To the Graduate Council:

I am submitting herewith a thesis written by Mitchell Raburn Cannon entitled "Takeoff Determination Using the Global Position System (GPS) and Hand-Held Receivers." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

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Takeoff Distance Determination

Using The Global Positioning System (GPS)

and Hand-Held Receivers

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Mitchell Raburn Cannon

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ABSTRACT

This research lends to the fact that Global Positioning System receivers can determine position accurately and precise enough for flight testing. It will be the author's declaration that Global Positioning System receivers are more precise than traditional systems and that traditional instrumentation systems are not accurate nor precise enough to adequately determine performance parameters for aircraft. The author will confirm the accuracy and precision of the Global Positioning System (GPS) receiver and validate the claim that data collected from GPS receivers may be used in experimental performance applications. This will be achieved by a comparative analysis of flight tests and other dynamic tests.

The data was compared to actual change of position to prove the accuracy of the tests. The data proved to be less than desirable. Accuracy of the tests showed that the distance required for takeoff distance can be within 90 feet with some data proving to be within 15 feet for ideal use. Some tests proved that the GPS method of takeoff determination can be beneficial; however, more testing will be needed to confirm the time of day for testing, and the number of satellites needed for accurate data. In conclusion, unaugmented GPS data is not accurate enough to produce takeoff distance, but collecting data under ideal conditions can prove beneficial.

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LIST OF ABBREVIATIONS

A/D .... Analog to Digital

AFB .... Air Force Base

AFS .... Air Force Station

A/J .... Anti-Jamming

A-S .... Anti-Spoofing

ATE .... Automatic Test Equipment

BIPM .... International Bureau of Weights and Measures

C/A .... Course/Acquisition Code

CEP .... Circular Error Probable

C/No. .... Carrier to Noise Ratio

DAC .... Digital to Analog Converter

dB .... Decibel

DGPS .... Differential Global Positioning System

DoD .... Department of Defense

dRMS .... Distance Root Mean Square

List of Abbreviations (continued)

EDM .... Electronic Measurement System

FAA .... Federal Aviation Administration

GDOP .... Geometric Dilution of Precision

GMT .... Greenwich Mean Time

GPS .... Global Positioning System

HV .... Host Vehicle

HQ USAF .... Headquarters US Air Force

ILS .... Instrument Landing System

L1 .... GPS Primary Frequency, 1572.42 Mhz

L2 .... GPS Secondary Frequency, 1227.6 Mhz

LEP .... Linear Area Probable

P-Code .... Precision Code

PPM .... Parts Per Million

PPS .... Precise Positioning Service

RMS .... Root Mean Square

List of Abbreviations (continued)

S/A .... Selective Availability

SEP .... Spherical Error Probable

TDOP .... Time Dilution of Precision

UT .... Universal Time

UTC .... Universal Time Coordinated

VDOP .... Vertical Dilution of Precision

1 PPM .... 1 Pulse Per Minute

1 PPS .... 1 Pulse Per Second

LIST OF DEFINITIONS [1, 8]

Clock Errors:

Errors caused by the small atomic clock deviations used on the satellites.

Differential Positioning:

Accurate measurement of relative positions of the two receivers tracking the same GPS signals. Usually one receiver is stationary and at an exact known location.

Dilution of Precision:

The multiplicative factor that modifies ranging error. This is caused solely by the geometry between the user and his / her set of satellites. Known as DOP or GDOP.

Ephemeris:

The predictions of current satellite position that are transmitted to the user in the data message.

Ionosphere:

A band of charged particles 80 to 120 miles above the earth's surface

Multipath Error:

Errors caused by interference of a signal that has reached a receiver by two or more different paths. This is usually caused by one path being bounced or reflected.

List of Definitions (continued)

Pseudo Random Code:

A signal with random like noise properties. However, it is a complicated series of 1's and 0's. These codes may be subjected to a mathematical rounding error or an electrical interference which might cause erroneous correlation. This seldom happens, but when it occurs, the error will be obvious.

Static Position:

Location determination when the receiver's antenna is presumed to be stationary on the earth. This allows for averaging techniques that improve accuracy by factors of over 1000.

CHAPTER I

INTRODUCTION

Determination of aircraft flying qualities is a necessary endeavor for aircraft manufacturers and consumers. The ability of a pilot to maneuver and control an airplane is an important and potentially life threatening peculiarity to the selection process of aircraft. Often times, design for performance will hinder the controlability of aircraft. Therefore, parameters are set by the Federal Aviation Administration (FAA), the U.S. military, large corporations, and other countries to restrict aircraft design and to test the final product.

In order to determine the flying qualities of an aircraft, one must perform many tests. The instruments needed to read the data require an accurate and precise system. With the arrival of GPS, position locations, velocity, and acceleration of aircraft can be established. With these data, one can perform multitudes of calculations to establish the necessary parameters associated with flight testing of aircraft.

It is the author's intent to show that takeoff performance can be determined by using hand held Global Positioning System (GPS) receivers. The runway length needed for liftoff can be determined using these receivers. Reduction of extra man power and expensive instrumentation from previous tests methods may be possible by the use of hand-held GPS recievers.

Reference material, previous tests, and related articles will show the accuracy and precision of GPS. A comparison to traditional methods and instruments will be made. Applications of the results will prove beneficial to other forms of flight testing.

Global Positioning System

In 1973, the United States Department of Defense (U. S. DoD) initiated a system to allow users to accurately navigate anywhere in the world. The system, known as the Global Positioning System (GPS), has become widely used for navigation and other means of position determination. The GPS is comprised of three major system segments: space segment, control segment, and user segment [1]. This includes, but is not limited to: satellites, control stations, and receivers. With the interaction of the systems segments, one's position can be accurately determined anywhere in the world.

Space Segment

The space segment of the GPS is comprised of 24 satellites. The satellites are placed in six nearly circular orbits at 10,900 nautical miles above the earth (see Figure I-2). A typical GPS satellite, known as the Rockwell NAVSTAR satellite, weighs 1900 pounds, with 17 foot solar panels. They have an orbital equatorial plane of 55^{o} and a period of 12 hours. The life expectancy of the satellites are 7.5 years [2] . The satellites are placed in such a manner that a user, located anywhere on earth, will have at least six in view at any one moment in time.

The satellites transmit two codes, C/A-code and P-code. Each satellite is also assigned an ephemerides and identification code so that the receiver can distinguish between other satellites and determine the position of the transmitting satellite. The C/A-code is at a chipping rate of 1.023 Mbps, wave length of 293 m, and a repetition rate of 1 ms. The P-code is used, in large part, by the military. It has a chipping rate of 10.23 Mbps, wave length of 29.3 m, and a repetition rate of one week. The P-code is more accurate than the C/A-code; however, only military and selected civilian users have access to the transmitted information. A comparison of the different codes are shown in Table I-1. In addition

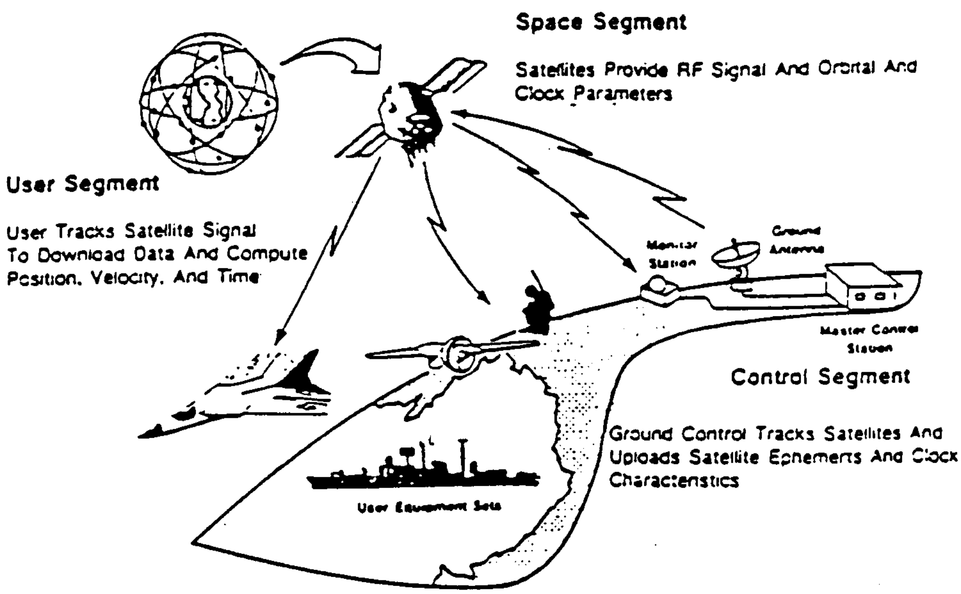


Figure I-1

NAVSTAR GPS SYSTEM SEGMENTS

Source: Adapted from (Arnold, J. L., and R. W. Blank. "GPS / INS Integration for Range Instrumentation." Rockwell International Corp. Publication. Cedar Rapids, IA, p. 227.)

