AIR DATA SYSTEM CALIBRATION FOR MILITARY TRANSPORT AIRCRAFT MODERNIZATION PROGRAM

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
AEROSPACE ENGINEERING

JANUARY 2013

Approval of the thesis:

AIR DATA SYSTEM CALIBRATION FOR MILITARY TRANSPORT AIRCRAFT MODERNIZATION PROGRAM

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ABSTRACT

AIR DATA SYSTEM CALIBRATION FOR MILITARY TRANSPORT AIRCRAFT MODERNIZATION PROGRAM

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January 2013, 45 pages

This thesis presents the calibration processes of the pitot-static system, which is a part of the air data system of a military transport aircraft through flight tests. Tower fly-by method is used for air data system calibration. Altitude error caused by the position of the static port on the aircraft is determined by analyzing the data collected during four sorties with different weight, flap and landing gear configurations. The same data has been used to determine the airspeed measurement error. It has been shown that both the altitude and airspeed errors are within the allowable limits specified by FAR 25. Same method is also used for trailing cone calibration that is used for high altitude test flights for RVSM certification.

Keywords: Flight Test, Tower Fly-By, Trailing Cone, Air Data System, Calibration, Pitot-Static System, Position Error.

ÖZ

ASKERİ NAKLIYE UÇAĞI MODERNİZASYON PROGRAMI İÇİN HAVA VERİ SİSTEMİ KALİBRASYONU

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Ocak 2013, 45 sayfa

Bu çalışmada modernizasyon projesi kapsamında bir askeri nakliye uçağına entegre edilmiş olan hava veri sisteminin uçuş testleri ile kalibrasyon süreci incelenmiştir. Hava veri sisteminin kalibrasyonu için kule geçişi metodu kullanılmıştır. Statik portun yerleşiminden kaynaklı oluşan irtifa hatası farklı ağırlıklarda, farklı iniş takımı ve flap konfigürasyonlarında yapılan dört sortilik test uçuşları sonrasında elde edilen verilerin analizi ile belirlenmiştir. Aynı verinin analizi ile bu hatanın hava hızı gösteriminde yol açtığı hata da bulunmuştur. Sistem tarafından sağlanan değerler FAR-25 sertifikasyonu açısından incelenmiştir. Aynı metot ile RVSM sertifikasyonu için gerekli yüksek irtifa testlerini yapmak için kullanılacak takip konisinin de kalibrasyonu yapılmıştır.

Anahtar Kelimeler: Uçuş Testi, Kule Geçişi, Takip Konisi, Hava Veri Sistemi, Kalibrasyon, pitot – statik sistem, pozisyon hatası.

to my family

ACKNOWLEDGEMENTS

I would like to express my great appreciation to my advisor Prof. Dr. Serkan ÖZGEN for supporting me. I'm grateful for his valuable understanding and help through my thesis period.

My grateful thanks are also extended for my supervisors and colleagues for providing me wonderful working atmosphere and give me chance to be a part of this exciting job.

I would like to offer my special thanks to Hasan Cemal SARGIN, Emre Can KAYA and Metehan YAYLA and my other colleagues for their valuable support on flight testing and analysis periods.

And finally, I would like to send my greatest appreciation to my family for their support, thrust and making everything much more meaningful.

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LIST OF ABBREVIATIONS

A/C	Aircraft
ADC	Air Data Computer
AFCS	Automatic Flight Control System
AFM	Aircraft Flight Manual
ASE	Altimetry Source Error
ASI	Air Speed Indicator
C.G.	Center of Gravity
CS	Certification Specifications
FAR	Federal Aviation Regulations
FL	Flight Level
fps	Frame per second
GPS	Global Positioning System
IAS	Indicated Air Speed
KIAS	Knots Indicated Air Speed
L/G	Landing Gear
MTOW	Maximum Takeoff Gross Weight
PEC	Position Error Correction
RVSM	Reduced Vertical Separation Minima (Minimum)
TAS	True Air Speed
TGOW	Take-off Gross Weight
VSI	Vertical Speed Indicator

LIST OF SYMBOLS

Symbol	Description	Unit
$\Delta H_{icA/C}$	Calibration value for pressure altitude of the aircraft	ft
$\Delta H_{ictower}$	Calibration value for pressure altitude of the tower	ft
ΔH_{pec}	Error in pressure altitude due to position error	ft
ΔP_d	Dynamic Pressure Error	psi
ΔP_s	Static Pressure Error	psi
ΔV_{pec}	Error in air speed due to position error	kt
g	Gravitational Acceleration	m/s^2
$h_{A/C}$	Height of the aircraft above reference line	ft
$H_{A/C}$	Actual pressure altitude of the aircraft	ft
H_{cref}	Actual Pressure altitude of the reference line	ft
H_{ctower}	Calibrated pressure altitude of the tower	ft
$H_{iA/C}$	Aircraft's indicated pressure altitude	ft
H_{itower}	Pressure altitude of the tower	ft
h_{offset}	Elevation between reference line and tower ground line	ft
h_{px}	Height of the aircraft in photo	px
$L_{A/C}$	Real length of the aircraft	ft
L_{px}	Length of the aircraft in photo	px
P_{ground}	Pressure measured at tower ground line	psi
T_{Ground}	Temperature mesasured at the tower ground	°K
$T_{iA/C}$	Aircraft's indicated temperature	°K
T_{itower}	Tower temperature	°K
T_s	Standard day absolute temperature at the test altitude	°K
T_t	The test day temperature	°K
V_c	Calibrated air speed for instrument and position errors	kt
$V_{iA/C}$	Aircraft's indicated airspeed	kt
V_{ic}	Indicated airspeed of the aircraft corrected for instrument errors	kt
V_{S0}	Stall speed or minimum flight speed in landing configuration	kt
V_{S1}	Stall speed or minimum steady flight speed for which the aircraft is still controllable in a specific configuration	kt
V_{wic}	Indicated airspeed of the aircraft after weight correction	kt
W_s	Standard aircraft weight	lb
W_t	Test weight of the aircraft	lb
θ	Relative angle between zero grid line and aircraft flight line	°

Symbol	Description	Unit
ρ	Density of air	kg/m^3
P_0	Density of air at sea level	kg/m^3
σ	Density ratio	-
ΔV_{pec}	Error in air speed altitude due to position error	kt
$V_{iA/C}$	Aircraft indicated airspeed	kt
ΔH_{icref}	Calibration value for pressure altitude reference system	ft
$\Delta H_{T/C}$	Pressure altitude error of trailing cone	ft
$P_{T/C}$	Static pressure reading of trailing cone	psi
H_{TFB}	Actual pressure altitude obtained by tower fly by	ft
$\overline{V}$	Average value of samples	-
S	Standard deviation	-
δ_1 & δ_2	Deviations	-
$V_{largest}$	Largest value of the samples	-
$V_{smallest}$	Smallest value of the samples	-
V_{NE}	Never exceed speed	kt
V_{MO}	Maximum operating air speed	kt

CHAPTER 1

INTRODUCTION

1.1. Pitot – Static System

Pitot-static system on an aircraft basically consists of pressure sensitive systems. It is one of the vital systems for air vehicles and consists of the pitot tube, static port(s) and pitot – static instruments, Basic pitot static system components are seen in Figure 1 [3]

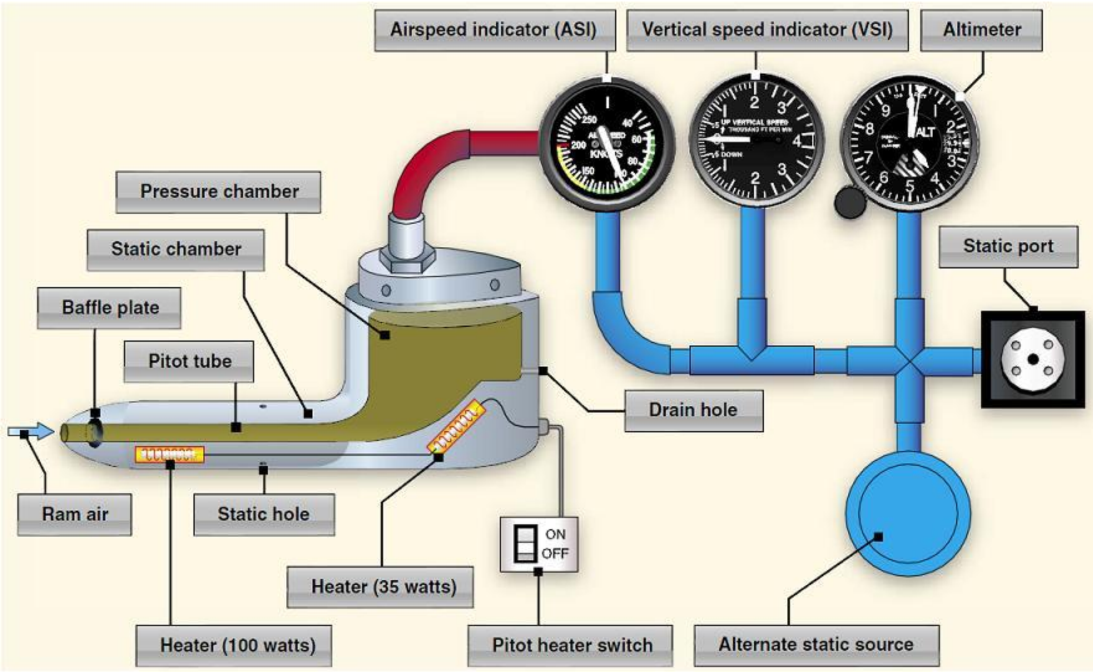

Figure 1 Basic Pitot - Static System.

The pitot-static system is a combined system that utilizes the static air pressure, and the dynamic pressure due to the motion of the aircraft through the air. These combined pressures are utilized for the operation of the airspeed indicator (ASI), altimeter, and vertical speed indicator (VSI), which are three of the six basic instruments in the cockpit of an air vehicle [3]. Therefore, the pitot-static pressure system must operate free of errors and provide accurate information to the pilot because the readings of the altimeter and the airspeed indicator are directly related to the safety of flight and performance.

Altimeter or the barometric altimeter determines the altitude of the aircraft according to the changes in the air pressure, since the pressure is a function of altitude. The altimeter is directly connected to the static port and the mechanism inside the altimeter is calibrated to indicate an altitude value for the sensed pressure.

Vertical speed indicator or the variometer shows the rate of change of altitude of the aircraft. Like the altimeter, vertical speed indicator is also connected to static port. Its mechanical structure allows indicating the rate of change in the static pressure that determines the vertical speed. Level flight can be attained with this instrument.

In addition to the altimeter and vertical speed indicator, airspeed indicator is also connected to the static port as well as pitot sources. Total pressure is obtained from the pitot sources, which is sometimes called total source. Using the total pressure from pitot and the static pressure from static source, dynamic pressure can be found which the difference between total and the static pressures. Airspeed can be found through the dynamic pressure, since it is directly proportional with the airspeed. Mechanical structure in the air speed indicator is capable of sensing the pressure difference between the sources and is calibrated to show this difference as the airspeed.

1.2. Air Data Computer

In modern aircraft avionic architectures, the pitot static system is connected to the air data computer as a replacement for pitot static instruments. Besides the basic instruments, air data computers can determine calibrated values for altitude, air speed, vertical speed using the input data from the pitot-static system.

Figure 2 Basic Air Data Computer.

Air data computers (ADC) are basically fed by the static and total pressures provided by the pitot static system's static and pitot sources. Ports for the pitot and static source can be easily seen in Figure 2 – Basic Air Data Computer [9]. In modern avionic architectures, air data computers generally receive the total air temperature from the total air temperature sensors of the aircraft also. With this data they can determine the true air speed (TAS) that is an important parameter for navigational calculations.

Outputs of the air data computer are visualized and shown to flight crew on digital displays. Especially for the modern systems, outputs are also important for other avionic components like automatic flight control systems or flight management systems.

1.3. Position Error

When a pitot static system like the one shown in Figure 1 [3] is examined, the instruments, lines, pitot and static sources may be the error source.

Pressure sensitive flight instruments may have instrument error. For air data computers of the modern avionic architectures, this error is neglected since calibrated values can be determined. Pitot and static lines are tested on ground for leakage and no error is expected.

When position error is considered, it is caused by the failure of the static and total pressure pickups to sense the actual free stream pressures. This is caused by the location of these pickups on the airframe [2].

For Pitot head/tube, it is placed on the aircraft clear from propeller wash and any other wake and also away from boundary layer on the aircraft. Pitot head is aligned with the air flow to capture the total pressure [11]. As long as these conditions are granted, no error is expected. For the tower fly-by and trailing cone flight test methods, pitot is assumed error free.

Because of the explanations above, most of the position error is due to the location of the static port alone. Static ports must be located at the locations where accurate free stream static pressure can be taken. These points are where static pressure variation is zero (Ps) like shown in Figure 3 [2].

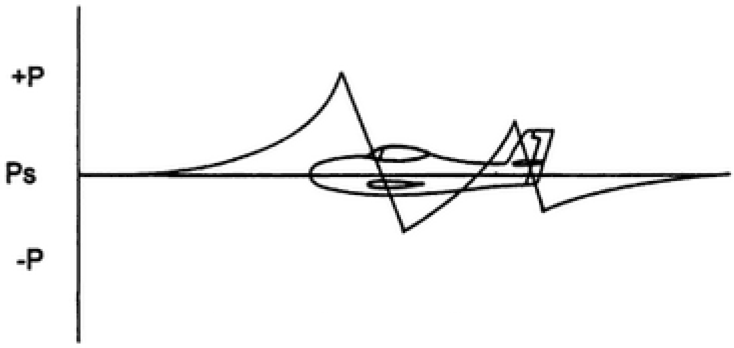

Figure 3 Static Pressure Variation With Aircraft Passage.

1.4. Military Transport Aircraft

Military transport aircraft are used to deliver troops, equipment or basically military cargo and support military operations around the world. Due to the nature of their area of operation, flight routes and delivery methods are different than those of the commercial aircraft.

The need for military transport aircraft started in World War II with different purposes. According to the change of the needs of the armed forces, military transport aircraft have continuously evolved.

Today, most of the military transport aircraft designs date back to 60's and 70's. Among the most well-known military transport aircraft, one can recall Douglas C-47 Dakota, Lockheed C-130 Hercules and C-5 Galaxy, Boeing C-17 Globemaster as well as Antonov An-24, An-76 and An-124. These are very reliable aircraft and most of them are still operational. In order to meet the modern world's needs, these aircraft are modernized in order to extend their lifespan.

Military aircraft have their own regulations approved by the governments. But since the military transport aircraft frequently fly in civilian airspace, they have to meet the requirements of civilian regulation such as FAR 25 or CS 25. This imposes strict requirements on the pitot-static systems among others. With the increase in air traffic in civil airspace, the introduction of the Reduced Vertical Separation Minima, the tolerated error margins have become even more stringent.

According to FAR requirements the allowable error limit for altitude measurement is ± 30 ft for airspeeds less than 100 knots and varies linearly between ±30 ft per 100 knots for airspeed greater than 100 knots. For the air speed value, allowable airspeed error is ±5 knots or ±3 percent whichever is greater [4].

1.5. RVSM

Reduced Vertical Separation Minima-Minimum (RVSM) is the reduction of the vertical altitude separation of 2000 ft to 1000 ft between the aircraft flying at altitudes from FL290 (29000 ft) to FL410 (41000 ft). By the reduction, it is aimed to meet the increasing demand of the air traffic by increasing the number of aircraft in airspace.

The separation was set as 2000 ft in the past because of the accuracy of the old avionic systems. Nowadays, with the development of the new age avionics, altimeters are equipped with air data computers that can make precise calculations with use of many sensors. Also developed flight control systems are now capable of maintaining aircraft states much more accurately. All these developments in the avionics allowed the reduction of the vertical separation from 2000 ft to 1000 ft without compromising flight safety.

To fly in the RVSM airspace, aircraft must be accordingly certified. Required equipment (air data computer, automatic flight control system, traffic avoidance collision system) must be certified for RVSM. Also the aircraft (as a system) must be tested and comply RVSM requirements. Aviation authorities require the ASE should not exceed ±80 ft in the RVSM flight envelope.

Compliance for the RVSM requirement should be shown with flight tests. There are some methods for approved for RVSM certifications. Most common flight test methods for the RVSM certification are the trailing cone method and the tower fly-by method.

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CHAPTER 2

LITERATURE REVIEW

Air data system is the most vital system of the air vehicles as mentioned before. System must be tested and calibrated for a new designed or modified aircraft. There are some calibration methods approved by the aviation authorities.
These methods all have some advantages and disadvantages. Proper method(s) must be chosen for aircraft type and flight envelope or even for opportunities or budget. In the flight test guide of Advisory Circular, it is stated that the flight test technique must be chosen by considering limitations and instrument accuracy criteria [4].

Due to the limitations of these flight test techniques, they are generally combined to cover the entire flight envelope. There are also benefits for using more than one flight test technique to verify test results with each other.

Digiacomo’s (2003) and Woolf’s (2008) researches are about air data calibration of a fighter aircraft. Most probably, they applied techniques together to scan the extensive airspeed and altitude envelope of the aircraft. Digiacomo (2003) mentioned tower fly by, cross pace, clover leaf, level accelerations and decelerations and angle of attack test techniques in his work. His effort is reanalyzed by Woolf (2008) for the same aircraft. Except the angle of attack test technique, Woolf used same methods and added trailing cone method in different way; a pacer aircraft equipped with a trailing cone system was flown with the test aircraft.

For the effort, tower fly by and trailing cone methods were chosen for air data calibration system and RVSM certification. In the inner loop tower fly by method is used to calibrate the trailing cone for higher altitude test flights.

Russell (1966) stated that each trailing cone to be used for the test flights should be calibrated by a ground radar or photothedolite method i.e. tower fly by method.

It is also mentioned in Woolf’s (2008) study, the pacer aircraft equipped with a trailing cone was also calibrated by tower fly by method.

