRL
C-FIGD Falcon Data
2002 and 2003 Data
Coeficient of Lift
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9
Alpha
Feb 2002
Oct 2002
Feb 2003

Figure 35

Figure 36

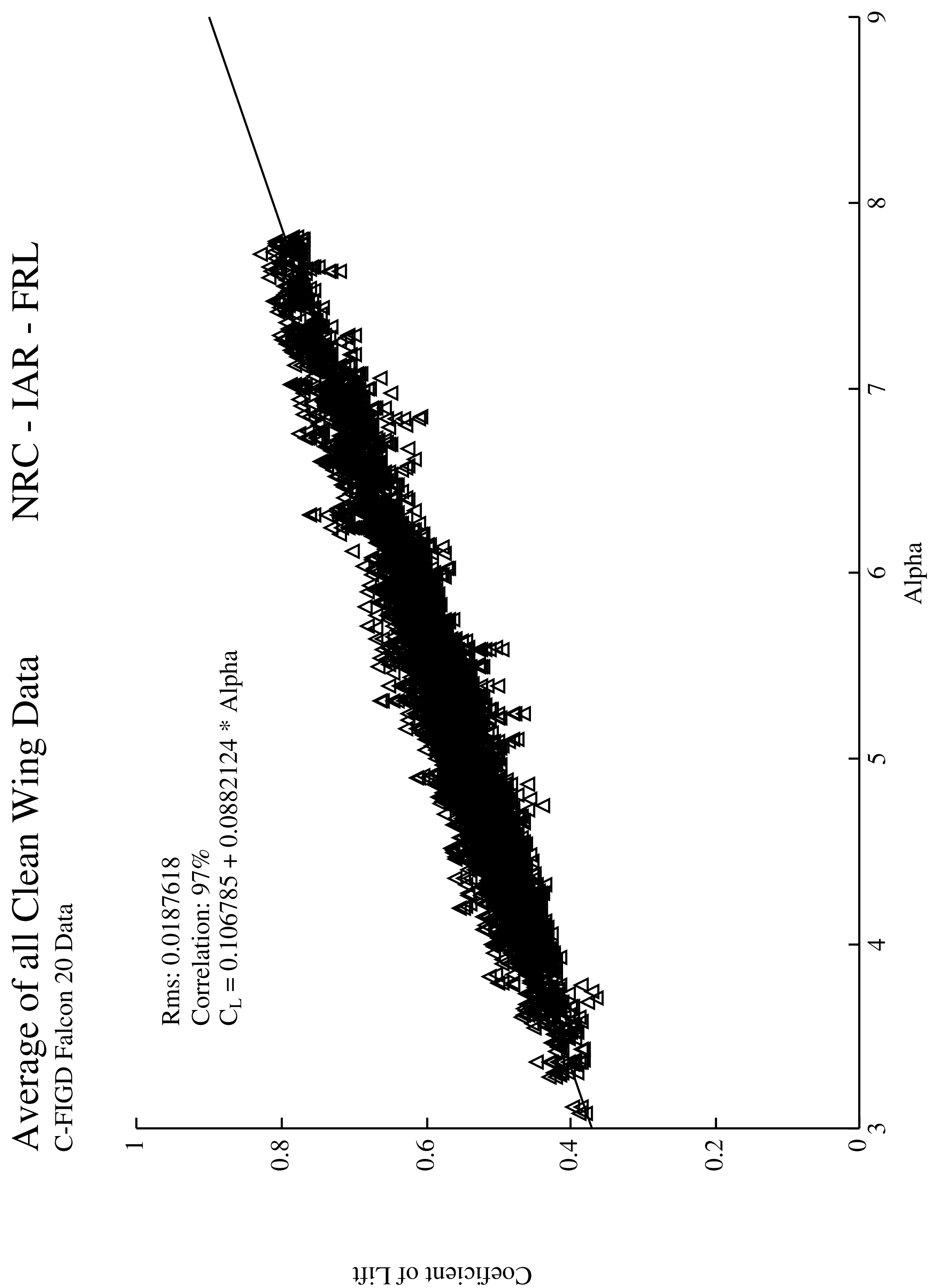

Average of all Clean Wing Data
C-FIGD Falcon 20 Data
NRC - IAR - FRL
Rms: 0.0187618
Correlation: 97%
C_L = 0.106785 + 0.0882124 * Alpha
Alpha
Coeficient of Lift
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 37

