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MODELING THE EFFECTS OF THE USE OF GPS DERIVED
ALTITUDE INDICATION IN THE C-17A AIRDROP SYSTEM

THESIS

Thomas R. Kogler
Major, USAF

AFIT/GSO/ENS/89D-9

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This study involves developing a computer model to simulate the C-17A airdrop system to determine the effects of altitude on airdrop performance. The simulation is a Simulation Language Alternative Modelling (SLAM) II, FORTRAN-based model. The results of the model show that the altitude positioning provided by the GPS has better airdrop performance than the altimeter's positioning and provides greater flexibility in a combat environment. The greatest difference is approximately one-hundred-seventy yards in fifty-percent circular error in the case of heavy winds with uncertainty in the atmospheric pressure at the drop zone; however, through the comparison of GPS altitude and barometric altitude, the atmospheric pressure error can be reduced, significantly improving airdrop accuracy. With the results of the study and knowledge of the smallest acceptable drop zone size, the accuracy requirement in the vertical plane can be inferred.

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THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Space Operations

Thomas R. Kogler, B.S.
Major, USAF

December 1989

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Preface

There are many people who helped me with this endeavor and deserve to be recognized. First, I give thanks to my advisor Ltc Jim Robinson who never failed to give me support or renew my enthusiasm when I needed it most. I also thank Maj T.S. Kelso who went beyond the call of duty in getting information on the Global Positioning System. A special thanks to those who dropped their own work to supply me with information and data that I so desperately needed. Particularly, I thank Mark Kuntavanish at the Aerial Delivery and Parachute Branch, Lt's Stewart DeVilbiss and Tom Doster at the C-17 SPO, and Maj John Roadcap for his meteorology expertise. Above all, I thank my wife Shauna for her unending support and many sleepless nights.

Thomas R. Kogler

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Abstract

The McDonnell-Douglas C-17A will use the Global Positioning System (GPS) for horizontal positioning during airdrops. Although GPS is capable of three-dimensional positioning, the primary reference for positioning in the vertical plane (altitude) is a barometric altimeter with an air data computer. The horizontal accuracy requirement with respect to the computed air release point (CARP) is one-hundred meters circular error probable (CEP). No accuracy requirement exists in the vertical plane. The purpose of this study is to determine if the vertical positioning provided by GPS allows for better airdrop performance, and to provide guidance in determining an accuracy requirement in the vertical plane.

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MODELING THE EFFECTS OF THE USE OF GPS DERIVED ALTITUDE INDICATION IN THE C-17A AIRDROP SYSTEM

I. Introduction

General Issue

In December of 1988 the Air Force reviewed its role in space and stated the current Air Force Space Policy. A key point of the Air Force Space Policy concerns the activity of force enhancement. With respect to space, force enhancement means using available space resources and capabilities to allow the "war fighters" to accomplish their tasks more effectively and efficiently. One area that affects all "war fighters" is the increased ability to accurately position themselves and/or their target(s). The Navstar Global Positioning System (GPS) *is a constellation of satellites that will give the "war fighter"* this increased accuracy in positioning.

The GPS was originally intended to be operational in 1984, but due to budget constraints and the Space Shuttle Challenger disaster, the operational date has been pushed back to the 1990's (14:1177). Although the constellation is not yet operational, the system can be modeled to predict superior capabilities when compared to current navigational systems (18:50). To comply with the Air Force Space Policy, if appropriate, future weapon systems will use the GPS as a means of force enhancement.

The McDonnell-Douglas C-17A is a future weapon system for Military Airlift Command (MAC) to accomplish the tactical airlift mission. With a crew compliment of only two pilots and one loadmaster (no navigator), the GPS will be the primary source of navigation and positioning on the C-17A.

Background

Airdrop. Tactical airlift is a mission unique to Military Airlift Command (MAC) in which frontline combat troops receive logistical reinforcement of food, supplies, ammunition, equipment, and personnel. This mission can be accomplished through three types of airlift: airland, airdrop, and extraction. The airdrop portion of the tactical airlift mission delivers reinforcements by dropping supplies/personnel out of an aircraft at the computed air release point (CARP).

The computed air release point is a point above the drop zone (DZ) where the airdropped load is planned to be released in order to place the load on the point of impact (PI). The point of impact is the "bull's eye" of the drop zone, the point for which the aircrew is "aiming". With present MAC aircraft, the CARP is manually determined by the aircrew (usually the navigator) and recorded on MAC Form 512 during mission planning (10:3-1). The CARP is computed by starting at the point of impact and applying the various CARP parameters to determine where the load should be released to fall on the point of impact.

Global Positioning System. Each satellite transmits a continuous navigation message. With four operational satellites in view of a receiver, the GPS will be capable of giving three-dimensional positioning, velocity, and time to anyone capable of receiving the satellite transmissions. There are three segments to GPS: the space segment, the control segment, and the user segment.

The space segment consists of twenty-one proposed satellites, broadcasting continuous positioning and timing signals. The control segment consists of monitoring stations, upload stations, and a master control station. The control segment "performs the tracking, computation, updating, and monitoring functions needed to control all of the satellites in the system on a day-to-day basis" (14:1181). The user segment consists of aircraft, ships, land vehicles, or anyone with a receiver capable of processing the broadcasted signals.

McDonnell-Douglas C-17A. Without a system to replace the navigator, the aircrew would be unable to accomplish the airdrop mission due to task saturation. Delco Electronics Corporation has been subcontracted to develop the mission computer and electronic display system for the C-17A (19:467). The mission computer determines the CARP and relays this information to the aircrew with the electronic display system. The electronic display system is a heads up display (HUD) system in which the information is displayed on the windscreen to reduce the need of the pilot's vision being drawn into the cockpit.

Specific Problem

Even though GPS is capable of three-dimensional positioning, the proposed mission computer will not use the GPS determined altitude as the primary altitude reference for airdrop missions. The primary altitude reference for the aircrew is a barometric altitude determined by an air data computer and relayed to the aircrew on the heads up display (3).

The computed air release point is to be computed by the Delco Electronics Corporation mission computer. The accuracy requirement is to position the aircraft no greater than 100 meters circular error probable (CEP) from the CARP (3). Circular error probable is the radius of a circle in which half of the strikes (such as bombs) will fall (4:85). This 100 meter circular error probable applies only in the horizontal plane. No requirement has been levied in the vertical plane, providing an infinite column in which the aircraft may be positioned.

Research Questions

The purpose of this study is to examine if the GPS is a valid means of force enhancement in future airdrop missions. With the use of simulation, the C-17A airdrop system is modeled to determine if GPS can reduce the errors involved in airdrop, and increase airdrop accuracy. To design the model, the following questions must be answered:

1. What are the factors that influence the computed air release point (CARP) and how do these factors vary?

2. What are the positioning errors associated with the GPS and how are these errors determined?

3. What are the errors associated with a barometric altimeter and how are these errors determined to provide an overall altitude error?

4. How are the CARP factors and the positioning errors to be implemented in the computer model?

This computer model will aid in answering the following questions:

5. How does the proposed C-17A airdrop system using barometric altimeter for vertical positioning compare with a system using the GPS for vertical positioning?

6. Can requirements in the vertical plane be inferred by varying the altitude error and comparing the drop accuracies?

The answers to the first four questions are provided in Chapters Two and Three. Chapter Two defines the causes of error in the CARP, the GPS, and the altimeter. Chapter Three determines how these errors can be computed and implemented into the computer model.

The answers to the last two questions are provided in Chapters Four and Five. Chapter Four analyzes the results of the computer simulations. Chapter Five finalizes with conclusions and recommendations.

Scope

The airdrop mission can be performed at both high and low altitudes. The majority of the airdrops occur at the lowest altitude possible to increase the accuracy of the airdrop. The higher the altitude the airdrop load is released, the longer time the load takes to reach the drop zone. The greater fall time allows the errors to be applied longer, giving a less accurate airdrop score. This model examines only the low altitude airdrops. The airdrop mission can be further broken down into: heavy equipment drops, container delivery system (CDS) drops, and personnel drops. Although personnel are dropped at various altitudes depending on the qualifications of the jumpers, of the cargo airdrops, heavy equipment drops have the highest minimum drop altitudes. Only the heavy equipment airdrop is examined. Airdrop missions can be flown with a single aircraft or a formation of numerous aircraft. Since formation procedures using GPS have not been developed, a single ship is examined in this study.

Although the proposed C-17A mission computer CARP computations are based on MACR 55-40, there is a difference in CARP computations of other MAC airdrop aircraft (C-130, C-141, and C-5) in that the CARP is computed by a human navigator. This model will compute the CARP with the same equations used by the proposed C-17A mission computer. Because the C-17A has not been flight tested, airdrop airspeeds have not been determined. Due to the similarity of size between the C-141 and the C-17A, this model will use the C-141 characteristics to simulate the C-17A.

II. Background

The first part of the first three research questions; what are the error-producing factors in the C-17A airdrop system, is discussed in this chapter. These error producing factors are separated into three groups and discussed individually. The subject areas of the groups are Computed Air Release Point, Global Positioning System, and Altimeter. Following the discussion of the error producing factors, the overview of the data and the overview of the model are given.

Computed Air Release Point

The document governing the computations of the computed air release point (CARP) is MACR 55-40. The CARP is "a computed air position at which the release of personnel, equipment, containers, and bundles is initiated to land on a specific point of impact (PI)" (10:1-1). CARP computations take into account the ballistics of the airdropped load and the drop zone conditions, to determine where the load should exit the aircraft to fall on the point of impact. The ballistics of the load depend on the type of airdrop (heavy equipment, container, or personnel), the weight of the load, and the size and number of the parachutes used. The drop zone conditions consist of the elevations, and the meteorological conditions.

Load Ballistics. Load ballistics are determined from airdrop tests. When a load initially exits the aircraft, the ballistics are considered to be nonlinear until the stabilization point (10:1-1). The stabilization point is where the deployment chute is fully deployed and stable. Because the rate of fall of the load after stabilization is never truly linear, the determination of the stabilization point may be a major cause of error in the load ballistics portion of the CARP computations. The human error associated with determining the stabilization point manifests itself in the determination of the vertical distance, the deceleration quotient, and the time-of-fall constant. The time the load takes to exit the aircraft is another source of error. The factors concerning the computations of the CARP and how these factors are related, are illustrated in Figure 1.

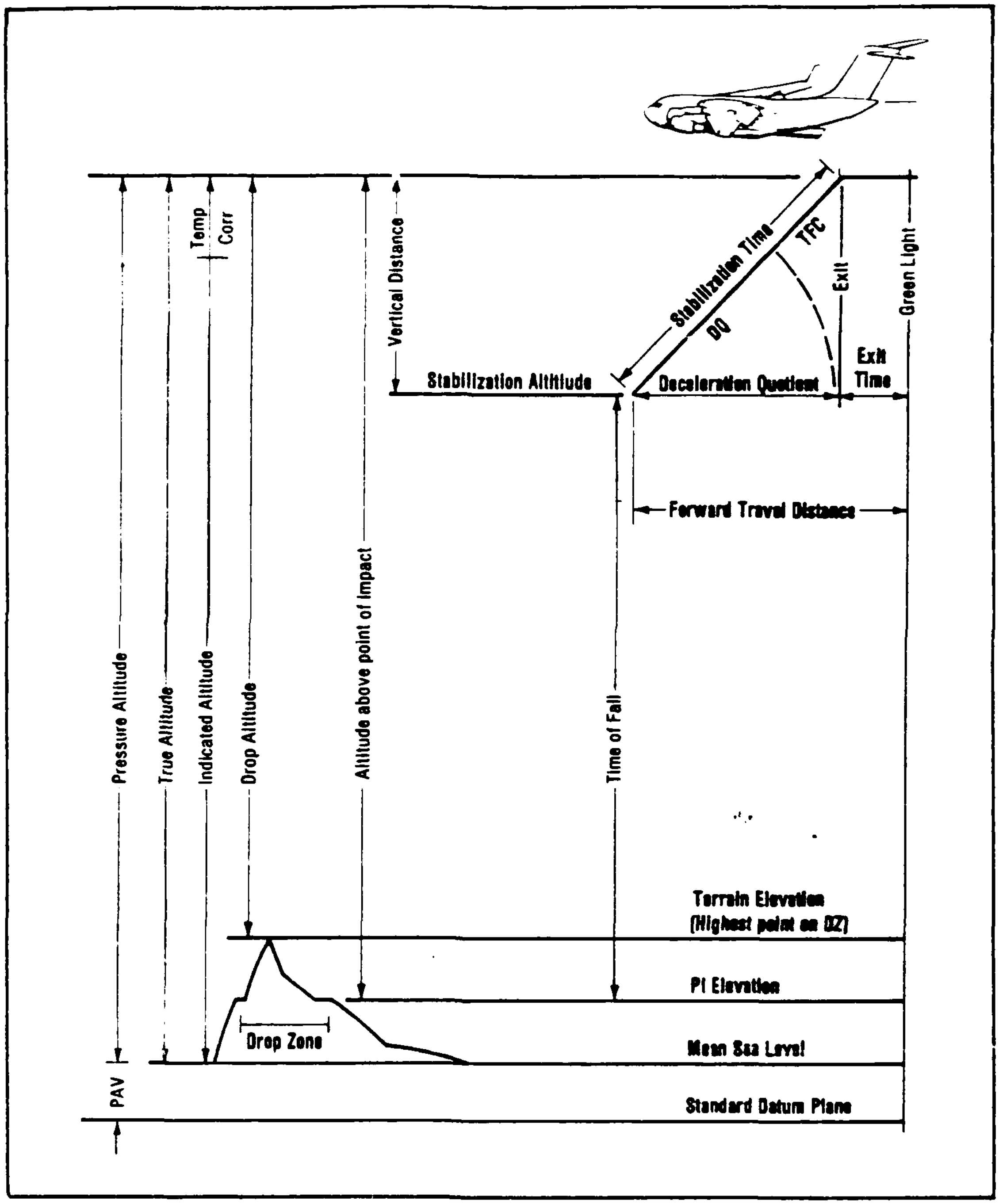


Figure 1. Computed Air Release Point parameters (2:1436)

Exit Time. When the aircrew has been given the green light to initiate the airdrop, an extraction chute enters the airstream to pull the airdrop load out of the aircraft. The load takes some small amount of time to exit the aircraft; the exit time. The exit time is dependent on the flight station (where the load is located in the aircraft), the friction of the load against the floor of the aircraft, and the extraction force applied to the load. The size of the extraction chute and airspeed of the aircraft determine the amount of force applied to the load (9).

Vertical Distance. After the load has separated from the aircraft, the extraction chute releases the deployment chute. The load will fall some distance before the deployment chute is fully deployed and stabilized. The distance the load falls to stabilization is called the vertical distance and is dependent on the size and number of the deployment chutes. Variability in vertical distance comes from the oscillations in the swinging of the load and the ballooning of the chutes (9).

Deceleration Quotient. When an airdrop load initially exits the aircraft, the load is traveling at the speed of the aircraft, minus the velocity imparted by the extraction force. When the load enters the airstream, the load quickly decelerates. The deceleration quotient is a constant that "compensates for the nonlinear deceleration in forward speed" of the load during the time to reach stabilization (10:1-1). The deceleration quotient is dependent on the size and number of the deployment chutes as well as the airspeed of the aircraft. Variability in the deceleration quotient is dependent on the surface areas of the load and the chutes, and how these surface areas react in the airstream.

Time-of-Fall Constant. The deceleration of the load is not the only nonlinear function. Before the deployment chutes reach stabilization, the rate of fall of the load is nonlinear (10:1-2). Like the deceleration quotient, the time-of-fall constant compensates for the nonlinearity and is dependent on the size and number of the deployment chutes and aircraft airspeed. The deceleration quotient plus the time-of-fall constant equals the time the load takes to reach stabilization.

Rate of Fall. Once the deployment chutes reach stabilization, the rate of fall of the load is assumed to be steady and constant for CARP computations. The rate of fall is dependent on the size and number of deployment chutes, and the weight of the load. This constant rate of fall determined from the ballistics data applies only to a standard day at sea level (10:1-2). Standard day is a base reference where the temperature equals 15 degrees Celsius and the atmospheric pressure is equal to 29.9213 inches of mercury (5:10). The rate of fall must be adjusted if the meteorological conditions are not standard day.

Drop Zone Conditions. The determination of planned altitude of the aircraft plays a major role in CARP computations. The distance the load falls and the rate of fall are used to determine the length of time of the fall. The length of time that the load is affected by the meteorological conditions is important in determining where the load will fall. For the purpose of this study, the meteorological conditions are the outside air temperature at altitude, the atmospheric pressure at the drop zone, and the wind velocities. The planned altitude of the aircraft for the airdrop is primarily determined from the elevations of the drop zone. The meteorological conditions affect the rate of fall and the airspeed.

Elevations. The two important elevations used in CARP computations are the terrain elevation and the point-of-impact elevation. The terrain elevation is the elevation of the highest point on the drop zone with reference to mean sea level (MSL). The terrain elevation is added to the minimum drop altitude to determine the drop altitude (MSL). The minimum drop altitude is the minimum altitude above ground level (AGL) that the load should be dropped to assure survival of the load, and is determined by ballistic tests. The point of impact elevation is the elevation of the planned impact point with reference to mean sea level. For CARP computations, the distance the load is assumed to fall is the distance from the minimum drop altitude to the point of impact elevation. The determination of the locations (coordinates) of the drop zone and the point of impact as well as the measurement of the elevations of the terrain and point of impact is a source of positioning error for the aircraft.

Outside Air Temperature. The main impact of the outside air temperature in CARP computations is in the determination of the true airspeed (TAS). Airspeed indicators on the aircraft do not give true airspeed. "The airspeed indicator is actuated solely by impact pressure and is calibrated to indicate true airspeed at sea-level density in the standard atmosphere; at altitude, however, the indicated airspeed is lower than the true airspeed" (5:1). True airspeed is the product of the Mach number and the speed of sound (5:14). The speed of sound is a direct function of temperature (5:17). True airspeed is needed with wind velocity to determine the forward distance the load travels from the initiation of the extraction (green light), to where the load reaches stabilization. The outside air temperature is measured from sensors on the aircraft and are subject to measurement error. As previously mentioned, the rate of fall determined from the ballistics data must be adjusted if the meteorological conditions are not standard day. This measurement error is applied to the adjusted rate of fall.

