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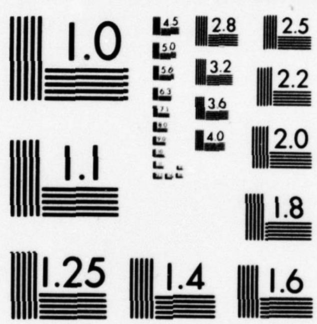

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A METHODOLOGY FOR AN EFFECTIVENESS ANALYSIS OF RPV'S IN A CHAFF DISPENSING ROLE

THESIS

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Preface

This paper describes a model developed to evaluate the effectiveness of different kinds of remotely piloted vehicles in the performance of a chaff dispensing mission. It is hoped that the model will be of value to the RPV System Program Office in performing effectiveness analyses of various RPV force structure alternatives.

I would like to thank my advisor, Captain Jon Knight, for his guidance and counselling during the preparation of this thesis. In addition, I would like to express my appreciation to Captain Paul Rumple for suggesting this thesis topic and for providing information and assistance when needed. Finally, I would like to thank my wife and children for their encouragement and support throughout this thesis effort.

Robert W. Neumann

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Abstract

The United States Air Force will possess the capability to employ several different remotely piloted vehicles (RPV's) for the conduct of chaff dispensing operations in the 1980's. An effectiveness analysis comparing force structure alternatives will provide information for decisions regarding RPV force mixes for that time frame.

A model which can be used to evaluate the effectiveness of various kinds of RPV's in the performance of chaff dispensing missions is developed in this thesis. Based on the two vehicle operating parameters expected to differ significantly among the kinds of vehicles, navigational accuracy and reliability, the model combines analytical and digital computer simulation techniques to predict the number of vehicles required to successfully complete a chaff corridor saturation mission.

The methodology developed in this thesis can aid the RPV System Program Office in performing effectiveness analyses comparing existing systems. In addition, with modification of the simulation portion of the model, the methodology can be used to analyze the effectiveness of RPV chaff mission employment options and to evaluate the benefits derived from modifications to the existing weapon systems.

I. Introduction

Future success in tactical air warfare will depend to a large degree on the effective execution of tactical electronic warfare support (TEWS) missions. One objective of TEWS missions is to screen strike and reconnaissance aircraft from electronic detection during their penetration of enemy airspace, and one means of accomplishing this objective is chaff dispensing. Chaff dispensing, the process of releasing millions of aluminum or aluminum-coated glass dipoles called chaff into the atmosphere, can be accomplished by manned aircraft or unmanned remotely piloted vehicles (RPV's). This thesis concerns the use of RPV's to perform a chaff dispensing mission.

The United States Air Force will possess the capability to employ several different RPV's for the conduct of chaff dispensing operations in the 1980's. A cost-effectiveness analysis comparing force structure alternatives would provide information for decisions regarding force mixes and the development of an optimal RPV force structure for that time frame.

This thesis develops a model which can be used to analyze the effectiveness of various RPV's in the performance of chaff dispensing missions. When used with a life cycle cost analysis previously performed by the RPV System Program Office (SPO), the model will permit the comparison of various force structure alternatives.

BACKGROUND

The United States Air Force currently envisions the employment of RPV's to perform three broad tactical air missions: strike, reconnaissance, and TEWS. The last of these missions, TEWS, consists of electronic jamming and chaff dispensing, and chaff dispensing includes blanket and corridor missions. Blanket chaff dispensing refers to the dispersion of chaff in a general area and requires less accuracy in chaff placement than corridor chaff dispensing, where a relatively narrow area is saturated with chaff to mask an attack force from enemy radar detection.

Chaff Effectiveness

First used in World War II by the British Royal Air Force, chaff remains an effective means of masking aircraft from enemy radar detection. Chaff dipoles, which are cut to resonate at the frequencies of the enemy radars anticipated in the objective area, reflect radar energy comparable to that reflected by an aircraft. Because of their light weight and high drag characteristics, the dipoles descend at a very slow rate (50 to 300 feet per minute depending on the specific dipole and atmospheric conditions), and aircraft flying behind dispensing vehicles in the slowly descending chaff "cloud" are masked from enemy radar detection.

The RPV Weapon System

Currently, all RPV weapon systems include four major subsystems: a launch and control DC-130 aircraft, a command

and control system, a recovery helicopter, and the RPV. While ground launch and recovery options are presently being developed to augment airborne launch and recovery subsystems in the future, the concept of remote control and monitoring of vehicles from an airborne aircraft or a mobile ground station will remain for the foreseeable future.

The system presently used for command and control of all airborne TEWS RPV's is called the Microwave Command Guidance System (MCGS). A replacement system now in development, the Multiple Drone Command and Control (MDCC) system, is expected to be operational through the 1980's. The MDCC system enables one remote control operator (RCO) to control or monitor the flight of up to eight RPV's. Using an antenna which sequentially locks on to each vehicle, the MDCC system directly measures range and relative bearing from an airborne DC-130 or mobile ground station to the RPV. These range and relative bearing measurements are then used to fix the position of the RPV on the RCO's plotboard for his information and action.