CHAPTER 3

TEST METHODOLOGY

3.1. Tower Fly-By Method

Tower fly by method is one of the methods which results in a direct determination of static error in indicated pressure altitude. The method is explained in the advisory circular[4].

Since the altimeter and airspeed system use the same static source, it is possible to correlate the altimeter position error directly to the airspeed error. This correlation assumes that there is no error in the total head (pitot) system.

The tower fly by method is the most accurate of the altimetry type of calibrations; however, only subsonic data can be taken. In addition only a few calibration points can be obtained during one flight.

Test Conditions for Tower Fly-by:

- Air Quality.

Smooth, stable air is needed for determining the error in pressure altitude. Very early in the morning is the preferred time of the day to this end. It is also important that the wind velocity is as close to zero as possible.

- Weight and C.G.

Airspeed calibrations are usually not c.g. sensitive but may be weight sensitive, especially at low airspeeds corresponding to high angles-of-attack. Initial airspeed calibration tests should be conducted with the airplane loaded at or near maximum takeoff gross weight (MTOW). Additional tests should be conducted at near minimum weight and at low airspeeds to spot check the maximum weight airspeed calibration results. If differences exist, an airspeed system calibration should be accomplished at minimum weight.

- Speed Range

The calibration should range from 1.3 V_{S0} to 1.8 $V_{S1.}$ Higher speeds up to V_{MO} or V_{NE} are usually investigated so that errors can be included in the AFM for a full range of airspeeds.

- Test Procedures.

The test technique is simple. One needs to fly the aircraft along a ground reference line, past the tower, in stabilized flight at a constant airspeed and at the approximate height of the tower. Piloting technique is important. The task is to maintain a constant indicated altitude during the run.

The tower is equipped with a sensitive altimeter and a means of determining the relative angle (θ) of the aircraft. The data recorded during each run are the indicated pressure altitude of the tower, (H_{itower}), the angle (θ), and the aircraft's indicated pressure altitude, airspeed and temperature ($H_{iA/C}$, $V_{iA/C}$, and $T_{iA/C}$) as it passes the tower. Note that the tower altimeter must be at the zero grid line position.

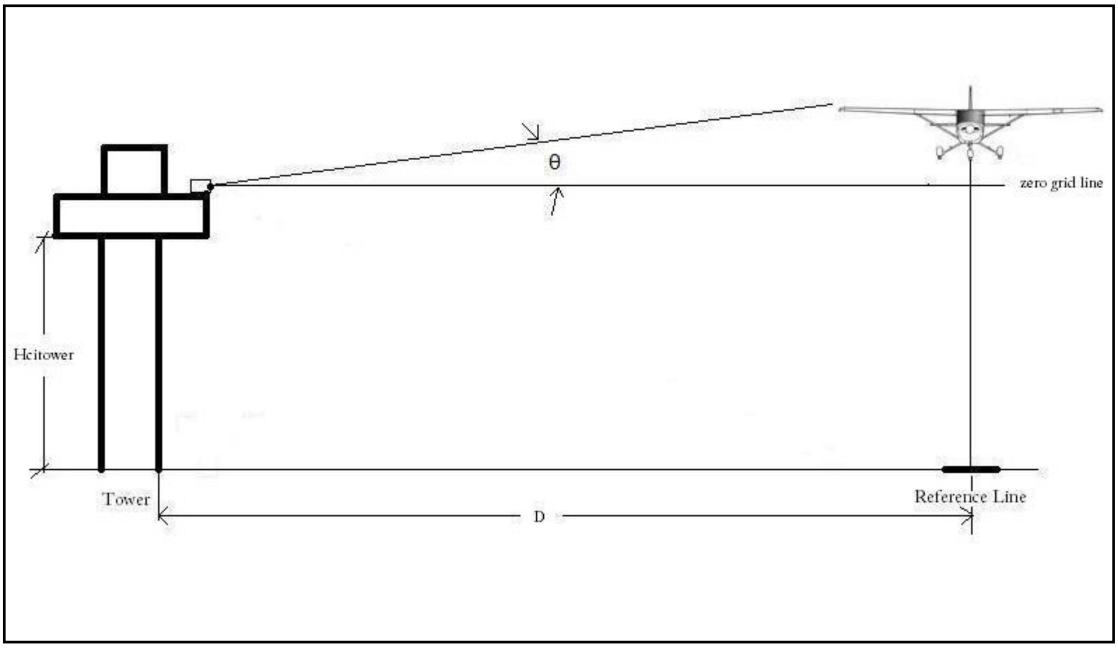

Figure 4 Tower Fly-By Geometry.

Tower fly-by is repeated for different air speeds to cover the required calibration range at different flap and landing gear combinations.

- Data Acquisition. Data to be recorded at each test point:
  - Airplane Airspeed $V_{iA/C}$ knots.
  - Airplane indicated pressure attitude, $H_{iA/C}$
  - Tower observer indicated pressure altitude, H_{itower}.
  - Angle θ of aircraft above the tower.
  - Wing flap position.
  - Landing gear position.
  - Fuel used in airplane.
  - $T_{iA/C}$ and T_{itower}

- Data Reduction.

From the geometry depicted in Figure 4, the actual pressure altitude of the aircraft is H_{cref} [4]:

$$H_{cref} = H_{itower} + \Delta H_{ictower} + D \tan\theta \frac{T_s}{T_t} \quad (1)$$

H_{itower} is the indicated pressure altitude of the tower with calibration factor of $\Delta H_{ictower}$. This value is obtained from the instrumentation on the tower.

The T_s / T_t temperature correction is to convert the geometric height of the aircraft above the reference zero grid line in the tower (D tanθ) to a pressure height that can be added to the pressure altitude of the tower H_{ctower}. Here T_s is the standard day absolute temperature at the test altitude and T_t is the test day temperature in absolute units.

The difference between the actual reference pressure altitude of the aircraft and the aircraft's instrument-corrected pressure altitude is the position error correction [4]:

$$\Delta H_{pec} = H_{cref} - H_{i\,A/C} + \Delta H_{ic\,A/C}$$

$$= H_{itower} + \Delta H_{ictower} + D\tan\theta \frac{T_s}{T_t} - (H_{iA/C} + \Delta H_{icA/C}) \quad (2)$$

ΔH_{pec} is calculated for every speed and aircraft configuration flown past the tower.

The airspeed system position error corrections can also be obtained from the tower fly-by method if it is assumed that the pitot tube (total head) errors are zero.

The hydrostatic equilibrium equation states that [4]:

$$\Delta P_s = -\rho g \Delta H_{pc} \quad (3)$$

Since it is assumed the total head (pitot tube) has no errors, and ignoring the compressibility effects for low speed aircraft, then total position error correction (ΔP_d) for pitot static system is defined as[4]:

$$\Delta P_d = -\Delta P_s = \frac{1}{2}\rho_0 (V_c^2 - V_{ic}^2) \quad (4)$$

Here V_c is the calibrated airspeed corrected for instrument and position errors. V_{ic} is the indicated airspeed of the aircraft corrected for instrument errors. Using the same equation airspeed error can be found [4]:

$$\Delta V_{pec} = V_c - V_{ic} \quad (5)$$

The tower fly-by method can be modified to use radar altimeter or differential GPS to determine geometric/tapeline height above a ground based pressure measuring station. The method is modified and a digital camera is used instead of a grid or theodolite.

Every fly by is captured with digital camera at a rate of around 3-4 fps. As a function of the airspeed of the test point, in every pass 9-14 frames can be recorded, which means that every pass yields data points as much as the number of frames.

In the modified tower fly-by method, $h_{A/C}$ is found in pixels (h_{px}) from the image and using the length of the aircraft ($L_{A/C}$ and L_{px}) as a reference, the height of the aircraft $h_{A/C}$ with respect to reference line is calculated, Figure 5 and 6:

$$\mathrm{h_{A/C}} = \frac{\mathrm{L_{A/C}}}{\mathrm{L_{px}}}\mathrm{h_{px}} \quad (6)$$

Geometric altitude $h_{A/C}$ is converted to pressure altitude using the temperature ratio [4]:

$$\mathrm{H_{A/C}} = (\mathrm{h_{A/C}} + \mathrm{h_{offset}})\frac{\mathrm{T_s}}{\mathrm{T_t}} \quad (7)$$

Here Ts is the standard day temperature and T_t is the test day temperature, where h_{offset} is the height difference between the reference line and the point where P_{ground} is measured. This value is added to geometric height of the aircraft.

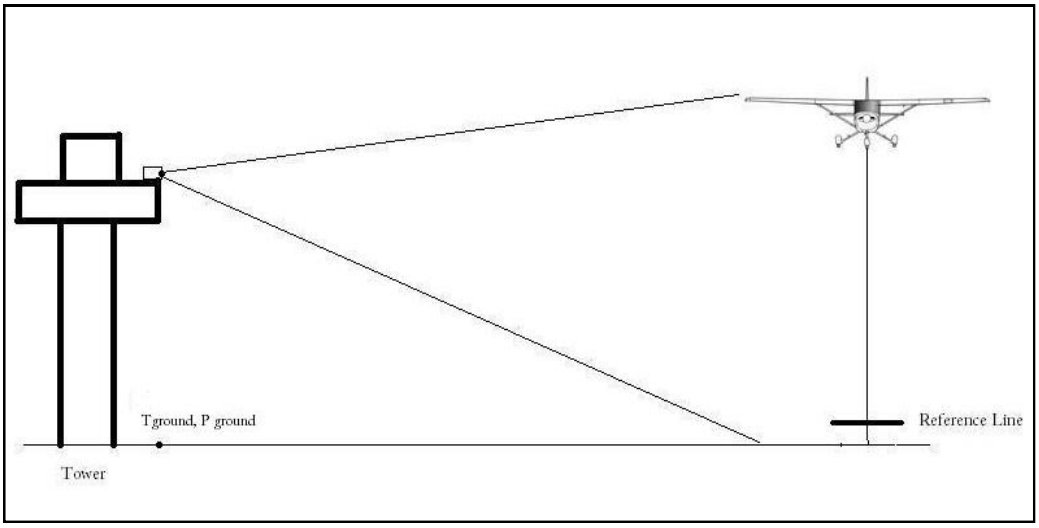

Figure 5 Modified Tower Fly By Geometry.

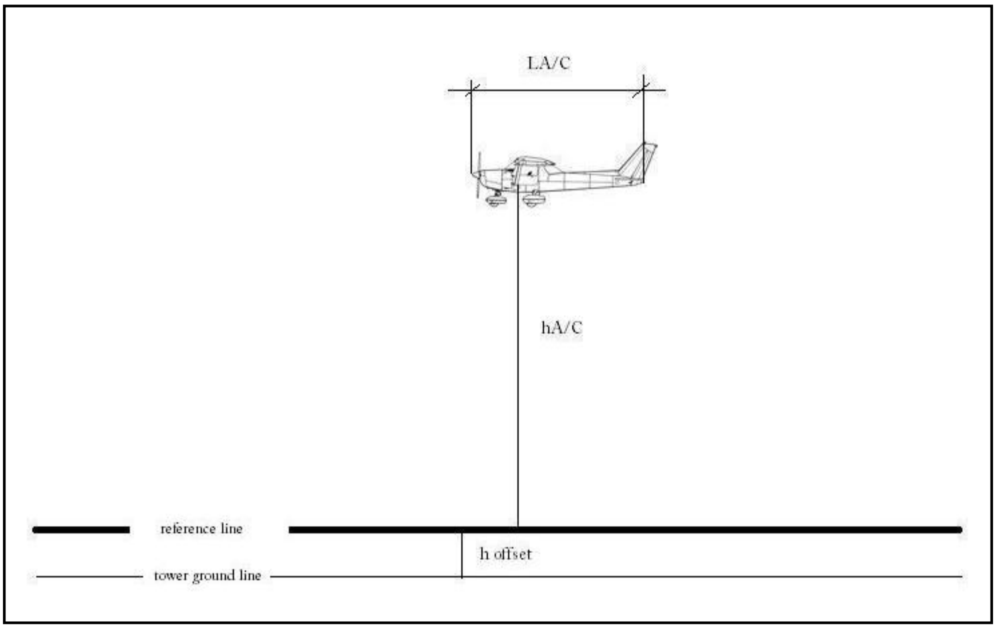

Figure 6 Determination of geometrical height of the A/C.

Pressure altitude of the reference line is calculated using the pressure value collected on ground (tower) (P_{ground}) and standard sea level pressure [10]:

$$H_{Cref} = \frac{1 - \left(\frac{P_{ground}}{P_{SSL}}\right)^{\frac{1}{5,255863}}}{6,8755856} \,.\, 10^6 \qquad (8)$$

$H_{iA/C}$, pressure altitude set by the aircraft is collected from the flight test instrumentation on the aircraft. Then altitude error is defined as;

$$\Delta H_{pec} = \ H_{Cref} + H_{A/C} \ - H_{iA/C}) = \Delta \text{Altitude} \qquad (9)$$

Eventually, ∆Altitude versus corresponding IAS graphs are created for different flap and landing gear combinations.

IAS values are also corrected for weight (V_{wic}) with the following equation [2]:

$$V_{wic} = V_{ic} \sqrt{\frac{W_s}{W_t}} \tag{10}$$

Here, W_s is the standard weight (TOGW) and W_t is the test weight which is calculated using the consumed fuel by time.

Using the hydrostatic equation, V_c can be found.[4]

$$\Delta P_s = -\rho_0 g \Delta H_{pec} \sigma \tag{11}$$

$$\sigma = \frac{\rho}{\rho_0} = \frac{\frac{P_{ground}}{P_0}}{\frac{T_{ground}}{T_0}} \tag{12}$$

By ignoring the incompressibility effects and total (pitot) head error, we have;

$$-\Delta P_s = \frac{1}{2}\rho_0 (V_c^2 - V_{wic}^2) \tag{13}$$

And ΔV_{pec} value is calculated for;

$$\Delta V_{pec} = V_c - V_{wic} \tag{14}$$

Plotting ΔV_{pec} versus V_{ic} graphs, the change of air speed due to the error is also created.

3.2. Trailing Cone Method

Trailing cone method is used to measure the static pressure of the ambient air around the aircraft. Trailing cone is sufficiently far behind the aircraft to be unaffected by the pressure field around the aircraft and can, therefore, be referred to as the reference static pressure (P_{Sref}).

The trailing cone is generally deployed to 1 to 1.5 times the wing span length behind the aircraft. Static pressure is measured on a tube placed forward of the cone that has several static ports. The cone part stabilizes the static ports and aligns them with the free stream. Static pressure is transferred to the sensors located at the aircraft by a high strength pressure tube that is attached the trailing cone and the aircraft, Figure 7 [6].

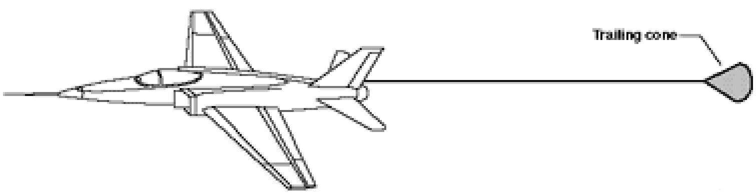

Figure 7 Trailing Cone

Test Conditions for Trailing cone:

- Air Quality.

Smooth, stable air is needed for determining the error in pressure altitude. It is also important that the wind velocity is as close to zero as possible.

- Weight and C.G.

Airspeed calibrations are usually not c.g. sensitive but may be weight sensitive, especially at low airspeeds (higher angles-of-attack). Initial airspeed calibration tests should be conducted with the airplane loaded at or near maximum takeoff gross weight. Additional tests should be conducted at near minimum weight and at low airspeeds to spot check the maximum weight airspeed calibration results. If differences exist, an airspeed system calibration should be accomplished at minimum weight.

- Speed Range

The calibration should range from 1.2 V_{stall} to V_{MO} or $V_{NE.}$

- Test Procedures.

Stabilize aircraft at level flight at test altitude approximately 30 seconds. Repeat this procedure for adequate speed increments.

- Data Acquisition. Data to be recorded at each test point:
    - Airplane Airspeed $V_{iA/C}$ knots.
    - Airplane indicated pressure attitude, $H_{iA/C}$
    - Trailing Cone altitude, H_{ref}.
    - Wing flap position.
    - Landing gear position.
    - Fuel consumed by airplane.

- Data Reduction.

A trailing cone can be used to calibrate the aircraft static source or to determine the Position Error Correction (PEC's) for the altimeter. Like the tower fly-by method, this method also assumes that the errors in the total head (pitot tube) are zero. The reference static sources could be connected to the altimeter, which would read the pressure altitude of the aircraft. The difference between the reference altitude from the trailing cone and the aircraft altitude, both corrected for instrument errors, would be the position error correction for the altimeter ΔH_{pec} for a particular aircraft configuration and speed [4]:

$$\Delta \mathrm{H_{pec}} = \mathrm{H_{ref}} + \Delta \mathrm{H_{ic}} - (\mathrm{H_{iA/C}} + \Delta \mathrm{H_{ic}}) \qquad (15)$$

H_{ref} is Reference altitude
ΔH_{ic} is the instrument correction to the altimeter
$H_{iA/C}$ is the indicated aircraft altitude

ΔH_{ic} term is different for the aircraft and reference system; they are denoted as $\Delta H_{icA/C}$ and ΔH_{icref} for aircraft and reference system, respectively.

$\Delta H_{icA/C}$ is instrument error of the altimeter. For modern air data computers, this term is generally neglected.

ΔH_{icref} is the instrument error of the trailing cone system that is denoted as $\Delta \mathrm{H_{T/C}}$.

$\Delta H_{T/C}$ is calculated for different airspeeds by tower fly-by's. Trailing cone is deployed for the tower fly-bys conducted in clean configuration. Readings for the trailing cone is correlated with the results of the tower fly-by results for calibration of the trailing cone for a certain trailing cone length.