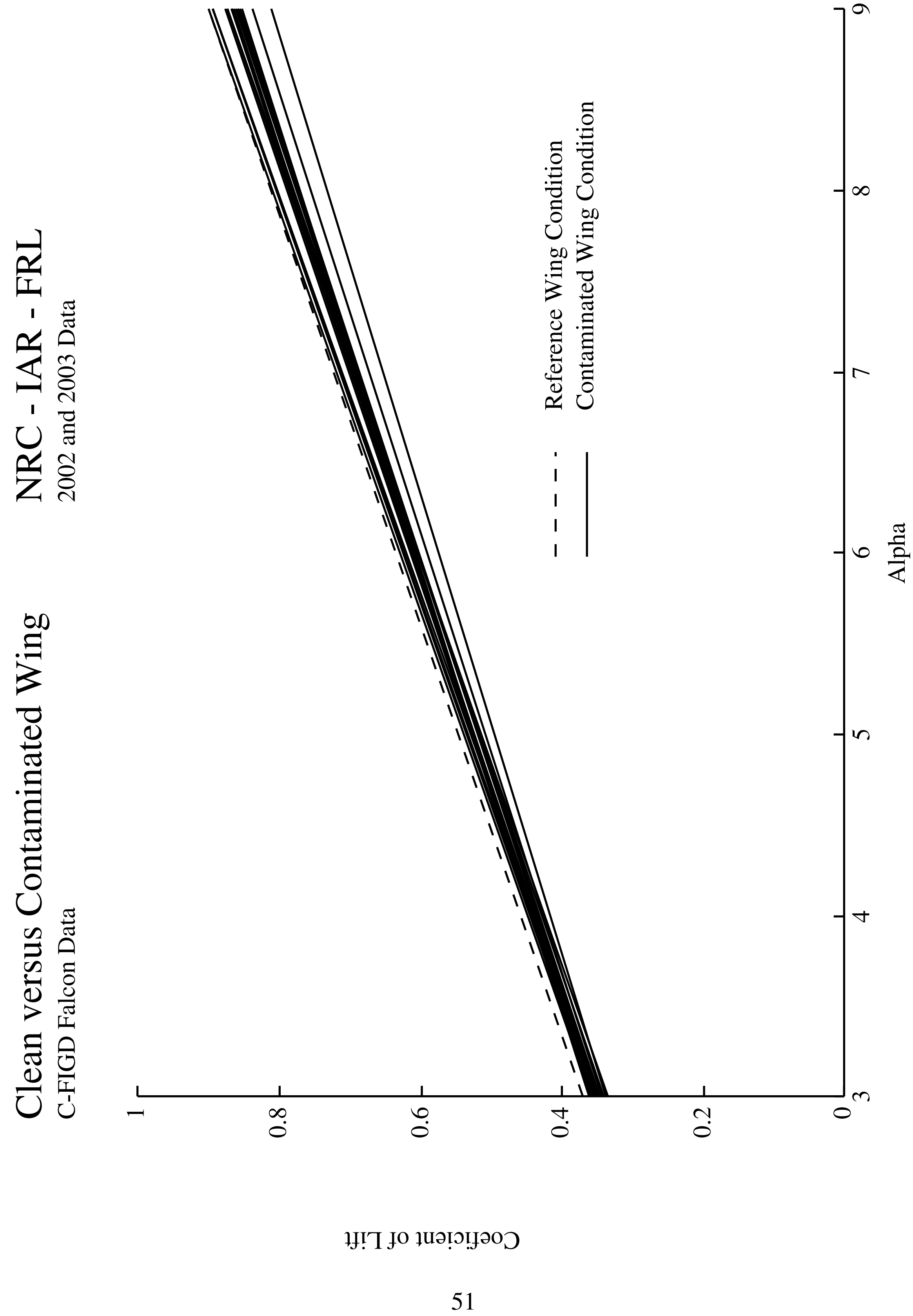