Statement of the Problem

Program Management Directive R-R5041(3), dated 7 July 1976, requested that the RPV SPO perform a life cycle cost analysis comparing reconnaissance and TEWS RPV force structure alternatives for the 1980's (Ref 24:6). In response to this request, the RPV SPO completed an analysis in February 1977. The analysis assumed equal effectiveness of all TEWS RPV's by assuming that all vehicles would be equipped with equally effective navigational systems to include doppler and LORAN C/D subsystems (Ref 7:3).

In an attempt to further refine the cost-effectiveness analysis and provide a more flexible model to assist force level decision making, the RPV SPO decided to analyze relative effectiveness of force structures in the performance of specific tactical missions without the assumption of system modifications made in the original analysis. The writer was requested to assist in this study by developing a model to compare the chaff mission effectiveness of different TEWS RPV's.

OBJECTIVES

This thesis has two objectives:

(1) To design and construct a model to determine the quantity of different TEWS RPV's required to successfully perform a chaff dispensing mission, and

(2) To demonstrate the use of the model by establishing the chaff mission effectiveness of two postulated RPV's possessing different operating parameters.

CHAPTER SYNOPSIS

The remainder of this thesis consists of three chapters and a summary. Chapter II presents the methodology used to develop the model. Chapter III describes the simulation portion of the model and briefly explains the computer program constructed for the model. Chapter IV discusses the experiments performed to achieve a degree of confidence in the validity of the simulation model and to demonstrate the use of the model by establishing the effectiveness of two postulated RPV's.

II. Methodology

This chapter presents the methodology used to accomplish the objectives of this thesis. First, the general analysis approach is described. Then, the scope and limitations of the study are addressed. The next section states the assumptions made in the thesis. Lastly, navigational accuracy and system reliability, the two operating parameters on which this effectiveness methodology is based, are each discussed in detail.

APPROACH

A prediction of the relative effectiveness of systems performing like functions begins with an analysis of each system to identify those elements, parameters, variables, relationships, and constraints which determine effectiveness. Once identified, ingredients common to each system can often be treated as constants and dropped from further consideration in the prediction process. The resulting prediction of relative effectiveness is then based on the unique ingredients of each system.

The first step in this analysis of RPV chaff mission effectiveness was a review of each of the TEWS RPV weapon systems expected to be operational in the 1980's to ascertain the ingredients differing among the systems. Concurrently, a review of Tactical Air Command and Air Force Security Service documents dealing with existing operations plans, RPV employment concepts, and electronic warfare tactics was conducted to provide the data necessary to develop the scenario and establish mission parameters for measurement of effectiveness.

The results of these reviews included a clear definition of the TEWS RPV systems to be evaluated and a perception of the analysis limitations required to reduce the problem to manageable proportions. Then, with the scope of the problem defined, a decision regarding analysis methodology could be made. The methodology selected for this thesis combines techniques of basic analytical mathematics and digital computer simulation. Where possible, such as in the treatment of system reliabilities, analytical approaches are used. The analysis of the navigational accuracy of different RPV's, however, requires a different approach. To deal with the stochastic nature of the navigational capability of each vehicle, a computer simulation model was designed, built, and exercised. The result of these approaches was an analysis methodology permitting the accomplishment of the objectives of this thesis.

SCOPE AND LIMITATIONS

The preliminary weapon system review performed for each TEWS RPV determined that the major weapon system elements including the launch and control aircraft, the command and control system, and the recovery helicopter are common to all RPV's. In addition, all but two vehicle operating parameters are expected to be very similar among the TEWS RPV's and, thus, will be considered constants for this analysis methodology. The two operating parameters that differ among RPV's are navigational accuracy and vehicle reliability. Each of these parameters will be addressed subsequently in this chapter.

The operations plans, employment concepts, and tactics review concluded that the most exacting chaff mission envisioned for TEWS RPV employment is chaff corridor seeding to conceal a follow-on strike force during the ingress phase of a tactical airstrike. Due to the accuracy required in both chaff positioning and chaff density, the ingress chaff corridor mission appears to be the ultimate test of the two unique operating parameters selected for analysis: navigational accuracy and vehicle reliability.

Because real world variables outside the scope of this analysis, such as follow-on strike mission priority, might influence decisions concerning egress and recovery procedures and routes of the RPV's, this analysis will be limited to the flight of each RPV from vehicle launch until the vehicle either exits the geographical boundaries of the intended chaff corridor or misses the corridor completely. Figure 1 shows the flight paths of two RPV's and depicts the portion of flight of each vehicle relevant to this analysis. Note that analysis of RPV 1 ends when the vehicle exits the desired corridor boundary, and analysis of RPV 2 ends when the vehicle passes abeam of the desired corridor leading edge outside the lateral boundaries.