Static pressure obtained from trailing cone ($Ps_{T/C}$) is converted to pressure altitude [10]:

$$H_{T/C} = \frac{1 - \left(\frac{P_{sT/C}}{P_{SSL}}\right)^{\frac{1}{5{,}255863}}}{6{,}8755856} \,.\, 10^6 \quad (16)$$

Error of the trailing cone is found by using the pressure altitude calculated by tower fly-by (H_{TFB}).

$$\Delta H_{T/C} = H_{TFB} - H_{T/C} = H_{Cref} + H_{A/C} - H_{T/C} \quad (17)$$

The error value $\Delta H_{T/C}$ is plotted versus airspeed. Calibration curve as a function of airspeed is obtained.

After calibration, high altitude static error calibration tests would be planned. But these flight tests could not be completed in the time of this thesis. Because of this fact, trailing cone flight tests are not included in the thesis. Only the calibration of the trailing cone is completed.

Again, it is assumed the total head (pitot tube) has no errors, speed calculation can be conducted in the same way as the tower fly by method. Higher altitudes may require the compressibility effects to be considered in the calculations.

3.3. Data Reduction

To evaluate the questionable data points, Outliers Method is used [5]. Average $\overline{V}$ and the standard deviation S of the data points are calculated. The outliers, δ deviation values are calculated as follows:

$$\delta_1 = V_{largest} - \overline{V} \quad (18)$$

$$\delta_2 = V_{smallest} - \overline{V} \quad (19)$$

Thompson's τ value is found Table 1 [5] for the sample size and multiplied by standard deviation, S to obtain $S\tau$.

Table 1 Thompson's Value Table.

Sample size n	τ	Sample size n	τ
3	1.150	22	1.893
4	1.393	23	1.896
5	1.572	24	1.899
6	1.656	25	1.902
7	1.711	26	1.904
8	1.749	27	1.906
9	1.777	28	1.908
10	1.798	29	1.910
11	1.815	30	1.911
12	1.829	31	1.913
13	1.840	32	1.914
14	1.849	33	1.916
15	1.858	34	1.917
16	1.865	35	1.919
17	1.871	36	1.920
18	1.876	37	1.921
19	1.881	38	1.922
20	1.885	39	1.923
21	1.889	40	1.924

If deviations δ_1 or $\delta_2$value exceeds $S\tau$, then that data point is rejected. Process is repeated for the remaining values. New deviations, δ_1 and $\delta_2$values are calculated and new τ value is found for new sample size. Process continues until δ_1 and $\delta_2$values are in the limits.

Besides this method, some irrelevant data is also rejected by hand. Due to the lag caused by the nature of the pitot-static system, fluctuations at the altitude of the aircraft caused rejection of some data points. This fact is much more important for trailing cone data due to the lag of the hose of the cone. Especially for entrance and leaving of the tower fly-by passes, this situation is observed and some data points are rejected considering the lag factor.

3.4. Test Instrumentation

Flight test instrumentation can be grouped in three parts.

- Aircraft: Aircraft's data bus are instrumented, so that all flight data including airspeed, altitude and vertical speed is recorded at 10 Hz. Readings of trailing cone are also recorded on the aircraft at 5 Hz.

- Tower: A digital camera is placed at the tower for capturing the tower fly-by.

- Ground: At the bottom of the tower (ground) temperature and pressure sensors are placed which are connected to data recorders collecting sample at 5 Hz.

All the instrumentation even the digital camera, are synchronized for GPS time for correlation of the test data.

Table 2 Test Instrumentation and Parameters

Source	**Parameter**
Aircraft – BUS monitor	$V_{iA/C}$
	$H_{A/C}$
	$T_{iA/C}$
Aircraft - Trailing Cone	$P_{T/C}$
Tower	Photo (h_{px} , L_{px})
Ground	P_{ground}
	T_{ground}

CHAPTER 4

TEST RESULTS

4.1. Test Configuration and Chronology

4 Tower fly-by sorties and 92 Tower Fly-By's are conducted. Aircraft configurations corresponding to these are given in Table 3.

Table 3 Tower Fly-By Flights

Flight #	Number of fly-by's	Weight	Configuration
1	20	Heavy	All passes are conducted for different flap and landing gear combinations. No clean configuration was flown.
2	20	Heavy	Same as the first sortie. Conducted in order to increase the number of samples.
3	24	Heavy	Clean configuration flights are conducted. Trailing cone is used.
4	28	Light	Spot check flight for light weight configuration. Different flap and landing gear combinations are flown. Clean configuration flight with trailing cone is also conducted.

4.2. Review of Test Results

The overall test objective was to determine static source error (position error) of the air data system. For the reasons mentioned in chapter one, aircraft pitot tubes are located in the nose section are assumed error free.

Position error values for overall test results are about 20 ft. FAR limit for altitude error is given as ± 30 ft per 100 kt. Figure 10-22 shows the altitude errors for different test days and test configurations as well as the FAR error limits. Figures 10-18 correspond to Flights # 1, 2 and 3 (heavy configuration), while Figures 19-22 correspond to Flight #4 (light configuration). Tests were conducted for airspeed values from 110 KIAS to 250 KIAS with different flap and landing gear configurations. Test flights are conducted at the heavy weight configuration to see the effects of the high angle of attack cases. Than a light weight test flight is conducted as a spot check of the effect of the light weight.

The first and most obvious inference after examining these figures is that all measurements are within the FAR limitations.

Comparing the Figure pairs, Figures 10 and 14, 11 and 15, 12 and 16, 13 and 17, which correspond to the same configurations in Flight #1 and Flight #2, respectively, One can infer that there is no significant repeatability issue in the measurements, since the errors in both flights are comparable for identical configurations, This comparison is facilitated in Figures 29-32, where the data of Flights #1 and #2 are co-plotted for similar flap and landing gear configurations.

When Figure 10 and 11 are compared, which correspond to the same weight and flap but different landing gear configurations, it can be said that the landing gear configuration has no effect on the measurements. This is expected because for the aircraft in hand, the main landing gear is behind the static ports so it is very unlikely that it has an effect on the measurements. The nose landing gear is below the fuselage, while the static ports are considerably above it, Therefore it is also very unlikely that the nose landing gear has any significant effect on the static pressure measurements. This inference is further supported by the data presented in Figures 12 and 13, which correspond to 50% flap configuration. Figures 14-17, which correspond to the same configuration as in Figures 10-11, do not present any information that alter the above inferences, as expected.

In order to assess the effect of the flap configuration, Figure pairs 10 and 12, 11 and 13 can be compared. Although 100% flap configuration flights are flown at lower airspeeds and 50% flap configuration flights at slightly higher airspeeds, they overlap at an airspeed range between 130-150 knots, The results show that there is no significant effect of flap setting on the results. This is also expected, since the flaps are behind the static ports, and it is very unlikely that the upstream flow is significantly affected by their presence. Figures 14-17, which correspond to the same configuration as in Figures 10-13, do not present any information that alter the above inferences, as expected.

Figure 18 corresponds to Flight #3, clean configuration. Although the airspeed range that this flight is conducted at is significantly higher than Flights #1 and #2 are conducted, we do not observe a significant effect of airspeed and configuration on the error levels. This further supports the inferences outlined above.

Figures 19-22 depict the results for the lightweight configuration, Flight #4. Examining these figures, one does not notice a substantial effect of different flap and landing gear settings on altitude errors for the lightweight configuration, similar to the conclusions of Flights #1 and #2, which correspond to the heavyweight configurations. In Figures 24-28, light- and heavyweight flight results are co-plotted in order to determine the effect of weight, hence angle of attack on error levels. Light and heavy test results are almost compatible. There is only a significant difference at 160 KIAS for 50% flap and L/G down configuration (Figure 27). Same result did not observe for 50% flap and L/G up configuration (Figure 25). Error values are still in limits for the test points but considering other test cases and configurations this difference caused by landing gear was not expected. For the overall results independency of error from landing gear is still considered valid.

For the light weight configuration, Figure 20, error values have the closest value to the border line for 110 KIAS that is the lowest air speed in the test envelope. This airspeed could not be tested for heavy configuration. Because of this fact effect of the weight and angle of attack could not be compared with heavy configuration in figure 25. But considering the other results, the point is not expected to be caused by weight.

By assuming the pitot head error is zero, effect of the static source error is examined for effects of airspeed. FAR limit for airspeed error is ±5 kt or ±3 percent whichever is greater. Error values and FAR limitations for airspeed errors are plotted in Figure 32-45.

Again the most obvious conclusion is that all error values are within FAR limitations.

As it was done above for altitude measurements, repeatability of the tests in terms of airspeed measurements can be examined comparing the Figure pairs, namely Figures 33 and 37, 34 and 38, 35 and 39, 36 and 40, which correspond to the same configurations in Flight #1 and Flight #2, respectively, One can infer that there is no significant repeatability issue in the measurements, since the errors in both flights are comparable for identical configurations, This is expected because the data used for the assessment of altitude measurement errors and airspeed measurement errors are the same, but post-processed in a different manner.

When Figure 33 and 34 are compared, which correspond to the same weight and flap but different landing gear configurations, it can be said that the landing gear configuration has no effect on the measurements. Since the airspeed measurement error can only arise from static pressure measurements, it is concluded that the landing gear configuration yields no effect on the airspeed measurements. As mentioned before, this is expected because for the aircraft in hand, location of the main and nose landing gear are unlikely to affect the static ports' pressure measurements. This inference is further supported by the data presented in Figures 35 and 36, which correspond to 50% flap configuration. Figures 37-40, which correspond to the same configuration as in Figures 33-36, do not present any information that alter the above conclusions, as expected.

Figure 41 corresponds to Flight #3, clean configuration, where airspeeds were higher than in Flights #1 and #2. Nevertheless, we do not observe a significant effect of airspeed and configuration on the error levels. This further supports the inferences outlined above.

Figures 42-46 depict the results for the lightweight configuration, Flight #4. Examining these figures, one does not notice a substantial effect of different flap and landing gear settings on airspeed errors for the lightweight configuration, similar to the conclusions of Flights #1 and #2, which correspond to the heavyweight configurations. Remembering the previous hypothesis that the pitot measurement is error free, the only reason that there may be an error in the airspeed measurements is the static pressure measurements. When the fuselage geometry and the locations of the static ports are considered, the above observations are largely expected because in the airplane studied, there is no component ahead of the static ports that may yield angle of attack dependency such as strakes, large radoms, non-streamlined contours, etc. The contours of the fuselage ahead of the static ports are rather smooth allowing the pressure readings and hence airspeed readings are not affected significantly with of angle of attack.

Trailing cone calibration curve is obtained from flights that trailing cone is deployed and given in Figure 47. A 6^{th} order polynomial curve is fit to the obtained data. Accuracy is increased by increasing the number of decimals of the coefficients. R^2 value over 0.9 is obtained.

CHAPTER 5

ERROR ANALYSIS

From results, it was seen that the dependency to airspeed, aircraft configuration and weight for the altitude error can be neglected for this case.

Considering all test points, deviation of the altitude error is illustrated in Figure 8.

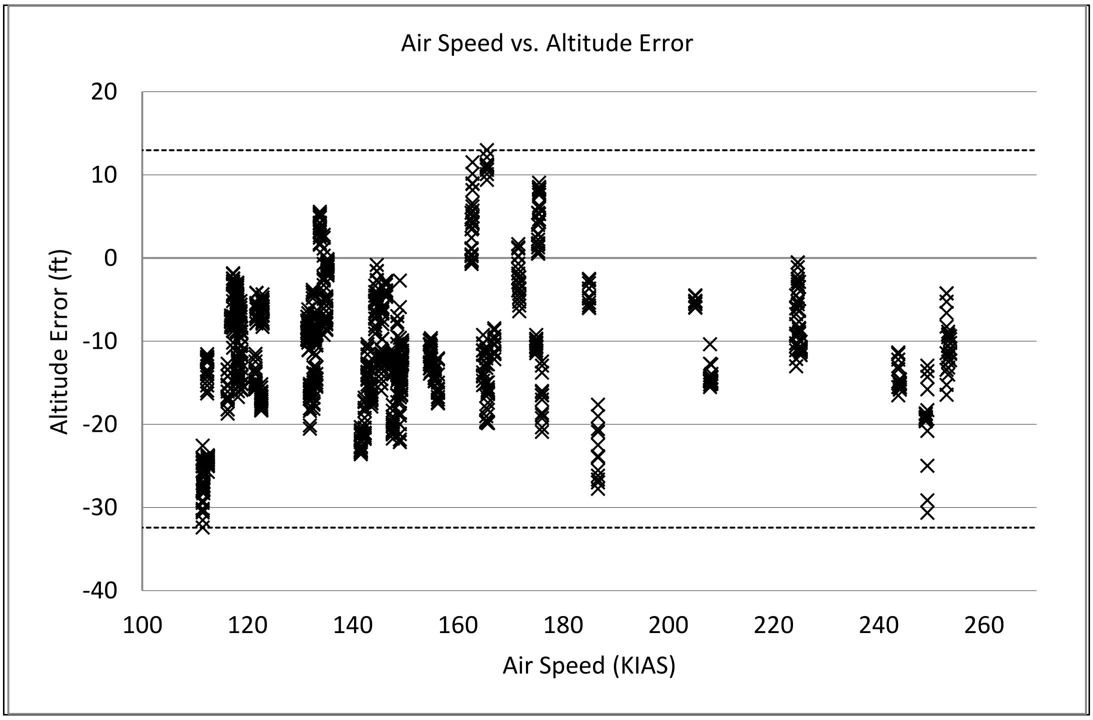

Figure 8 Deviation of altitude

Average error is calculated as -10,66 ft for all data points. (Bias Error)

Using the minimum and maximum values of the readings for Figure 8, accuracy limits are found as -32,42 ft and +12,47 ft. Tower fly by was conducted about 2900 ft MSL. Accuracy limits corresponds to an error between -1,11 % and 0,43 % for the given test altitude.

Deviation of the airspeed caused by the static source error is plotted in Figure 9.

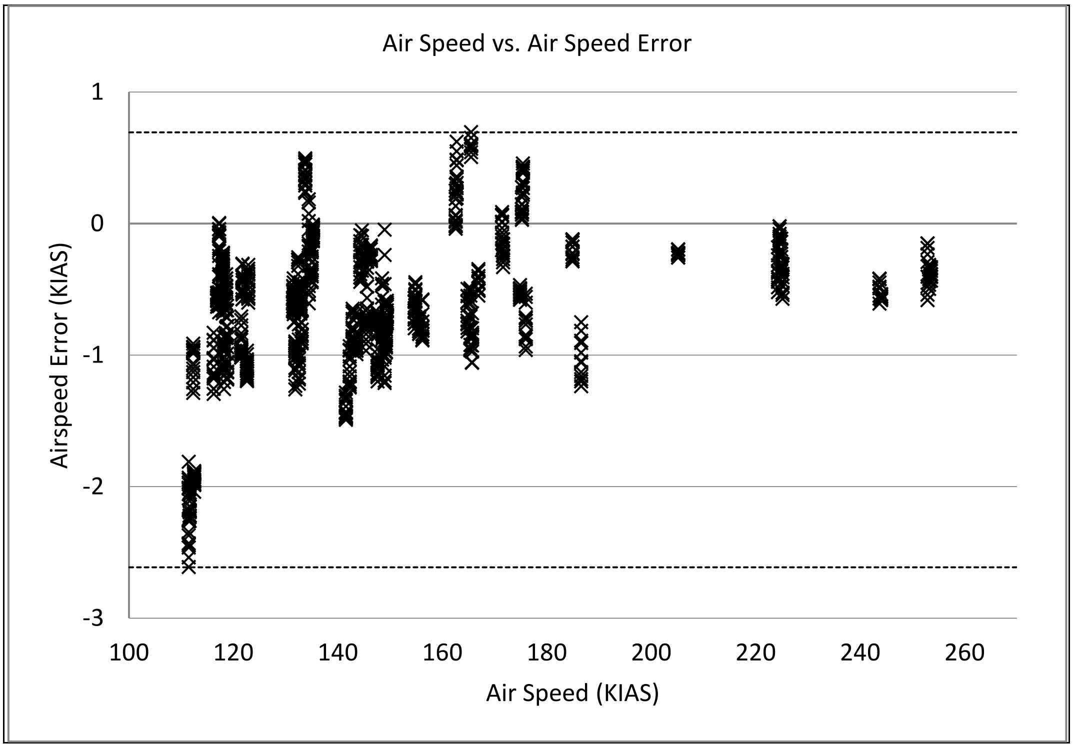

Figure 9 Deviation of Airspeed

Average error is calculated as -0,6365 kt for all data points. (Bias Error)

Using the minimum and maximum values of the readings for Figure 9, accuracy limits are found as -2,61 knot and +0,7 knot. Outputs for the air speed values vary from 108,88 knot to 253,28 knot. Considering the lowest air speed value, accuracy becomes +2,39 % and -0,64 % of the output span [5].

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1. Conclusion

Although all the results seem in limits, in some results, for a certain air speed value, error values are distributed for the altitude error along y axis. Even these values are in the limits; this is most probably caused by the variations in the altitude of the aircraft during the tower fly-by. During the tests, due to ground proximity, the aircraft were flown manually, where precise altitude holding is not practically possible. Lag is in the nature of the pitot-static systems. Furthermore static ports of the trailing cone are flying behind the aircraft and it takes time for them to react to the altitude changes of the aircraft and stabilize. These facts caused the data to spread about 10ft for the same flight configuration at the same airspeed. Another reason for the errors may be non-zero wind speeds. Although the tests were conducted in still air as possible, it is practical to obtain an absolute zero wind contribution. Nevertheless, it is thought that this effect of wind is marginal on the results presented.

The test aircraft has 4 static ports located in the fuselage just before the cockpit section. These port locations were determined by the aircraft manufacturer and verified for the old flight instruments most probably by flight test results.

By the flight tests conducted in the focus of this thesis, position error is verified for FAR limits. If position error was found out of the limits, software of the ADC would be updated and the corrected values would be shown to flight crew and send to other avionics since the ADC used on the current aircraft is not a certified equipment to be used on the current aircraft type.