Atmospheric Pressure. Atmospheric pressure is also related to true airspeed in that the atmospheric pressure is used with the indicated airspeed to determine the Mach number (5:16). For CARP computations, the atmospheric pressure at the drop zone can be determined by two methods. The first method is to receive the atmospheric pressure information through radio communication. The accuracy of this information is a function of the measurement error of the measuring device, the time of the pressure measurement, and the distance to the drop zone from the measurement location. The second method used to determine the drop zone atmospheric pressure is through a briefing of the forecasted drop zone pressure. This briefing is received prior to the aircraft takeoff. The accuracy of the forecasted pressure is primarily a function of the length of time into the future the information is required and the presence of weather fronts. Distance is not a major factor in forecasting as long as the forecaster has sufficient and current weather data. Again, the rate of fall must be adjusted for deviations from standard day. The error associated with the determination of the atmospheric pressure at the drop zone is also incorporated in the adjusted rate of fall.

Wind Velocities. Two types of wind velocities are used in CARP computations, altitude winds and surface winds. Since the winds may come in any direction in relation to the line of flight of the aircraft, the winds are broken into along track and cross track components. The along track component of the altitude wind is added to the true airspeed to determine the ground speed. The ground speed determines the forward travel distance of the airdropped load. The surface wind velocity is used with the altitude wind velocity to determine the mean effective wind velocity. The mean effective wind velocity "is a theoretical wind of constant speed and direction, extending from the DZ [drop zone] surface to drop altitude", and is used to determine the drift effect of the winds on the airdropped load (10:2-2). Wind velocities at both the altitude and the surface can be highly variable and can be a major source of error. With a large mean effective wind speed, errors in determining the time of fall of the airdropped load may have a major impact on the drop score.

Global Positioning System

As mentioned in Chapter One, four satellites are required to obtain three-dimensional positioning and velocity. Each satellite sends navigation data on two frequencies in the L band. L1 is 1575.42 MHz and L2 is 1227.60 MHz (20:227). The C/A (coarse/acquisition) code is transmitted on the L1 carrier only, whereas the P (precision) code is transmitted on both the L1 and L2 frequencies (20:227). The P code provides the greatest positioning accuracy and is designed for military use and for selected civilian users. Following is a discussion on how the signals are used for navigation and the sources of error in the Global Positioning System.

Navigation Technique. Satellite navigation is the means of determining a position by knowing the location of the satellites and the distance from the satellites. By drawing an arc of known radii from each of two known satellite positions, the position can be determined in two dimensions from the intersection of the two arcs. In three dimensional space, the position is determined from the intersection of three spheres of known radii. In GPS, "the transmitted message contains ephemeris parameters that enable the user to calculate the position of each satellite at the time of transmission of the signal" (11:3). By comparing the time between the transmission and receipt of the signal, the delay can be transferred into a distance by assuming the signal travels at the speed of light (11:3).

Given the position of the satellites, the ranges to the satellites can be determined by solving the following equation (19:55):

$$R_i = ((X_i - U_x)^2 + (Y_i - U_y)^2 + (Z_i - U_z)^2)^{1/2} + cT_B \qquad (1)$$

where

R_i = known range to satellite i
X_i = known X position of satellite i
Y_i = known Y position of satellite i
Z_i = known Z position of satellite i
U_x = user's unknown X position
U_y = user's unknown Y position
U_z = user's unknown Z position
c = speed of light
T_B = unknown clock bias

Since there are four unknown variables in Equation (1), four satellites (equations) are required to determine user position.

Errors in the system provide the user with incorrect information as to the range of the satellites. The user determined distance from the satellite is called the pseudo-range because the determined range contains errors, and the total of these errors is called the User Equivalent Range Error (UERE) (11:4). Determining position from the pseudo-range will obscure the intersection of the spheres from a point to an indistinct area (see Figure 2). Errors in positioning come primarily from factors affecting the signal, the timing, and the geometry of the satellites. These errors are discussed with reference to the three segments of the Global Positioning System (space, control, and user segments), and the satellite geometry.

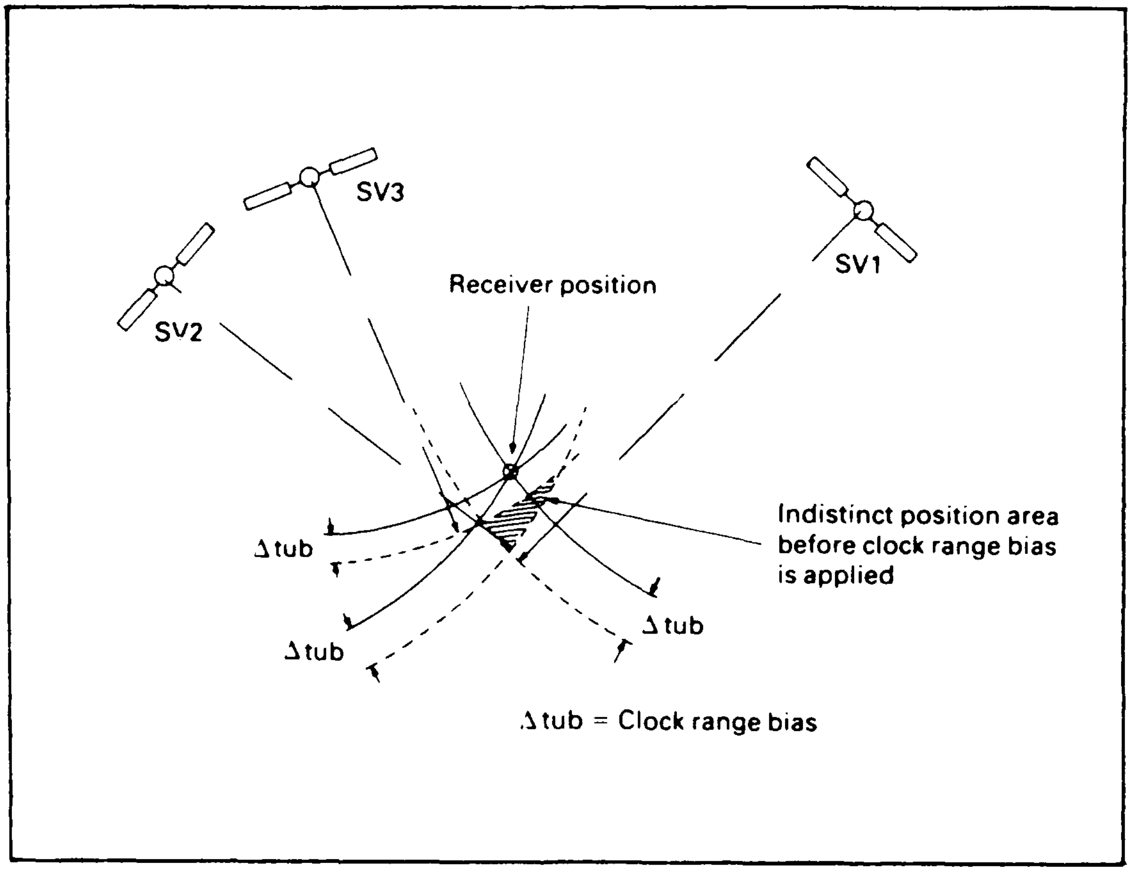


Figure 2. Determination of user position (two dimensions) (20:231)

Space Segment. As mentioned in Chapter One, the constellation of satellites make up the space segment. The role of the satellite is to broadcast a signal indicating the satellites position and time of transmission. Errors in the space segment come primarily from the satellite clock. If the clock deviates one nanosecond (one billionth of a sec), this time error is "equivalent to approximately 0.3 meters (.984 ft) of range error" (11:4-5). Although the satellites carry a highly stable and accurate clock, the "clock may deviate by up to 1 millisecond over a seven day period" (20:231)

Control Segment. The control segment is responsible for maintaining the satellites in their assigned orbits and updating the satellite ephemerides. Many factors such as the gravitational pull of the sun and moon can perturb the satellite's orbit about the earth. These perturbations cause the true position of the satellites to be different from the transmitted positions. The positional errors affect the pseudo-range and decrease the certainty of the users position.

User Segment. For the purpose of this discussion, the user segment will not only cover the user's receiver, but will also include any deviations of the path of the signal. The means of receipt of the signal are a source of error. "Noise and resolution errors resulting from the processing of signals by the receiver hardware and software will contribute to errors in the determination of range" (11:10). Before the signal reaches the user's receiver, the signal must pass through the earth's atmosphere. For this discussion, the atmosphere is separated into the ionosphere (upper atmosphere) and the troposphere (lower atmosphere).

"Simply stated, the apparent path length -- hence, the pseudo-range measurement to any satellite will increase due to refraction through the ionosphere" (14:1183). The refraction is "due to the free electrons in the ionized gases of the upper atmosphere" (13:12.0). By transmitting on two frequencies (L1 and L2), the delay through the ionosphere can be estimated by comparison of the time delay between the two frequencies (20:232). The effects of the ionosphere can be reduced by this frequency comparison, but not eliminated.

The troposphere is the portion of the atmosphere below 50 kilometers (13:12.0). Error in pseudo-range measurement in the troposphere is caused by the changing indices of refraction due to the changing amount of moisture in the air. IBM has examined numerous tropospheric models and has determined that 90 percent of the tropospheric effect "can be compensated for by static models" (13:12.1) The error induced by the troposphere reduces to a "judicious" selection of an overall index of refraction (13:12.1.1). Like the ionosphere, the effects of the troposphere can be reduced but not eliminated.

Another source of error from the signal to the receiver is the receipt of the same signal from different paths. This kind of error is called a multipath error and "multipath errors result from the combination of data from more than one propagation path that distorts the signal characteristics from which the range measurements are made" (11:9-10).

Satellite Geometry. The geometry of the satellites has a major impact on the overall positioning error by acting as a multiplier of the ranging error (determined from the above error sources). To get an understanding of how the position of the satellites (geometry) can influence position error, the two-dimensional case is examined. If the distances from the user to two satellites are known, the user's position is at the intersection of the arcs of the known radii (distances). The point of intersection is most distinct when the arcs intersect at right angles. If the arcs do not intersect at right angles, the point of intersection is indistinct and obscured. The same obscurity occurs in the higher dimensions. The error in position due to the geometry of the satellites is called the geometric dilution of precision (GDOP). The geometric dilution of precision can be broken down into smaller parameters.

> Extended to the GPS system, with fixes in three dimensions plus time, the parameters include PDOP, which reflects the dilution of precision in position in three dimensions; HDOP, dilution of precision in the two horizontal dimensions; VDOP, dilution of precision in the vertical dimension; and TDOP, dilution of precision in time, i.e., in the estimate of the range equivalent of the user clock bias. (11:10)

Altimeter

Aircraft altitude is determined with the use of an altimeter. An altimeter measures the atmospheric pressure and determines an altitude with respect to standard day. Errors in the determination of altitude can have a major impact on the accuracy of an airdropped load. The altitude is a major factor in the determination of the time the airdropped load takes to fall to the drop zone. Strong winds can quickly degrade the accuracy of the airdrop if the aircraft is not at the planned altitude. The errors related to the determination of altitude are: static pressure error, lag time error, and instrument error. Following is a detailed discussion of each of these errors.

Static Pressure Error. Static pressure is the atmospheric pressure at the altitude of the aircraft. Static pressure error is the difference between the true static pressure and the indicated static pressure (5:7). Static pressure errors can be quite large "but for a given flight condition, the errors are essentially repeatable and hence can be determined by calibration" (5:7-8). This error is primarily a function of where the pressure sensor is in relation to the flow of the airstream and varies with the Mach number and the angle of attack (5:44). Angle of attack is the angle between the line of airflow and the line drawn from the trailing edge to the leading edge of the airfoil (wing) (12:51).

Lag Time Error. The lag time error is simply the delay in transferring the pressure reading from the sensor to the instrument. This lag time varies with the rate of change of the pressure and "depends primarily on the length and diameter of the pressure tubing and on the volume of the instruments connected to the tubing (5:8). The speed that pressure signals travel in the tubing is the speed of sound (5:147). Since the lag time is the ratio of the length of tubing to the speed of sound, with proper design, the lag tima is negligible due to the relatively short length of tubing (5:147).

Instrument Error. The error associated with the instrument can be divided into scale error and hysteresis error. Scale error is usually the largest of the instrument errors and is the difference between pressure at the instrument and what the instrument is indicating (5:152). Scale error is repeatable and corrections can be applied to achieve greater accuracy (5:152). Hysteresis error is error in returning to the proper indication after a change in pressure. Hysteresis errors have decreased with better design of altimeters and are much lower than the specified tolerances (5:154).

Overview of Data

Computed Air Release Point. The data required to determine the computed air release point comes primarily from raw load ballistics data. This data is used to determine the variability of the five key parameters in airdrop: exit time, vertical distance, deceleration quotient, time-of-fall constant, and rate of fall. Load ballistics data was obtained from the Aeronautical Systems Division, Aerial Delivery and Parachute Branch at Wright-Patterson Air Force Base. The Aerial Delivery and Parachute Branch has the responsibility for analyzing and storing the data used to determine chute characteristics. These chute characteristics are published in MACR 55-40 as the governing authority on CARP computations. The proposed algorithm used to compute the CARP for the mission computer is provided by Aeronautical Systems Division, C-17A Systems Program Office, Avionics Engineering Section at Wright-Patterson Air Force Base.

Global Positioning System. The data required to determine the positioning errors associated with the Global Positioning System is derived from various sources. The data for determining the errors from the geometry of the satellites comes from interviews with the GPS Joint Program Office/Systems Engineering Organization at Los Angeles Air Force Base, and from correspondence and interviews with Aerospace Corporation at Los Angeles. Aerospace Corporation supports the GPS Joint Program Office. The data required to determine the positioning errors associated with the space, control, and user segments comes from an article by Lawrence Hogle of the Mitre Corporation, McLean, Virginia, and reconfirmed with the GPS Joint Program Office.

Altimeter. The data to determine the C-17A pressure altitude errors is provided by the Aeronautical Systems Division, C-17A Systems Program Office, Avionics Section. The data for determining the errors in actual atmospheric pressure versus the forecasted atmospheric pressure is supplied by the Aeronautical Systems Division, Avionics Laboratory Meteorologist at Wright-Patterson Air Force Base.

Overview of Model

A model is a description of a system and may take the form of a scaled physical object, mathematical equations, or graphical representation (15:4). The mathematical nature of the CARP equations indicate the C-17A airdrop system requires an abstract (mathematical) model for simulation. Simulation is appropriate for analyzing the C-17A airdrop system because the system is not yet in existence. Simulation allows inferences on what the future performance will be. Due to the many error producing factors and their relationships with each other, simulation is an effective means to determine the future performance. The repetitive nature of simulating a mathematical model dictates the use of a computer. This model uses SLAM (Simulation Language for Alternative Modeling) II (15:2).

The three major areas of interest, Computed Air Release Point, Global Positioning System, and Altimeter were discussed in this chapter to provide background information on the problem of this study. This discussion has answered the first part of the first three research questions by naming the major error producing factors in the C-17A airdrop system, and showing how these factors are related. The remaining chapters show the development of the model, and answer the remaining research questions.

III. Methodology

In this chapter, the assumptions of the model are discussed, and the answers to the second half of the first three research questions; how are the error producing factors determined, are given. The error producing factors are again separated into the three subject areas of Computed Air Release Point, Global Positioning System, and Altimeter; and discussed individually. Following the discussion of error determination, the model design and model accuracy are discussed.

Assumptions of the Model

In order to use the model for simulation and the prediction of future performance, assumptions are made and applied to the model. Below is the list of the assumptions.

1. There is no human error involved in the error determinations. This assumption implies that a "perfect" pilot controls the aircraft and is capable of maintaining exactly the planned airspeed, altitude and flight direction. The no human error assumption implies that the stabilization point determined from the load ballistics is the true stabilization point for the planned airdrop.

2. The C-17A has the same flight characteristics as the C-141. This assumption is made because the flight characteristics of the C-17A are unknown. Due to the similarity in size (in comparison with the C-130 and the C-5), C-141 airdrop parameters are used.

3. The drop zone and airdrop load do not change. This assumption implies that the same drop zone and airdrop load is used for every drop.

4. The elevations and the locations of the drop zone and point of impact are perfectly known. This assumption implies that any positioning errors of the aircraft are related only to the systems on the aircraft.

5. The airdrop load is assumed to fall to the point-of-impact elevation. Because there is a difference in the elevations of the drop zone and point of impact, this distinction is important in determining the time of fall of the airdrop load.

6. The Global Positioning System has twenty-one satellites, and a five degree mask angle from the horizon is used in determining which satellites are in sight. This assumption is important in determining the best satellites to choose in minimizing the error from the geometry of the satellites.

7. The P-Code is used for GPS positioning. The P-Code is for military users and is more accurate than the C/A code.

These are general assumptions and do not fully cover the more detailed assumptions of the model.

Computed Air Release Point

As discussed in Chapter Two, CARP computations take into account the load ballistics and the drop zone conditions. In determining the load ballistics, recall the assumption of no human error. This assumption implies that the stabilization point determined from analyzing the load ballistics data is the true stabilization point, and no variability is due to an error in the selection of this point.

Load Ballistics. The load ballistics depend on the weight of the load, where the load is situated in the aircraft, the type and number of extraction chutes, and the type and number of deployment chutes. With this information, the aircrew looks up the charts and tables in MACR 55-40 for the minimum drop altitude and the expected values of exit time, vertical distance, deceleration quotient, time-of-fall constant, and rate of fall. Table 3.1 displays the load parameters that are used in the model.

TABLE 3.1

Load Parameters

Parameter	Value
Load Weight(lbs)	20000
Flight Station	1070
Extraction Chute	28' RS
Deployment Chute	G-11B
Number of Deployment Chutes	4
Minimum Drop Altitude(ft)	750

In determining the load parameters for the model, consideration was given for the greater capabilities of the C-17A, and the most likely types of chutes available. The C-17A, with the ability to carry larger loads, will have the opportunity to airdrop heavier loads. The load weight was chosen to reflect the greater capability. The type of chute was chosen due to its availability. The G-11B will be the deployment chute most often used for airdrops due to the phasing out of the G-11A chutes (9). The number of deployment chutes was chosen due to the availability of ballistics data. The with the load weight established, the extraction chute can be determined (Appendix A). The minimum drop altitude is normally determined by the type and number of deployment chutes as exampled in Appendix B.