All TEWS RPV's are capable of operation in two modes: manual and pre-programmed flight. While all RPV's are launched and flown initially in a pre-programmed mode with all flight inputs controlled by a computer or programmer on board each

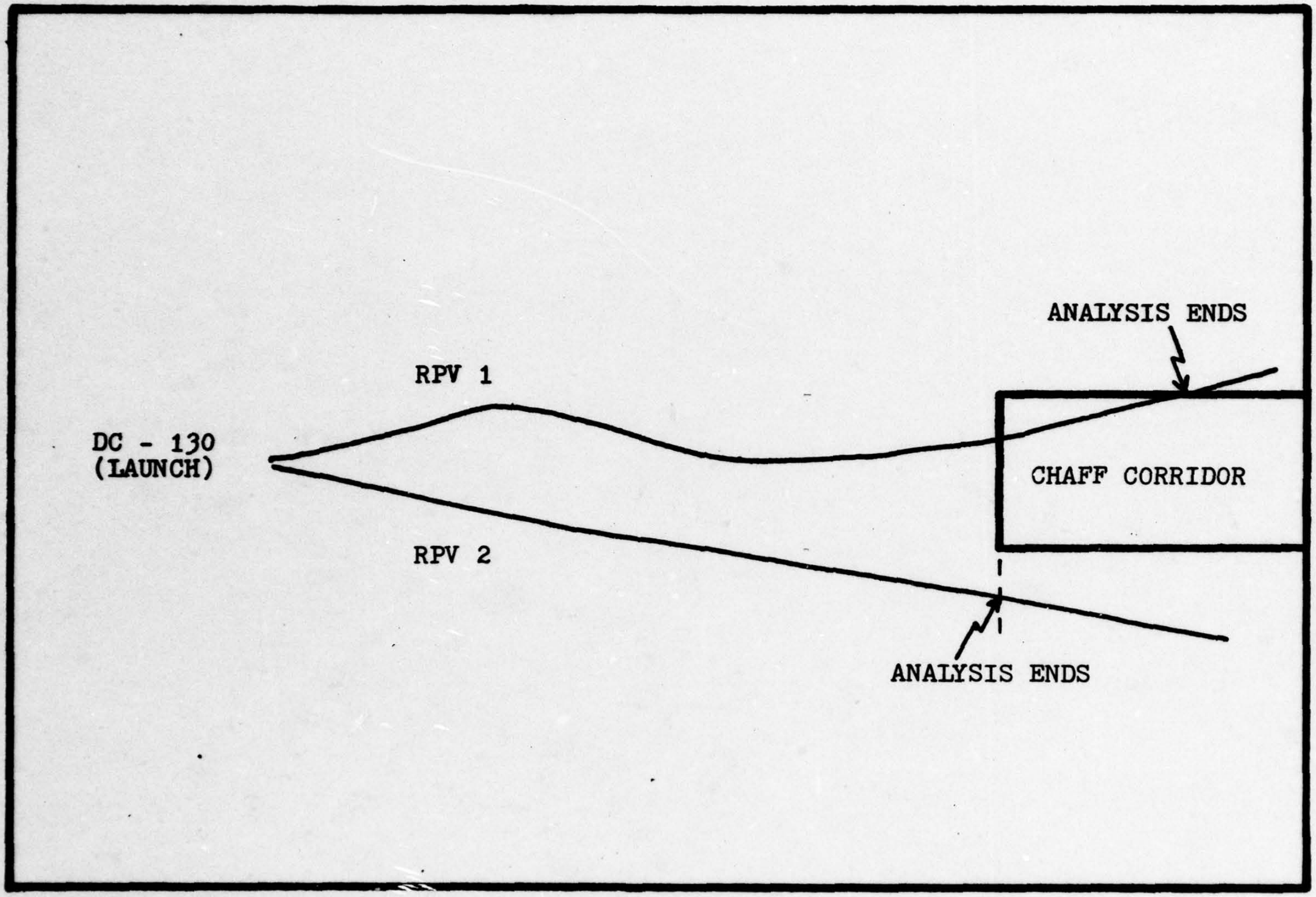

Figure 1. The Portion of Flight Relevant to This Analysis

RPV, the MDCC system provides the capability for the RCO to take control away from the pre-programmed guidance system and manually "fly" the vehicle at any time during flight. Because the MDCC system sequentially tracks each of the up to eight assigned RPV's in turn, however, RCO attention required to manually fly one vehicle prohibits the monitoring of all other vehicles. This requirement to sacrifice ability to monitor other vehicles in order to manually control one vehicle makes a decision to operate in the manual flight mode rather remote, especially for a chaff mission requiring a number of vehicles to achieve corridor saturation. Thus, this analysis will address only the pre-programmed mode of RPV control.