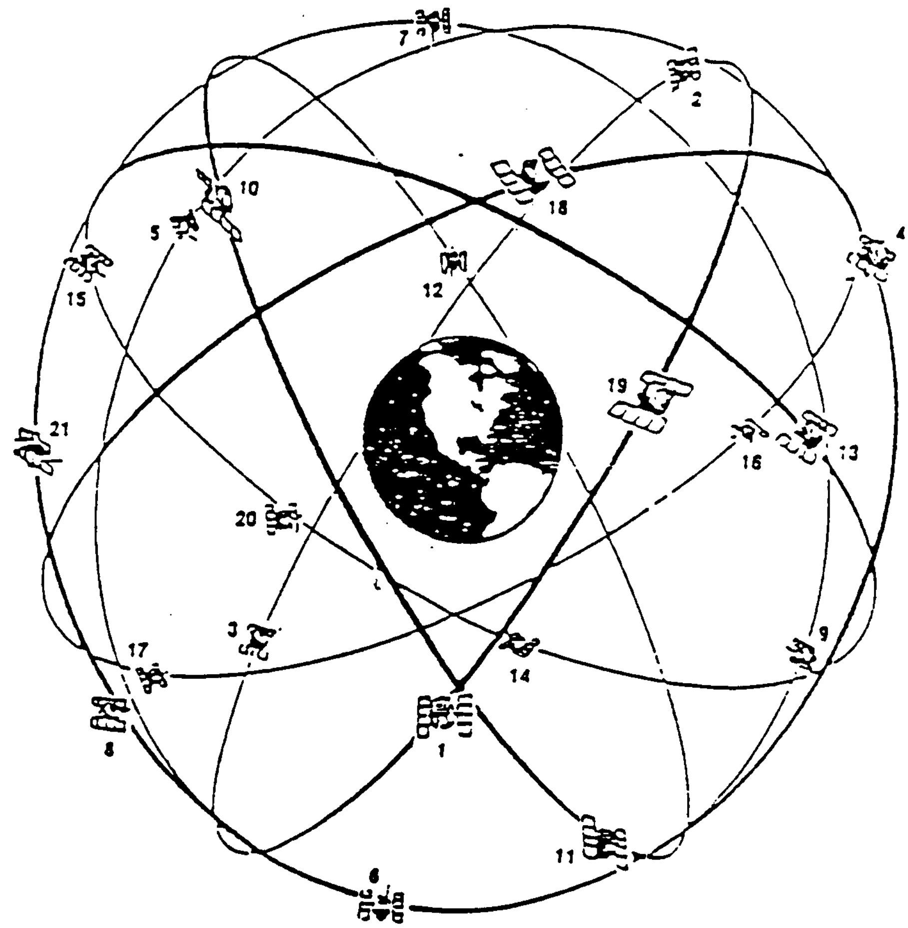


Figure I-2

Operational Satellite Constellation

Source: Adapted from (GPS overview, SCI Technology, Inc., 8600 S. Memorial Parkway, Huntsville, AL 35807, Nov. 1990 p. 1-3)

Table I-1 SUMMARY OF GPS CODES [3]

	C/A	P	Navigation Data
Chipping Rate	1.023 Mbps	10.23 Mbps	50 bps
Length	293 m	29.3 m	5950 km
Repetition	1 ms	1 week	N/A
Features	Easy to Acquire	Precise Positioning Jam resistant	Time Ephemeris

The satellites transmit a signal on two L-band carrier frequencies. The fundamental frequency of 10.23 MHz is multiplied by 154 and 120 to obtain L-band frequencies of L1=1575.42 MHz and L2=1227.60 MHz, respectively. The fundamental frequency is governed by a set of atomic clocks. The L1 and L2 frequencies are modulated with a precision code (P-code) at a chipping rate of 50 bps. The course/acquisition codes (C/A-code) are available on the L1 frequency and are mutually exclusive to each satellite, allowing for receivers to distinguish individual satellites [3] .

Control Segment

The control segment of the GPS is responsible for a major portion of the accuracy of the complete global positioning system. The Consolidated Satellite Operations Center (CSOS), located at the Falcon Air Force Station near Colorado Springs, has the main function of the control station to update the navigational messages of the satellites[4]. The CSOS, along with other monitor stations, monitor and communicate necessary correction data to the satellites for the purpose of obtaining the desired accuracy needed for navigational purposes (16 m with full P-code access, 100 m 2-D civilian). The relevant information includes: clock correction factors, satellite epheremeris constants (predicted for 14 days), and information on the earth's current ionosphere. See Figure I-3.

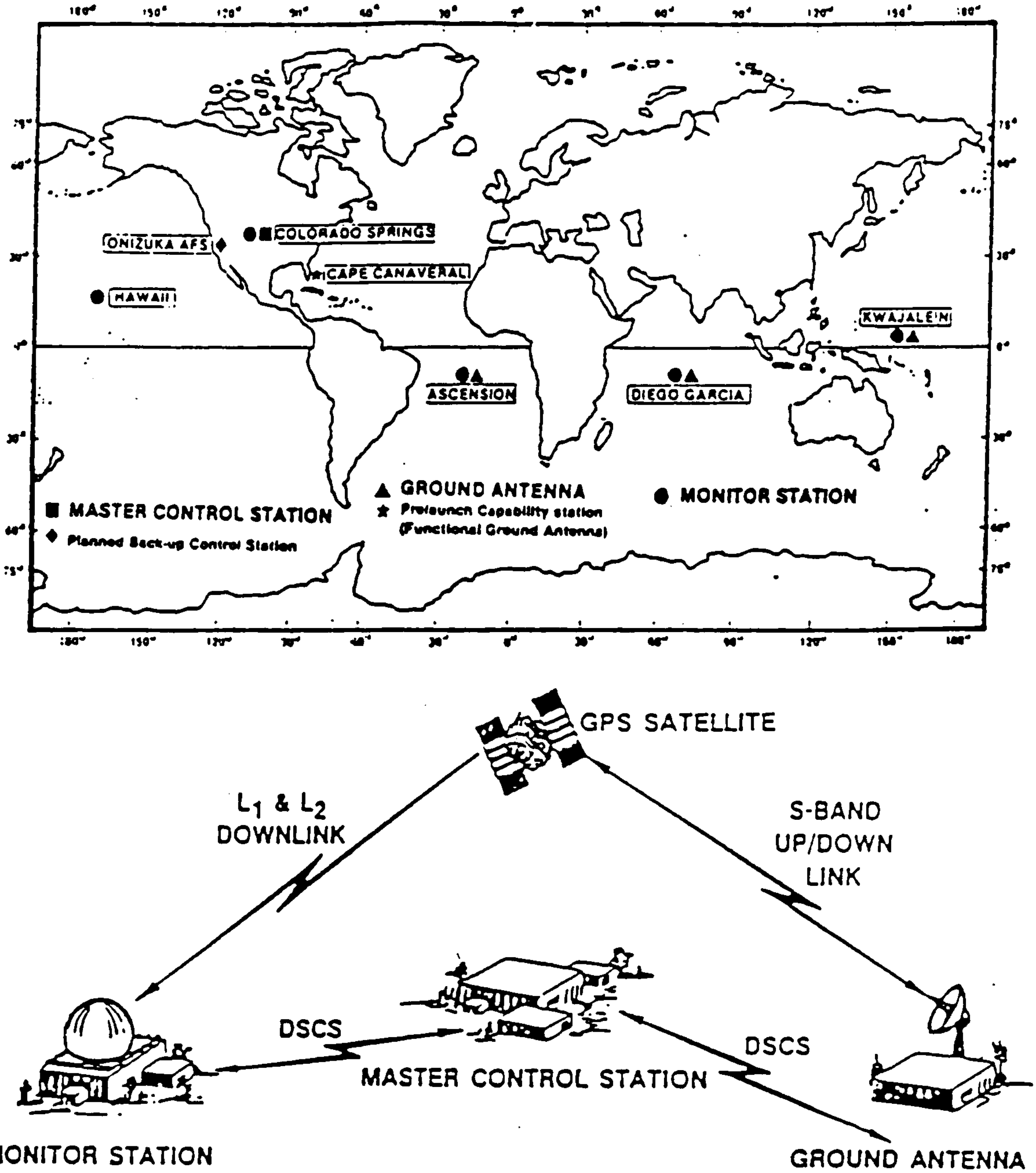


Figure I-3

GPS Control Segment and Locations

Source: Adapted from (GPS overview, SCI Technology, Inc., 8600 S. Memorial Parkway, Huntsville, AL 35807, Nov. 1990 p. 1-3)

User Segment

The user segment usually consists of two groups: military, and civilian. It may consist of aircraft, ships, automobiles, or any user with a GPS receiver. The receivers, with a built in code analysis program and clock, can take information from at least four satellites to determine position. This is achieved by the calculation of distance from a satellite. From four known satellite positions, a receiver can calculate, by triangulation, an exact position in three dimensions.

Some systems can cost as much as a million dollars. However, the hand held receivers currently cost as little as $300. Although some receivers are capable of transmitting data, not all receivers transmit any information as a function in the GPS. Thus, the receivers and the users play a passive role in the GPS.

Errors / Accuracy

The accuracy of the GPS is controlled by several factors. Errors are inherent, as in any system, and need to be taken into consideration. The largest portion of error, when implemented, is from the U.S. DoD. This is known as "Selective Availability" (S/A). The U.S. DoD can, at will or when necessary, purposely induce an error to the system for the intent of denying the enemy or hostile forces precise use of the system. The U.S.

DoD will implement S/A for purposes such as war or when a threat to the U.S. is perceived. Other errors include, but are not limited to: satellite clock error, ephemeris error, receiver errors, atmospheric / ionospheric errors, and antenna errors. These errors are illustrated in Table I-2.