With the load parameters established, using the tables and charts in MACR 55-40, the CARP parameters can be determined. The charts and tables in MACR 55-40 come from lines and curves of best fit of the ballistic data points. From Appendix A, the expected exit time is determined with knowledge of the load weight, flight station, and type extraction chute. With knowledge of the type and number of deployment chutes, the expected values of the vertical distance, deceleration quotient, and time-of-fall constant are established in Appendix C. Also in Appendix C, the expected rate of fall is determined with the additional knowledge of the load weight. Table 3.2 displays the expected values for the model's CARP parameters.

TABLE 3.2

CARP Parameters

Parameter	Expected Value
Exit Time (sec)	5.55
Vertical Distance (ft)	585.00
Deceleration Quotient (sec)	2.30
Time-of-Fall Constant (sec)	11.70
Rate of Fall (ft/sec)	20.25

The variability of the CARP parameters is a source of error and must be established. Due to the expense of flying an aircraft to get the load ballistics data, not many points of data are available for analysis. Table 3.3 shows the load parameters of the available ballistics data using four G-11B deployment chutes. Table 3.4 displays the CARP parameters for the ballistics data.

TABLE 3.3

Ballistics Data
Load Parameters

Run	Load Weight (lbs)	Flight Station	#/Type Extraction Chute	#/Type Deployment Chute
1	20000	960	2/28' RS	4/G-11B
2	17320	1045	1/22' RS	4/G-11B
3	20010	990	1/28' RS	4/G-11B
4	17320	1060	1/28' RS	4/G-11B
5	17340	960	1/22' RS	4/G-11B
6	20300	1095	2/28' RS	4/G-11B

TABLE 3.4

Ballistics Data
for 4 G-11B Parachutes
for C-141 at 150 KIAS

Run	Load Weight (lbs)	Exit Time (sec)	Vertical Distance (ft)	Decel Quotient (sec)	Fall Constant (sec)	Rate of Fall (ft/sec)
1	20000	6.3	578.3	2.2	11.6	23.9
2	17320	6.5	617.4	2.3	12.3	21.4
3	20010	5.0	567.4	2.6	11.5	19.7
4	17320	5.1	567.2	2.6	9.7	19.9
5	17340	4.7	580.9	1.7	12.2	22.0
6	20300	4.8	602.0	2.5	13.1	23.3

The CARP parameter errors are defined as the difference between the planned parameter from the tables and charts in MACR 55-40, and the actual observed parameter from test flights. Due to the small sample size, assumptions must be made on the distribution of the parameter errors to incorporate into the model. The CARP parameter error distributions are assumed to be normal for this model. The CARP parameter errors are shown in Table 3.5 through Table 3.9.

TABLE 3.5

Exit Time Errors

Run	Expected Exit Time (secs)	Actual Exit Time (secs)	Exit Time Error (secs)
1	5.41	6.30	0.89
2	6.20	6.50	0.30
3	5.71	5.00	0.71
4	6.20	5.10	0.90
5	5.35	4.70	0.65
6	5.41	4.80	0.61
		Mean	0.677
		Std Dev	0.221

TABLE 3.6

Vertical Distance Errors

Run	Expected Vertical Distance (ft)	Actual Vertical Distance (ft)	Vertical Distance Error (ft)
1	585.0	578.3	6.7
2	585.0	617.4	32.4
3	585.0	567.4	17.6
4	585.0	567.2	17.8
5	585.0	580.9	4.1
6	585.0	602.0	17.0
		Mean	14.57
		Std Dev	12.28

TABLE 3.7

Deceleration Quotient Errors

Run	Expected Deceleration Quotient (secs)	Actual Deceleration Quotient (secs)	Deceleration Quotient Error (secs)
1	2.30	2.20	0.10
2	2.30	2.30	0.00
3	2.30	2.60	0.30
4	2.30	2.60	0.30
5	2.30	1.70	0.60
6	2.30	2.50	0.20
		Mean	0.250
		Std Dev	0.207

TABLE 3.8

Time-of-Fall Constant Errors

Run	Expected Time-of-Fall Constant (secs)	Actual Time-of-Fall Constant (secs)	Time-of-Fall Constant Error (secs)
1	11.7	11.6	0.1
2	11.7	12.3	0.6
3	11.7	11.5	0.2
4	11.7	9.7	2.0
5	11.7	12.2	0.5
6	11.7	13.1	1.4
		Mean	0.80
		Std Dev	0.75

TABLE 3.9

Rate-of-Fall Errors

Run	Expected Rate of Fall (ft/sec)	Actual Rate of Fall (ft/sec)	Rate-of-Fall Error (ft/sec)
1	20.26	23.90	3.64
2	18.85	21.40	2.55
3	20.26	19.70	0.56
4	18.85	19.90	1.05
5	18.86	22.00	3.14
6	20.41	23.30	2.89
		Mean	2.305
		Std Dev	1.225

Drop Zone Conditions. As shown in Chapter Two, the drop zone conditions consist of the drop zone elevations, the outside air temperature, the atmospheric pressure and the wind velocities. Recall the assumption that the drop zone and point of impact locations and elevations are perfectly known. This assumption deletes the requirement for determining the errors associated with the elevations.

Outside Air Temperature. The difference from the planned outside air temperature and the actual outside air temperature is an error that must be determined for the model. As shown in Chapter Two, the primary error is due to measurement error from the sensors on the aircraft. The true measurement error of the sensors has not been determined, so the specifications levied by MAC will be used. The requirement for the static air temperature measurement is plus or minus one degree Celsius (3). The assumption for the error distribution is a uniform distribution between minus one and plus one.

Atmospheric Pressure. To determine the difference between the planned atmospheric pressure and actual atmospheric pressure, two scenarios are examined. The first scenario is a local airdrop training mission. The drop zone is assumed to be one-hundred miles from the pressure observation, and the time from the last observation is thirty minutes. The distance and time were chosen to reflect a typical airdrop training mission. The second scenario is a combat mission. In the combat scenario, the only pressure information the aircrew receives is from a weather briefing prior to takeoff, and will not be updated in flight (radio out). To further examine the effects of time on the accuracy of the atmospheric pressure forecast, the combat scenario is examined with three different times from the forecast (2, 4, and 6 hours). Each of these ranges is examined with and without the presence of a major weather front in the area of the drop zone.

No specific meteorological data is available to determine the error distributions associated with the two scenarios. Weather conditions around the earth vary greatly. It is impractical to establish error distributions concerning all areas of the earth for this model. To enable the model to simulate the effects of atmospheric pressure, the ASD Avionics Lab

Meteorologist gave error estimates on the two scenarios. These estimates are based on experience in aviation forecasting. In making these estimates, the forecaster was assumed to know when and where the drop was to occur, as well as having all the information and weather data available to make an intelligent forecast. The measurement error from the observation is assumed to be negligible in comparison with the other errors. Assuming a triangular distribution, the estimates are given as the minimum error, maximum error, and most likely error. Table 3.10 displays the errors associated with the two scenarios.

Wind Velocities. The surface and altitude winds are extremely variable and difficult to find a distribution of error from the planned velocities. To determine the effects of the wind velocities, the model is run with light and heavy steady winds, and light and heavy variable winds. Table 3.11 shows what quantities the model uses for each of the variations. The light winds were chosen because it is impractical to assume no wind velocity, and the speed of the wind normally increases with altitude. The heavy winds were chosen to approach the maximum winds before the aircrew would call for a "no-drop" situation. Assuming a normal distribution, the variability of the wind speed and direction is increased by increasing the standard deviation.

Global Positioning System

User Equivalent Range Error. As shown in Chapter Two, the errors associated with the GPS stem from the space, control, and user segments, as well as the error associated with the geometry of the satellite positions. The error distributions associated with the various segments are assumed to be Gaussian normal with a mean of zero.

> The variability of the error in making pseudo-range measurements can quite properly be assumed to be Gaussian. The validity of this assumption arises from the fact that these measurement errors are the composite of a large number of individual error sources which are generally uncorrelated. Thus the Central Limit Theorem can be applied to the composite error and lends credence to the validity of the Gaussian assumption for the pseudo-range measurement errors (7:8).

TABLE 3.10

Atmospheric Pressure Errors

Scenario 1

Distance from Observation (miles)	Time from last Observation (hours)	Minimum error from Observation (in of Hg)	Maximum error from Observation (in of Hg)	Most likely error from Observation (in of Hg)
100	.5	.01	.04	.02

Scenario 2A

	Forecasted time into the future (hours)	Minimum error from forecast (in of Hg)	Maximum error from forecast (in of Hg)	Most likely error from forecast (in of Hg)
With No Major Weather Fronts	6	.03	.12	.06
	4	.02	.09	.04
	2	.01	.05	.02

Scenario 2B

	Forecasted time into the future (hours)	Minimum error from forecast (in of Hg)	Maximum error from forecast (in of Hg)	Most likely error from forecast (in of Hg)
With a Major Weather Fronts	6	.04	.20	.08
	4	.03	.15	.06
	2	.02	.10	.04

TABLE 3.11

Model Wind Velocities

Light and Steady

	Planned Speed (knots)	Std Dev From Planned (knots)	Planned Magnetic Direction (degrees)	Std Dev From Planned (degrees)
Surface	3	1	60	5
Altitude	10	2	60	5

Light and Variable

	Planned Speed (knots)	Std Dev From Planned (knots)	Planned Magnetic Direction (degrees)	Std Dev From Planned (degrees)
Surface	3	3	60	30
Altitude	10	5	60	30

Heavy and Steady

	Planned Speed (knots)	Std Dev From Planned (knots)	Planned Magnetic Direction (degrees)	Std Dev From Planned (degrees)
Surface	13	1	60	5
Altitude	25	2	60	5

Heavy and Variable

	Planned Speed (knots)	Std Dev From Planned (knots)	Planned Magnetic Direction (degrees)	Std Dev From Planned (degrees)
Surface	13	3	60	30
Altitude	25	5	60	30

The probability distribution of the pseudo-range error components are shown in Table 3.12. These components have a mean of zero and one standard deviation as shown below.

TABLE 3.12

User Equivalent Range Error
Standard Deviations for P-Code

	Bias Errors Std Dev (ft)	Random Errors Std Dev (ft)
Space Segment	11.5	
Control Segment	14.1	
User Segment		
Ionospheric Delay	7.5	
Tropospheric Delay		6.6
Receiver Noise		4.9
Multipath		3.9
Other		1.6

In the model operation, an error is randomly selected from the appropriate probability distribution for each range error, as described in Table 3.12. The range errors are broken into bias and random errors to take into account the effect of Kalman filtering. "Kalman filtering can reduce the influence of random errors by a factor of 1/3" (6:333). The model is designed to simulate the effect of Kalman filtering. Since the errors are assumed to be uncorrelated and independent, the randomly selected range errors can be added to find the total random and bias errors. The total random error with Kalman filtering is:

$$\mathrm{Rand}_{err} = 2/3\,(\mathrm{Trop}_{delay} + \mathrm{Rx}_{noise} + \mathrm{Multi}_{int} + \mathrm{Other}_{err}) \qquad (2)$$

where

Rand_{err} = Total Random Error
Trop_{delay} = Tropospheric Delay
Rx_{noise} = Receiver Noise
Multi_{int} = Multipath Interference

Other_{err} = Other Errors

The total bias error is:

$$\text{Bias}_{err} = \text{SS}_{err} + \text{CS}_{err} + \text{Ion}_{delay} \quad (3)$$

where

Bias_{err} = Total Bias Error
SS_{err} = Space Segment Error
CS_{err} = Control Segment Error
Ion_{delay} = Ionospheric Delay

The total User Equivalent Range Error is:

$$\text{UERE} = \text{Rand}_{err} + \text{Bias}_{err} \quad (4)$$

where

UERE = User Equivalent Range Error

<u>Satellite Geometry</u>. The position dilution of precision (PDOP) is determined from the geometry of the satellite and is a multiplier of the user equivalent range error. The smaller the PDOP, the better the overall positioning error. The distribution of PDOP is not easily determined.

> There is no analytical method for determining the statistical variability of the GDOP parameters. The only practical way of approaching the problem is to perform large numbers of computations that cover all latitudes, longitudes, and time (7:8).

In order to determine the distribution of PDOP, Aerospace Corporation performed the large numbers of computations, covering all latitudes and longitudes, for a period of one day. Choosing a period of one day assumes the formations of the satellites is cyclical and should be repeated somewhere on the planet during the twenty-four hour period. The graph of the distribution and the corresponding data is shown in Appendix D. In the computer model, this distribution is drawn upon for the PDOP and determines the position dilution of precision. Assuming the aircraft position error is a spherical error, angles in the horizontal and vertical planes are drawn from a uniform distribution between 0 and 360 degrees. The three dimensional coordinates of the error can be determined by the following equations:

$$X_{err} = (PDOP)(UERE)(\cos\varphi)(\cos\theta) \tag{5}$$

where

X_{err} = X coordinate position error (ft)
PDOP = precision dilution of precision
φ = the angle from the horizontal plane
θ = the angle in the horizontal plane from due north

and

$$Y_{err} = (PDOP)(UERE)(\cos\varphi)(\sin\theta) \tag{6}$$

where

Y_{err} = Y coordinate position error (ft)

and

$$Z_{err} = (PDOP)(UERE)(\sin\varphi) \tag{7}$$

where

Y_{err} = Z coordinate position error (ft)

Altimeter

The C-17A will determine altitude with pressure inputs from aircraft sensors, but will also use an air data computer. This computer "can correct for both the scale error of the capsule [pressure-sensing element] and the position error of the static pressure installation" (5:167). Assuming the static and scale errors are corrected with the air data computer, assuming the lag time error to be negligible due to proper design, and assuming hysteresis errors to be negligible due to design; the only error remaining is the error due to the air data computer. Like the outside air temperature sensors, the true error of the air data computer has not been determined, so the accuracy requirements for the air data computer will be used for this model. Table 3.13 shows the accuracy requirements for the air data computer (3).

TABLE 3.13

Air Data Computer Pressure Altitude Accuracy

± 15 ft. at -1000 to 0 ft.
± 20 ft. at 10,000 ft.
± 40 ft. at 30,000 ft.
± 80 ft. at 50,000 ft.

The air data computer error is assumed to come from a uniform distribution. Because the model is only examining low altitude drops, the air data computer error is assumed to come from a uniform distribution between minus fifteen and plus fifteen feet.

Model Design

The logic behind the design of the model is shown in the algorithm of Figure 3. With the load and CARP parameters defined from the initialization in the FORTRAN subroutine, the CARP is computed to show the point of the desired position of the aircraft. With the error distributions determined, SLAM II randomly draws from these distributions to determine the positioning and CARP parameter errors for each simulated airdrop. The SLAM II network diagram is displayed in Figure 4. The true position of the aircraft is determined by adding the positioning errors to the planned position. The true CARP parameters are determined in the user defined FORTRAN subroutines by adding the errors to the planned CARP parameters. The CARP is recomputed with user defined FORTRAN subroutines, using the true altitude of the aircraft and the true CARP parameters. Because the true CARP is determined with the true aircraft altitude (same horizontal plane) the drop score is the difference between the true aircraft horizontal position and the true horizontal CARP. Again, the drop score is determined with a user-defined FORTRAN subroutine. All the drop scores are collected in SLAM II, and the radius of the circle that includes one-half of the drop scores (fifty-percent circular error) is determined.