While the subject of RPV attrition due to enemy defensive action (surface-to-air missiles, anti-aircraft artillery, and fighter aircraft) would be critical to a study of chaff mission effectiveness given a specific enemy scenario, this analysis methodology will not address such a scenario. Instead, because the TEWS RPV's fly at approximately the same airspeed and have the same basic airframe (and thus same radar cross section), the probabilities of damage and destruction for each vehicle due to enemy defense would be approximately equal and will be assumed equal for this study. Thus, this probability will not be a factor in establishing relative chaff mission effectiveness.

ASSUMPTIONS

The following assumptions are made for this study:

1. All TEWS RPV weapon systems include DC-130 launch

and control aircraft and the MDCC system.

2. All TEWS RPV's possess like vehicle operating parameters except for navigational accuracy and system reliability.

3. All RPV's will fly only in the on-program mode without reverting to off-program manual control.

4. All resources required to complete the assigned chaff dispensing missions are available for this analysis.

5. Probabilities of RPV damage and destruction due to enemy defensive action are the same for each vehicle.

6. All navigational aids (LORAN, doppler, and inertial navigational systems) used by the DC-130 aircraft and RPV's remain functional during all flights.

7. The desired chaff corridor is rectangular in shape.

8. To permit a two-dimensional analysis, all RPV's will be launched at chaff dispensing altitudes.

NAVIGATIONAL ACCURACY

The preliminary TEWS RPV system review revealed that vehicles differed greatly in one operating parameter: navigational accuracy. As a result, the major thrust of this thesis has been the development of a model to measure the chaff mission effectiveness of different RPV's based on the unique navigational accuracy of each vehicle.

It became evident that the sources and the nature of RPV navigational error preclude an analytical approach to chaff mission effectiveness based on navigational capability. However, it was determined that various factors affecting the navigational accuracy of each vehicle could be statistically described in terms of several navigational error probability distributions, and an experimental approach using digital computer simulation seemed appropriate. Consequently, the design and construction of a simulation model to evaluate the chaff mission effectiveness of different RPV's based on navigational capability has received the largest attention and effort during this study, and the model resulting from that effort is the subject of Chapter III of this paper.

Vehicle Navigational Accuracy Statistics

While a complex analysis of the control and navigation subsystems of TEWS RPV's is not a prerequisite for a statistical treatment of navigational accuracy, a basic appreciation of each system provides understanding and insight into the application of the statistics in the effectiveness model. In terms of navigational capability, RPV's can be categorized into two groups: those possessing a dead reckoning system and those employing sophisticated navigation avionics including LORAN C/D.

RPV's with dead-reckoning systems operate with reference to pre-programmed heading and engine power setting information. Prior to flight, a series of heading and power setting instructions corresponding to the desired flight profile is stored in a programmer on board each vehicle. At launch time, a program pulse generator begins to issue pulses which advance a stepping switch, and the flight control system of the vehicle attempts to maintain the first heading and power setting stored in the programmer. When the stepping switch advances to a pre-programmed pulse point stored in the programmer, the vehicle turns to maintain the next stored heading and/or changes engine power setting.

Since the dead-reckoning system has no ability to fix actual position after launch, no corrective mechanism exist to reduce errors as they occur. Thus, position errors due to differences between programmed and actual heading and/or power settings are cumulative throughout flight. While specific probability distributions used to describe the navigational errors associated with TEWS RPV's in this model will be discussed in more detail in Chapter III, it is apparent from the preceeding description that the cross-track error distribution would be symmetric about the mean, since left or right heading error is equally probable, and would have a variance which is a function of distance flown, since navigational errors are cumulative.

RPV's employing sophisticated navigation avionics including doppler and LORAN C/D frequently compare their actual position with desired pre-programmed position and correct errors as they occur. Desired geographical coordinates are read into a computer on board each vehicle prior to flight. After launch, the flight control system of the RPV updates its position on the order of every hundred milliseconds (.1 seconds) and corrects vehicle performance as necessary to bring actual and programmed position differences within tolerances (Ref 23). Consequently, a probability distribution describing the cross-track navigational error of these vehicles would be symmetric about the mean and would have a constant variance, since the navigational errors are not cumulative.

RCO Correction Capability

While this analysis assumes that all RPV flights will be conducted in the on-program mode, the RCO possesses the capability to influence dead-reckoning system vehicle flight profiles to some degree. This capability may be categorized as a cross-track influence and an along-track influence.