To sum up, after conducting four tower fly by's for different flight configurations, altitude and airspeed error caused by the static source (position error) is found to be within the FAR limits. Trailing cone is calibrated for the high altitude flight tests for the RVSM certification.

6.2. Future Work

Trailing cone flights planned to be flown at higher altitudes could not be achieved in the proper time to be included in this thesis. Hence, only the calibration curve is obtained; data obtained from these altitude flights can be processed.

Higher altitude flights may need some more calculations because of compressibility effects. At higher altitudes, higher speeds up to V_{MO} may reach to Mach numbers 0.5, where compressibility effects may be prominent.

Generally, first and last portion of the trailing cone data was rejected due to the lag between aircraft and the trailing cone. Because of this fact, even the collected data was enough for calculations, trailing cone passes may be repeated by planning an earlier positioning over the reference line.

An automatic flight control system was also integrated to the aircraft by the modernization program. While these tests were being conducted, the AFCS was not operational due to incomplete test flights which were planned after air data calibration tests. Since outputs of the air data system is used by AFCS, it was mandatory. Use of AFCS for the tower fly-by could also be considered to obtain better results.

Test results may be supported with the use of another calibration method. GPS method may be used for airspeed calibration. In this method, system is calibrated with the use of a GPS that is free from a pressure reading. In this method, level flight is conducted to perpendicular directions. Using the ground speed data, wind component is eliminated and air speed is calculated.

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APPENDIX A: Results Obtained by Tower Fly-By's

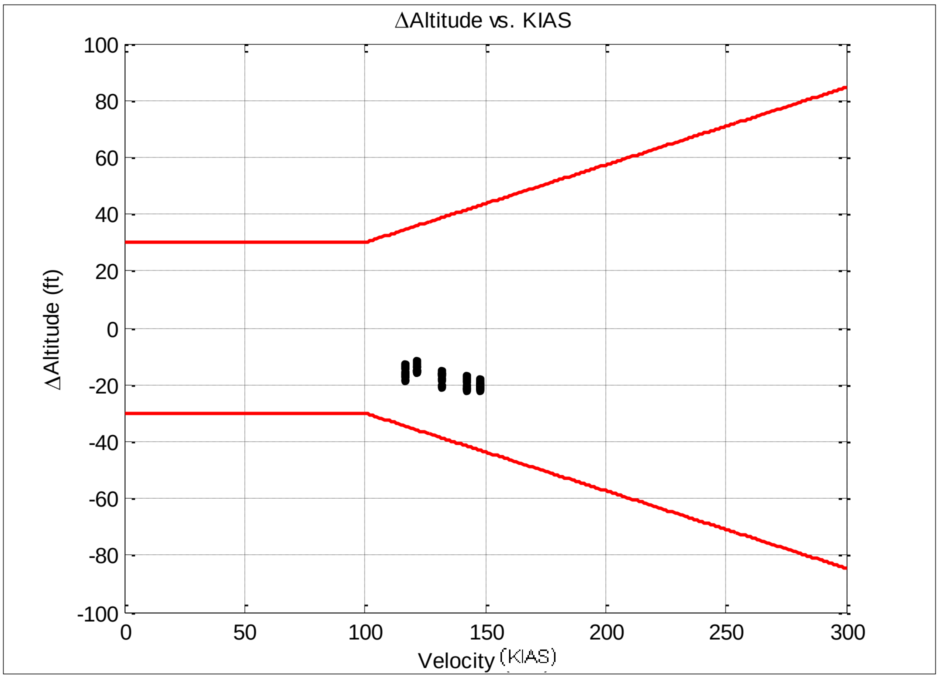

Figure 10 Altitude Error Flight #1 – Heavy, 100% Flap, Landing Gear Up.