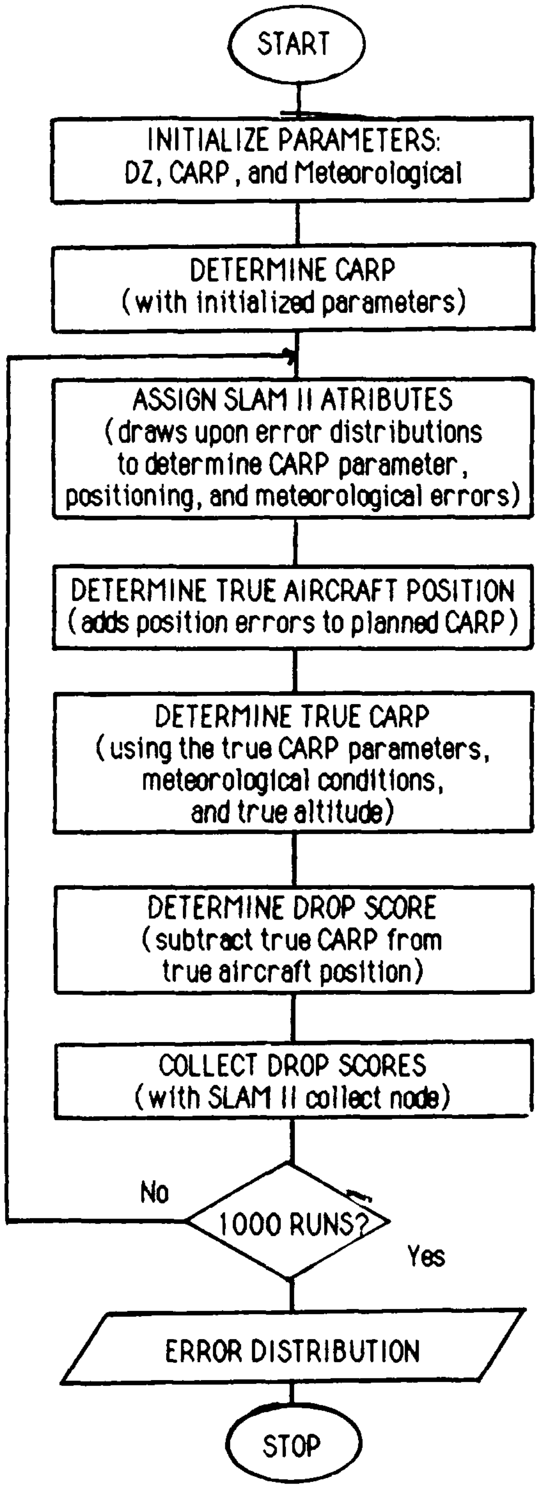


Figure 3. Model Flow Chart

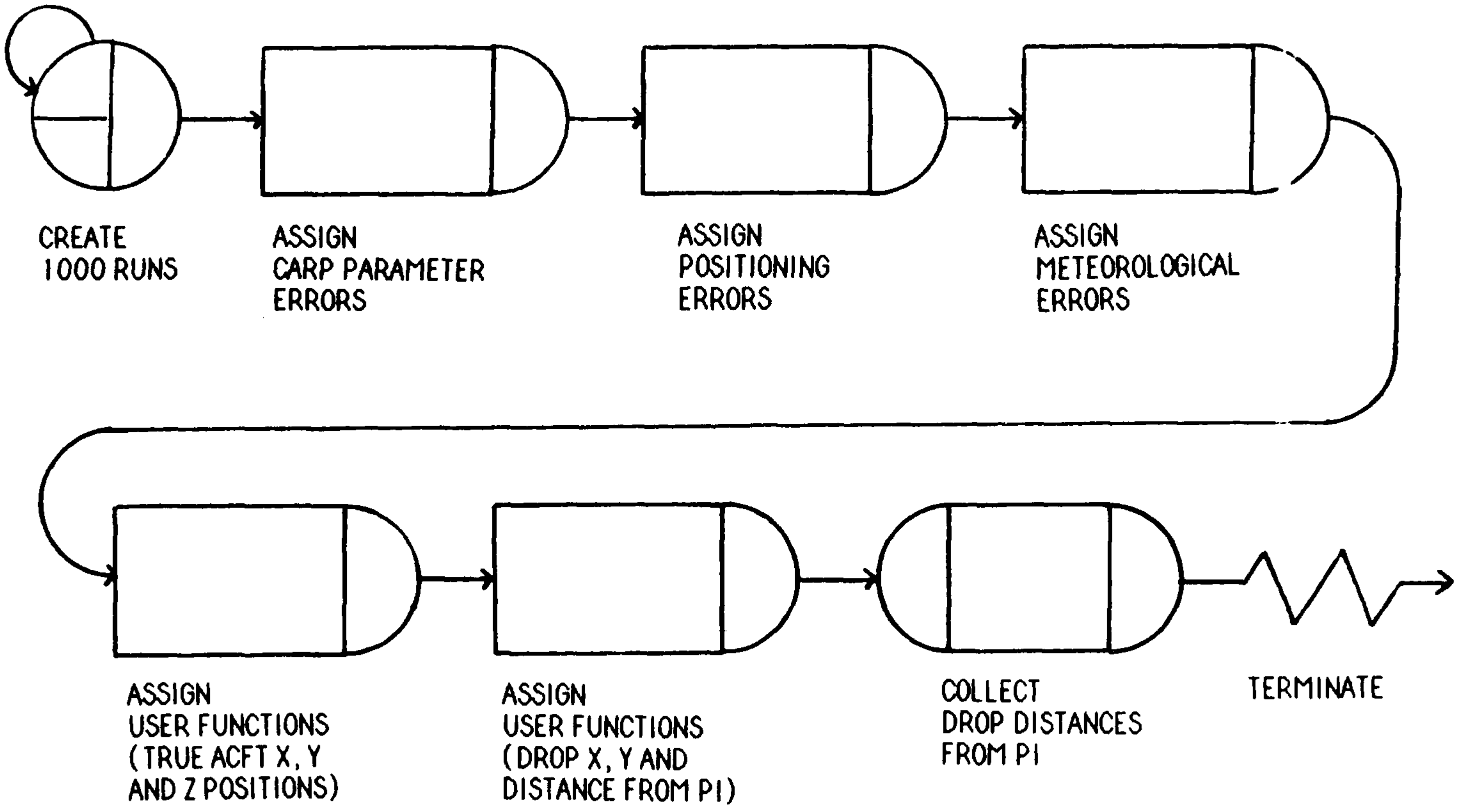


Figure 4. SLAM II Diagram

In order to accomplish the above described design, a coordinate system must be chosen. For this model, an X, Y, Z coordinate system is used with the point of origin at the point of impact (PI). The Y axis points north (000 degrees) and the X axis points east (090 degrees) (Figure 5). For simplicity, the X axis is also the drop zone axis. The identical axes mean that the aircraft's planned direction of flight is along the X axis. The Z axis points upward and indicates the altitude. With this coordinate system, the CARP, the aircraft positions, and drop scores can be determined.

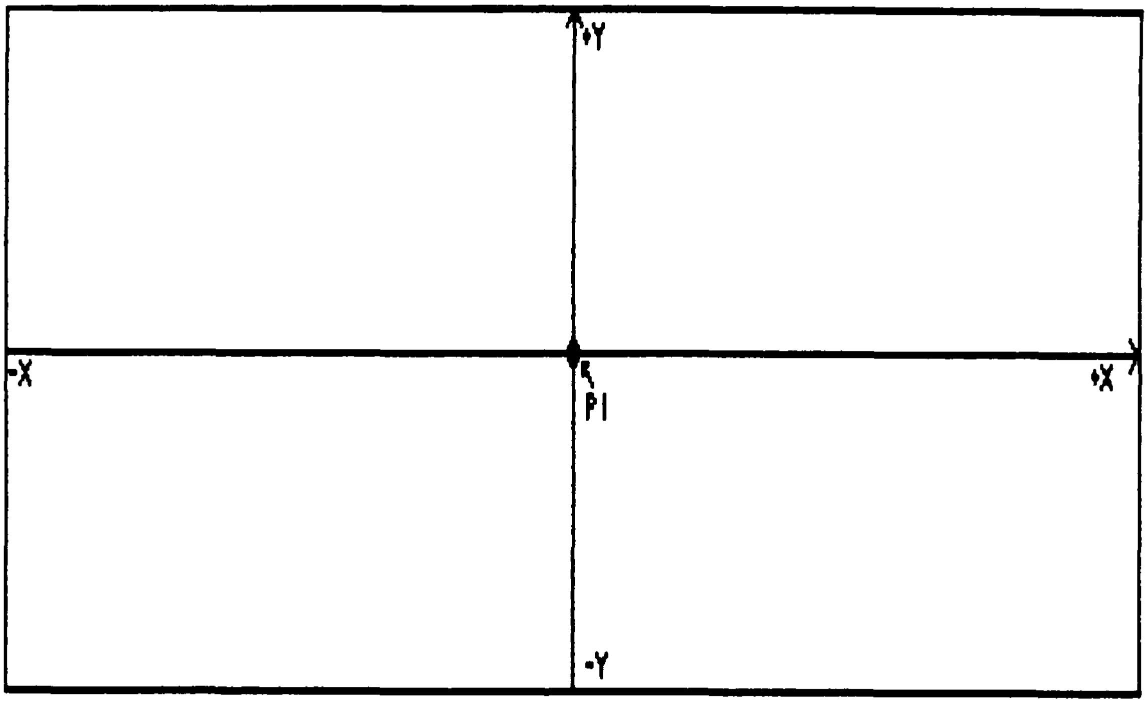


Figure 5. Model Coordinate System

The main parameters that are changed to observe the effects on performance are the wind velocities and the atmospheric pressure errors. With the wind velocities defined in Table 3.11, the initialization of the wind speed is controlled in the FORTRAN code, and is varied between light and heavy winds. The variability of the winds (steady or variable), and the atmospheric pressure errors are controlled with the SLAM II code.

Since many airdrops are simulated with the same CARP, comparing each drop score is impractical. Another means of determining performance is required. Circular error is the means of comparing performance in this model. Circular error is the radius of a circle that contains the desired percentage of drop scores. Since circular error probable is the measure of merit for the positioning accuracy requirement to the CARP, the fifty-percent circular error is the measure of merit in measuring airdrop accuracy.

Model Accuracy

An underlying assumption of the model is that the CARP is a valid model of an airdrop. This assumption must be made because the CARP computations defined in MACR 55-40 govern the airdrops of the Military Airlift Command, of which the C-17A will be a part. Likewise, the equations used to determine the CARP are also assumed to be valid because the equations used in this model are the same equations to be used by the C-17A mission computer designed by Delco Electronics Company. Given that the CARP is a valid model, the validity of determining the airdrop scores for this model must be shown.

Three validation techniques or tests are applied to this simulation model: face validity, fixed values, and extreme-condition tests. "Face validity is asking people knowledgeable about the system whether the model and/or its behavior is reasonable. This technique can be used in determining if the logic in the model flow-chart is correct and if a model's input-output relationships are reasonable" (17:34). If the data is valid and the method described in Figure 3 is valid, then the output should be valid if the calculations are performed correctly. The fixed values technique is used to validate the calculations. "Fixed values are used for all model input and internal variables. This should allow checking the model results against hand calculated values" (17:34). The load, CARP, meteorological, and drop zone parameters are fixed values. The variation comes from assigning errors from the error distributions. By making one run instead of one thousand, the errors drawn from the error distributions can be considered fixed, and hand calculations can be performed. The results of the hand calculations are identical to the model results. Even if the calculations are correct, the extreme conditions should be examined. "The model structure and output should be plausible for any extreme and unlikely combination of levels of factors in the system, e.g., if in-process inventories are zero, production output should be zero" (17:33). An unlikely situation for this model is when all errors (CARP parameter, positioning, and meteorological errors) are zero. If all of the errors are zero, then every load should land exactly on the point of impact, giving a one-hundred percent circular error of zero. The model of this study does produce a one-hundred percent circular error of zero when all errors are zero.

By defining the error distributions, the second part of the first three research questions; how are the error producing factors determined, has been answered. The design of the model answers the fourth research question of how the errors are to be implemented in the model. Finally in this chapter, the accuracy of the model was discussed. Chapter Four discusses the results of the simulations.

IV. Results

Using the methodology discussed in Chapter Three, simulations were performed on both the training and combat scenarios to determine the fifty-percent circular error. The results of the runs are discussed below in Scenario One and Scenario Two. The effects of altitude error only were also simulated to determine the fifty-percent circular error and are discussed in Altitude Error.

Scenario One

In order to compare the results of modifying the variabilities of wind and atmospheric pressure, as a base reference, airdrops were simulated with perfect knowledge of the meteorological conditions. Perfect knowledge of the meteorological conditions is no variability in winds, atmospheric pressure and temperature; what was planned for in the CARP computations for winds, pressure, and temperature is what was observed. The results of the simulation are displayed in Figure 6. As shown, with perfect knowledge of the meteorological conditions, there is little difference between using GPS or the altimeter for altitude positioning. The difference between the effects of heavy and light winds is also negligible. The heavy winds produced slightly lower fifty-percent circular errors than the light winds which is opposite to expected results. This result may be due to the randomness of the test, or it may indicate that the CARP parameters have a bias for which the effects of the heavier winds compensate.

Recall that Scenario One is a local training mission with atmospheric pressure information one-half an hour old, with a drop zone one-hundred miles from the pressure observation. The results of the Scenario One simulations in terms of fifty-percent circular error are displayed in Figure 7. GPS and altimeter altitude positioning is compared with respect to the four different types of winds (light and steady, light and variable, heavy and

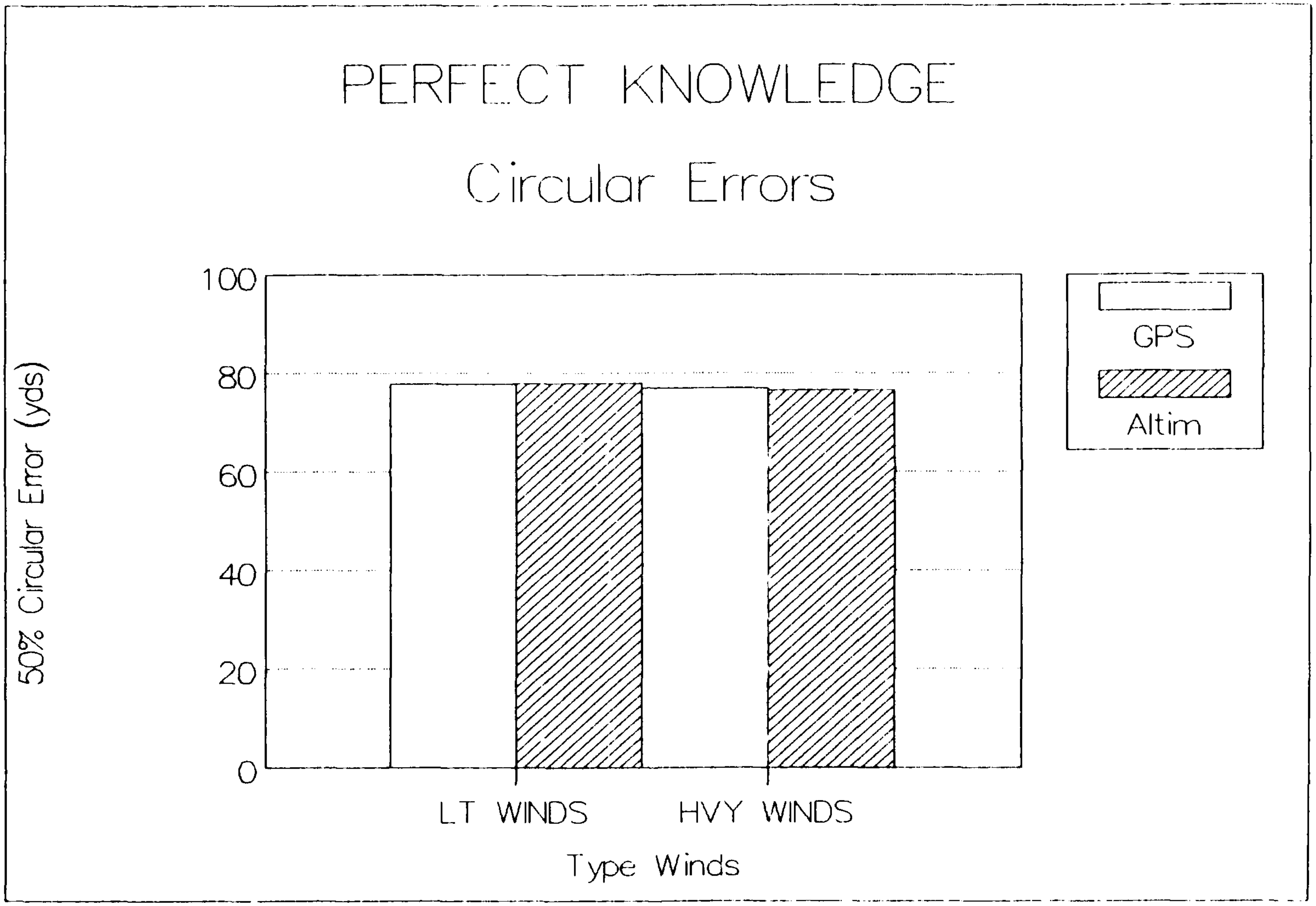


Figure 6. 50% Circular Errors with Perfect Knowledge of the Meteorological Conditions

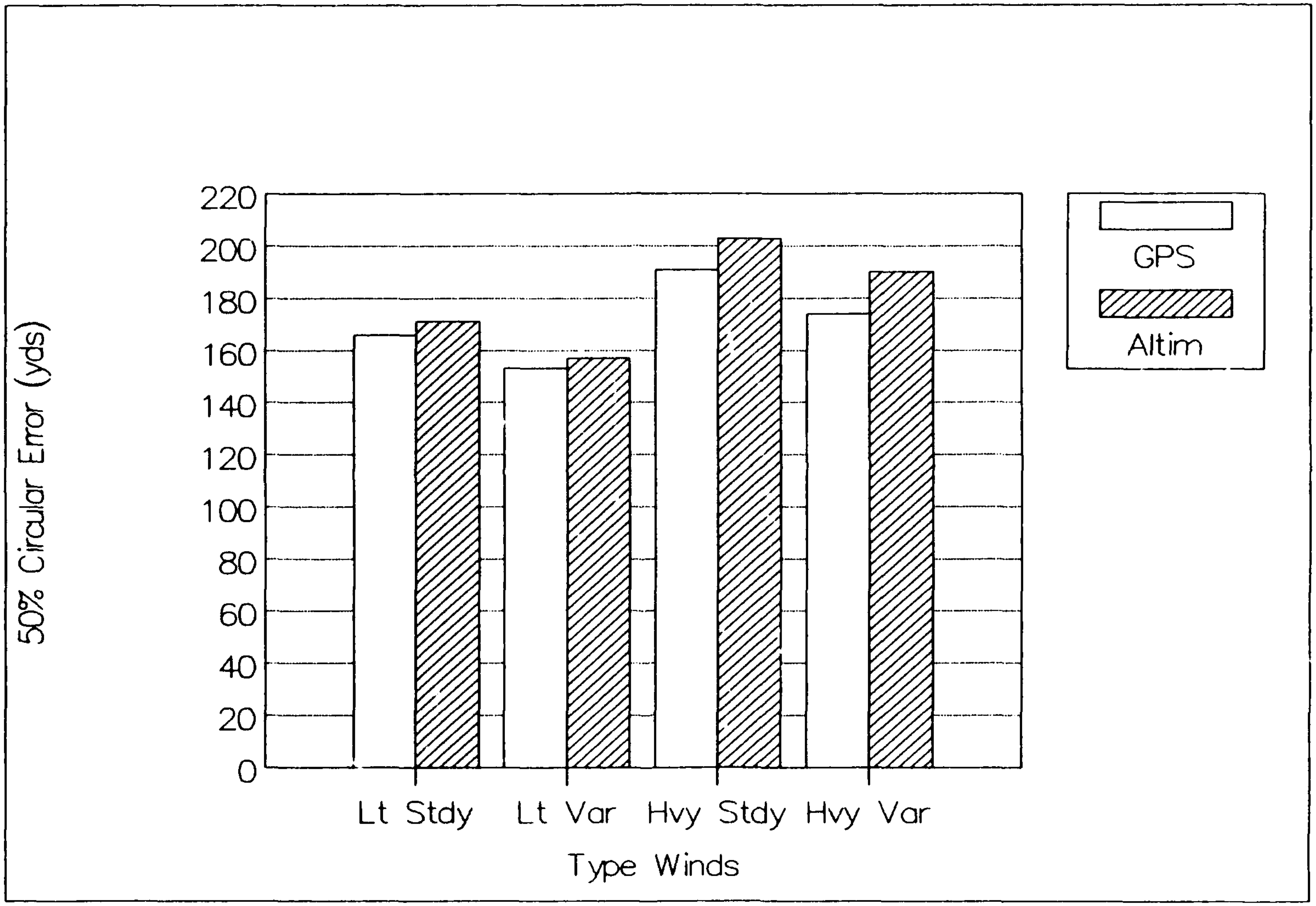


Figure 7. Scenario 1 50% Circular Errors

steady, and heavy and variable). In all cases, the GPS altitude positioning had better (lower) airdrop scores than the altimeter altitude positioning airdrop scores; however, the greatest difference (heavy and variable winds) is only sixteen yards. The overall fifty-percent circular errors did increase with an increase in wind speed. The difference between the airdrop scores of GPS altitude positioning and altimeter altitude positioning also increased with an increase in wind speed. Perhaps of some importance is the effect of the variability of the winds. As the variability increased, the overall fifty-percent circular error decreased. This effect is due to the cancelling out of errors from the higher variability of the winds.