The potential cross-track influence of the RCO consists of a heading trim capability. This trim capability permits the RCO to command a heading change by remotely adjusting vehicle control surfaces (Ref 6:16). Useful in compensating for unprogrammed wind effects, airframe or payload asymmetries, or heading gyro precession, the heading trim remains constant until removed by the RCO or zeroed out when the vehicle turns to the next programmed heading. Since this trim capability is available in the on-program mode and does not require the constant attention of the RCO, it is a viable potential influence on vehicle navigational accuracy, and its effects are incorporated in the model described in Chapter III.

The capability of the RCO to influence along-track navigational accuracy of a RPV in the on-program mode consists of programmer pulse advance and inhibit commands (Ref 6:30). When activated by the RCO, the programmer advance command causes the vehicle programmer to immediately advance to the next program step. Likewise, the programmer inhibit command prevents the next program step from being activated. Because dead-reckoning system TEWS RPV's begin and terminate chaff dispensing automatically at preselected program steps, these remote pulse controls allow the RCO to prevent early or late chaff release due to along track navigational inaccuracies by advancing or inhibiting program steps. As with the heading trim capability, because remote pulse controls are available in the on-program mode and do not require the constant attention of the RCO, they are viable influences on vehicle navigational accuracy, and their effects are represented in the model described in Chapter III.

The effectiveness of both the heading trim control and the pulse advance and inhibit controls depends on the ability of the RCO to accurately fix the position of a vehicle before making a decision to use either control capability. The subject of RCO perception accuracy is discussed in detail in Chapter III.

MISSION RELIABILITY

In addition to navigational accuracy, reliability was selected as a parameter to be considered in evaluating chaff mission effectiveness because mission reliability, like navigational capability, varies among TEWS RPV's. The following discussion presents the methodology for the treatment of reliability data in this chaff mission effectiveness model.

The United States Air Force defines reliability as "the probability that a part, component, subassembly, assembly, subsystem, or system will perform for a specified interval under stated conditions with no malfunction or degradation that requires corrective maintenance actions" (Ref 21:1). Generally, for any time t, reliability may be stated as follows:

$$R(t) = \lim_{N_0 \to \infty} N_s(t)/N_0 \qquad (1)$$

where $N_s(t)$ is the number of survivors at time t, and N_0 is the total number of units in the population (Ref 2:242).

Because total system reliability is a function of the reliability of each individual component and the importance of that component to the operation of the system, RPV reliability can be measured and defined in many ways. For this chaff effectiveness model, however, all RPV reliability data will be in terms of mission completion success probability (MCSP), where MCSP is "the probability that the system will complete the specified mission or mission mix without failure of mission essential system functions" (Ref 22:4).

MCSP was selected as the basis for reliability measurement for this model for several reasons. First, it offers a convenient means of comparing RPV reliabilities in terms of mission completion, the underlying parameter of interest in this model. Hence, reliability associated with post-mission flight and recovery is not addressed. In addition, MCSP can be determined empirically from actual mission data, thus removing the possibility of comparing historical reliability measurements of one RPV with analytically determined reliability estimates of another RPV. Lastly, MCSP is a broad, general reliability measurement which can be readily determined during the test phase or early in the operational life of an RPV. This early determination permits early availability of reliability data for use with this model in predicting the chaff mission effectiveness of RPV's just entering the operational inventory (Ref 10).

Given MCSP, RPV reliability will be treated analytically with the following relationship:

$$N = n/r \tag{2}$$

where N is the total number of RPV's which must be available to complete the mission, n is the number of RPV's which must be launched and flown as determined by the navigational accuracy of each kind of vehicle, and r is MCSP.

III. The Simulation Model

This chapter describes a simulation model designed to determine the number of RPV's which must be flown to achieve a stated level of chaff corridor saturation using the navigational capability of each kind of vehicle as the relevant operating parameter. As discussed in Chapter II, the total number of vehicles which must be available to accomplish a given chaff mission is obtained by adjusting the results of the simulation model to account for specific vehicle reliabilities. This will be demonstrated in the example presented in Chapter IV of this paper.

Chapter III consists of three parts. First, specific modeling considerations are addressed. The second section is a discussion of the simulation model design. Finally, a brief description of the computer program constructed for the simulation model is presented.

MODEL CONSIDERATIONS

The simulation model presented in this chapter was developed by dividing the modeling problem into two parts: the representation of the flight of each vehicle, and the representation of the effect of that flight in achieving saturation of the chaff corridor as defined by the model input parameters. This section addresses each of these parts and presents the facts which impacted on decisions about the final simulation model design.

RPV Flight Accuracy Considerations

The writer's initial plan was to develop a stochastic simulation model to represent the flight of all TEWS vehicles. This plan, however, assumed that the flight of all TEWS RPV's should be represented stochastically in this chaff effectiveness analysis. Further study revealed that this is not the case.