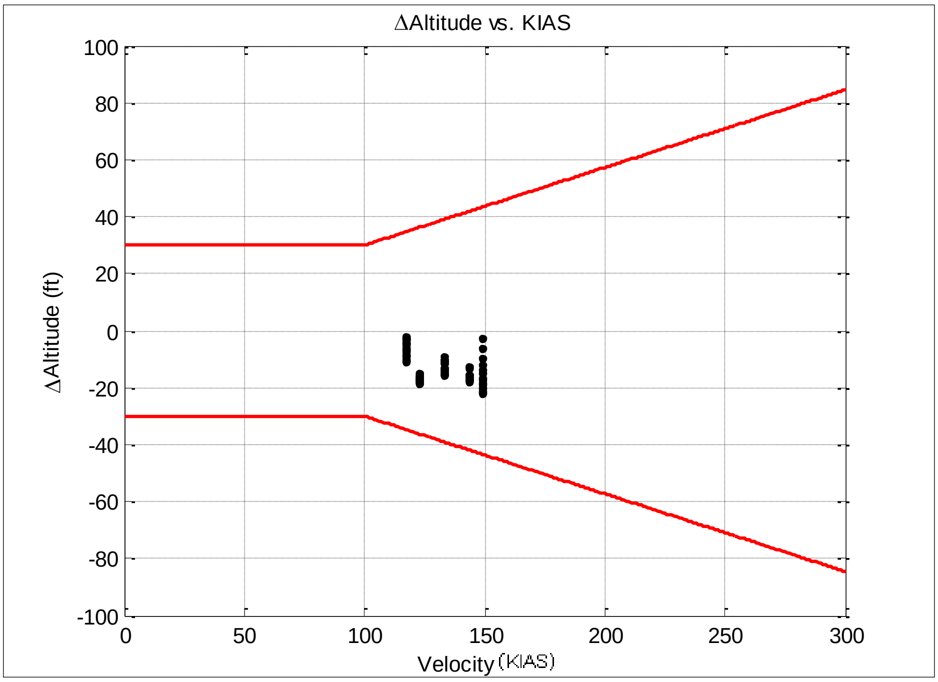

Figure 11 Altitude Error Flight #1 - Heavy,100% Flap, Landing Gear down

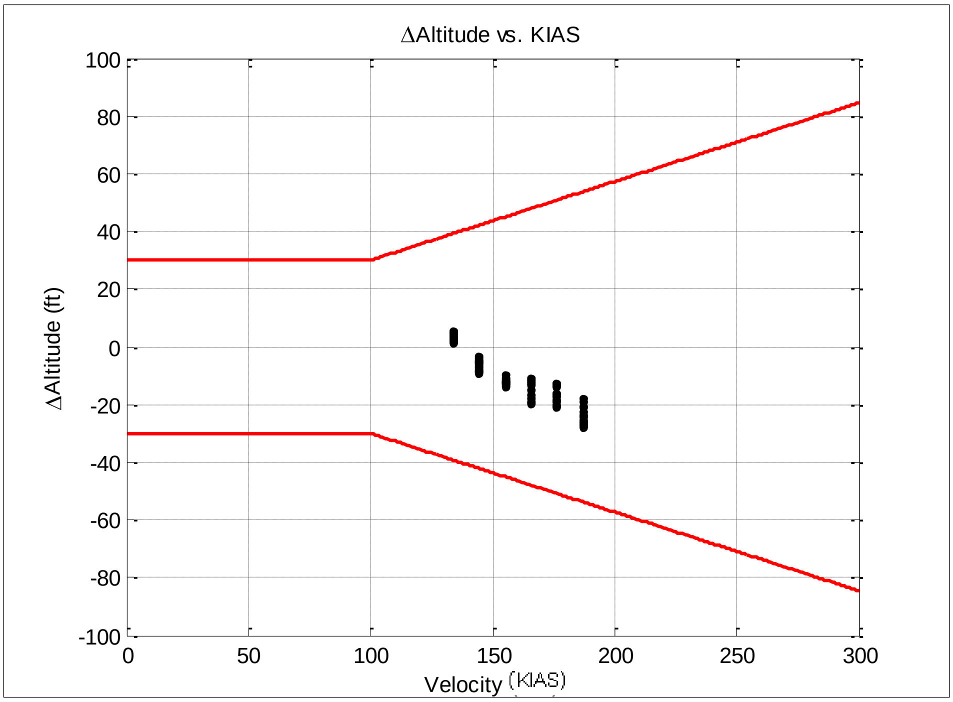

Figure 12 Altitude Error Flight #1 - Heavy,50% Flap, Landing Gear Up

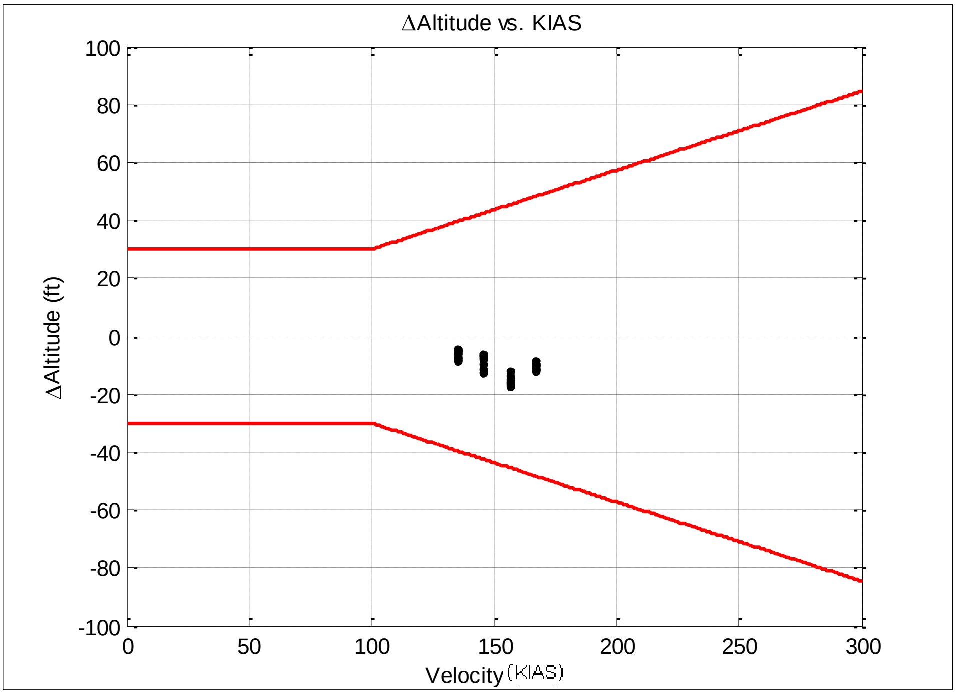

Figure 13 Altitude Error Flight #1 - Heavy,50% Flap, Landing Gear down

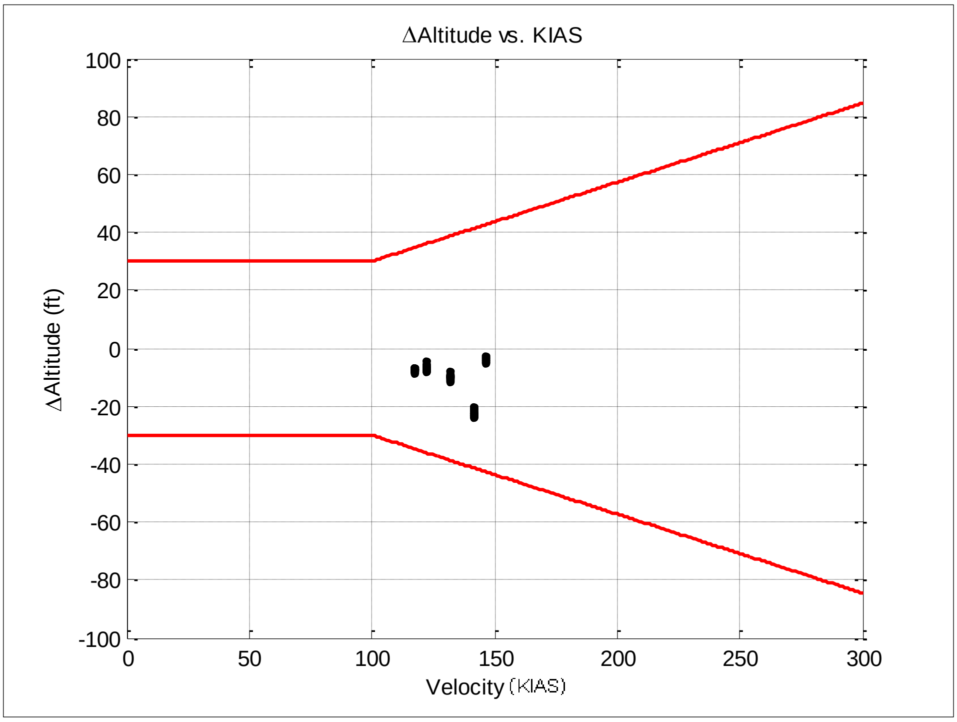

Figure 14 Altitude Error Flight #2 - Heavy, 100% Flap, Landing Gear Up

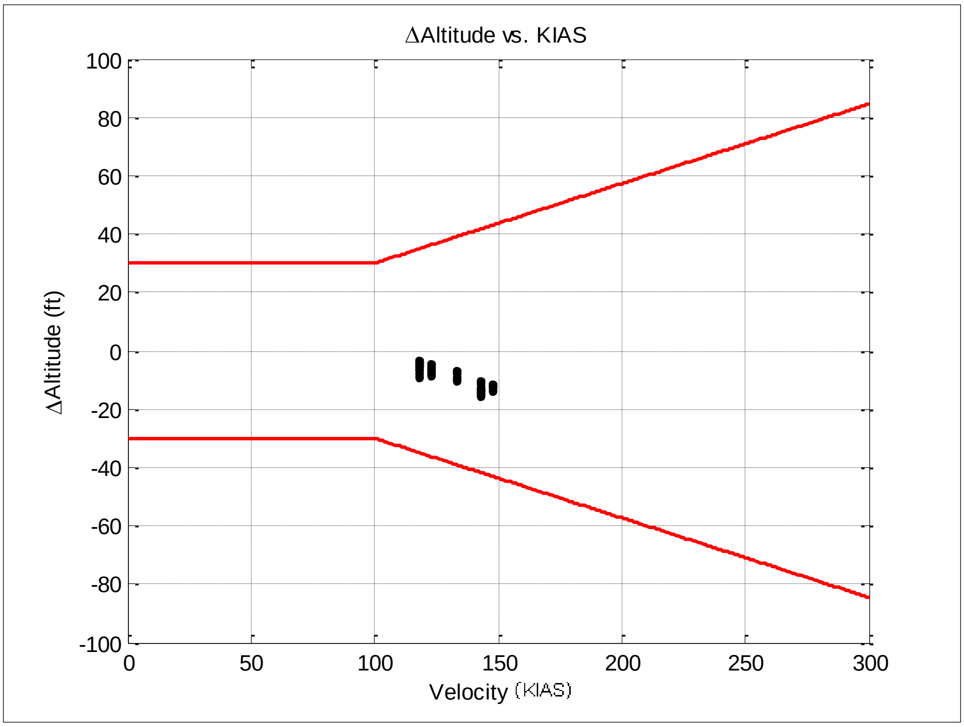

Figure 15 Altitude Error Flight #2 - Heavy, 100% Flap, Landing Gear Down

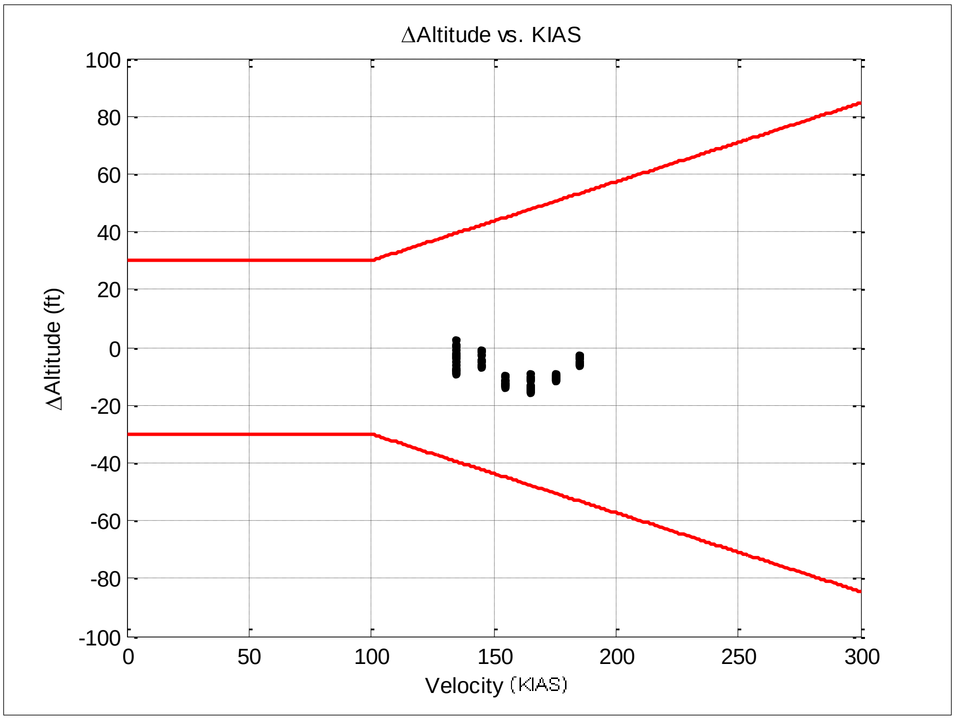

Figure 16 Altitude Error Flight #2 - Heavy, 50% Flap, Landing Gear Up

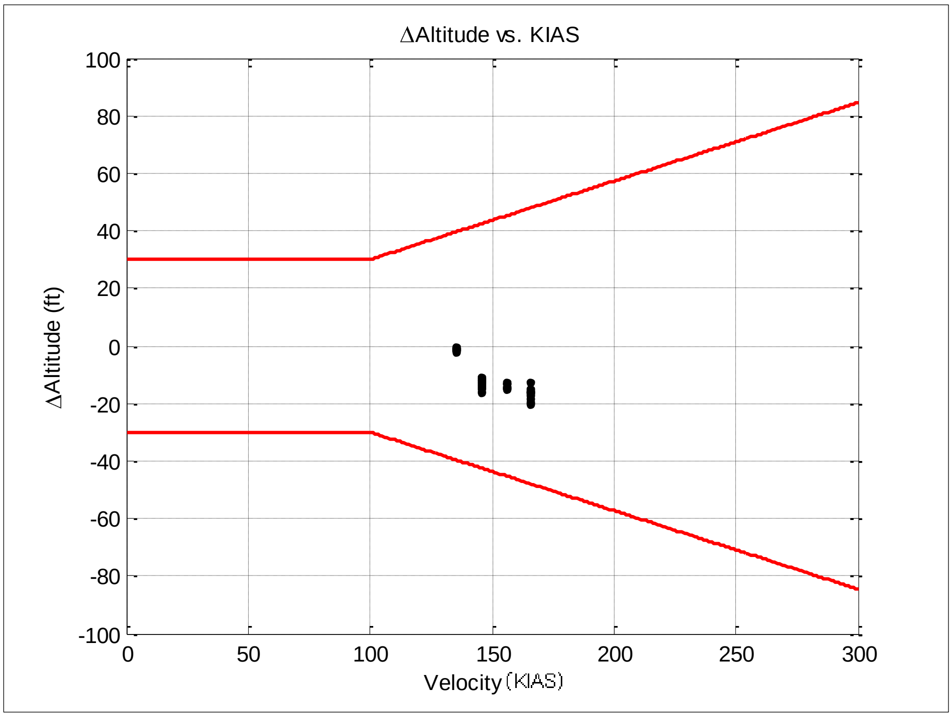

Figure 17 Altitude Error Flight #2 - Heavy, 50% Flap, Landing Gear Down

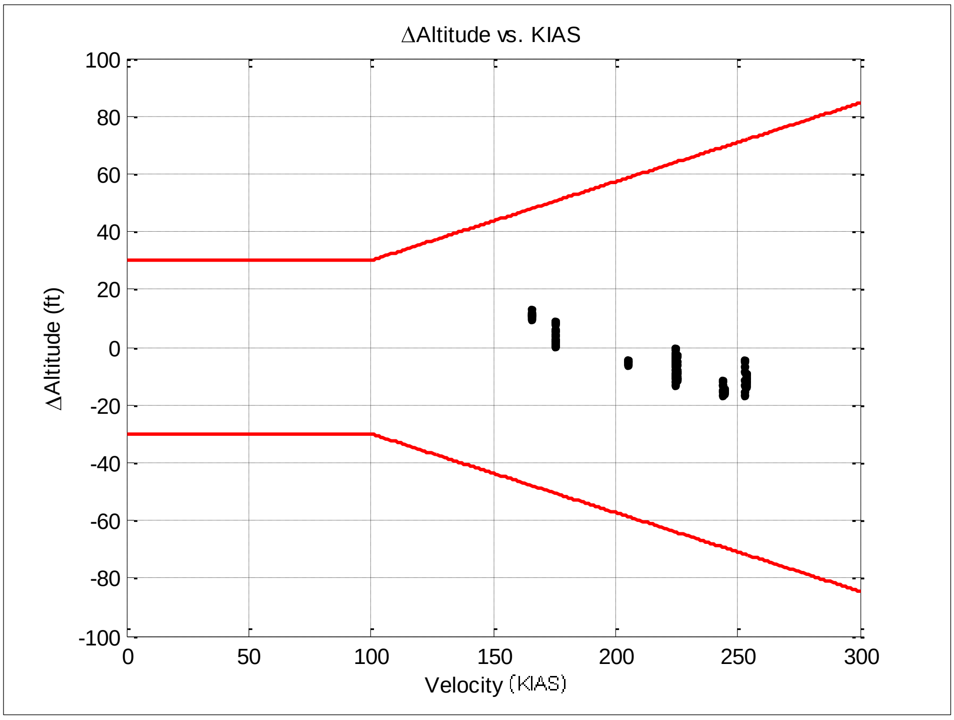

Figure 18 Altitude Error Flight #3 – Heavy, Clean Configuration

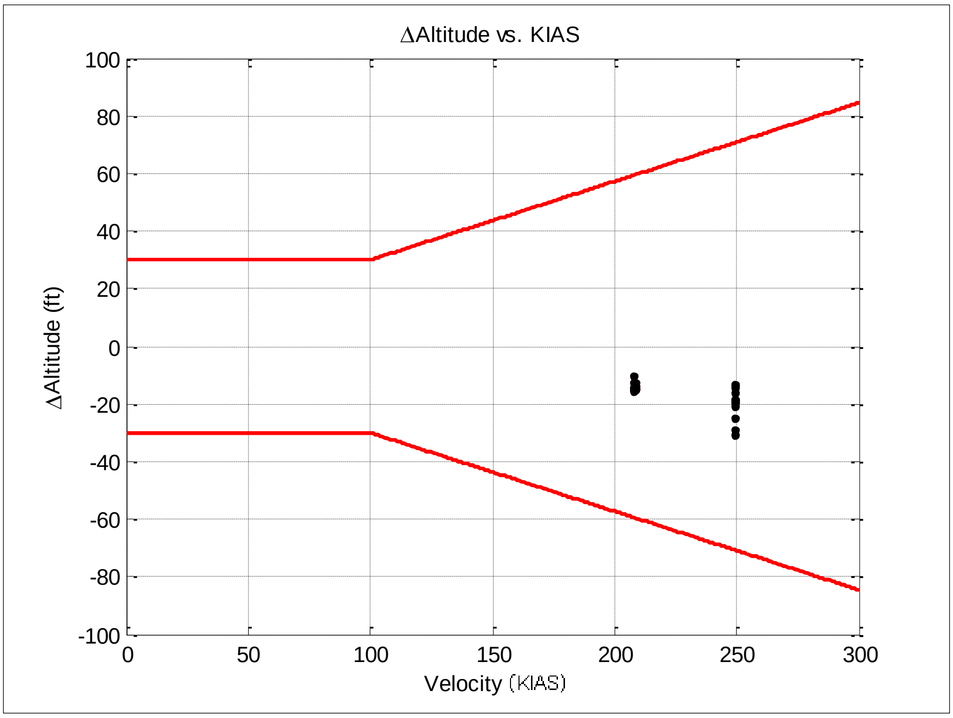

Figure 19 Altitude Error Flight #4 – Light, Clean Configuration

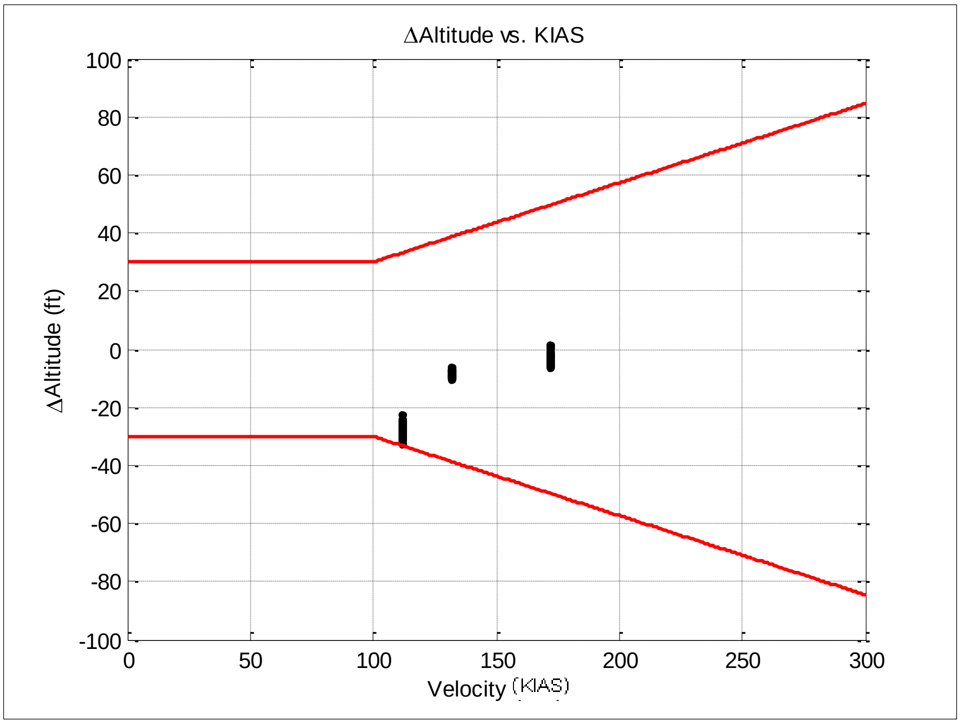

Figure 20 Altitude Error Flight #4 – Light, 50% Flap Landing Gear Up