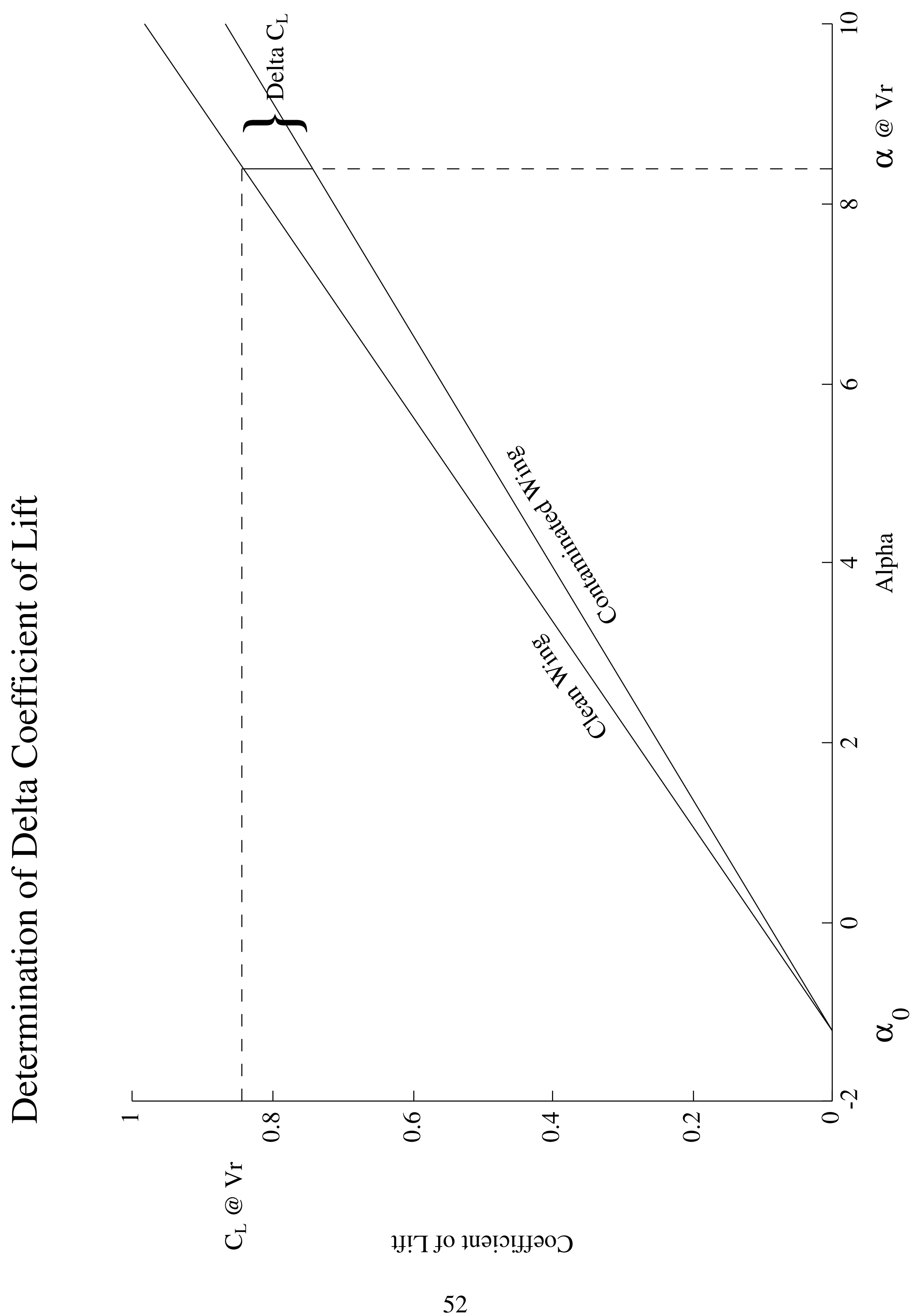