Table I-2, ERROR BUDGET (as seen by Block I satellites) [2]

Error	**Position (Feet)**
Satellite Errors	2
Ephemeris Errors	2
Receiver Errors	4
Atmospheric / ionospheric	12
S/A-worst case (if implemented)	25
Total (root-square sum)	15 to 30

The error budget is determined, for the most part, by S/A. The total source of errors can range from 15 to 30 feet, as shown by Table I-2. In order to calculate the predicted accuracy, one must determine the Position Dilution of Precision (PDOP). Under good conditions, the PDOP can range from 4 to 6. Multiplying PDOP by the total error budget, one can expect accuracy of a typically good receiver to be within 60-100 feet of the actual position, to 200 feet for the worst case, and 350 feet if S/A is implemented [5] . Although many of these errors can accumulate, many errors are reduced by mathematical modeling and by the fact that, in nature, errors can compensate for each other. Trimble Navigation, Avionics Products Division, claims a root mean squared (RMS) accuracy of 49 feet for their *Flighhtmate Pro GPS*™ hand held GPS navigation receiver [6] . The receiver is shown in Figure I-4. This accuracy seems to be common in most hand held units of the same class and price range. The factors influencing accuracy can be manipulated and / or controlled, but an understanding of the errors are essential for precise calculation associated with position determination.

Figure I-4

PHOTOGRAPH OF *FLIGHTMATE PRO* ™

Source: Adapted from Trimble Navigation Advertisement 2-221 0159B, 4/95.

CHAPTER II

LITERATURE REVIEW

With the advent of GPS technology, many uses of position determination from GPS signals have been applied to the military and civilian user market. Navigation of the lands, seas, and atmosphere has been made simpler and more accurate. That was the main intention for the implementation of the GPS. However, many other uses of the system have become apparent. The marine, land, and aviation user has applied the use of GPS signals for almost everything conceivable from determining the position of a stolen or lost automobile to determining the attitude of near-earth satellites or the detection of sub-millimeter movements of bodies of land.

Previous users of the GPS have used kinematic differential relative position information to an accuracy of 10 cm for aircraft and less than 10 mm for slow moving land vehicles [7]. Differential Global Positioning System (DGPS) is similar to GPS except in the fact that DGPS implements a reference receiver that sends a correction signal to field receivers or other users. The reference receiver is placed at an exact and precisely surveyed location. As a result, the position of a user can be determined to within 1.3 m and better [8]. Stanford University has used DGPS to produce 0.5 m vertical accuracy on a United Airlines 737 [9]. Table II-1 shows a typical error budget comparison.

Table II-1 SUMMARY OF GPS ERROR SOURCES (in meters) [8]

Summary of Error Budget comparison

Per Satellite Accuracy	Standard GPS	Differential GPS
Satellite Clocks	1.5	0
Orbit Errors	2.5	0
Ionosphere	5.0	0.4
Troposphere	0.5	0.2
Receiver Noise	0.3	0.3
Multipath (reflections)	0.6	0.6
S/A	30.0	0
Typical Position Accuracy		
Horizontal	50	1.3
Vertical	78	2.0
3-D	93	2.8

Related Flight Tests

The GPS has been used for various types of flight testing. The calibration of instruments used for airspeed indication, groundspeed determination, attitude determination and many other forms of flight testing systems have been integrated with the GPS. GPS system accuracy has been checked against DGPS for accuracy and precision determination.

Using the DGPS method of checking GPS accuracy, the testing of the United States Air Force A-10 aircraft proved to be beneficial. These tests proved that an accuracy of 10 meters Circular Error Probable (CEP) is possible. When the GPS receiver was integrated with an INS, the system improved to 9.3 CEP. Other tests indicate that GPS will be an effective tool in flight testing. In 1991, a Boeing 737 was tested to determine position using GPS. The data was compared to tests completed simultaneously by the Microwave Airplane Positioning System (MAPS). MAPS two-sigma accuracy is between 2 and 3 m. Altitude differences averaged approximately -3 meters and a spread of plus or minus two meters. Anticipated accuracies are proposed to approach 0.1 meter [11].

Generally, airplanes can takeoff at any speed above stall speed (V_S). With this in mind, airplanes can theoretically liftoff at V_S. However, this practice can lead to accidents. Therefore, a commonly accepted value for takeoff speed (lift off speed-V_{LO}) is $1.2V_S$ [12]. The takeoff distance can be determined from the derivation of liftoff distance (s_{LO}) required to accelerate from zero to $1.2V_S$ (V_{LO}). This is achieved by Newton's second law:

$$F=ma=m\frac{dV}{dt}$$

$$dV=\frac{F}{m}dt$$

(Eq. 2.1)

Assuming the airplane starts from rest (V = 0), at location s = 0, time (t) = 0, force (F) and mass (m) are constant, the airplane is accelerated to V over distance s at time t. By integrating Equation 2.1 we have:

$$\int_0^V dV=\frac{F}{m}\int_o^t dt$$

$$V=\frac{F}{m}t$$

$$t = \frac{Vm}{F}$$

(Eq. 2.2)

Assuming an instant when V, the incremental distance (ds) covered during an incremental time (dt) is ds=Vdt [13] then we have:

$$ds = Vdt = \frac{F}{m} t \, dt$$

$$\int_0^s ds = \frac{F}{m} \int_0^t t dt$$

$$s = \frac{F}{m} \frac{t}{2} t$$

Since $t = \frac{Vm}{F}$, *Eq. 2.2, then* $$s = \frac{V^2 m}{2F}$$

(Eq. 2.3)

Equation 2.3 gives the distance s required for a body of mass m to accelerate to velocity V under the control of a constant force F [13]. Several factors affect the sum of forces that act in the opposite or same direction as the thrust. They include: rolling resistance (friction), slope of the runway, head or tailwinds, air density, air temperature, aircraft weight, pilot technique, wing height and span (ground effect) and runway surface conditions. The forces acting on an aircraft during takeoff are shown in Figure II-1.

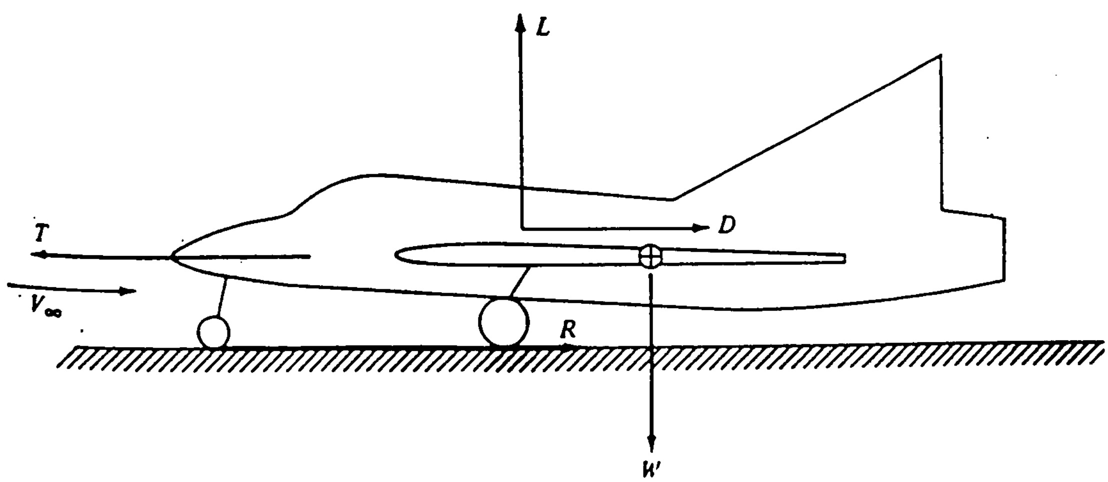


Figure II-1

FORCES ACTING ON AIRPLANE DURING TAKEOFF

Source: Adapted from (Anderson, John D. Jr.. Introduction to Flight. McGraw-Hill, Inc. New York, New York, p. 319.)

The rolling forces (R) acting on the airplane during takeoff ground roll are dependent on the coefficient of rolling friction (μ_r), weight (w), and the lift (L) created by dynamic pressure, which varies with velocity. This shown is in Equation 2.4:

$$R = \mu_r(W - L)$$

(Eq. 2.4)

Drag and ground effect contribute to the forces acting on an airplane. Drag is defined by Bernouli's Equation and is described as:

$$D = \frac{1}{2}\rho_\infty V_\infty^2 S\left(C_{D,0} + \phi \frac{C_L^2}{\pi e A R}\right)$$

Where e is a aerodynamic quantity of Oswalds Efficiency Factor, s is wing area, and ϕ is the reduction of drag effect as a result of ground effect caused by the close proximity of the wings to the ground. The wing tips vortices induce a down wash effect which is approximated in Equation 2.5:

$$\phi = \left(16h/b\right)^2 / \left[1 + \left(16 + h/b\right)^{(2)}\right]$$

(Eq. 2.5)

where h = height of the wing above the ground, and b = wing span (13). Similarly lift is described as:

$$L = \frac{1}{2}\rho_\infty V_\infty^{\ 2} S C_L$$

(Eq. 2.6)

Using Newton's second law and summing all forces acting parallel to the ground on the airplane during takeoff run , we have:

$$F = T - D - R = T - D - \mu_r(W - L) = m\frac{dV}{dt}$$

(Eq. 2.7)

In order to properly calculate a variation of velocity with time during ground roll to determine takeoff distance, Equation 2.7 must be numerically integrated. However, since D and L are proportional to dynamic pressure, they reasonably appear linear. Hence, T is relatively constant and can be approximated by Equation 2.8 [13]. This is shown by Figure II-2.