Scenario Two

Recall that Scenario Two is a combat scenario with the atmospheric pressure errors increasing as the time from forecast increases. Simulations were performed to model the effects of Scenario Two with and with out the presence of a major weather front. Scenario Two-A is with out a major weather front and Scenario Two-B is with a major weather front. The results of the simulation runs with Scenario Two-A are displayed in Figures 8 through 11. Scenario Two-B results are displayed in Figures 12 through 15.

As expected from the results of Scenario One, the fifty-percent circular error increased with an increase in wind speed in both Scenarios Two-A and Two-B. Like Scenario One, increasing the variability of the winds decreased the fifty-percent circular error. With increasing atmospheric pressure errors, the results demonstrate the anticipated increase in the fifty-percent circular error. The difference in performance of the two methods of altitude positioning (GPS and altimeter) increases with both increasing wind speed and increasing time from atmospheric pressure forecast. The greatest difference (approximately 170 yards) occurs with Scenario Two-B, six hours from the forecast and with heavy winds. Increasing the variability of the winds appears to have little effect on the difference in performance of the two methods of altitude positioning.

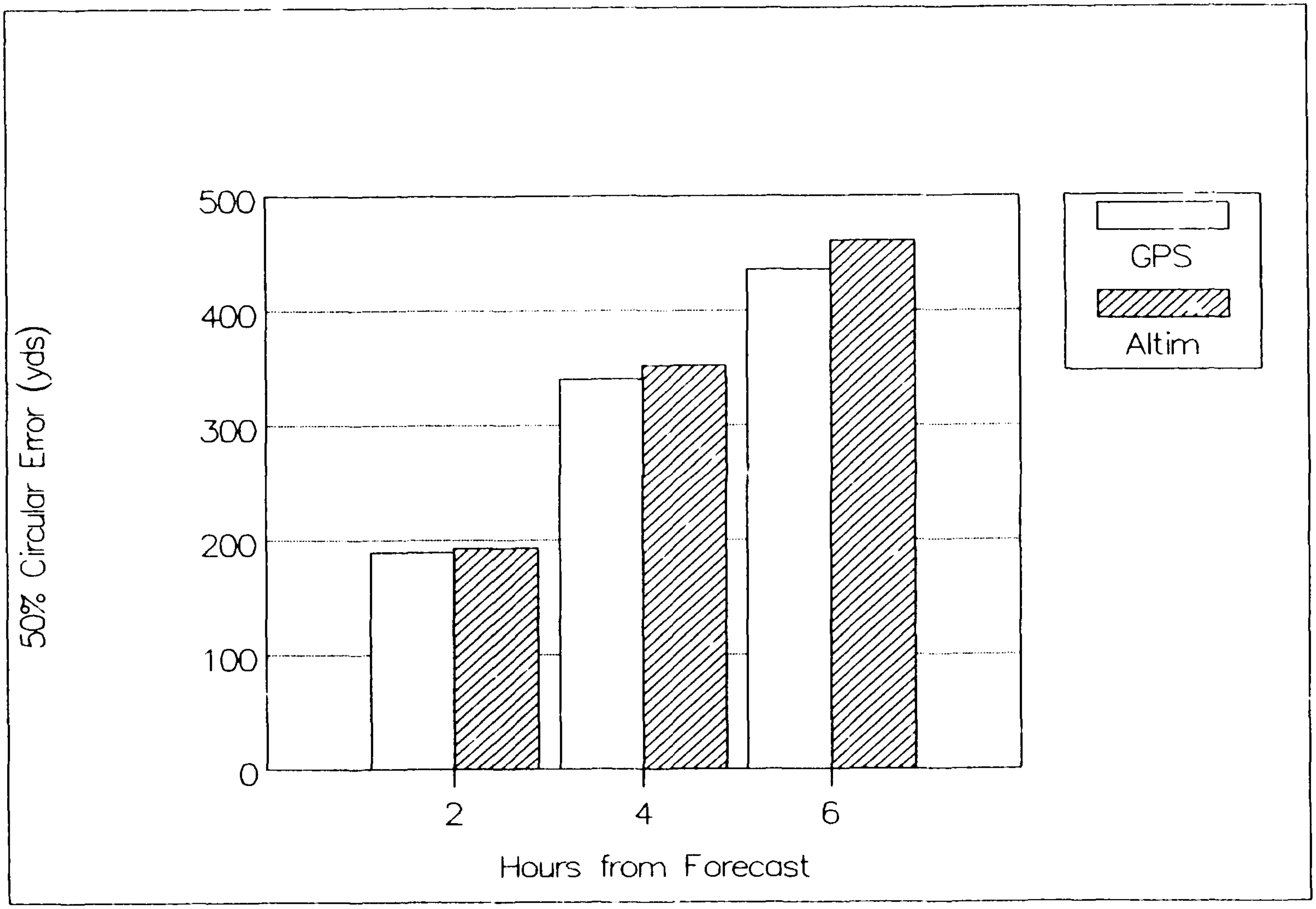


Figure 8. Scenario 2A 50% Circular Errors With Light and Steady Winds

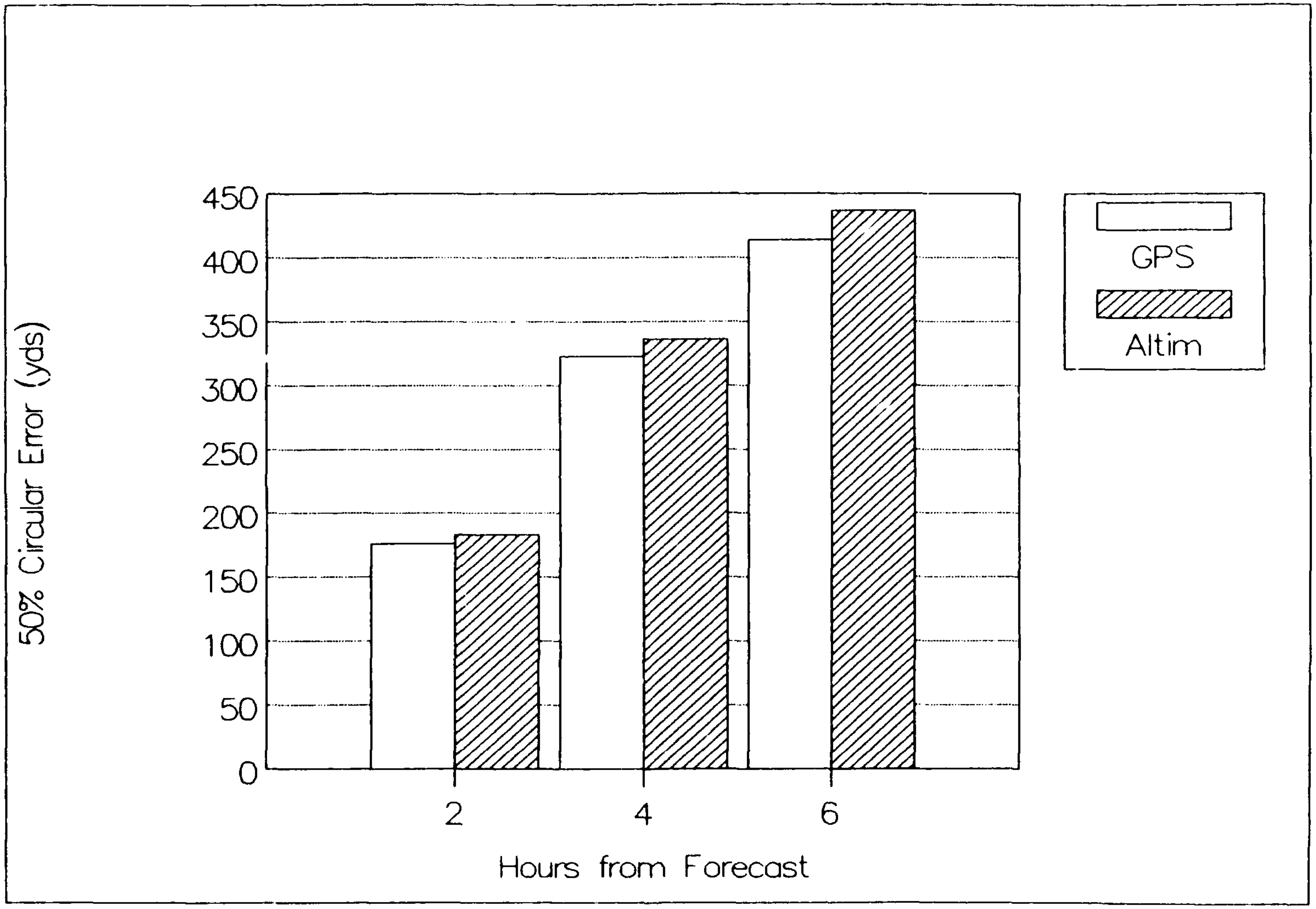


Figure 9. Scenario 2A 50% Circular Errors With Light and Variable Winds

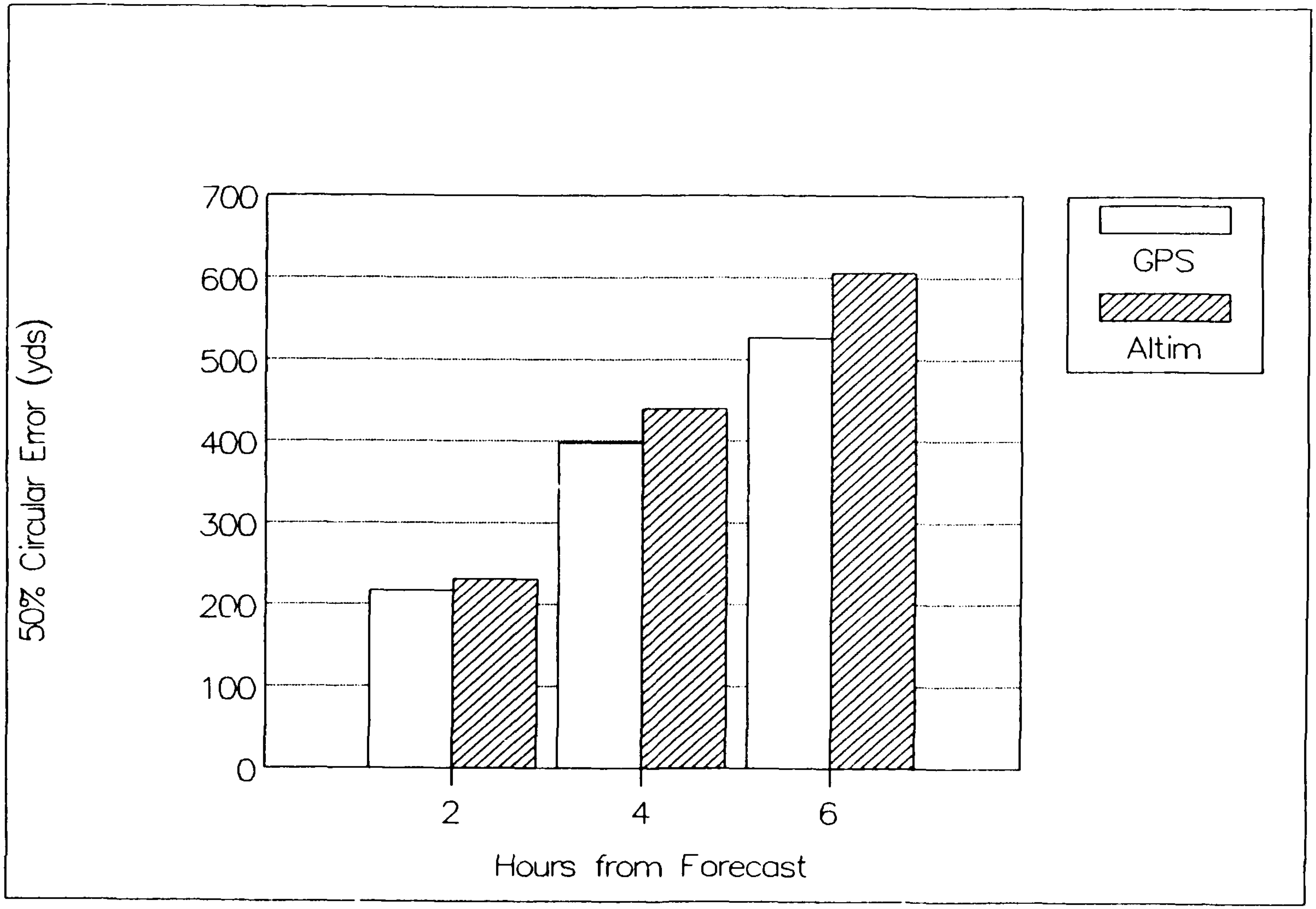


Figure 10. Scenario 2A 50% Circular Errors With Heavy and Steady Winds

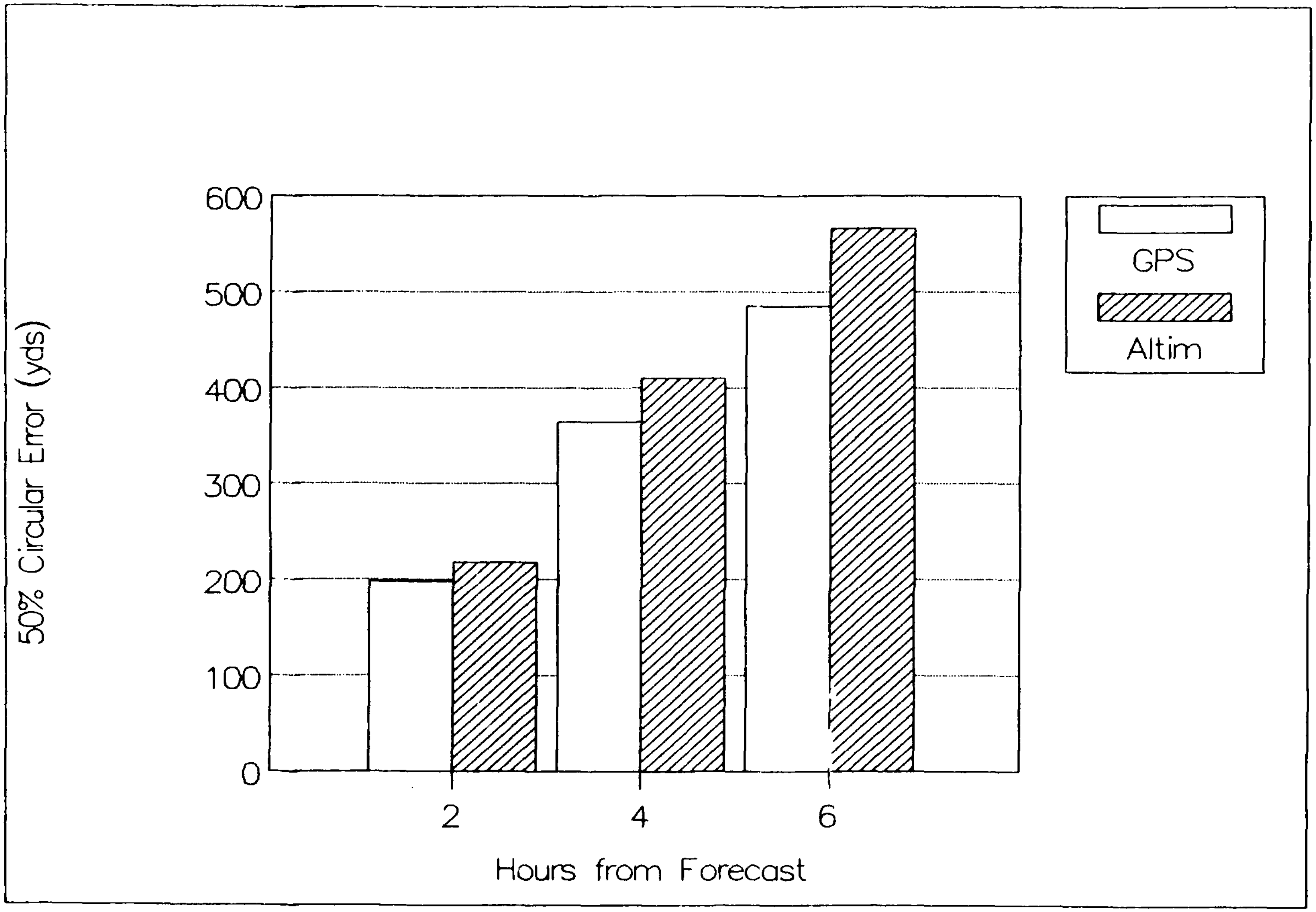


Figure 11. Scenario 2A 50% Circular Errors With Heavy and Variable Winds

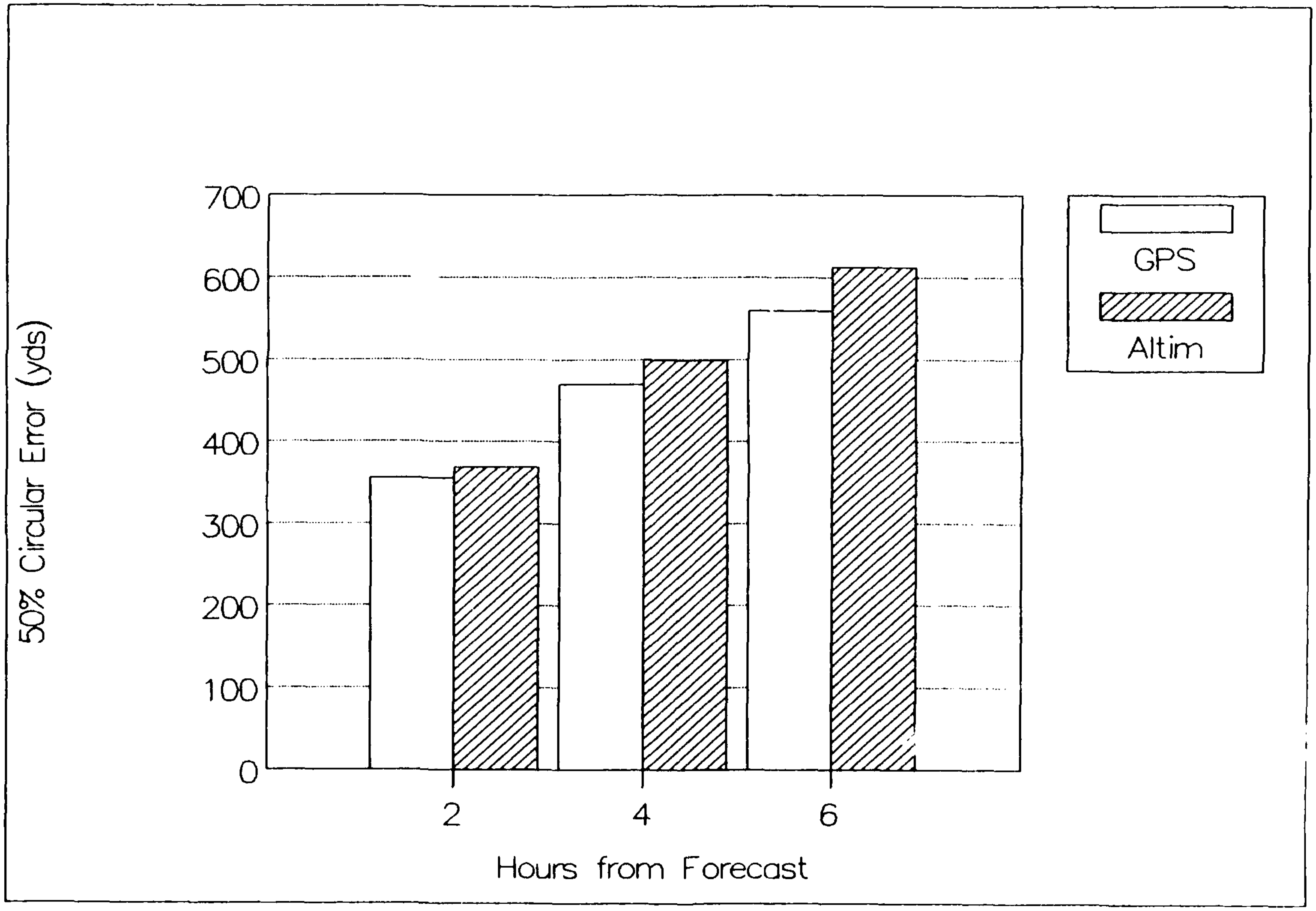


Figure 12. Scenario 2B 50% Circular Errors With Light and Steady Winds

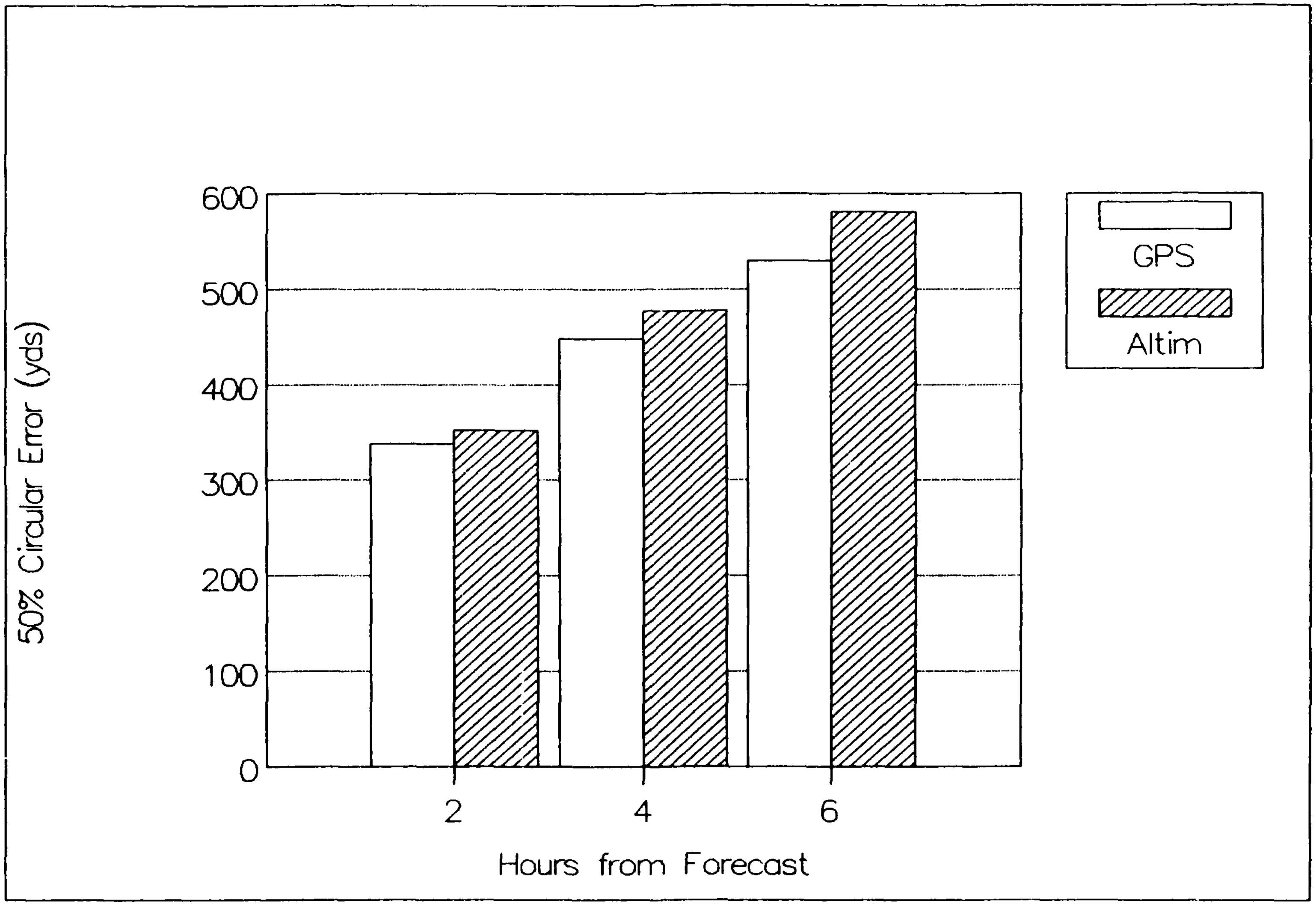


Figure 13. Scenario 2B 50% Circular Errors With Light and Variable Winds

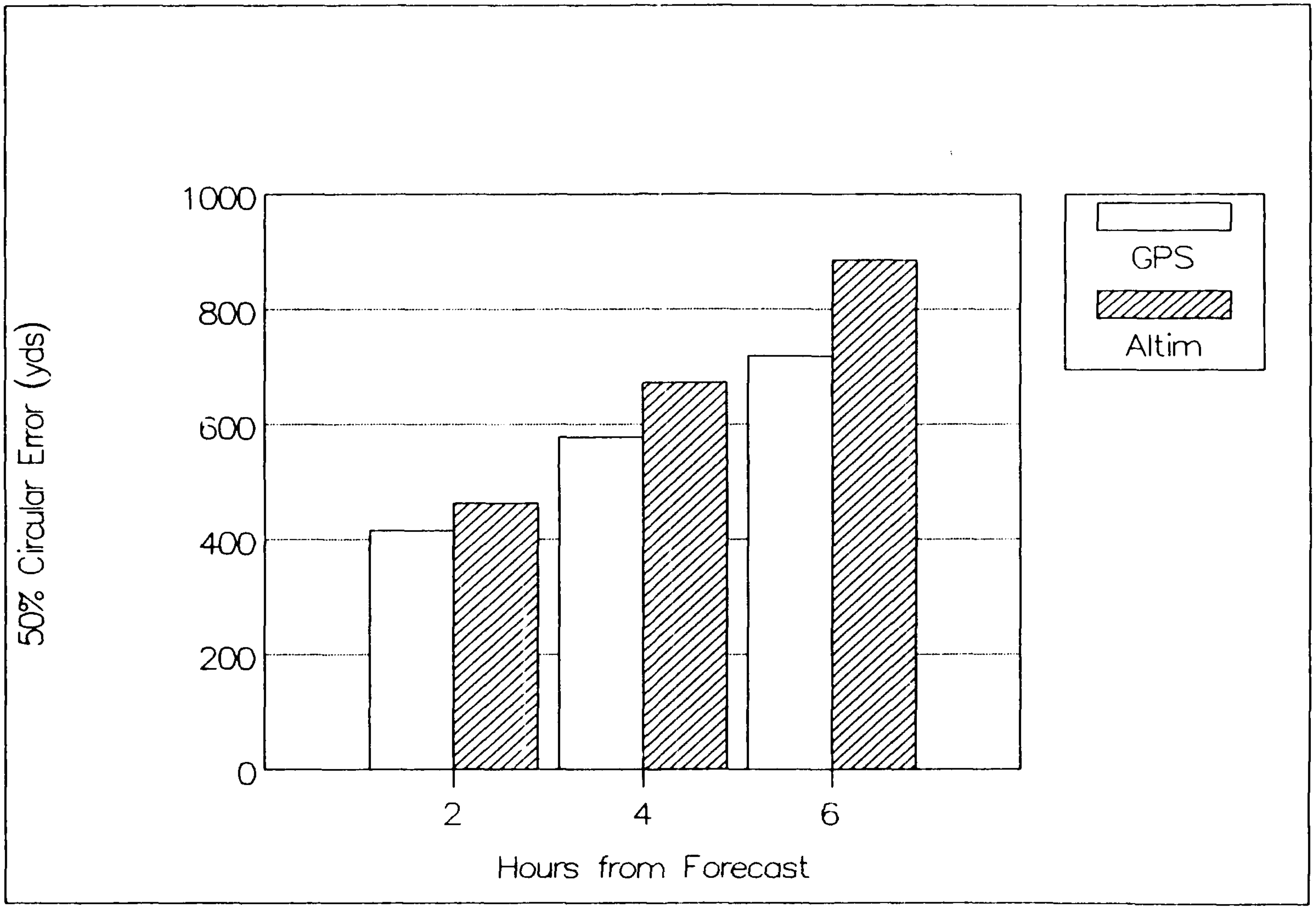


Figure 14. Scenario 2B 50% Circular Errors With Heavy and Steady Winds

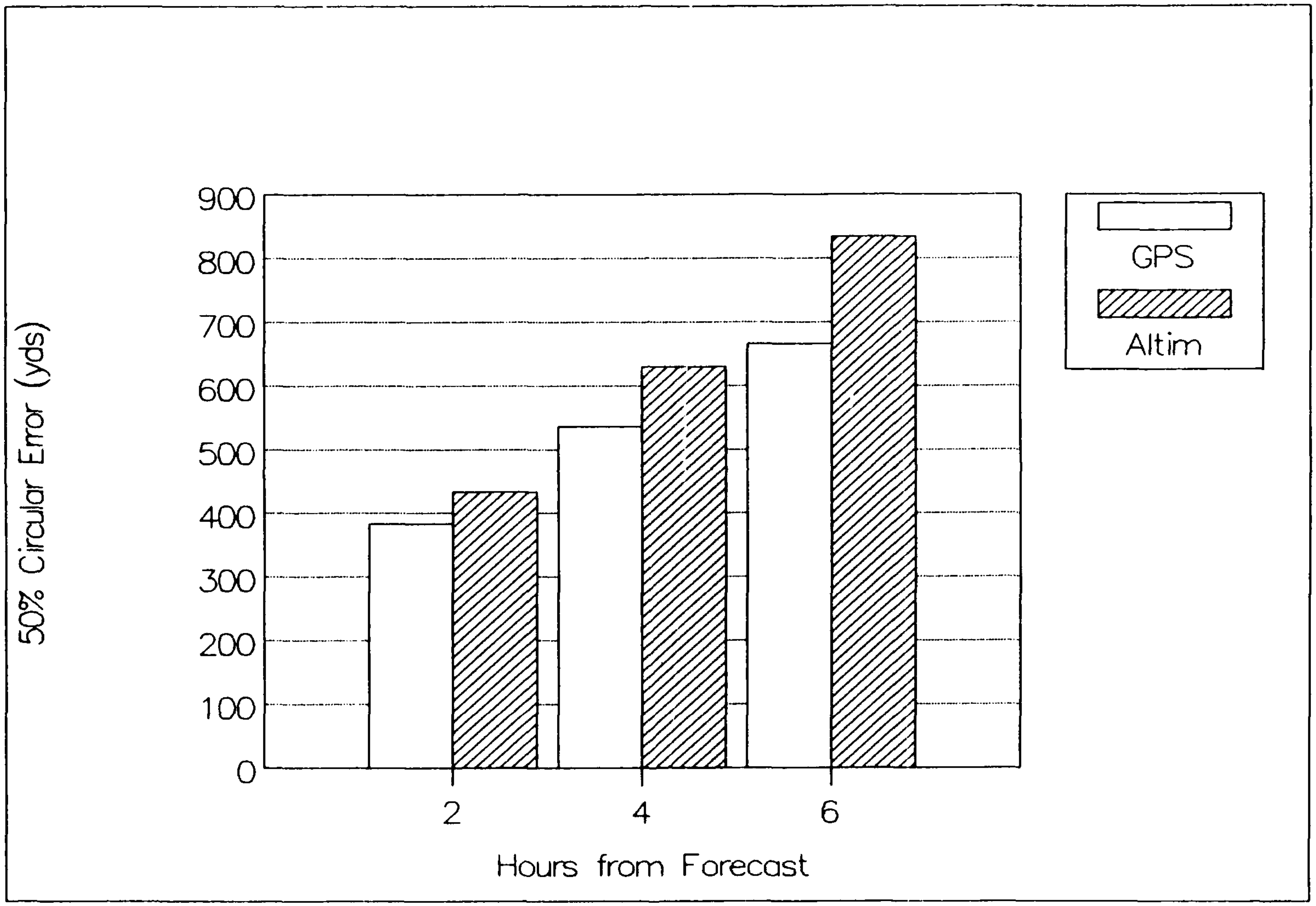


Figure 15. Scenario 2B 50% Circular Errors With Heavy and Variable Winds