Clean versus Contaminated Wing
C-FIGD Falcon Data
NRC - IAR - FRL
2002 and 2003 Data
Reference Wing Condition
Contaminated Wing Condition
Coeficient of Lift
Alpha
0
0.2
0.4
0.6
0.8
1
3
4
5
6
7
8
9

Figure 38



Determination of Delta Coefficient of Lift
Coefficient of Lift
CL @ Vr
Alpha
α @ Vr
α0
Clean Wing
Contaminated Wing
Delta CL
0
0.2
0.4
0.6
0.8
1
-2
0
2
4
6
8
10

Comparison of RMS Error and Wind Speed

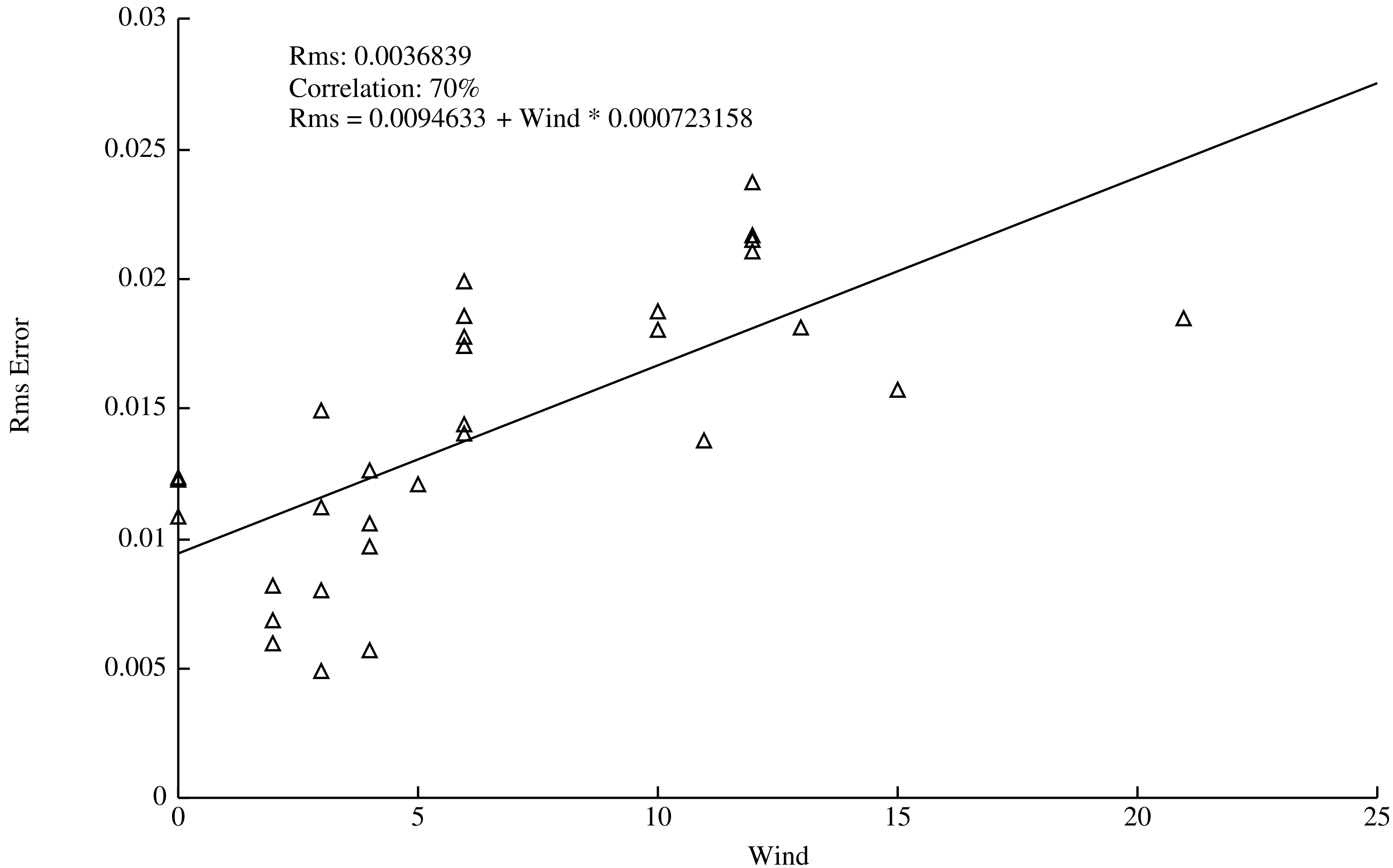


Figure 39

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3.	M. Chaput	Aircraft Takeoff Test Program for Winter 2002-2003: Testing to Evaluate the Aerodynamic Penalties of Clean or Partially Expended De/Anti-icing Fluid. Transportation Development Centre, TP14147E, Noveber 2003
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