$$F_{eff} = T - \left[\mu_r(W - L)\right]_{ave} = \text{constant}$$

(Eq. 2.8)

From Equation 2.3 and Equation 2.8, distance required for takeoff is defined by:

$$S_{LO} = \frac{\left(V_{LO}^2\right)\left(W / g\right)}{2\left\{T - \left[D + \mu_r(W - L)\right]_{ave}\right\}}$$

(Eq. 2.9)

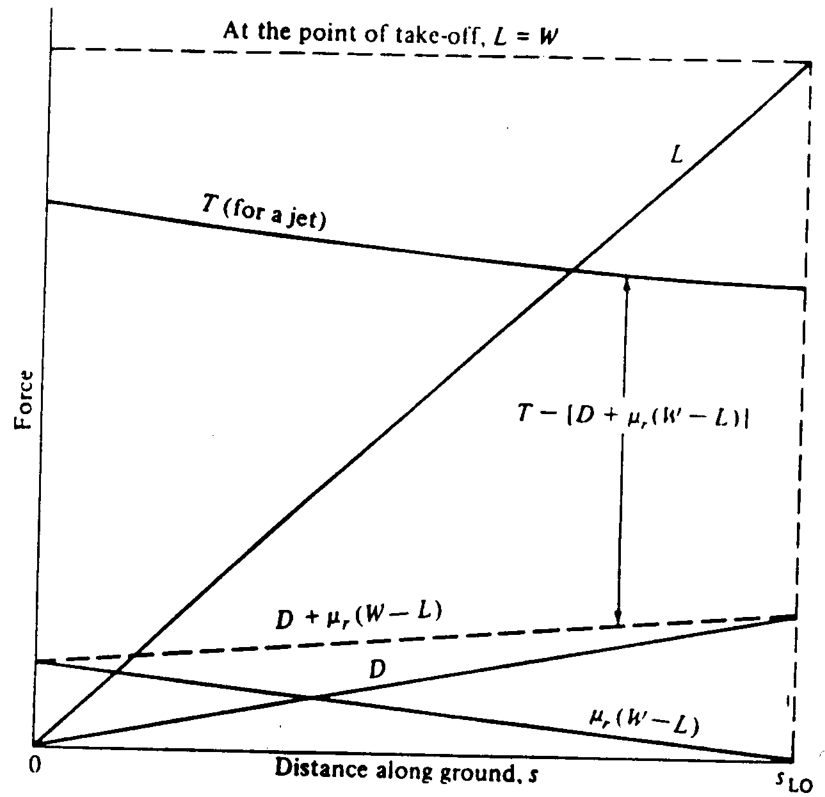


Figure II-2

TYPICAL FORCE-DISTANCE CURVE OF AIRPLANE DURING TAKEOFF

Source: Adapted from (Anderson, John D. Jr.. Introduction to Flight. McGraw-Hill, Inc. New York, New York, p. 321.)

Since

$$V_{LO} = 1.2V_S = 1.2\sqrt{\frac{2W}{\rho_\infty s c_{L,\max}}}$$

and by substituting into Equation 2.9, we get

$$S_{LO} = \frac{1.44W^2}{g\rho_\infty S C_{L,\max}\left\{T - \left[D + \mu_r(W - L)\right]_{ave}\right\}}$$

(Eq. 2.10)

This equation can be formulated and simplified assuming that the forces at $0.7V_{LO}$ = average forces during takeoff run [13].

Typical values for μ_r vary depending on the condition of the runway, the runway surface material (concrete, asphalt, grass, etc.), temperature, and humidity. These values vary from 0.02 for concrete to 0.10 - 0.30 for soft ground [12].

The previous equations present a mathematical description for the liftoff point on the runway. However, many performance factors are presented for the clearance of a 50 foot obstacle at the end of a runway. The distance required would have to be introduced in order to adequately represent a takeoff distance. The Federal Aviation Regulations require that total takeoff distance be the sum of ground roll distance plus the distance along the ground required to clear a 50 foot obstacle height (35 foot for jet powered civilian transports) [13]. These figures can be produced from climb out velocities (1.2 V_S), and rate of climb equations. Many methods of determining climb out distance have been introduced, but simple approximations have proved beneficial.

In order to adequately determine the takeoff distance to clear an obstacle one must also consider Rotation Distance (S_R), Transition Distance (S_{TR}), and Climb out Distance (S_{CL}) [15] . This is represented in Figure II-3 ($S_G = S_{LO}$).

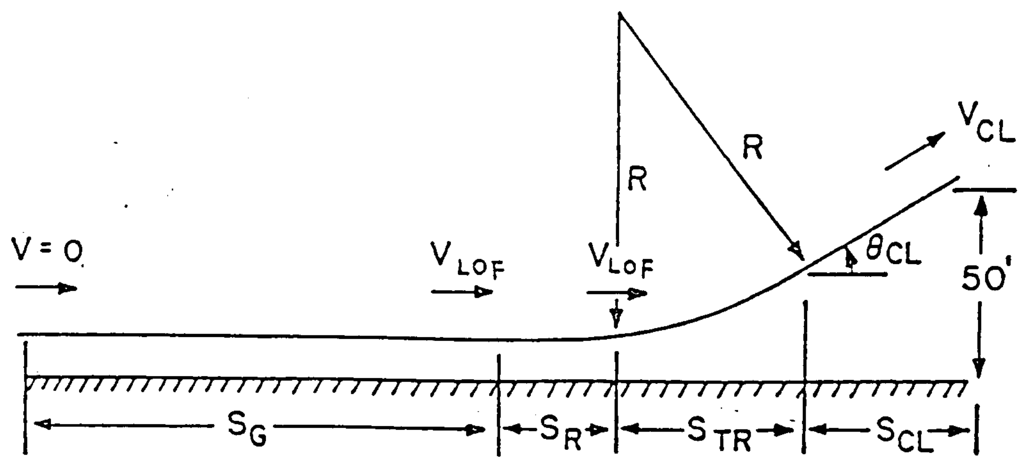


Figure II-3

GEOMETRY FOR TAKEOFF ANALYSIS

Source: Adapted from (Lan, Chuan- Tau Edward, and Roskam, Jan. Airplane Aerodynamics and Performance. Roskam Aviation and Engineering Corp., Ottawa, Kansas. 1988. p. 421.)

An approximation for Rotation Distance is simplified by time, velocity, and distance equations, where rotation time is less than 3 seconds for light aircraft [15]. This is shown in Equation 2.11.

$$S_R = t_R V_{LO}$$

Eq. 2.11

In the determination of transition distance, one must make several assumptions: (a) The geometry of the rotation is circular, (b) the lift condition during rotation is same during liftoff, and (c) there is a constant pitch rate. Looking at Figure II-3, one can determine transition distance and methods of analysis. In reality, piloting techniques play a major factor in determining transition distance, and ultimately, the takeoff distance. However, the theoretical transition distance is given by [15]:

$$S_{TR} = R \sin \theta_{CL}$$

Eq. 2.12

Where, θ_{CL} is approximately equal to (T-D)/W at liftoff velocity, and $C_{L(TR)}/C_{L(MAX)} = 0.8$, and the radius of circular arc flare is determined by [15]:

$$R = \frac{V_{LO}^2}{\left(\frac{V_{LO}^2 C_{L(TR)}}{V_s^2 C_{L(MAX)}} - 1 \right) g}$$

An approximation for the determination of climb distance is given by [15]:

$$S_{CL} = \frac{50 - h_{TR}}{\tan\theta_{CL}}$$

Where:

$$h_{TR} = R - R\cos\theta_{CL} = \frac{S_{TR}}{\sin\theta_{CL}}\left(1 - \cos\theta_{CL}\right)$$

$$= S_{TR}\,{}^{\theta_{CL}}\!/_{2} \text{ if } \theta_{CL} \text{ is small}$$

unless h_{TR} is greater than 50 feet (or 35 feet, depending on aircraft). In that case then climb distance is zero. In the summation of liftoff distance, rotation distance, transition distance, and climb distance, one can determine the total takeoff distance. This is shown in Equation 2.13:

$$S_{Total} = S_{LO} + S_R + S_{TR} + S_{CL}$$

Eq. 2.13

Winds and non-standard conditions should be taken into consideration in the velocity of dynamic pressure related equations. Winds affect the takeoff performance of airplanes. A tailwind or headwind will reduce or enhance the performance of the airplane. Assuming that the airplane is flown into the wind, the headwind component may be added to the velocity. When winds are not accounted for in the initial analysis, some correction factors are implemented such as Diehl's correction factor [12]. It is shown in Equation 2.11.

$$S_0 = \left(\frac{V_{TO}}{V_{TO} - V_W} \right)^{1.85} S_W$$

(Eq. 2.11)

where S_0 = zero wind takeoff distance, S_W = takeoff distance with headwind, and the exponet "1.85" is derived from experiments.

In addition to atmospheric conditions, runway slope corrections need to be considered. The total force acting upon an airplane during ground roll will be increased for downhill slopes and decreased for uphill slopes. The percent slope multiplied by the airplane weight is added or subtracted from the total thrust (resultant forces)[14].