As stated in Chapter II, existing RPV's can be categorized in one of two groups according to navigational capability: those possessing a dead-reckoning system and those possessing a navigational system composed of sophisticated avionics including doppler and LORAN C/D. The dead-reckoning vehicles do not possess the ability to detect position errors or initiate corrections autonomously, but the LORAN-equipped vehicles constantly compare actual position with desired position and independently correct the vehicle flightpath to remain within system tolerances. Thus, the dead-reckoning vehicles accumulate position errors throughout their flight while the LORAN-equipped vehicles correct position errors as they occur.

The ability of the LORAN-equipped vehicles to constantly correct small position errors as they occur results in a capability to remain within 300 to 500 feet or less of desired position at any point in flight, depending on the specific LORAN system used (Ref 16). When this flight accuracy is compared with the accuracy requirements of a chaff corridor mission, it becomes apparent that a deterministic model of flight is feasible. Provided these vehicles remain fully operational, the number of LORAN-equipped RPV's required to saturate a given chaff corridor depends only on the size of the corridor and the dispersion characteristics of the chaff which is dispensed. Consequently, the stochastic simulation model presented in the next section was developed to represent the flight of TEWS RPV's without an operational LORAN capability.

Chaff Corridor Considerations

Much effort was devoted early in this study to determine criteria which could be used to measure vehicle chaff dispensing effectiveness once the flight portion of the model had been completed. The requirement was a method to measure the contribution made by each vehicle toward the overall mission objective of achieving a stated level of chaff corridor saturation. The key to this measure appeared to be the dispersion of the chaff dipole cloud dispensed by each vehicle, and the relationship of that cloud to the growth of the chaff corridor.

Accordingly, an investigation of chaff cloud characteristics was begun. First, available electronic warfare documents were reviewed. When that review proved largely futile, agencies involved with the study of chaff aerodynamics and the testing and development of electronic warfare tactics were contacted and requested to provide information. As with the literature review, the agency survey was ineffective. To date, very little is known about the nature of chaff clouds, and no capability to accurately predict the dispersion properties of chaff dipoles in the atmosphere appears to exist (Ref 9; Ref 15; Ref 17).

The most advanced research concerning chaff dispersion characteristics discovered during the agency survey consists of a stochastic simulation model developed at the United States Army Office of Missile Electronic Warfare, White Sands Missile Range, New Mexico. Correspondence with the individual responsible for that effort revealed that the model is undergoing validation and was not currently available for application in predicting chaff dispersion characteristics (Ref 19).

With all reasonable avenues for obtaining chaff dispersion characteristics exhausted, an alternative method of determining the chaff effectiveness of each vehicle inside the chaff corridor had to be developed. That method is explained in detail in the next section of this chapter.

DESIGN OF THE SIMULATION MODEL

This section provides a detailed description of the simulation model. Conceptually, the model combines a stochastic representation of the flight of RPV's without operational LORAN capability and a deterministic representation of chaff corridor saturation.

All RPV flight in this simulation model is represented with respect to a two-dimensional rectangular coordinate system, and all distances are expressed in nautical miles (NM). With the RPV launch position located at or near the origin and the longitudinal centerline of the desired chaff corridor always oriented along the positive abscissa or x-axis, all flight vectors can be defined in terms of along-track distance (along the x-axis) and cross-track distance (along the y-axis).

The accuracy of each RPV flight depends on two factors: the ability of the vehicle to autonomously fly the desired route and the ability of the RCO to control vehicle accuracy with heading trim and programmer pulse adjustments. In this model, autonomous flight accuracy is represented by a navigational error probability distribution, and RCO control effectiveness is limited by a RCO perception error probability distribution.

RCO Perception

The accuracy with which a RCO on board a DC-130 aircraft can perceive the true position of a RPV using the MDCC system depends on five different error sources:

(1) The range measurement from the DC-130 to the RPV,

(2) The relative bearing measurement between the DC-130 and the RPV,

(3) The DC-130 location,

(4) The DC-130 bearing, and

(5) Plotting of the RPV position on the RCO's plotboard (Ref 8:3ff).

The first four of these, all related to measurement errors, are depicted in Figure 2. The cumulative effect of all five of the errors is illustrated in Figure 3.