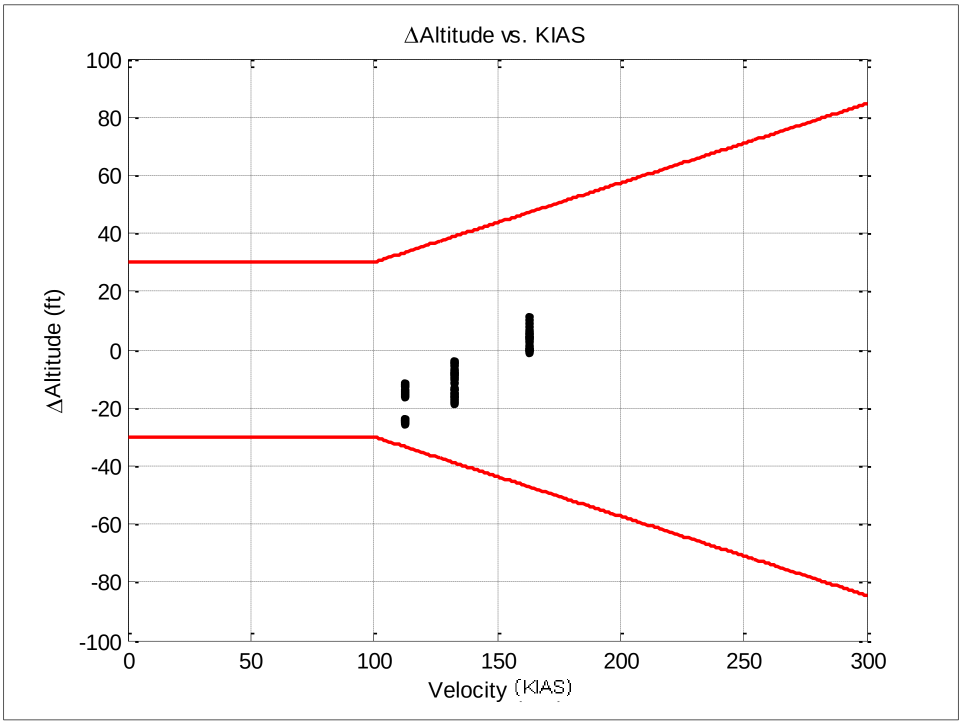

Figure 21 Altitude Error Flight #4 – Light, 50% Flap Landing Gear Down

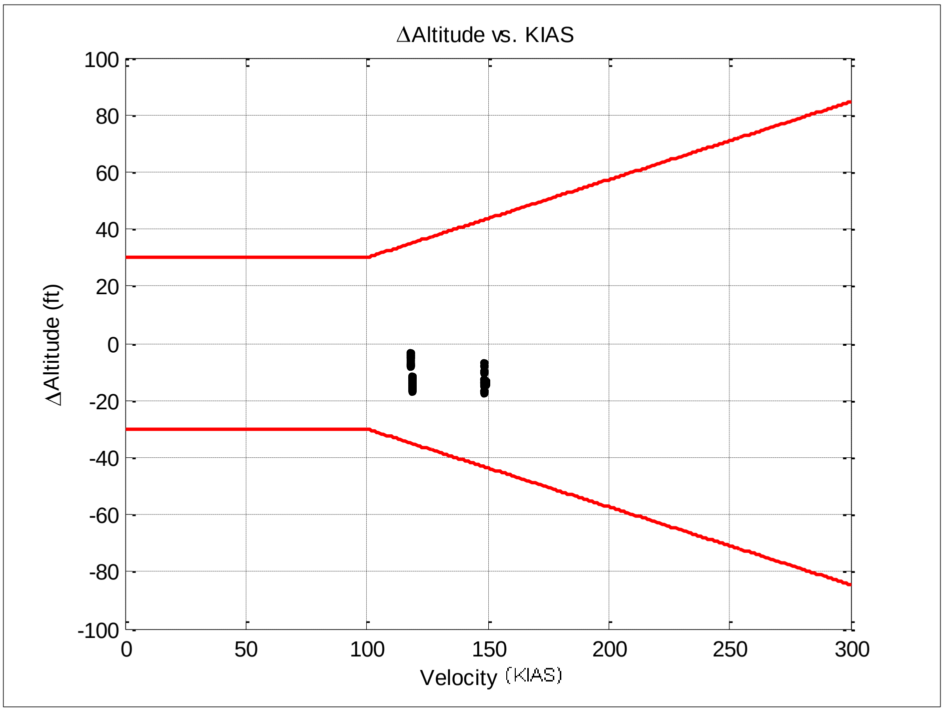

Figure 22 Altitude Error Flight #4 – Light, 100% Flap Landing Gear Up

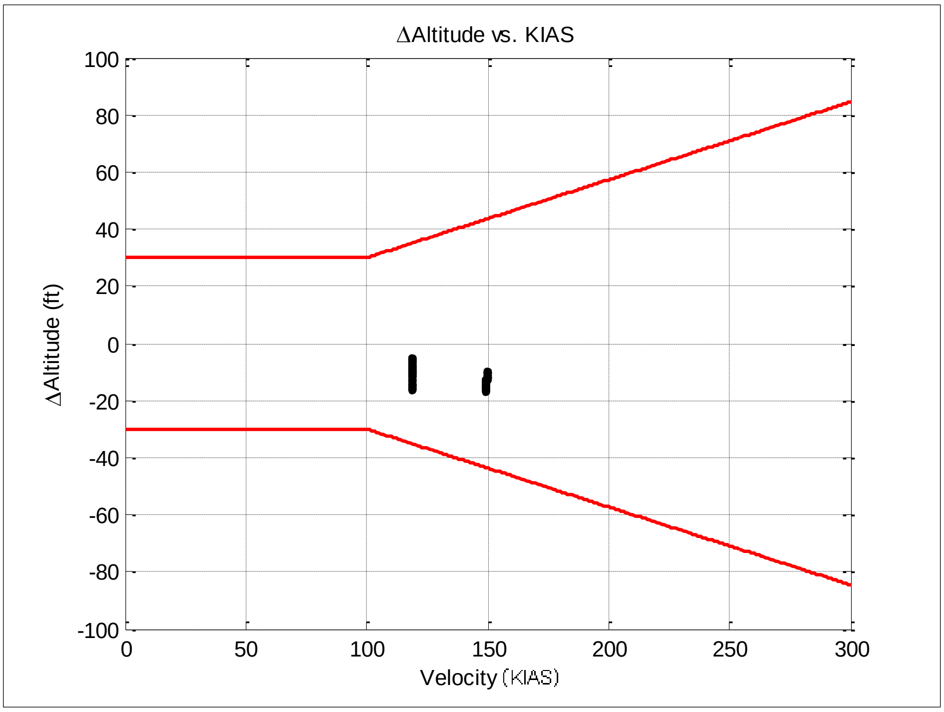

Figure 23 Altitude Error Flight #4 – Light, 100% Flap Landing Gear Down

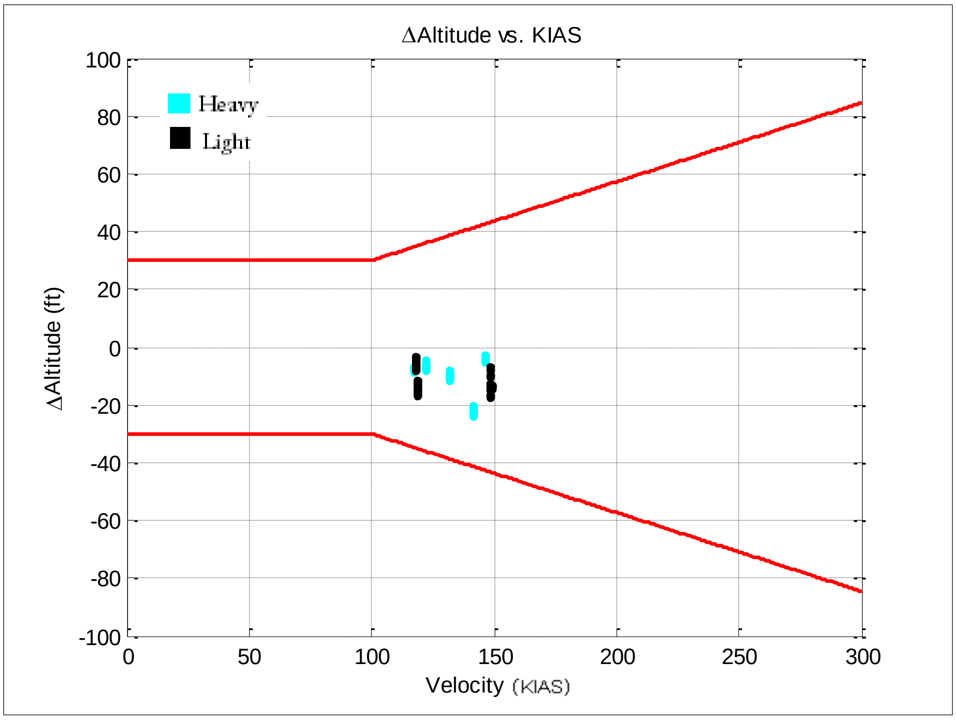

Figure 24 Altitude Error Flight # 2&4 – Heavy & Light 100% Flap L/G Up

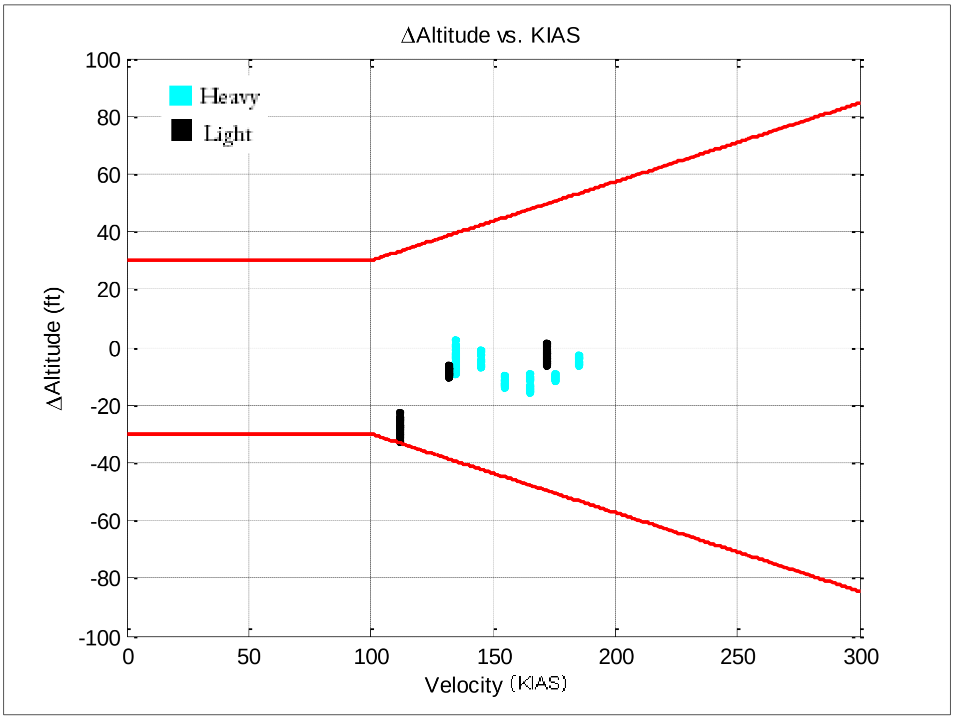

Figure 25 Altitude Error Flight # 2&4 – Heavy & Light 50% Flap L/G Up

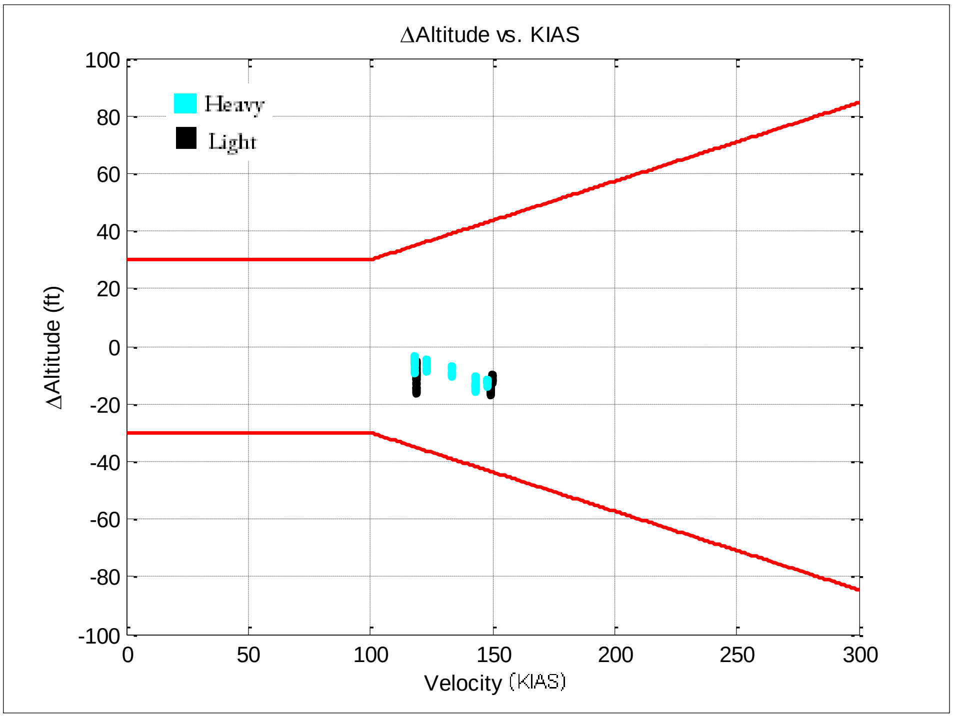

Figure 26 Altitude Error Flight # 2&4 – Heavy & Light 100% Flap L/G Down

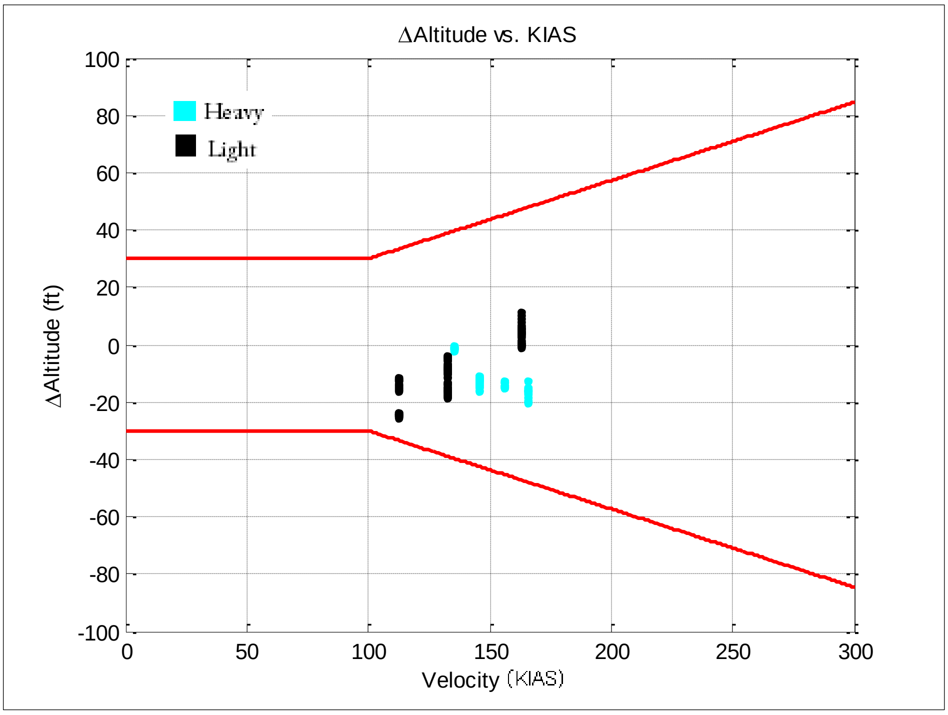

Figure 27 Altitude Error Flight # 2&4 – Heavy & Light 50% Flap L/G Down

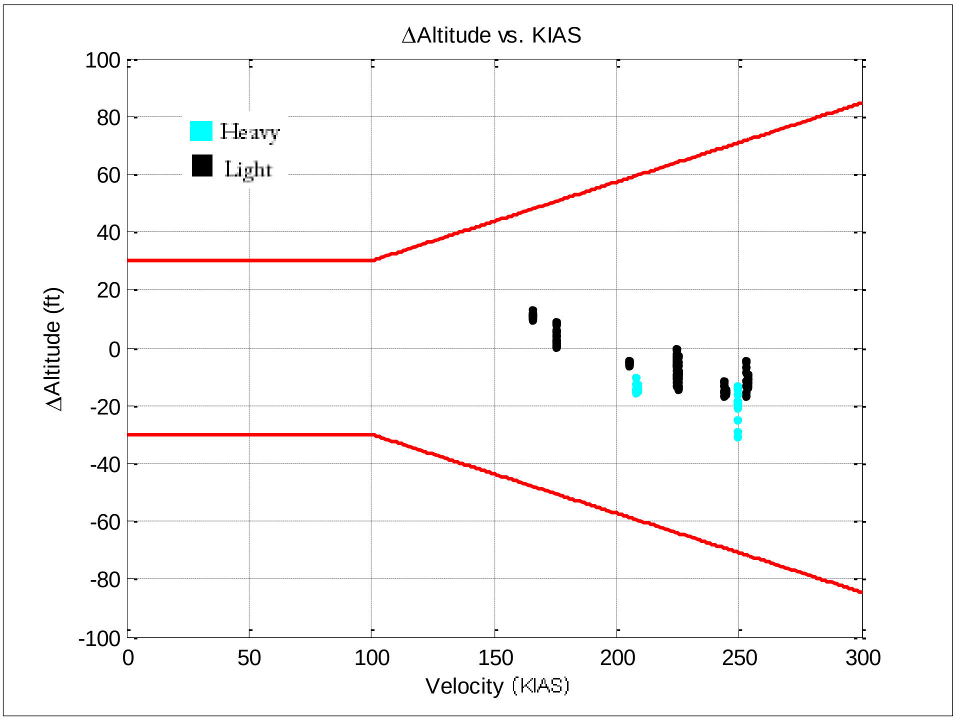

Figure 28 Altitude Error Flight # 3&4 – Heavy & Light Clean Configuration

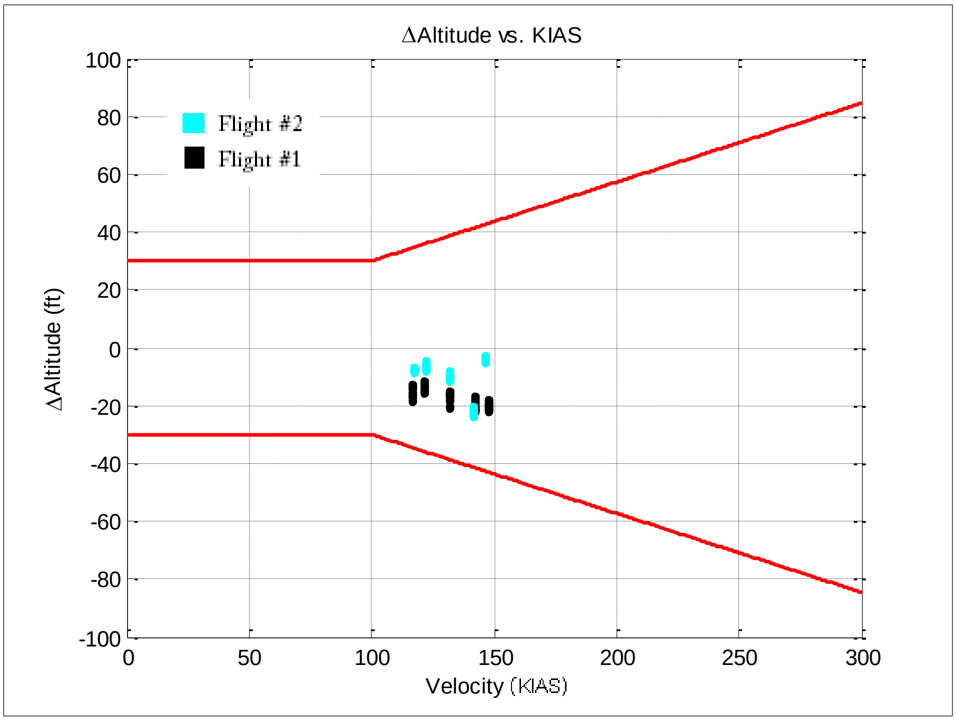

Figure 29 Altitude Error Flight # 1&2 –100% Flap Landing Gear Up

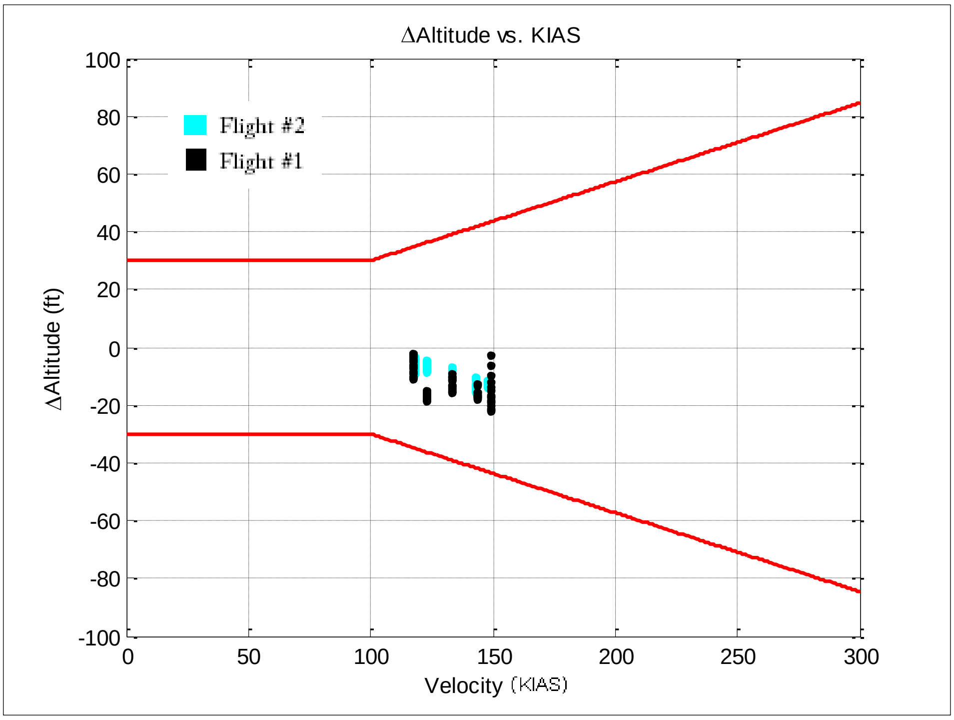