As the atmospheric pressure error increases, the decrease in performance with the GPS method of positioning is due to the effects of atmospheric pressure error on the rate of fall of the airdrop load. If the atmospheric pressure error could be eliminated, or greatly reduced, a dramatic improvement in airdrop performance should be noted. Assuming with the GPS method of altitude determination that the atmospheric pressure error can be determined by referencing the difference between the the GPS altitude and the barometric altimeter altitude, corrections can be applied to the CARP computations to reduce or eliminate the effect on the rate of fall. Figure 16 displays the comparison of Scenario Two-B with heavy and steady winds to the GPS method of altitude determination with the CARP computed with the true atmospheric pressure. The results are dramatic.

Altitude Error

To observe the effects of altitude error on airdrop performance, simulations were performed with all errors equal to zero except for the wind errors and the controlled altitude error. This setup provides for perfect horizontal positioning at the CARP. This setup also removes any variability due to the CARP parameters. The reasoning for this setup is that the winds are the only parameters that are uncontrollable. Improvements can be made in better positioning and in decreasing the variability of the CARP parameters, but winds are not controllable. The results of these simulations are the best that the C-17A can achieve. Simulations were performed with the altitude error starting at zero and increasing by twenty-five feet up to two-hundred-fifty feet. The small increments in altitude error were made to better examine the performance at the lower altitudes. More simulations were performed at three-hundred, four-hundred, five-hundred, and one-thousand feet altitude errors to examine the trends from lower to higher altitude errors.

The results of the simulations on altitude error are displayed in Figure 17. The results are discussed with reference to low and high altitude errors. For this study, low

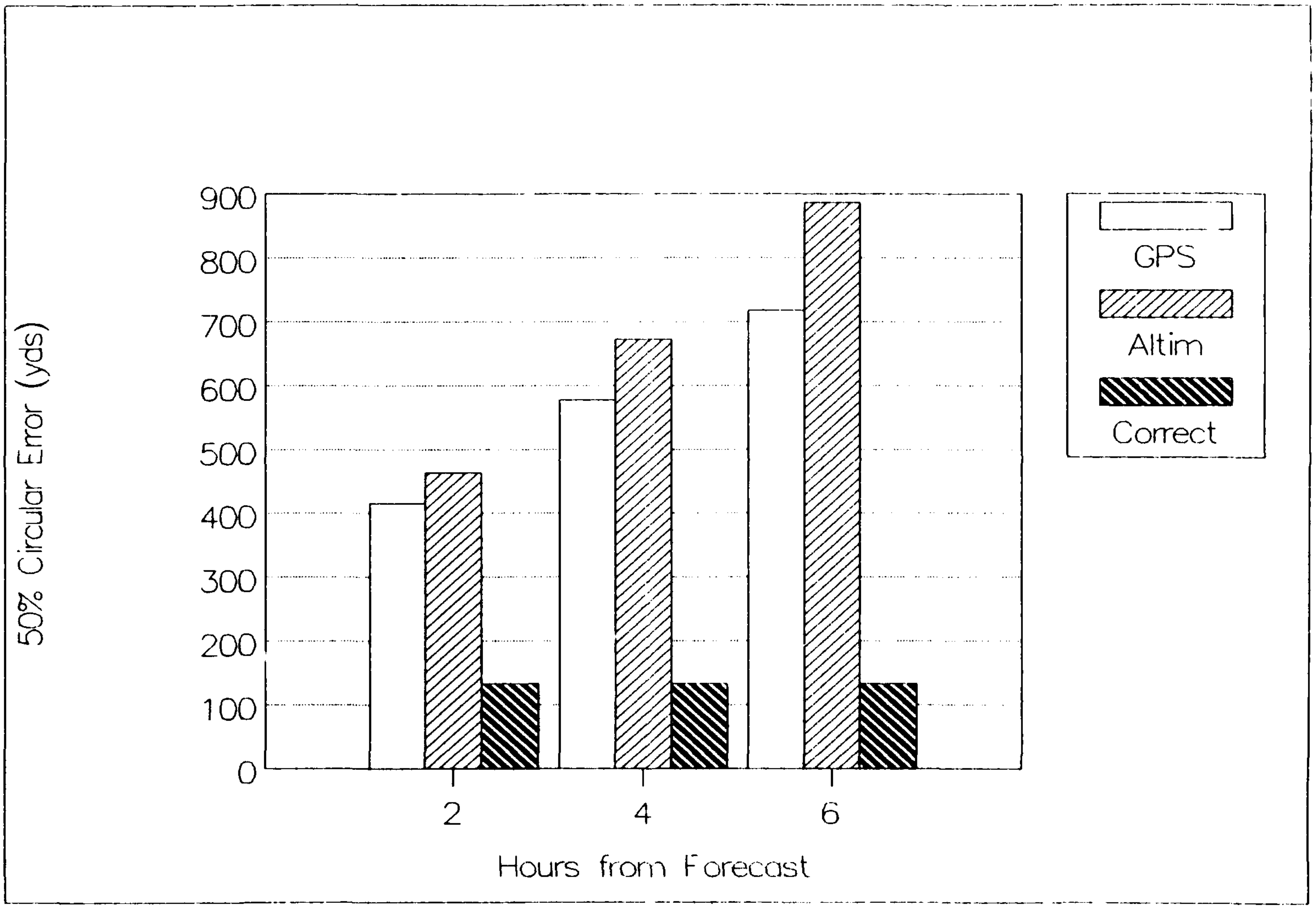


Figure 16. Comparison of Scenario 2B 50% Circular Errors (Heavy and Steady Winds) With Corrected Atmospheric Pressure