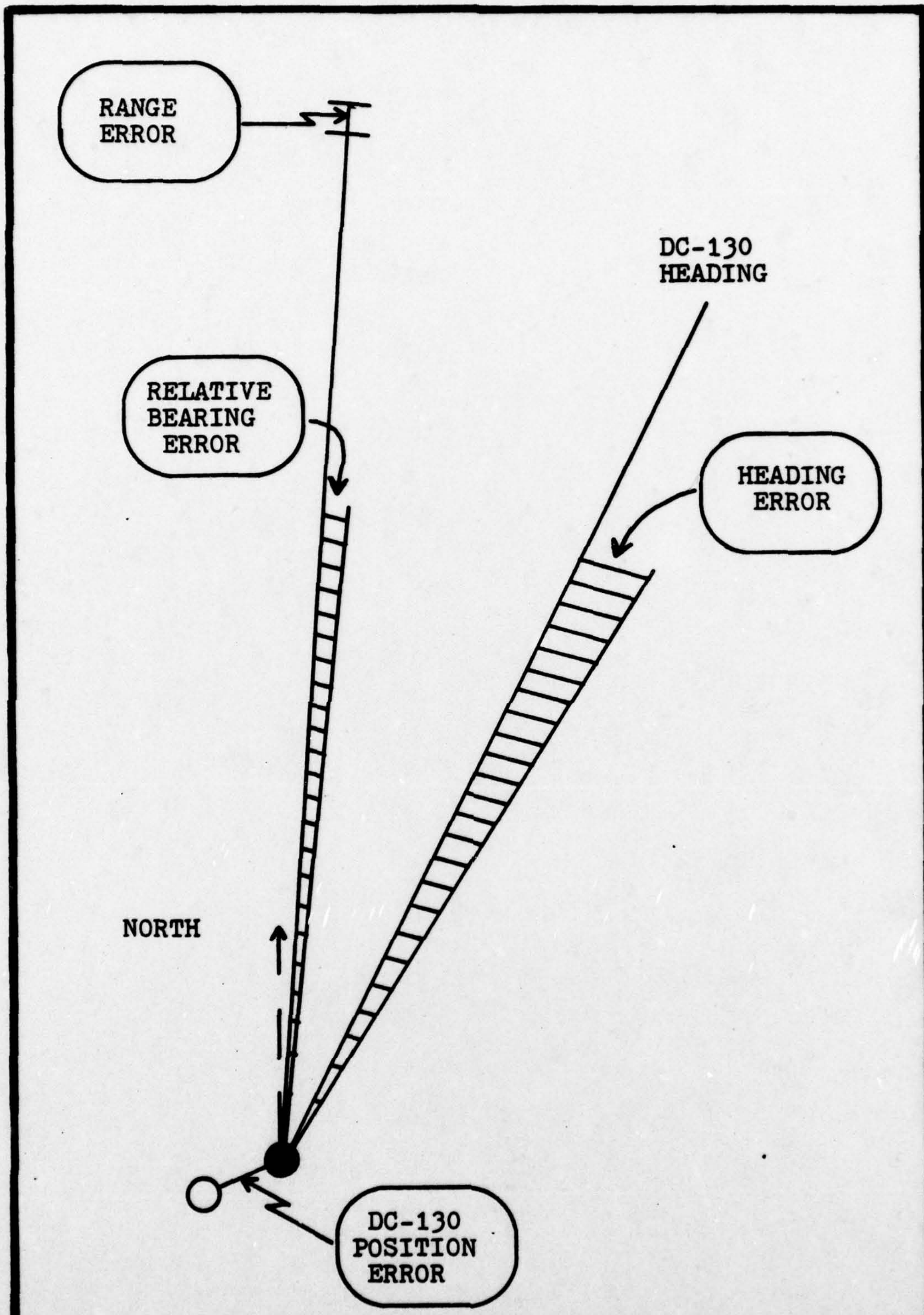

Figure 2. Measurement Errors (From Ref 8:8)