Traditional Test Methods

Takeoff distance determination can be an expensive endeavor. Often times, it requires several people, and expensive equipment in order to determine takeoff distance Many factors play a role in the test method associated with takeoff distance determination. Winds, aircraft weight, air density, air temperature, ground effect, runway conditions and pilot technique play an important part in the determination of takeoff distance. Pilot technique and pilot consistency can be the major variable in the tests method for takeoff performance. There are several test methods for takeoff determination. They include, but are not limited to: The Sight Bar Method, The Strip Camera Method, Movie Theodolite, On -Board Theodolite, and Del Norte Trisponder [16]. Most of these methods require expensive equipment, external equipment, extra observers, or time for film development. Thus, they will not be discussed. These methods can be costly and require great effort. However, simple and less expensive methods exist.

Sight Bar Method

The Sight Bar Method is relatively inexpensive and simple. Thus, this method is often used for quick and easy takeoff distance determination. This method requires extra people and equipment to acquire the data for the test. One or two sight bars are mounted along the path of the runway. The sight bar is made of a cylindrical tube with a small hole at one end. The tube is mounted on a plane in a manner such that an observer can view the airplane during takeoff. The observer follows the airplane track with the eye peice that rotates until the airplane crosses a 50 foot altitude modeled on the sight bar plane. The modeled vertical and horizontal positions are marked on the sight bar and are determined by the geometry of the relational distance between the sightbar and the airplane. This is achieved by similar triangles and is illustrated in Figure II-4, and Figure II-5. The distance is read from the scale on the sight bar plane. The test is timed and the data are recorded. The Sight Bar Method is dependent on other observers which reduces the accuracy of the test [16]. However, the reduction in accuracy is compensated by simplicity and lack of relative expense.

Marker Measurement

Other methods include physical measurements or placing pre-determined markers at a convenient fixed distance. A typical separation may be 50 feet or 100 feet. The airport runway has marker signs or painted numbers to represent the position or length from another position. An airplane, for example, may start from marker position "1" and liftoff at marker position "11". Assuming the markers are seperated by 100 feet, the airplane traveled 1100 feet before the liftoff point. These systems may exist at airports where takeoff and landing distance determination frequently occurs. An obvious advantage of this system relies on the accuracy and simplicity for major considerations.

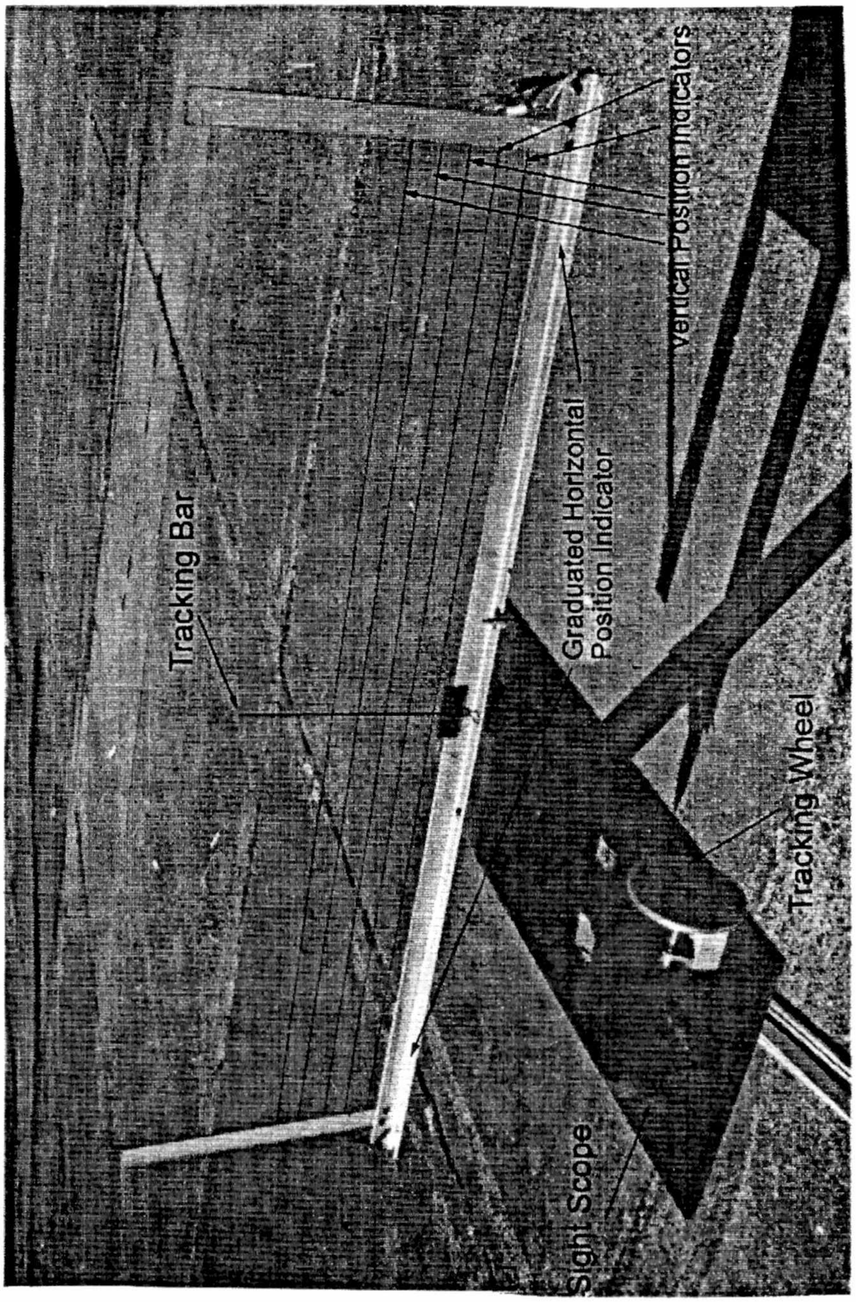


Figure II-4

SIGHTING BAR HARP

Source: Picture of Sighting Bar used for takeoff determination. Property of The University of Tennessee, Space Institute: Flight Research, Tullahoma, Tennessee

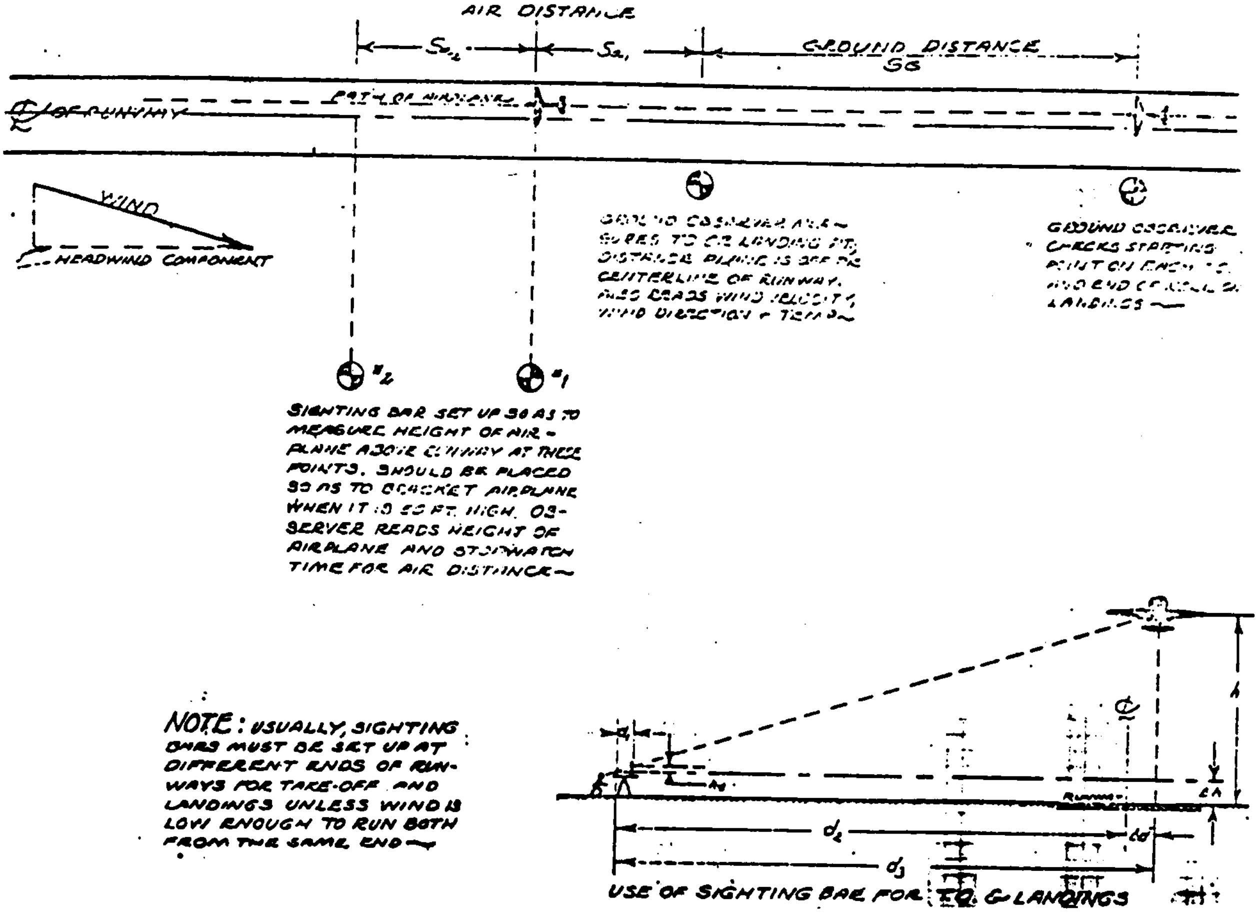


Figure II-5

TAKEOFF COURSE (SIGHTING BAR)

Source: Adapted from (Kimberlin, Ralph Dr. Performance Flight Testing Lecture Notes. Unpublished Class Notes. The University of Tennessee, Space Institute. Fall 1994

Chapter III

Conceptual Development of theTest and Description of the Test Aircraft

Conceptual Development

The purpose of the test is to confirm that hand held GPS receivers are accurate and precise enough to determine takeoff performance of an aircraft. Although it has been shown that GPS receivers, in idea conditions, are only accurate to within 60-100 feet, the author's test is designed to show that the accuracy of the relative positions between a starting point A and liftoff point B will be considerably better than the individual absolute positions. This postulation is based on the fact that a distance required for liftoff is relatively small and subjected to the same atmospheric and S/A errors. Thus, the accuracy of the difference between the two points will be substantially better than the accuracy of a single point.