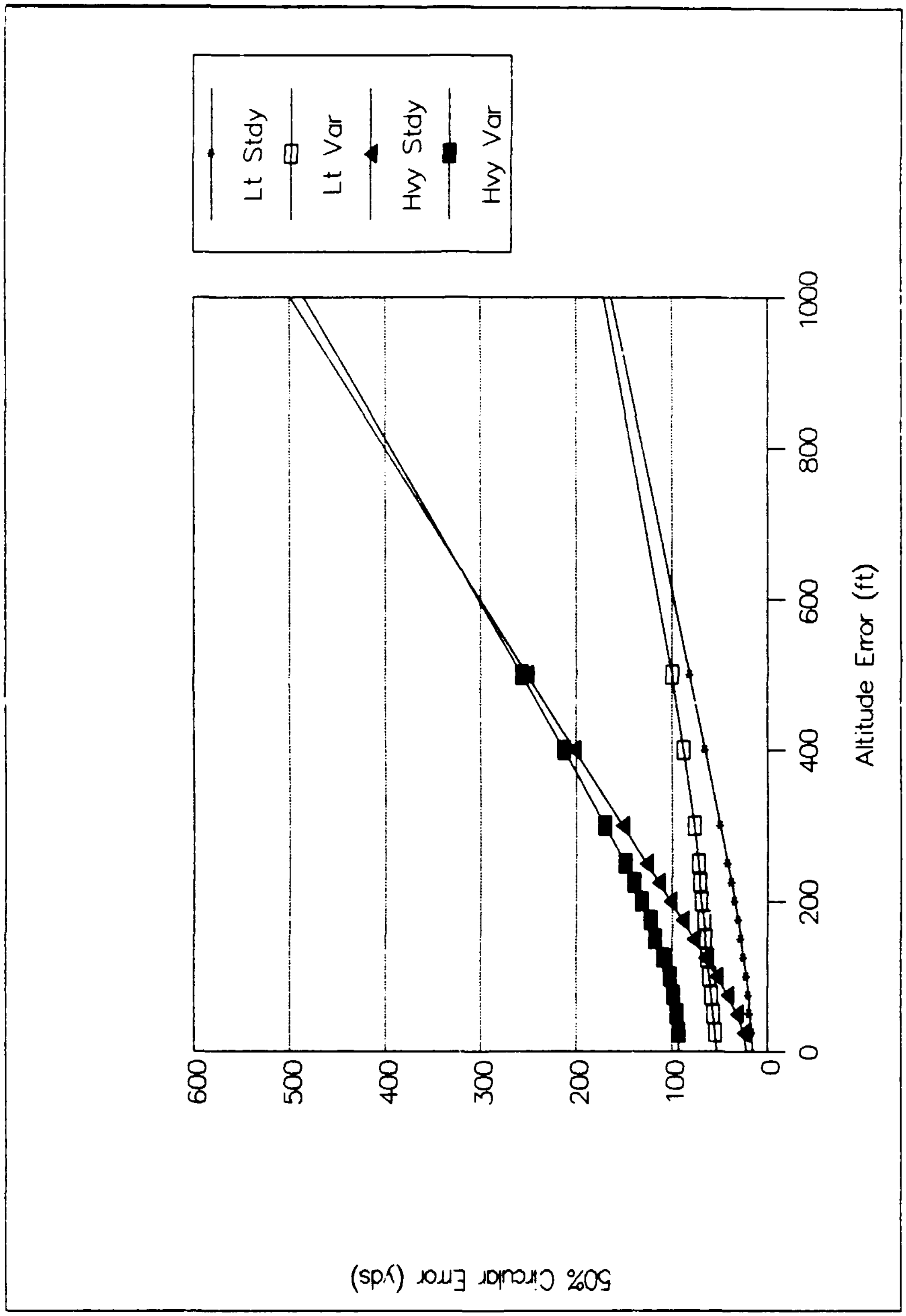


Figure 17. Effects of Wind and Altitude on 50% Circular Error

altitude errors are errors at two-hundred feet and below and high altitude errors are errors greater than two-hundred feet. The two-hundred feet cut-off was chosen due to the trends shown in Figure 17. Below two-hundred feet, the variability of the winds is the dominant factor in airdrop performance, with the steady winds permitting the better airdrop performance. After two-hundred feet, the variability has little effect on performance and wind speed becomes the dominant factor, with the light winds permitting the best results. Before two-hundred feet, the heavy wind performance is clearly nonlinear. After two-hundred feet, the performance is approximately linear for all four types of winds. This linear trend allows for predictability in performance. In the worst case (heavy winds), every two-hundred feet increase in altitude error corresponds with a one-hundred feet fifty-percent circular error increase in airdrop performance.

The methodology established in Chapter Three was used to provide the above results. The results are used to determine the effects of wind and altitude error on C-17A airdrop performance. The results demonstrate the expected decrease in airdrop performance with increases in wind speed, atmospheric pressure errors, and altitude errors. Counter to expectations, increasing the variability of the winds does not indicate decreasing airdrop performance. GPS altitude positioning outperformed the altimeter altitude positioning in all scenarios, with a maximum difference in Scenario Two-B with heavy winds. These results will be used in the next chapter in answering the final two research questions.

V. Conclusions and Implications

In this chapter, the two remaining research questions are answered in Conclusions. The implications of the study and the implications of the model are also discussed in this chapter. Following the implications, recommendations are made as to future research and the role of GPS in tactical airlift.

Conclusions

The altitude positioning provided by GPS performed better than the altitude positioning provided by the altimeter in both scenarios; however, the difference in airdrop scores is not greatly significant except with heavy winds in Scenario Two-B. The difference in performance increases as uncertainty increases. The underlying question is, should the GPS be the primary system for determining altitude in airdrops? The answer depends on the type of situations in which the C-17A will be flying, and the desired accuracy of the airdrop.

If the C-17A will always be within two hours of the drop zone, then there is little advantage in using the GPS over the altimeter; however, in a combat environment, having a high cost resource based close to the enemy to keep within two hours of a drop zone may not be the ideal solution. By basing the aircraft at a safer distance, the uncertainty of the atmospheric pressure increases and the drop accuracy decreases. With the GPS as the primary reference for altitude in airdrops, the basing problem disappears, providing greater flexibility in the airdrop mission.

Perhaps the greatest advantage in having GPS altitude available is the ability to compare the GPS altitude with the barometric. Assuming the ability is designed into the mission computer, through this comparison, a more accurate estimate of the true atmospheric pressure can be obtained. With a better estimate, the adjustments made to the rate of fall in the CARP computations are more accurate, improving the airdrop performance significantly.

The final research question concerning accuracy requirements in the vertical plane is addressed with the aid of Figure 17. As an example, assume a drop zone with the dimensions of six-hundred by one-thousand yards. By observing the worst case (heavy winds), in order to keep one-half of the airdrops on the drop zone, the maximum altitude error is six-hundred feet. Recall that the results displayed in Figure 17 do not include errors in horizontal positioning or errors in the CARP parameters. Since the accuracy requirement in the horizontal plane is one-hundred meters (approximately one-hundred-nine yards) to the CARP, the maximum altitude error is reduced to four-hundred feet. Again, this maximum error does not take into account any deviations from the planned CARP parameters. Figure 6 shows the errors from positioning and the CARP parameters. By assuming that fifty yards of error is due to the CARP parameters, the maximum altitude error is further reduced to three-hundred feet. By choosing the smallest acceptable drop zone size, MAC can determine the altitude accuracy requirement.

Implications of the Study

Models can lead to insight to improve a system. In the model of this study, by varying the different parameters, the factors that have the greatest effect on airdrop accuracy can be determined, or where improvement is still possible. Concerning GPS, the problem of satellite geometry will continue to remain. The only possible means of decreasing the effect of geometry is to increase the number of satellites in orbit. Satellites are costly, and in the wake of current deficits, an increase in the number of satellites is not currently probable. Greater technology is the means to decrease the errors due to the space, control, and user segments.

The meteorological conditions are and will continue to be a major source of error. The only way to reduce the meteorological errors is to have the personnel and equipment necessary for meteorological observations at the drop zone at the time of the drop. Such actions are not usually practical in combat and would reduce the flexibility to perform covert airdrops where friendly forces are not present.

The variability of the CARP parameters can be a major source of error, which decreases airdrop accuracy. More airdrop tests will establish more accurate error distributions, but the greatest benefit will come from decreasing the variability in the errors.

Implications of the Model

Since the coarse/acquisition code of GPS will be available to all, as the value and capabilities of GPS become known and accepted, GPS will become a major space resource. This space resource will change the way the military uses navigation and positioning. New tactics and procedures must be developed to take advantage of the greater capabilities of GPS. Models, particularly simulation models, can provide information on future performance to better develop the new tactics and procedures.

The model of this study examined only the heavy equipment airdrops in the airdrop mission. The error distributions of the CARP parameters of the other types of airdrop (container delivery and personnel) can be established to predict the effects of GPS on airdrop performance. With this information, requirements can be matched with the type of accuracy required. In particular, if a drop zone size is established, the load configuration (weight and type extraction and deployment chutes) can be matched with the drop zone and meteorological conditions to achieve the desired accuracy. If a certain amount of supplies or equipment is required at a drop zone, the number of sorties (missions) required can be predicted to achieve the desired goal.

The C-17A airdrop model is designed to be flexible. By individually assigning an error to each of the error producing factors, as technology decreases the variability of one of the errors, this model is capable of easily being modified to account for the change. Specifically, if a satellite clock is developed that changes the distribution of the space segment error, the model can easily accept the change (provided that the new distribution is known).

Recommendations

The CARP method is a proven method of aerial delivery, and GPS improves the accuracy of the CARP method; however, GPS is a new technology and should not be limited to the traditional roles of navigational aids. The C-17A will have the latest technology in avionics available. The role of GPS can be expanded by linking these technologies. This joining of technologies may bring about new airdrop procedures with greater accuracies or flexibility that will make the CARP method obsolete.

An example of flexibility in linking technologies is in using the heads up display. With the present CARP method, the drop zone location and elevations must be known. If the drop zone is visible to the pilot, a marker on the heads up display can be moved to where the load is requested to land, and the mission computer can determine the CARP. Using a marker (pipper) is not unlike a fighter or bomber aircraft in trying to accurately deliver ordinance on a target. An example of greater accuracy and greater flexibility is if the load could guide itself to the point of impact. With small enough GPS receivers and guidance systems, the load could steer itself to the drop zone, providing greater accuracy and greater flexibility. Instead of a computed air release point, a computed air release zone would be computed to determine where the load should be released. These are just two examples of what may be possible. New ideas should be explored to further advance the capabilities of newer technologies. These ideas should not be limited to only the proven, standard procedures.

Appendix A: C-141B Heavy Equipment Exit Time

From MACR 55-40

C-141B HEAVY EQUIPMENT
EXIT TIME
150 KIAS/0-2000 FT AGL

EXTRACTION CHUTE SIZE	LOAD WEIGHT (LB)	LOAD C.G. FUSELAGE STATION							
		350-530	530-650	650-770	770-890	890-1010	1010-1130	1130-1250	1250-1370
R-15' RS	2500	5.95	5.91	5.85	5.73	5.63	5.43	5.27	5.05
	3500	6.22	6.17	6.09	5.95	5.79	5.63	5.44	5.18
	4500	6.73	6.59	6.33	6.15	5.98	5.79	5.58	5.31
	5500	6.80	6.67	6.52	6.35	6.15	5.92	5.70	5.42
	6500	6.90	6.80	6.69	6.49	6.36	6.05	5.80	5.51
15' RS	5000	6.35	6.25	6.13	5.99	5.83	5.59	5.46	5.21
	6000	6.56	6.44	6.30	6.14	5.96	5.77	5.56	5.33
	7000	6.70	6.58	6.44	6.28	6.08	5.88	5.64	5.38
	8000	6.86	6.73	6.58	6.41	6.20	5.98	5.74	5.45
	9000	7.00	6.87	6.71	6.53	6.33	6.08	5.83	5.51
	10000	7.20	7.02	6.84	6.65	6.46	6.17	5.92	5.77
22' RS	10000		6.42	6.28	6.13	5.99	5.81	5.62	5.45
	11000		6.51	6.36	6.20	6.04	5.87	5.67	5.49
	12000		6.56	6.43	6.28	6.11	5.93	5.72	5.52
	13000		6.63	6.51	6.35	6.17	5.97	5.76	5.54
	14000		6.69	6.56	6.41	6.23	6.04	5.81	5.57
	15000		6.74	6.63	6.47	6.29	6.08	5.85	5.60
	16000		6.85	6.71	6.54	6.35	6.14	5.89	5.63
	17000		6.95	6.78	6.60	6.41	6.19	5.93	5.66
	18000		7.03	6.85	6.66	6.47	6.23	5.97	5.69
28' RS	16000			5.81	5.69	5.57	5.43	5.27	5.12
	18000			5.89	5.76	5.63	5.48	5.32	5.14
	20000			5.97	5.83	5.71	5.55	5.36	5.17
	22000			6.05	5.90	5.76	5.59	5.41	5.21
	24000			6.10	5.97	5.81	5.66	5.46	5.25
	26000			6.17	6.02	5.88	5.70	5.49	5.28
	28000			6.23	6.07	5.94	5.75	5.52	5.31
	30000			6.29	6.12	6.00	5.80	5.55	5.34
	32000			6.34	6.16	6.06	5.84	5.58	5.36
2 28' RS	30000			5.91	5.76	5.61	5.43	5.24	5.00
	32000			5.97	5.81	5.65	5.47	5.28	5.02
	34000			6.01	5.86	5.69	5.51	5.31	5.05
	36000			6.07	5.91	5.74	5.55	5.34	5.09

Appendix B: Guidance for Airdrop Parachutes

From MACR 55-40

Type	Description	Minimum Airdrop Alt Feet (AGL)	Airdrop Speed Knots (KIAS)	Wt Ranges	Remarks
(G-11A Continued)		1100	125 - 150	(*) 2/ 3501 - 6500 3/ 6501 - 10000 4/10001 - 13000 5/13001 - 17000 6/17001 - 25000	Applies to platform, extracted, cargo/ equipment loads using a cluster of a maximum of six parachutes
		1300	125 - 150	25001 - 35000	Applies to platform, extracted, cargo/ equipment loads, using a cluster of eight parachutes.
G-11B	100'	550	125 - 150	2520 - 5000	Applies to single parachute, platform, extracted cargo/ equipment loads.
		650	125 - 150	(*) 2/ 5000 - 10000 3/10000 - 15000	Applies to platform, extracted, cargo/ euqipment loads using cluster of two or three parachutes.

NOTES:

1. Minimum altitudes shown are intended to provide guidance, not to restrict the Army/Air Force commanders in their planning of combat cargo/equipment airdrop missions. Altitudes are based on the technical design characteristics of the parachutes and represent the minimum at which the parachutes may be expected to perform their intended function with acceptable reliability. Use of lower altitudes than shown may result in the parachute failing to achieve their design performance/reliability and result in unacceptable damage to the loads.

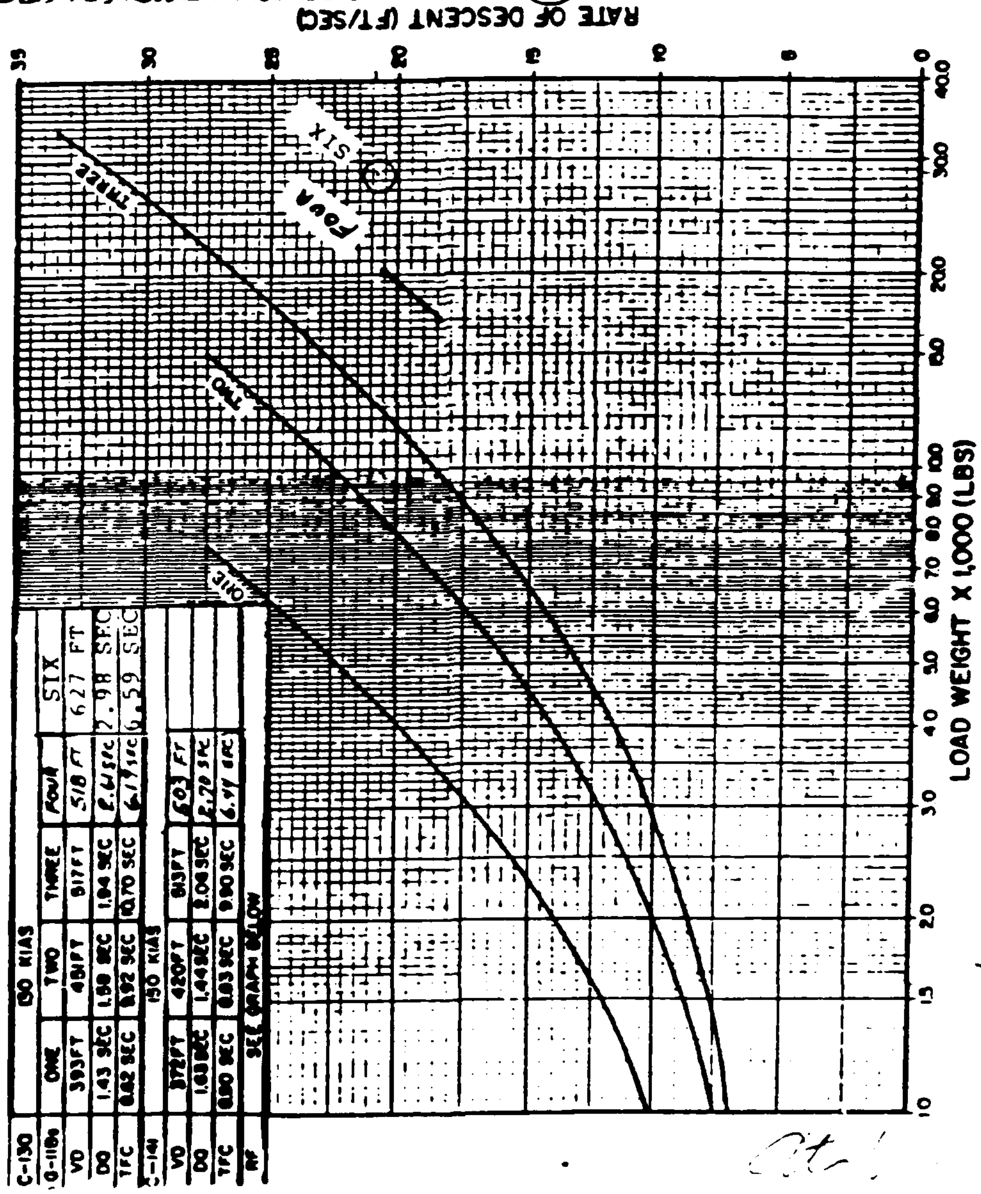
Appendix C: G-11B Rate of Descent vs. Load Weight

From MACR 55-40

NOTE: Exit times (ET) are the same as those for the G-11A (see this attachment, charts 1 and 2).
CAUTION. Minimum drop altitudes for the G-11B for unilateral/MAC training are.