Figure 30 Altitude Error Flight # 1&2 – 100% Flap Landing Gear Down

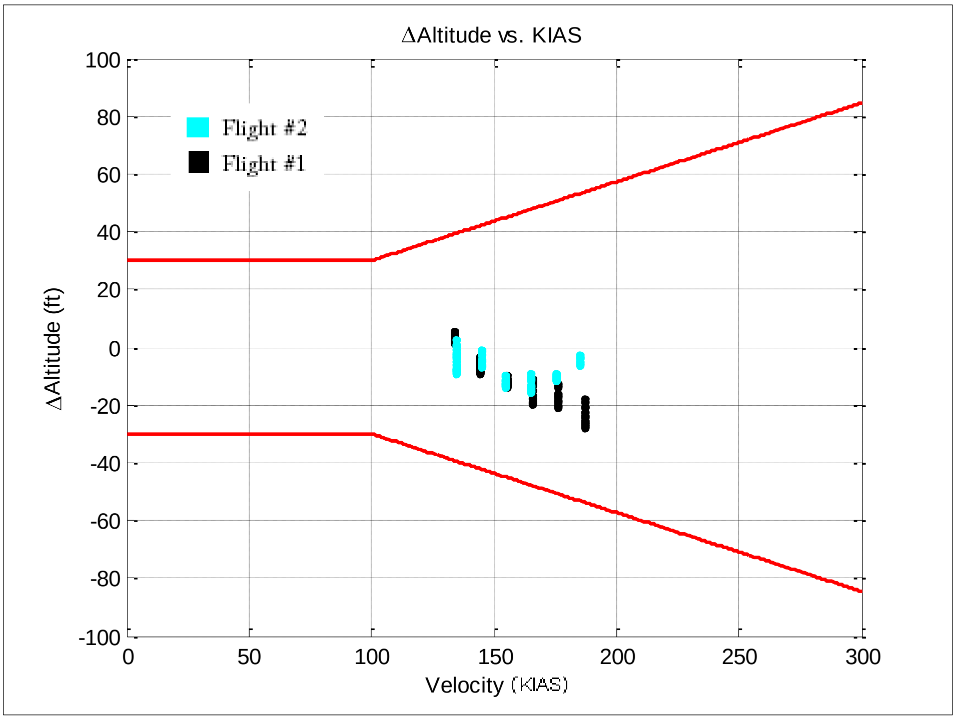

Figure 31 Altitude Error Flight # 1&2 – 50% Flap Landing Up

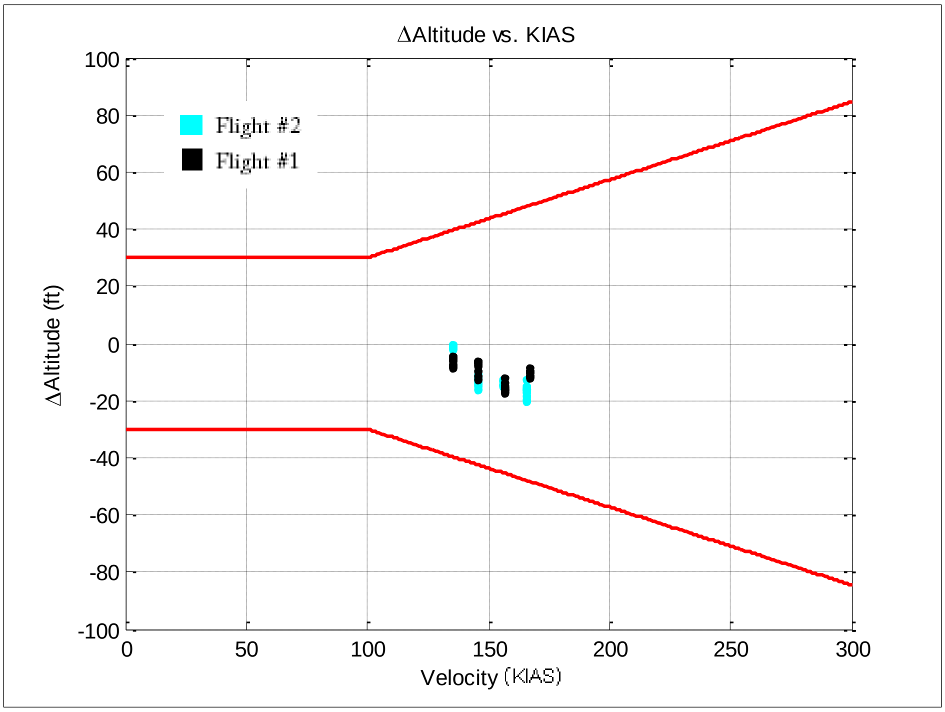

Figure 32 Altitude Error Flight # 1&2 – 50% Flap Landing Down

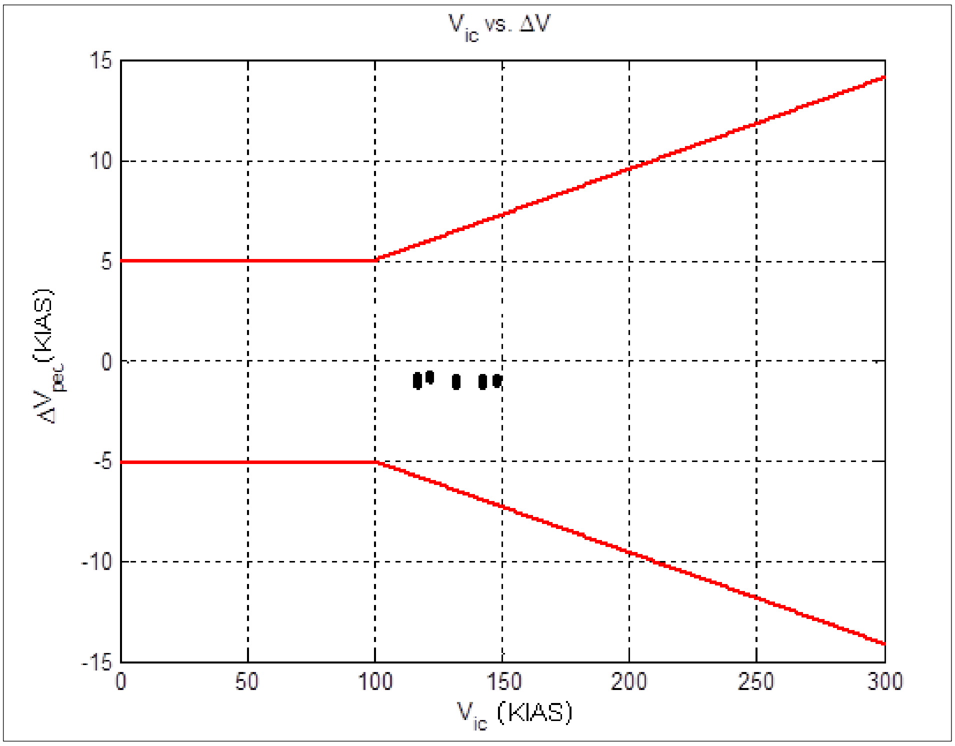

Figure 33 Air Speed Error Flight # 1 – 100% Flap L/G Up

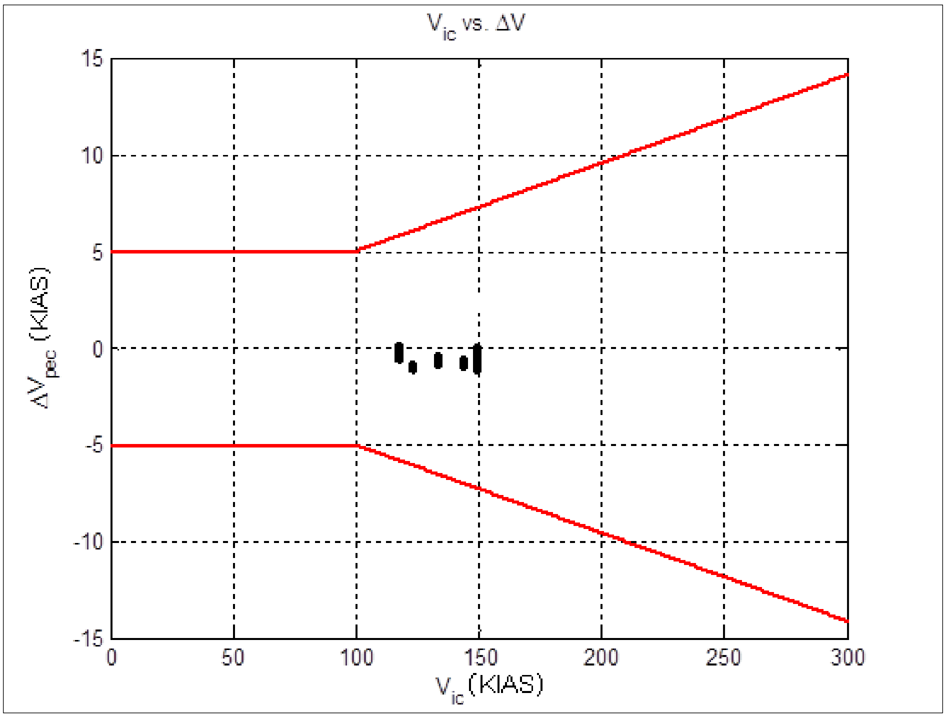

Figure 34 Air Speed Error Flight # 1 – 100% Flap L/G Down

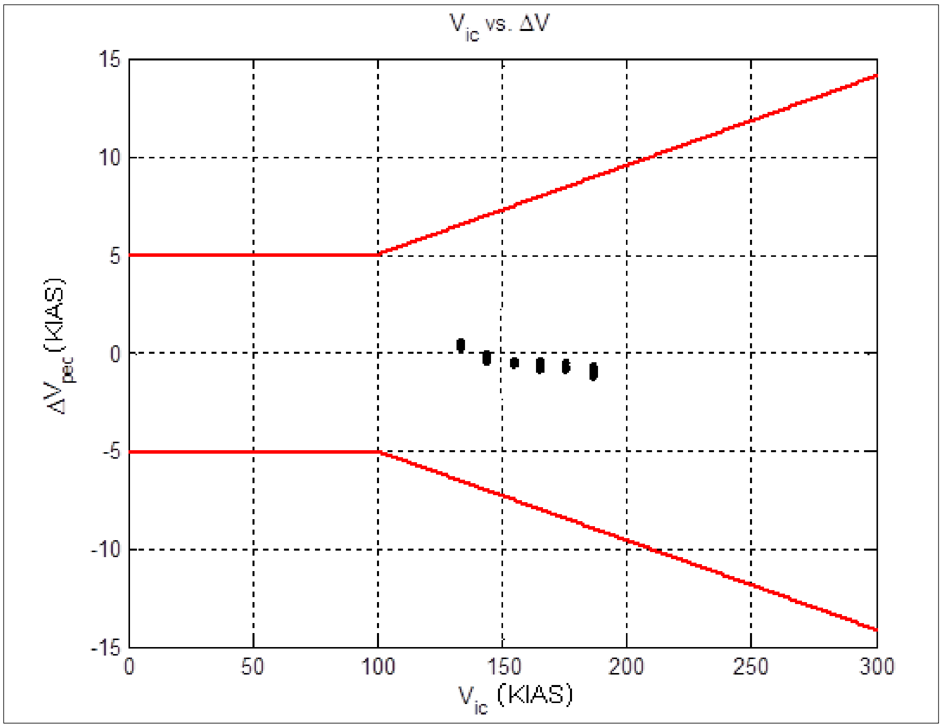

Figure 35 Air Speed Error Flight # 1 – 50% Flap L/G Up

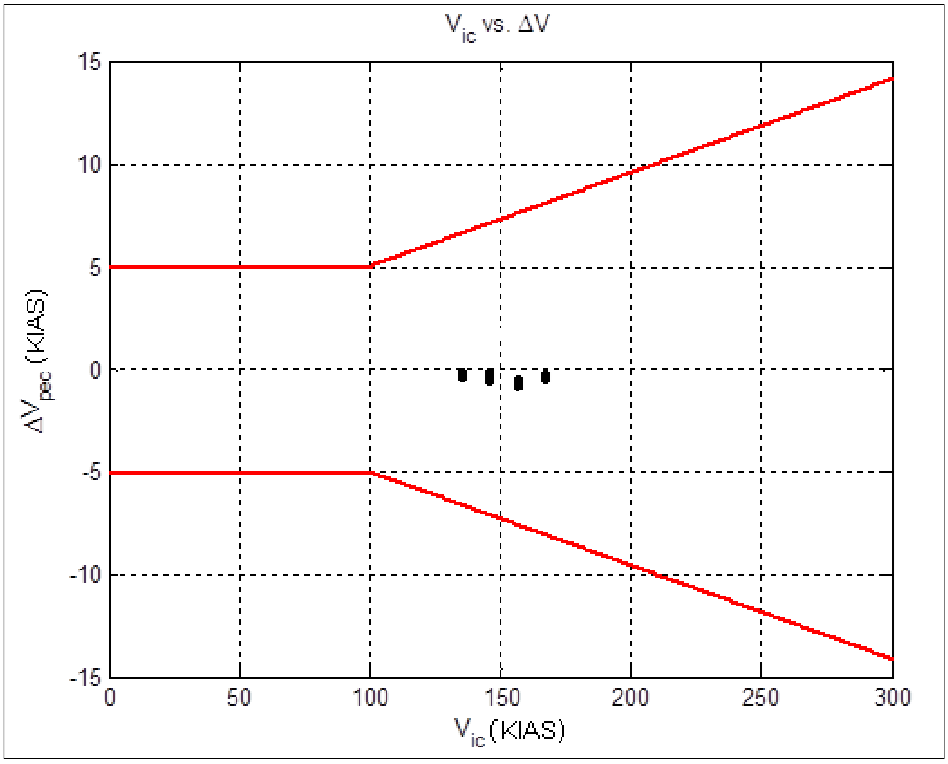

Figure 36 Air Speed Error Flight # 1 – 50% Flap L/G Down

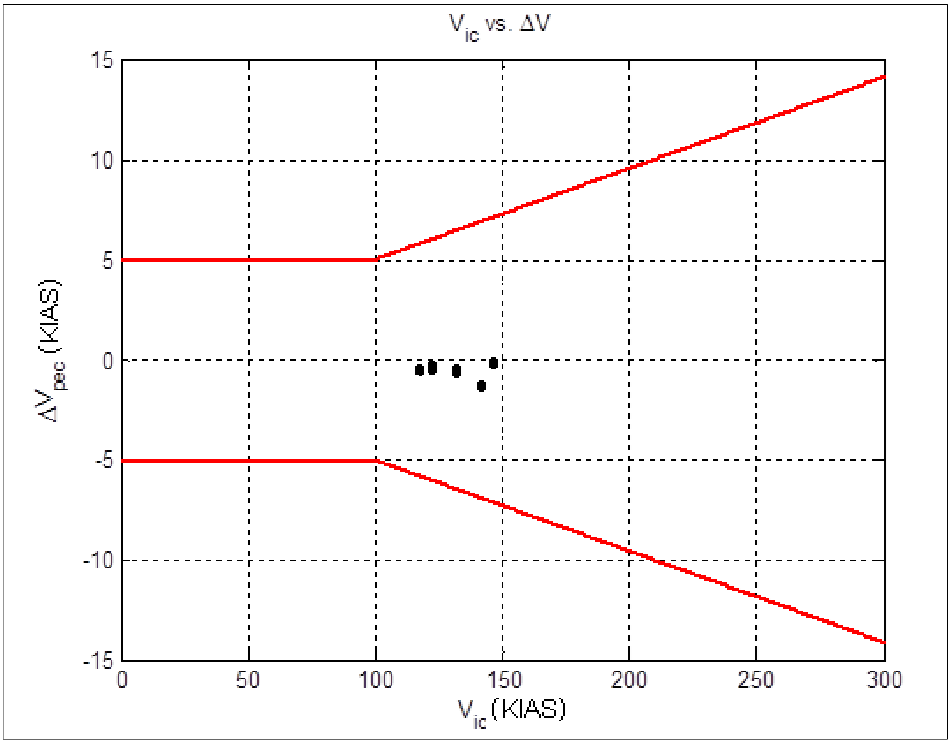

Figure 37 Air Speed Error Flight # 2 – 100% Flap L/G Up

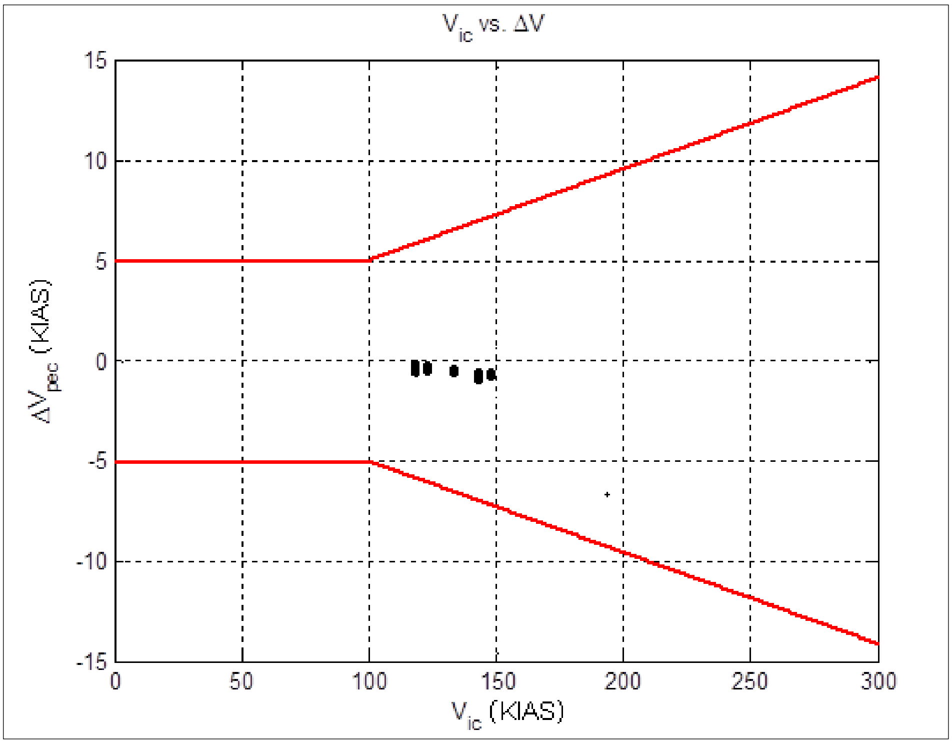

Figure 38 Air Speed Error Flight # 2 – 100% Flap L/G Down

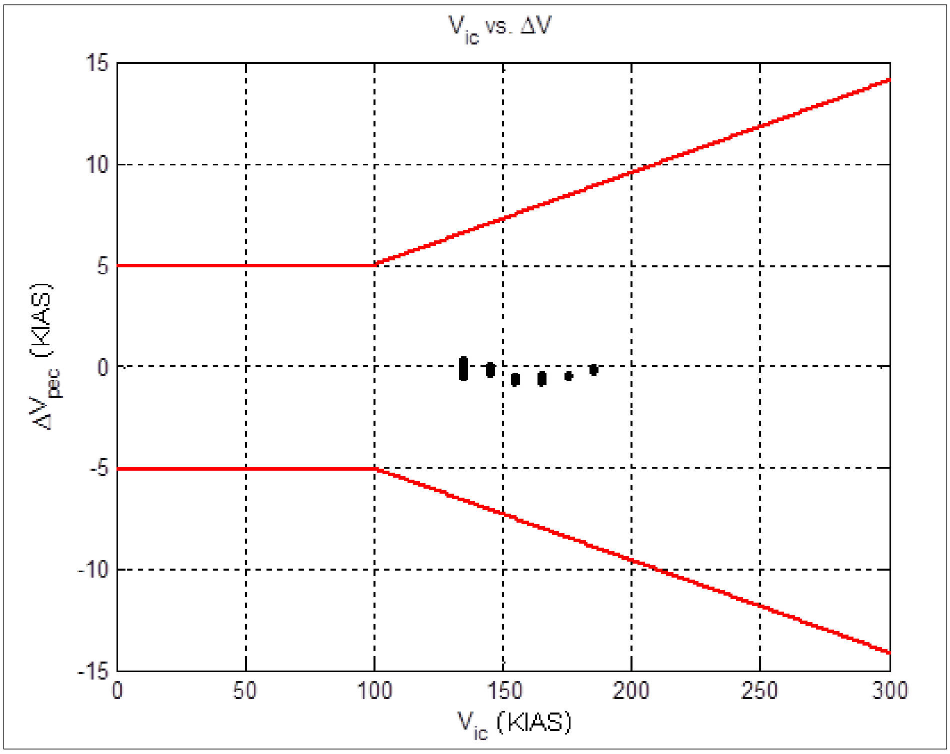

Figure 39 Air Speed Error Flight # 2 – 50% Flap L/G Up

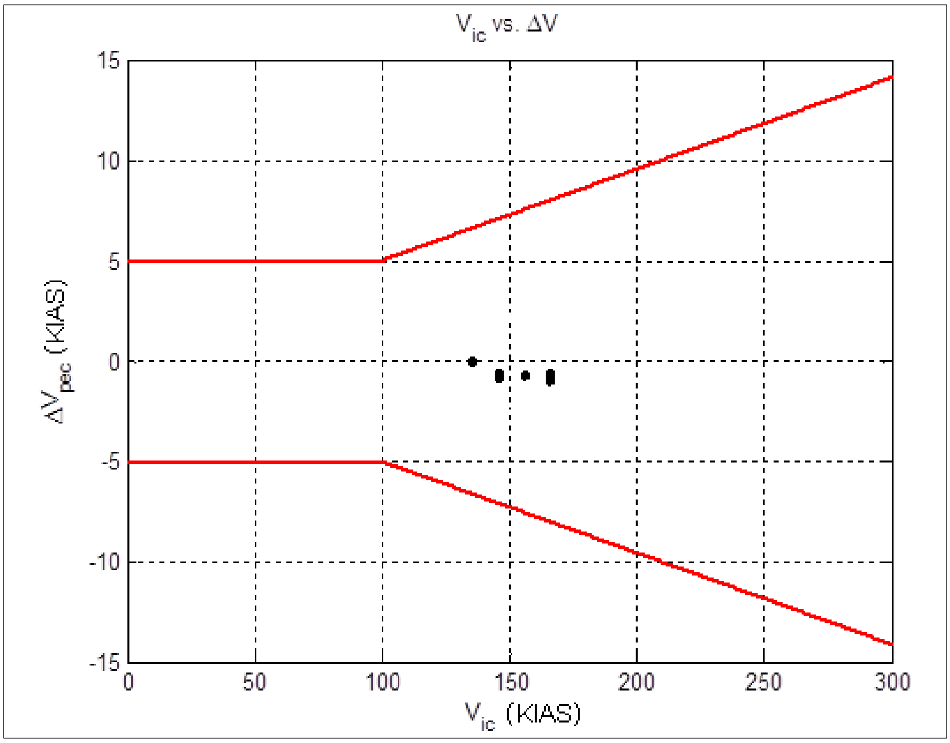

Figure 40 Air Speed Error Flight # 2 – 100% Flap L/G Down

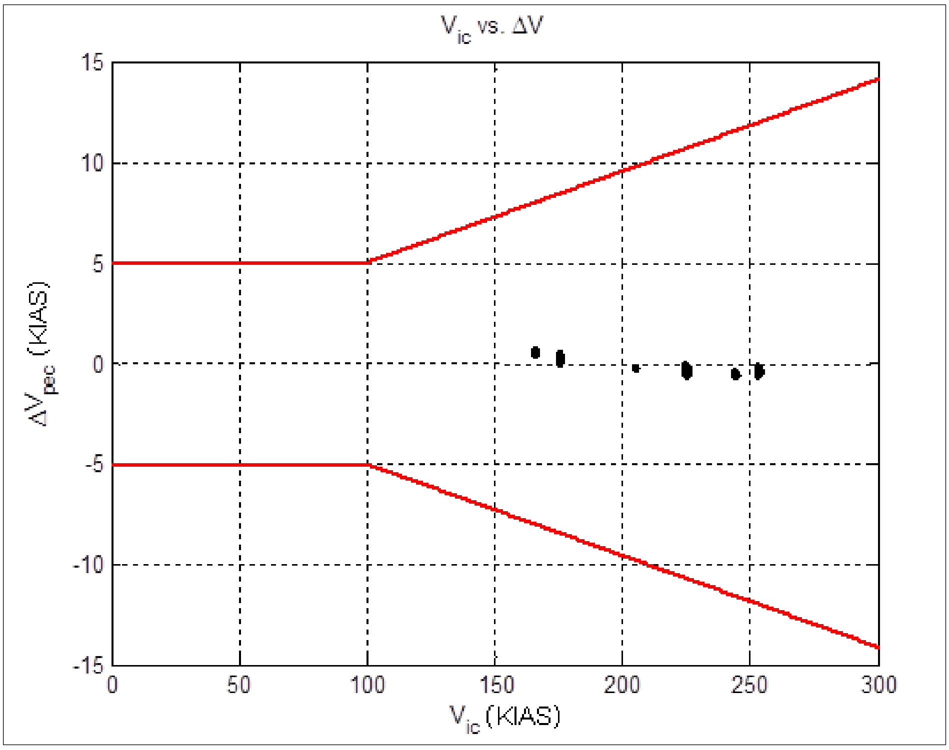