Two tests are performed to show the accuracy of the GPS unit, a static test and a dynamic test. The static test involves the use of GPS receivers at rest or placed at a still position for a predetermined amount of time to resolve the position. The dynamic test involves the use of a moving GPS receiver placed in a moving automobile to determine a position instantaneously.

The static tests were performed at Tullahoma Regional Airport. The North-South runway is graduated with numbered markers. These markers are located at precisely 100 foot increments, ranging from "1" to "48." The pavement is separated by expansion seams at an approximate 20 foot pitch. These seams run perpendicular to the runway allowing an oberver to interpolate the liftoff point more accurately.The test aircraft started from a common point on the graduated runway. The takeoff point, although surveyed with a GPS unit, is at marker number "48." The aircraft were accelerated at maximum power until a preset liftoff indicated airspeed was achieved. Upon accomplishment of the airspeed, the pilot pulled the aircraft elevator controls to maintain the liftoff speed and the aircraft cleared the runway. An observer can interpolate a position to within 20 feet by comparing the liftoff position with the markers. The data is recorded and later analyzed. This process was repeated at least 10 times on two different aircraft. The test aircraft are shown in Figure III-1 and Figure III-2.

After each run, the observer stood in line with the markers at the liftoff point with a GPS receiver to determine the position. The GPS position was recorded and compared to the data from the interpolated marker position. To confirm the results, GPS readings were compared at marker number "48" and marker number "38," which is a true measurement of 1000 feet. The true difference of 1000 feet was then compared to the difference from the GPS readings.

The dynamic tests were also performed at Tullahoma Regional Airport. These tests were performed in a moving automobile. The automobile was accelerated at full power from an exact known position to another exact known position. A GPS receiver antenna was mounted on the dash. The GPS receiver start and finish positions were stored in the memory of the unit. The data were recorded and compared with the exact known relative positions. The results were subjected to a statistical analysis and are presented in Chapter IV, Results of Tests.

Test Aircraft

The static tests involve the use of two aircraft, Aircraft A and Aircraft B. Both aircraft are single engine, four place, general aviation aircraft. The aircraft belong to or are under contract lease to The University of Tennessee, Space Institute: Flight Research, located at the Tullahoma Regional Airport, shown in Figure III-3.

Aircraft A is a Piper Warrior III, PA-28-161, Serial Number 2842002. The aircraft has a single engine Lycoming O-320-D3G, 160 horsepower, four cylinder powerplant. The propeller is a two-blade, 74" Sensenich model. The manufacturer's takeoff performance data are shown in Figure III-4.

Aircraft B is a Ruschmeyer R 90-230 RG, Serial number 022. The aircraft has a single engine Lycoming IO-540-C4D5, 231 horsepower, six cylinder powerplant. The propeller is a 4-blade, 74.8" Muhlbauer model. The manufacturer's takeoff performance is shown in Figure III-5.

Figure III-1

PIPER WARRIOR III PA-28-161

Source: Picture of aircraft A taken at UTSI Flight Research. Property of The University of Tennessee, Space Institute: Flight Research, Tullahoma, TN

Figure III-2

RUSCHMEYER R 90-230 RG

Source: Picture of Aircraft B taken at UTSI, Flight Research. Property of The University of Tennessee, Space Institute: Flight Research, Tullahoma, Tennessee

In the dynamic tests, a 1989 Ford Mustang, four cylinder, manual transmission automobile was used. The car was used to simulate the typical General Aviation takeoff performance and acceleration. The model satisfies all requirements for an actual aircraft takeoff test.

Figure III-3

UNIVERSITY OF TENNESSEE, SPACE INSTITUTE: FLIGHT RESEARCH

Source: Picture taken at UTSI: Flight Research, Property of The University of Tennessee, Space Institute: Flight Research, Tullahoma, TN

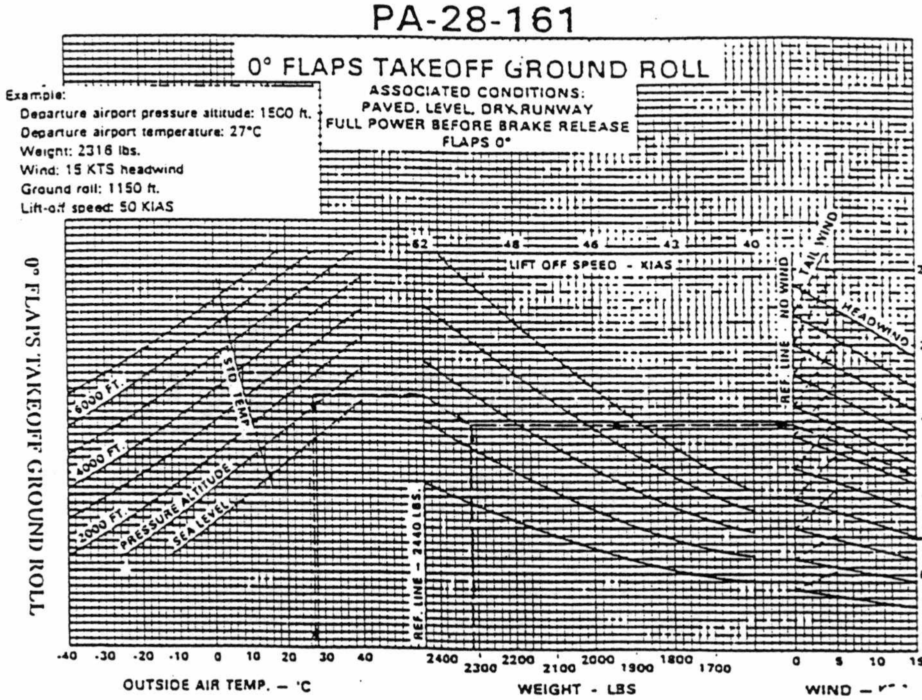


Figure III-4

TAKEOFF PERFORMANCE; PIPER WARRIOR III

Source: Adapted From: Warrior III Pilot's Operating Handbook, Piper Aircraft Company

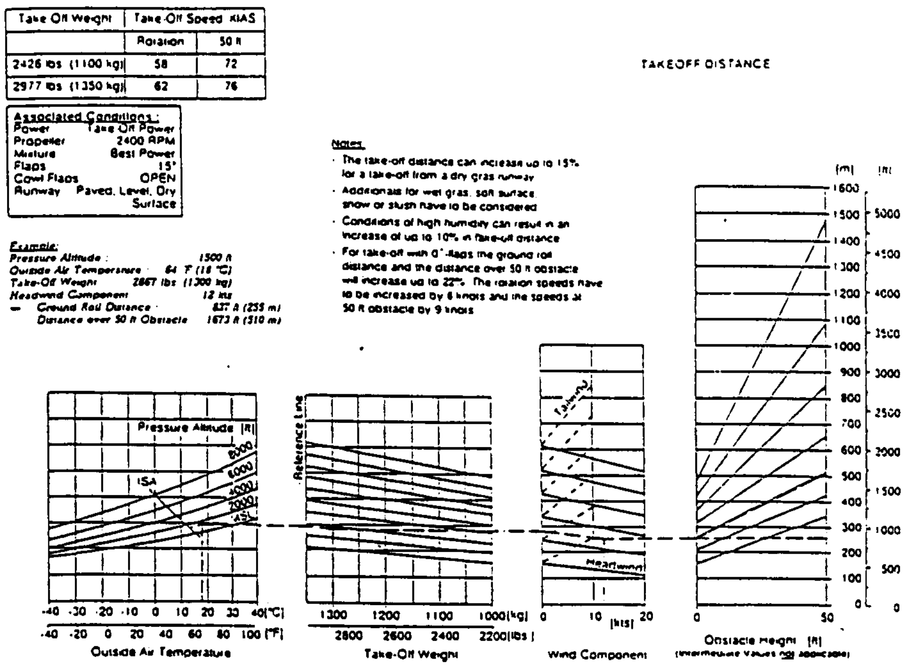


Figure III-5

TAKEOFF PERFORMANCE RUSCHMEYER R 90-230 RG

Source: Adapted from Ruschmeyer R 90-230 Airplane Flight Manual.

Horst Ruschmeyer Aircraft Production, Germany

CHAPTER IV

RESULTS OF TESTS

Many factors go into the development of a test. Factors that are beyond control of the test team must be considered and worked around. These factors must also be manipulated in order to provide adequate data for analysis of the tests. A Dynamic Test, a Static Test, and a Reference Static test was performed. Several of these tests were performed with varying degrees of success. An elaboration of the results can be seen in Chapter V.