ACFT	1 Chute	2 Chutes	3 Chutes	4 Chutes	6 Chutes
C-130	750 ft AGL	800 ft AGL	1000 ft AGL	1000 ft AGL	1600 ft
C-141	750 ft AGL	750 ft AGL	900 ft AGL	900 ft AGL	

US Army airdrop loads configured with one, two or three G 11-B cargo parachutes will NORMALLY (EHM) be dropped from 750 feet AGL. The Army assumes full responsibility for load survivability for G-11B configured loads, dropped from this altitude
IMC AIRDROPS MAY REQUIRE HIGHER AIRDROP ALTITUDES (EHM)



G-11B RATE OF DESCENT VS LOAD WEIGHT

C-130	130 KIAS				
G-11Bs	ONE	TWO	THREE	FOUR	SIX
VD	393FT	481FT	517FT	518 FT	627 FT
DO	1.43 SEC	1.58 SEC	1.94 SEC	2.64 SEC	2.98 SEC
TFC	8.82 SEC	8.92 SEC	10.70 SEC	6.19 SEC	6.59 SEC
C-141	150 KIAS				
VD	372FT	420FT	513FT	603 FT	
DO	1.68 SEC	1.44 SEC	2.06 SEC	2.70 SEC	
TFC	8.80 SEC	8.83 SEC	9.90 SEC	6.44 SEC	
RF	SEE GRAPH BELOW				

NOTE: Load wt = Suspended wt and parachute wt.

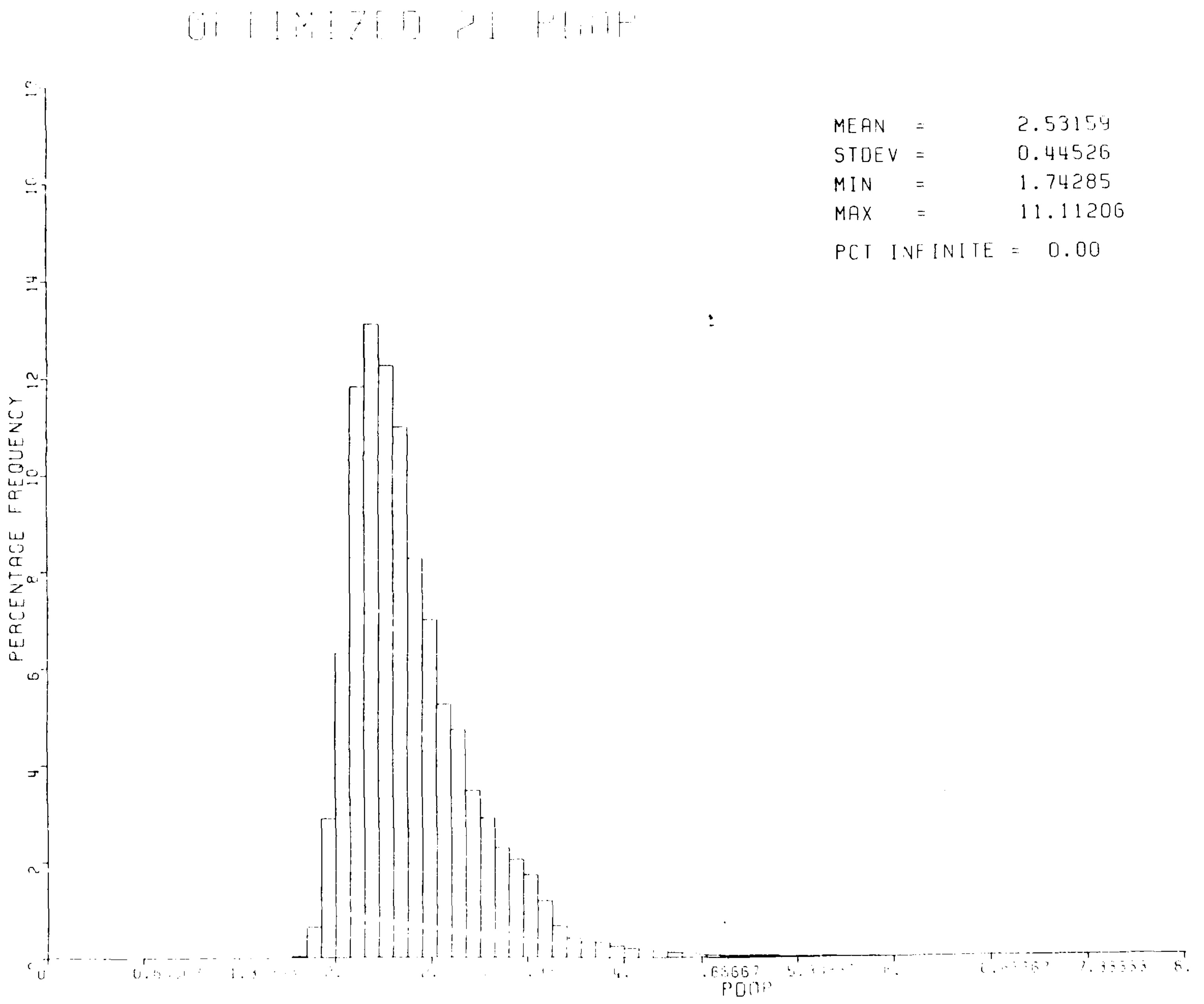
Appendix D: PDOP Data and Histogram

From Aerospace Corporation

```
FITS HEADER

SIMPLE  =                    T          / STANDARD FITS FILE
BITPIX  =                    8          / NUMBER OF BITS FOR DATA
NAXIS   =                    3          / NUMBER OF AXES FOR DATA
NAXIS1  =                  287          / NUMBER OF TIME POINTS
NAXIS2  =                   18          / NUMBER OF LATITUDE POINTS
NAXIS3  =                   36          / NUMBER OF LONGITUDE POINTS

COMMENT   OPTIMIZED 21 PDOP4


CRVAL1  =           0.00000000          / START TIME (MINUTES)
CRVAL2  =           0.00000000          / FIRST LATITUDE (DEGREES)
CRVAL3  =           0.00000000          / FIRST LONGITUDE (DEGREES)
CDELT1  =           5.00000000          / DELTA TIME (MINUTES)
CDELT2  =           5.00000000          / DELTA LATITUDE (DEGREES)
CDELT3  =           5.00000000          / DELTA LONGITUDE (DEGREES)

COMMENT    TO RECOVER DATA, PERFORM THE TRANSFORMATION:
COMMENT                Y = BSCALE*X + BZERO
COMMENT                  THIS WILL GIVE PDOP

BSCALE  =           1.00000000          / SCALE FACTOR FOR DATA
BZERO   =           0.00000000          / BIAS FOR DATA

COMMENT       EPOCH USED FOR RUN    = 1989. 11. 26.   0.   0. 0.0000
COMMENT       NUMBER OF SATELLITES =  21
COMMENT       MINIMUM ELEVATION     =  5.00 DEGREES



END

PERCENT OF DATA INCLUDED IN HISTOGRAM =  99.9976
PERCENT OF DATA WHERE DOP IS INFINITE =   0.0000
     PERCENT OF DATA LESS THAN DOPMIN =   0.0000
```

```
MEAN =  2.53158946      STANDARD DEVIATION = 0.445255822      MINIMUM =  1.74284688      MAXIMUM =  11.1120587

FREQ(  1) = 0.000000000        FROM 0.000000000     TO 0.100000000
FREQ(  2) = 0.000000000        FROM 0.100000000     TO 0.200000000
FREQ(  3) = 0.000000000        FROM 0.200000000     TO 0.300000000
FREQ(  4) = 0.000000000        FROM 0.300000000     TO 0.400000000
FREQ(  5) = 0.000000000        FROM 0.400000000     TO 0.500000000
FREQ(  6) = 0.000000000        FROM 0.500000000     TO 0.600000000
FREQ(  7) = 0.000000000        FROM 0.600000000     TO 0.700000000
FREQ(  8) = 0.000000000        FROM 0.700000000     TO 0.800000000
FREQ(  9) = 0.000000000        FROM 0.800000000     TO 0.900000000
FREQ( 10) = 0.000000000        FROM 0.900000000     TO  1.00000000
FREQ( 11) = 0.000000000        FROM  1.00000000     TO  1.10000000
FREQ( 12) = 0.000000000        FROM  1.10000000     TO  1.20000000
FREQ( 13) = 0.000000000        FROM  1.20000000     TO  1.30000000
FREQ( 14) = 0.000000000        FROM  1.30000000     TO  1.40000000
FREQ( 15) = 0.000000000        FROM  1.40000000     TO  1.50000000
FREQ( 16) = 0.000000000        FROM  1.50000000     TO  1.60000000
FREQ( 17) = 0.000000000        FROM  1.60000000     TO  1.70000000
FREQ( 18) = 0.255791135E-01    FROM  1.70000000     TO  1.80000000
FREQ( 19) = 0.665566949        FROM  1.80000000     TO  1.90000000
FREQ( 20) =  3.57124140        FROM  1.90000000     TO  2.00000000
FREQ( 21) =  9.87787435        FROM  2.00000000     TO  2.10000000
FREQ( 22) =  21.7088183        FROM  2.10000000     TO  2.20000000
FREQ( 23) =  34.8191368        FROM  2.20000000     TO  2.30000000
FREQ( 24) =  47.0831892        FROM  2.30000000     TO  2.40000000
FREQ( 25) =  58.0797299        FROM  2.40000000     TO  2.50000000
FREQ( 26) =  66.3499728        FROM  2.50000000     TO  2.60000000
FREQ( 27) =  73.3482665        FROM  2.60000000     TO  2.70000000
FREQ( 28) =  78.5968401        FROM  2.70000000     TO  2.80000000
FREQ( 29) =  83.3306590        FROM  2.80000000     TO  2.90000000
FREQ( 30) =  86.8025044        FROM  2.90000000     TO  3.00000000
FREQ( 31) =  89.7035010        FROM  3.00000000     TO  3.10000000
FREQ( 32) =  91.9814205        FROM  3.10000000     TO  3.20000000
FREQ( 33) =  94.0081483        FROM  3.20000000     TO  3.30000000
FREQ( 34) =  95.7217893        FROM  3.30000000     TO  3.40000000
FREQ( 35) =  96.9063576        FROM  3.40000000     TO  3.50000000
FREQ( 36) =  97.5670027        FROM  3.50000000     TO  3.60000000
FREQ( 37) =  97.9701445        FROM  3.60000000     TO  3.70000000
FREQ( 38) =  98.2907258        FROM  3.70000000     TO  3.80000000
FREQ( 39) =  98.6041859        FROM  3.80000000     TO  3.90000000
FREQ( 40) =  98.8458513        FROM  3.90000000     TO  4.00000000
FREQ( 41) =  99.0329613        FROM  4.00000000     TO  4.10000000
FREQ( 42) =  99.1977892        FROM  4.10000000     TO  4.20000000
FREQ( 43) =  99.3534504        FROM  4.20000000     TO  4.30000000
FREQ( 44) =  99.4570119        FROM  4.30000000     TO  4.40000000
FREQ( 45) =  99.5478519        FROM  4.40000000     TO  4.50000000
FREQ( 46) =  99.6139417        FROM  4.50000000     TO  4.60000000
FREQ( 47) =  99.6641246        FROM  4.60000000     TO  4.70000000
FREQ( 48) =  99.7109993        FROM  4.70000000     TO  4.80000000
FREQ( 49) =  99.7503351        FROM  4.80000000     TO  4.90000000
FREQ( 50) =  99.7883529        FROM  4.90000000     TO  5.00000000
FREQ( 51) =  99.8286682        FROM  5.00000000     TO  5.10000000
FREQ( 52) =  99.8695253        FROM  5.10000000     TO  5.20000000
FREQ( 53) =  99.8944187        FROM  5.20000000     TO  5.30000000
FREQ( 54) =  99.9189635        FROM  5.30000000     TO  5.40000000
FREQ( 55) =  99.9416231        FROM  5.40000000     TO  5.50000000
FREQ( 56) =  99.9583507        FROM  5.50000000     TO  5.60000000
FREQ( 57) =  99.9658242        FROM  5.60000000     TO  5.70000000
```

```
FREQ( 58) =  99.9755712      FROM  5.70000000    TO  5.80000000
FREQ( 59) =  99.9875858      FROM  5.80000000    TO  5.90000000
FREQ( 60) =  99.9896517      FROM  5.90000000    TO  6.00000000
FREQ( 61) =  99.9906132      FROM  6.00000000    TO  6.10000000
FREQ( 62) =  99.9909554      FROM  6.10000000    TO  6.20000000
FREQ( 63) =  99.9919821      FROM  6.20000000    TO  6.30000000
FREQ( 64) =  99.9923243      FROM  6.30000000    TO  6.40000000
FREQ( 65) =  99.9923243      FROM  6.40000000    TO  6.50000000
FREQ( 66) =  99.9923243      FROM  6.50000000    TO  6.60000000
FREQ( 67) =  99.9926666      FROM  6.60000000    TO  6.70000000
FREQ( 68) =  99.9926666      FROM  6.70000000    TO  6.80000000
FREQ( 69) =  99.9926666      FROM  6.80000000    TO  6.90000000
FREQ( 70) =  99.9933511      FROM  6.90000000    TO  7.00000000
FREQ( 71) =  99.9943125      FROM  7.00000000    TO  7.10000000
FREQ( 72) =  99.9943125      FROM  7.10000000    TO  7.20000000
FREQ( 73) =  99.9943125      FROM  7.20000000    TO  7.30000000
FREQ( 74) =  99.9952739      FROM  7.30000000    TO  7.40000000
FREQ( 75) =  99.9952739      FROM  7.40000000    TO  7.50000000
FREQ( 76) =  99.9956162      FROM  7.50000000    TO  7.60000000
FREQ( 77) =  99.9956162      FROM  7.60000000    TO  7.70000000
FREQ( 78) =  99.9956162      FROM  7.70000000    TO  7.80000000
FREQ( 79) =  99.9956162      FROM  7.80000000    TO  7.90000000
FREQ( 80) =  99.9956162      FROM  7.90000000    TO  8.00000000
FREQ( 81) =  99.9956162      FROM  8.00000000    TO  8.10000000
FREQ( 82) =  99.9956162      FROM  8.10000000    TO  8.20000000
FREQ( 83) =  99.9956162      FROM  8.20000000    TO  8.30000000
FREQ( 84) =  99.9956162      FROM  8.30000000    TO  8.40000000
FREQ( 85) =  99.9956162      FROM  8.40000000    TO  8.50000000
FREQ( 86) =  99.9965776      FROM  8.50000000    TO  8.60000000
FREQ( 87) =  99.9965776      FROM  8.60000000    TO  8.70000000
FREQ( 88) =  99.9965776      FROM  8.70000000    TO  8.80000000
FREQ( 89) =  99.9965776      FROM  8.80000000    TO  8.90000000
FREQ( 90) =  99.9972621      FROM  8.90000000    TO  9.00000000
FREQ( 91) =  99.9972621      FROM  9.00000000    TO  9.10000000
FREQ( 92) =  99.9972621      FROM  9.10000000    TO  9.20000000
FREQ( 93) =  99.9972621      FROM  9.20000000    TO  9.30000000
FREQ( 94) =  99.9972621      FROM  9.30000000    TO  9.40000000
FREQ( 95) =  99.9972621      FROM  9.40000000    TO  9.50000000
FREQ( 96) =  99.9972621      FROM  9.50000000    TO  9.60000000
FREQ( 97) =  99.9972621      FROM  9.60000000    TO  9.70000000
FREQ( 98) =  99.9972621      FROM  9.70000000    TO  9.80000000
FREQ( 99) =  99.9976043      FROM  9.80000000    TO  9.90000000
FREQ(100) =  99.9976043      FROM  9.90000000    TO  10.0000000
```



MEAN = 2.53159
STDEV = 0.44526
MIN = 1.74285
MAX = 11.11206
PCT INFINITE = 0.00

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Vita

Major Thomas R. Kogler [redacted] As an Air Force brat, he grew up predominantly at Robins AFB, Georgia and Beale AFB, California. [redacted] Upon receiving an appointment, he attended the United States Air Force Academy, and earned a Bachelor of Science Degree in Behavioral Science (Organizational Behavior). After graduating from the Air Force Academy in 1978, he received his commission and was sent to Williams AFB, Arizona for undergraduate pilot training. Earning his wings in 1979, he attended C-130 training at Little Rock AFB, Arkansas. As a C-130 driver, he was sent to the "real" Air Force at Yokota AB, Japan from 1980 to 1983. Returning stateside, he once again found himself at Little Rock AFB from 1983 to 1988. While at Little Rock AFB, he served as a C-130 aircraft commander, command post duty controller, and wing current operations scheduler. He entered the School of Engineering, Air Force Institute of Technology in June 1988 and is supported by his lovely wife, Shauna Denine Kogler, and his daughter, Sarah Evelyn.