Figure 41 Air Speed Error Flight # 3 – Clean Configuration

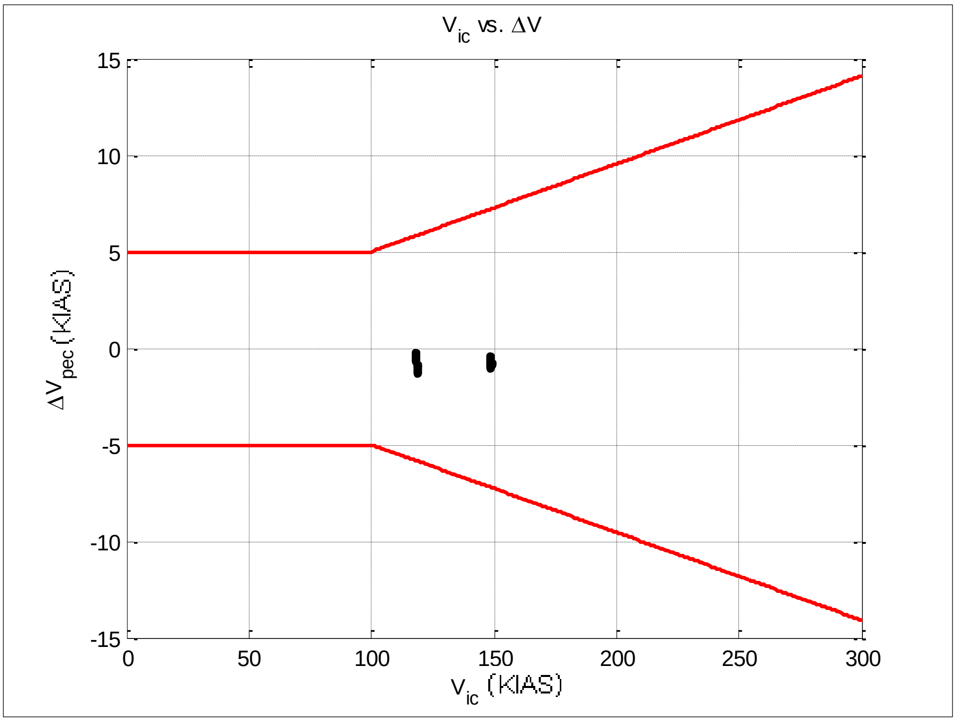

Figure 42 Air Speed Error Flight # 4 – 100% Flap Landing Up

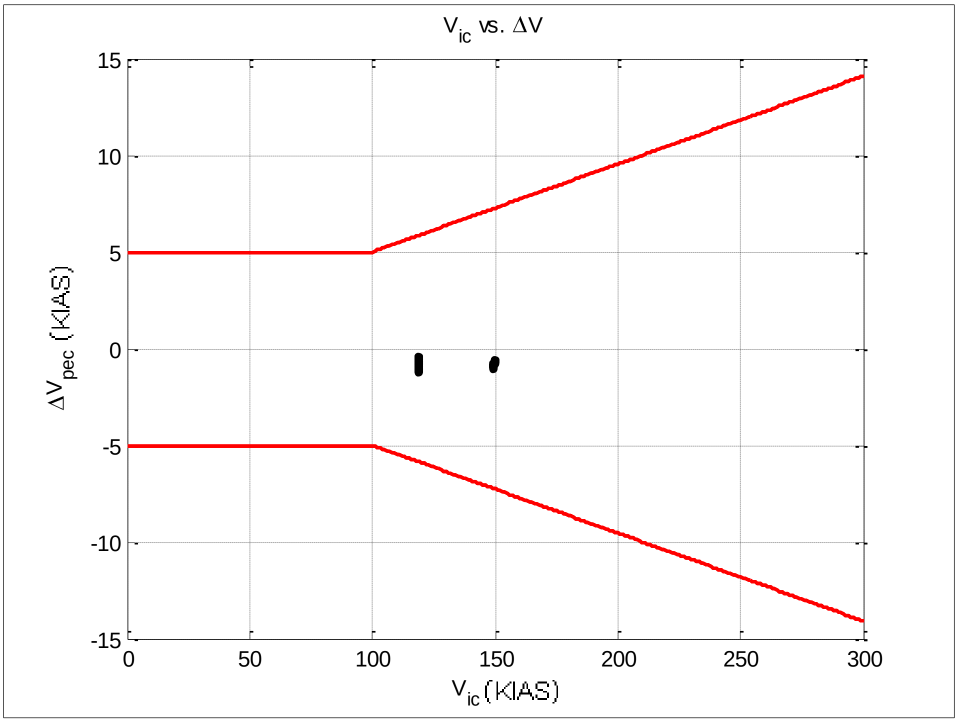

Figure 43 Air Speed Error Flight # 4 – 100% Flap Landing Down

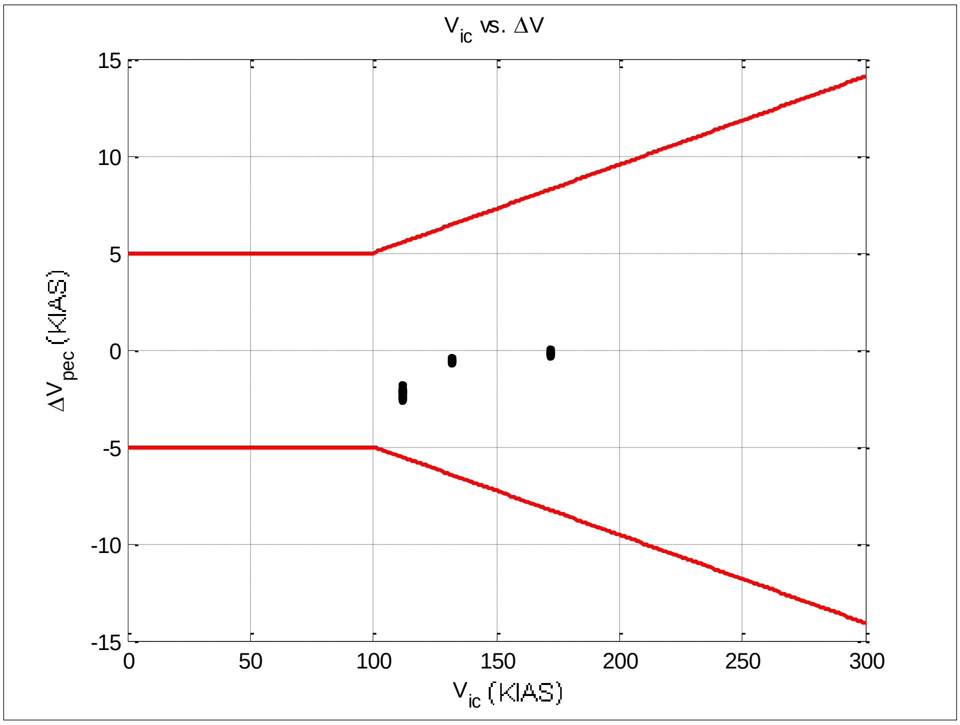

Figure 44 Air Speed Error Flight # 4 – 50% Flap Landing Up

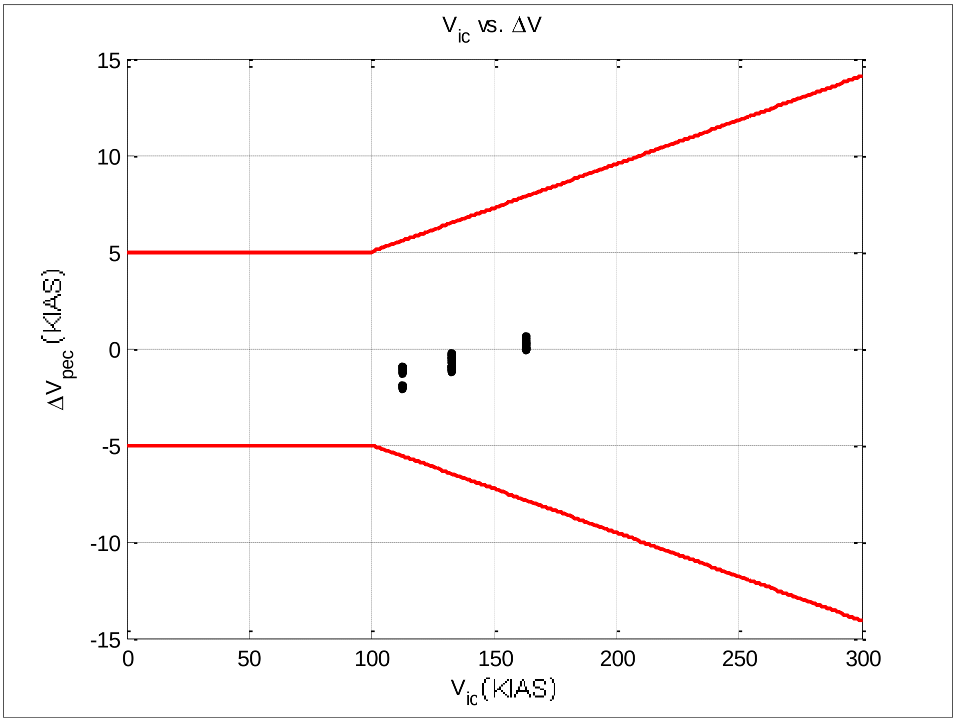

Figure 45 Air Speed Error Flight # 4 – 50% Flap Landing Down

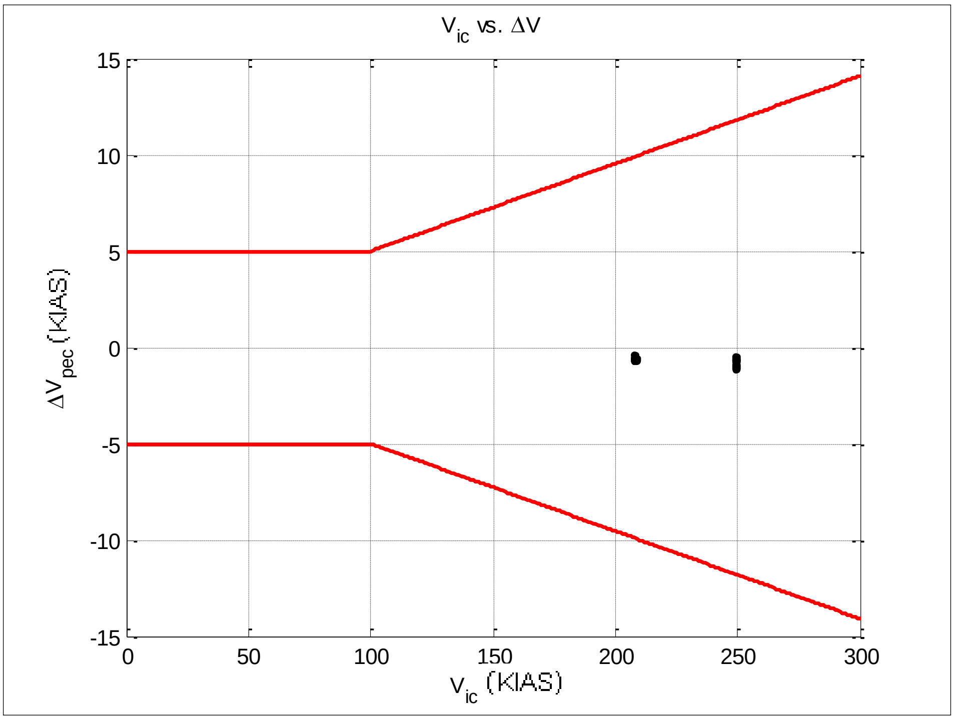

Figure 46 Air Speed Error Flight # 4 – Clean Configuration

APPENDIX B: Results Obtained by Trailing Cone Tests

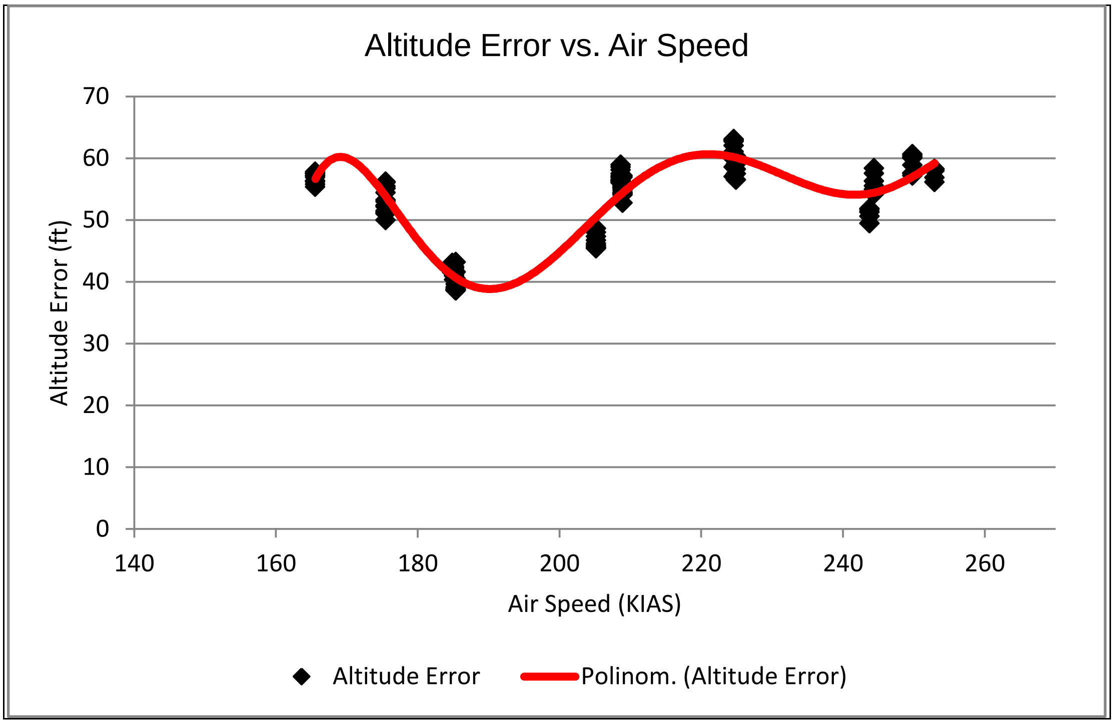

Figure 47 Trailing Cone Calibration Curve

$$Altitude\ Error = -0{,}0000000110269(\mathrm{IAS})^6 + 0{,}0000142971976(\mathrm{IAS})^5 - 0{,}0076795481929(\mathrm{IAS})^4 + 2{,}1869225755788\mathrm{x}(\mathrm{IAS})^3 - 348{,}1686926106460(\mathrm{IAS})\mathrm{x}^2 + 29.377{,}4169035719000(\mathrm{IAS}) - 1.026.175{,}7665867900000$$

$$R^2 = 0{,}9007999620560$$

Figure 48 Trailing Cone Calibration Equation