Dynamic Tests

The Dynamic test involves the use of an automobile fitted with a GPS receiver. Two positions, separated by 1074 feet, are surveyed by GPS with 10 minute averaging implemented. The GPS data from the 10 minute averages are assumed to be accurate for the purpose of the test. The automobile and the GPS unit are accelerated from Point A to Point B (two surveyed positions). The GPS unit is set in the instantaneous mode to read the data. The data are updated approximately every 1.5 seconds. The positions at Point A and Point B are stored and recorded for analysis. The data sheet is shown in Figure IV-1.

CHANGE OF POSITION DETERMINATION
FOR TAKEOFF - DYNAMIC TEST

Date: 11 December 1995 — 1989 Ford Mustang, 4 Cylinder Manual Transmission — 19:45 Z TO 19:55 Z

Driver: Mitchell Cannon — Observers: O'Connor, Sims — Location: North - West Runway (Inactive), Tullahoma Airport, Tennessee

	(Degrees/Minutes)		in Feet				
Run	Dynamic Start Position	Dynamic Finish Position	Dynamic ΔPosition	Static** ΔPosition	True* ΔPosition	Dynamic Deviation	Static Deviation
1	N 35° 22.577′ W 86° 14.641′	N 35° 22.669′ W 86° 14.759′	810	778	1074	264	296
2	N 35° 22.591′ W 86° 14.643′	N 35° 22.705′ W 86° 14.766′	924	983	1074	150	91
3	N 35° 22.580′ W 86° 14.638′	N 35° 22.678′ W 86° 14.750′	815	801	1074	259	273
Average			850	854	1074	224	220
Std.Deviation			49.67	86.0			

* = True Δ Position derived from static 10 minute average of start and finish positions, which is 1074.2 feet.
The Start Point: N 35° 22.564′ W 86° 14.669′
The Finish Point: N 35° 22.706′ W 86° 14.798′

** = Static: Static start point and dynamic finish point.

Dynamic = Moving while position was determined by visual reference. GPS position read from receiver.

Each test with at least 7 satellites received. Automobile accelerated from 0 to 61 Miles/Hour each run.

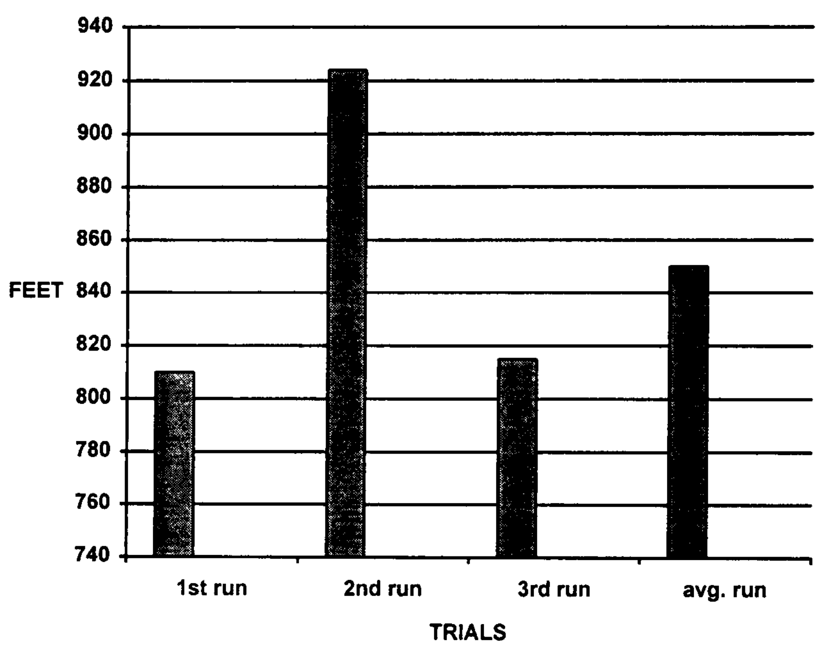
Figure IV-1

DATA SHEET FOR DYNAMIC TESTS

Data recorded December 11, 1995: Ford Mustang Dynamic Tests

A statistical analysis of the data revealed an average position separation of 850 feet with a standard deviation of 49.67 feet. Since the true change of position is 1074 feet, the average distance calculated by dynamic tests proved to be shy 254 feet. Although the data are 20.8% in error, each trial of the test is compared and the data are represented in Table IV-1.

Table IV-1, Dynamic Tests of Ford Mustang (in feet)



Distance (in feet) Vs. Trials

Static Tests

The static tests involved the use of two aircraft. The aircraft accelerated from a common start point to a takeoff point, then initiated a climb. At the point of liftoff, an observer recorded the liftoff point from the markers. Another observer stood at the same point to get a reading from the GPS receiver. The data were recorded, analyzed and compared. The data and results are shown in Figure IV-2 and Figure IV-2.

Aircraft A's actual average takeoff distance is 940 feet. The GPS calculated distance is shown to be 984.2 feet. Thus, the average error is 44.2 feet. The standard deviation is shown to be 97 feet. One datum point is extremely afar from the others in the test. When the point was omitted from the statistical analysis, the standard deviation proved to be 52.75 feet, and the average error is 28.25 feet.

Aircraft B's actual average takeoff distance is 860 feet. The GPS calculated distance is shown to be 816 feet, thus lending to the fact that the average error becomes 44 feet. The standard deviation is calculated to be 89 feet.

When all data are considered for the static test, the average error proves to be 44 feet and the standard deviation is 94.7 feet. The static tests are performed without consideration for time of day. The military S/A errors are different at and on the hour. These factors are not considered in the statistical analysis. All data are illustrated in Table IV-2.

CHANGE OF POSITION DETERMINATION FOR TAKEOFF - STATIC TEST

Date: 22 December 1995 PA28-161 N92555 8:22 AM to 9:25 AM

Pilot: Kimberlin Observers: Cannon, Sims Location: North - Tullahoma Airport, Tennessee

Run	(Degrees/Minutes) Dynamic Liftoff Position	in Feet L.O. Position Marker	Static ΔPosition	Actual ΔPosition	Deviation
1	N 35° 22.686′ W 86° 14.618′	3800	1274	1000	274*
2	N 35° 22.608′ W 86° 14.578′	3910	791	890	99
3	N 35° 22.635′ W 86° 14.587′	3850	954	950	4
4	N 35° 22.644′ W 86° 14.609′	3860	1015	940	75
5	N 35° 22.623′ W 86° 14.607′	3880	887	920	33
					97
Average			984.2	940	97

Average Error: 44.2 Feet

Note: Minimum five (5) satellites in view on each run. Common start point at marker 4800 {GPS: N35° 22.478′ W86° 14.585′} C.G. 88" @2435#, Fuel: 5.9 Gallons added at shutdown, total six runs, only five counted.

* = Bad datum point: When datum omitted,then Standard Deviation is 52.75 Feet.

Figure IV-2

DATA SHEETS FOR STATIC TESTS: AIRCRAFT A, PIPER WARRIOR

CHANGE OF POSITION DETERMINATION FOR TAKEOFF - STATIC TEST

Date: 22 December 1995 R90-230RG N230RG 10:09 AM to 11:06 AM

Pilot: Kimberlin Observers: Cannon, Sims Location: North - Tullahoma Airport, Tennessee

Run	(Degrees/Minutes) Dynamic Liftoff Position	in Feet L.O. Position Marker	Static ΔPosition	Actual ΔPosition	Deviation
1	N 35° 22.630′ W 86° 14.596′	3920	925	880	45
2	N 35° 22.593′ W 86° 14.609′	3960	707	840	133
Average			816	860	89

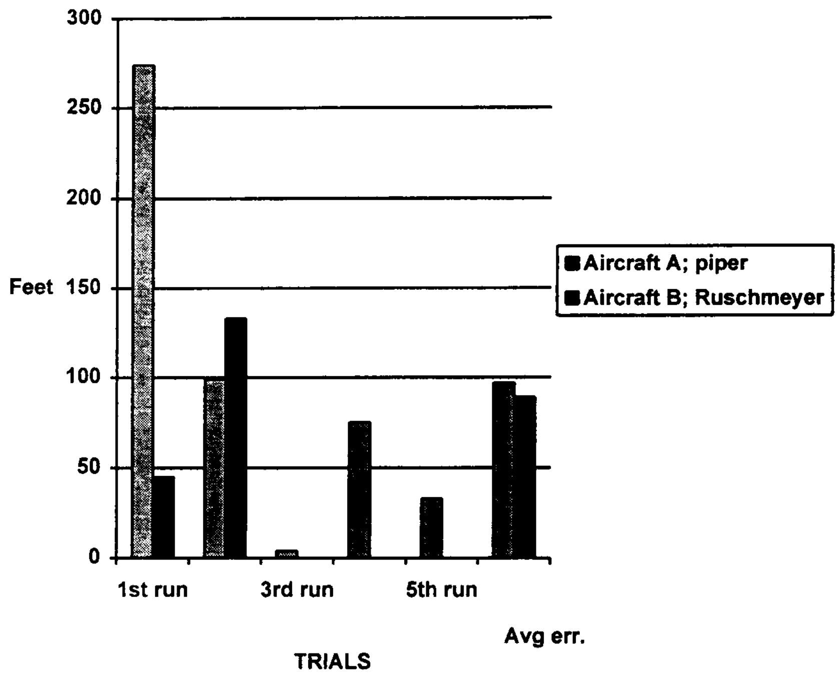
Average Error: 44 Feet

Note: Minimum five (5) satellites in view on each run. Common start point at marker 4800 {GPS: N35° 22.478′ W86° 14.585′} C.G. 88.9" @2906#, Fuel: 10.5 Gallons added at shutdown, total six runs, only two counted.

Figure IV-3

DATA SHEET FOR STATIC TEST: AIRCRAFT B, RUSCHMEYER

Table IV-2 Static tests of Aircraft A and Aircraft B, Deviation Chart (in feet)



Note: A large portion of the scatter in this type of data is contributed to differences in pilot technique and is not necessarily due to the errors in GPS measurement.

Reference Static Test

The Reference Static Test involved the use of GPS receivers and a graduated marked runway. The runway was marked at 100 feet increments. Data points are recorded at marker number "48", "43", and "38." These positions are located at precisely 500 and 1000 feet apart. The purpose for the tests is to determine if the time of day influences the tests results and to confirm others test data. Readings are taken for five minutes at each point and recorded for analysis. The data are recorded at 30 minutes past the hour and during the time frame of greatest S/A error, on the hour. A comparison is made for both periods of testing.

During the time of greatest S/A, the standard deviation is 102.5 feet, whereas, during the "half past the hour" test conditions, the standard deviation proved to be 13 feet. When the time factor of the test was not considered, the standard deviation is 62.75 feet. The tests were not taken in ideal conditions. An average of 5 satellites were in sight during the Reference Static tests. The data are shown in Figure IV-4 and illustrated in Table IV-3.

CHANGE OF POSITION DETERMINATION
AGAINST KNOWN MARKER POSITIONS

Date: 21 December 1995 GPS Receiver, Flitemate Pro, Trimble Navigation 9:55 AM to 10:32 AM
Tested by: Mitchell Cannon Observers: O'Connor Location: Tullahoma Airport, Tennessee

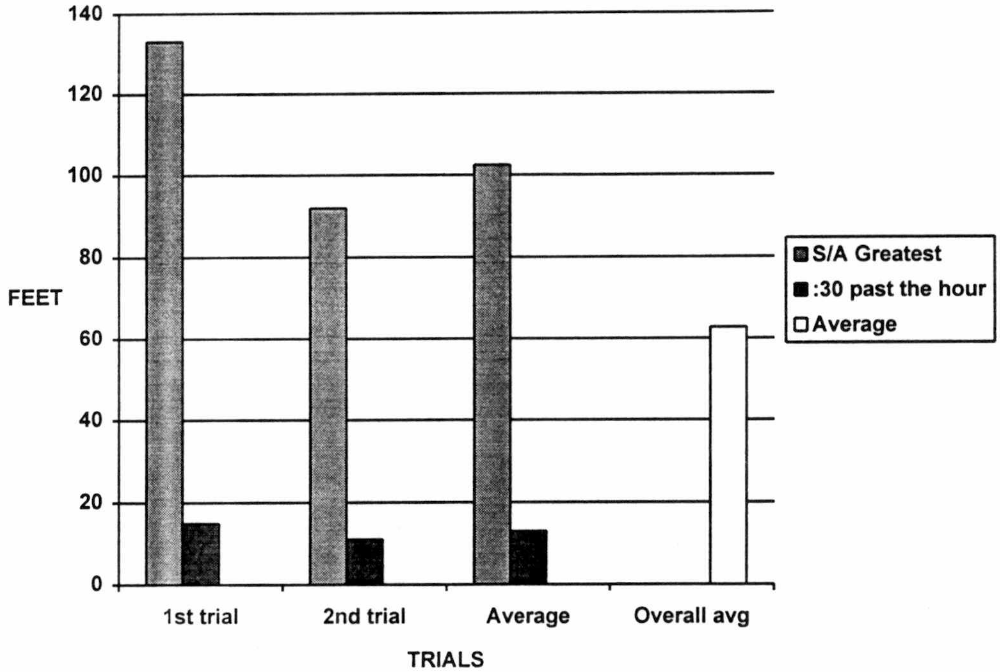
	(Degrees/Minutes)	In Feet				
Reading	GPS 5 Minute Static Position	Calculated ΔPosition	Actual ΔPosition	All Deviation	S/A Deviation	On the Hour Deviation
1	N 35° 22.645' W 86° 14.585'	1015	1000	+15	---	+15
2	N 35° 22.663' W 86° 14.568'	1133	1000	+133	+133	---
3	N 35° 22.562' W 86° 14.580'	511	500	+11	---	+11
4	N 35° 22.575' W 86° 14.608'	592	500	+92	+92	---
Average				+62.75	+102.5	+13

Notes: Minimum of four (4) satellites in view for each trial.

Figure IV-4

DATA SHEET FOR REFERENCE STATIC TESTS

Table IV-3, Reference Static Tests (in Feet)



Error in feet Vs. Trials

CHAPTER V

DISCUSSIONS AND CONCLUSIONS

The determinations of takeoff distance have been determined by various means. Most methods are either complex, expensive, or require several people to conduct the test. The purpose for this thesis is to determine takeoff distance using hand held GPS receivers. It is the author's opinion that hand-held GPS receivers can accurately determine the takeoff distance. Although there are indications that some tests prove to be very accurate, the deviation between data points are too great to perform tests in the dynamic mode. Many trial runs are needed to determine an actual takeoff distance. Initial tests indicate that hand held GPS receivers are practical for some flight test use. This is shown by tests that indicate that hand held GPS receivers are accurate enough in the right conditions.

Three tests were performed using the GPS units. Two of the tests show that the receivers were not accurate nor precise enough to produce the desired data. However, the tests were not conclusive. With the limited number of tests performed, very little indication of decisive evidence can be inferred. Some of the data showed promise, but the only significant indication of realistic and practical use involves the use of static testing using GPS receivers. The tests proved that the thesis statement of determining the accuracy of takeoff distance is adequate in precision and accuracy for the static test.

The dynamic tests involved the use of an automobile. These tests clearly indicate that a hand held GPS receiver is not accurate enough to determine takeoff distance. The average simulated takeoff distance is 850 feet, whereas, the true change of distance is 1074 feet. However, the precision of the data revealed promising results. The standard deviation proved to be 49.67 feet. Although the true position was measured using a 10 minute averaging technique, there were errors associated with using the receiver and the technique. The true distance was calculated from the cosine of the length of the equator. The true distance is slightly less for the test area of the country. Furthermore, the data update rate for the receiver is approximately 1.5 seconds. Initial tests indicate that tests in the dynamic mode are not accurate enough to determine takeoff distance and that other tests are required to determine the validity of the previous tests. It can be reasoned that a receiver that does no averaging may improve the relative distance rate and thus, prove beneficial for dynamic testing.

Although the dynamic tests proved ineffective, other tests were implemented. Static tests using stationary receivers were initiated. The test aircraft starts on a common point on the runway. At the liftoff point, an observer records the position from a visual marker. The another observer records a GPS waypoint. The change of positions are recorded and analyzed. The tests using Aircraft A, Aircraft B, and the Reference Static tests proved usable, but not accurate enough for commercial takeoff distance determination. The average error proved to be approximately 44 feet and the standard deviation is shown to be 83 feet. The data are significantly improved when points of data are omitted that are possibly in error as a result of pseudorandom error. This data is ommited only because of a such large deviation and a small sampleand could possibly be contributed to psuedo random error. Clearly, more tests are needed to accurately determine errors. The data are also greatly improved when the time of day is considered during testing. When "half past the hour" tests, that is, when tests with minimum S/A, are considered, the accuracy and precision are greatly enhanced. The deviation from true position is only 13 feet.

The results of the static tests indicate the potential for precise and accurate use in the determination of takeoff distance for commercial operations at various airports with out conventional instrumentation. Anyone with an interest in determining the takeoff distance may be able to accurately determine takeoff distance easily.

Most of the tests prove that hand held GPS receivers are not accurate nor precise enough to determine takeoff distance of an airplane. It is the author's conclusion that additional dynamic testing with receivers that do not average the data needs to be done to confirm that accurate dynamic testing is possible. Other considerations such as the time of day, the number of satellites, the direction of runway, the number of trials, and the amount of time needed to determine each point need to be implemented in these tests. Some static tests show that accurracies of 11 feet can be achieved. However, other tests are needed to prove or disprove this assessment. In conclusion, hand held GPS receivers, when used properly, can be used accurately for takeoff distance determination in the static mode.

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VITA

Mitchell Cannon was born in Seneca, South Carolina on November 24, 1967. He attended several elementary schools in the Oconee County School District. In June of 1986, he graduated from West-Oak High School in Westminster, South Carolina. The following Fall, he simultaneously attended Tri-County Technical College, in Pendelton, South Carolina and worked full time, as an Engineering Technician at Square D. Company, located in Seneca, South Carolina. Upon graduating with an Associate of Science (A.S.) degree, he transferred to the Electrical Engineering Department at Clemson University in Clemson, South Carolina. In June of 1991, he transferred, as a Senior, to Middle Tennessee State University, in Murfreesboro, Tennessee. In August of 1992, He acquired a Bachelor's of Science (B.S.) degree in Aerospace Technology with minors in Math and Industrial Studies (Engineering Technology). He also acquired a Master's of Education (M. Ed.) in Aerospace in August of 1993. In 1993, he entered the Aviation Systems Department at The University of Tennessee, Space Institute, located in Tullahoma, Tennessee. He received a Master's of Science (M.S.) degree in Aviation Systems on August of 1996.

He has one year of experience at Aircraft Conversions L.L.C. as an Aircraft Design Engineer. Currently, he is employed as an Engineer of Structures and Interiors at the Cessna Aircraft Completion Center, located in Wichita, Kansas.