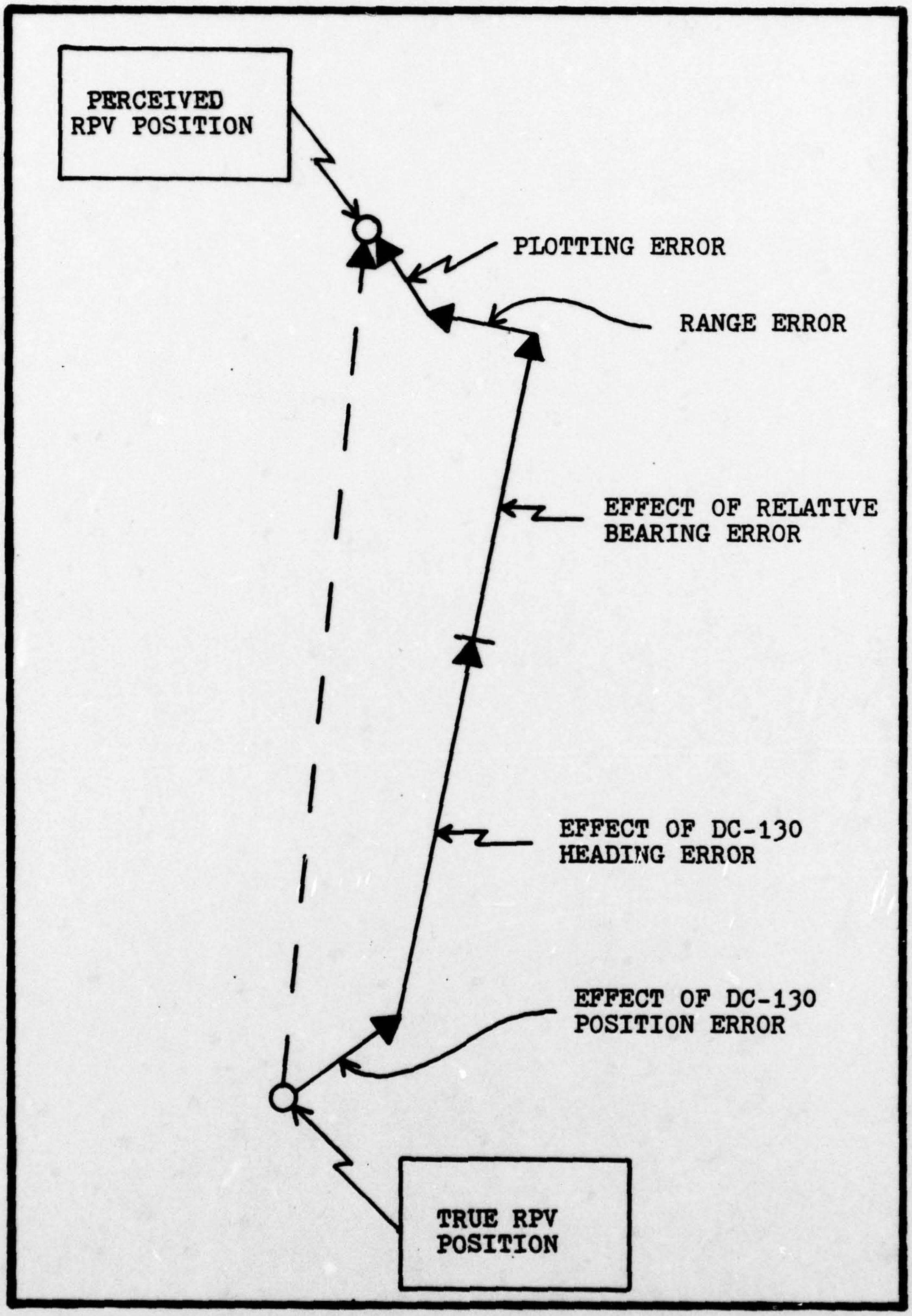

Figure 3. Cumulative Effect of the Five Error Sources (From Ref 8:9)

As part of a recent DC-130 aircraft capability study, an error analysis was performed by the Systems Analysis Branch of Aeronautical Systems Division, Air Force Systems Command, to determine the accuracy of RPV location as a function of the navigational equipment of the DC-130 aircraft and the MDCC system (Ref 8). That analysis assumed that DC-130 location error and plotting error are circularly distributed, and that the other three errors are normally distributed.

Table I list the results of the error analysis. The error value listed for each of the five sources is a root sum square (RSS) value calculated from root mean square (RMS) values within each error source. Divided into along-track and cross-track components, each error value represents one standard deviation (1σ) at 100NM RPV range. Because DC-130 aircraft are currently equipped with either a conventional attitude and heading reference system (AHRS) or an inertial navigational system (INS), and because a decision has not yet been made regarding which system will be used in the 1980's, two error values are provided in the DC-130 heading error section of Table I, one for each system.

A comparison of Table II, depicting total RSS error at 200 NM RPV range, and the bottom of Table I, listing the total RSS error at 100 NM RPV range, reveals a 100% increase in cross-track error and a 33% increase in along-track error as RPV range is doubled. This difference in increased error values is due to the nature of the error sources, where cross-track errors are primarily a result of angular measurement

Table I

EFFECT OF ERRORS

SOURCE OF ERROR	NOMINAL VALUE (RMS)	RPV POSITION UNCERTAINTY AT 100 NM: ALONG TRACK (1σ)	CROSS TRACK (1σ)
RANGE MEASUREMENT			
Transponder Delay	0.7 μs	700 ft	
Other Equipment	0.1 μs	100 ft	
Propagation	.005 μs/NM	500 ft	
RSS		866 ft	
RELATIVE BEARING			
Boresight & Radome	2 MIL		1200 ft
Tracking	7 MIL		4200 ft
RSS			4368 ft
DC-130 LOCATION			
LORAN C	400 ft	283 ft	283 ft
Map Conversion	50 ft	35 ft	35 ft
RSS		285 ft	285 ft
DC-130 HEADING			
AHRS (Slave Mode) RSS	1.5°		15,900 ft
INS (Alternative) RSS	.3°		3,180 ft
PLOTTING (1:100,000)			
Equipment Drive	.02 in	113 ft	113 ft
Alignment/Calibrate	.04 in	226 ft	226 ft
RSS		253 ft	253 ft
TOTAL RSS ERROR WITH AHRS		946 ft	16,493 ft
TOTAL RSS ERROR WITH INS		946 ft	5,416 ft

(From Ref 8:11)

Table II

TOTAL RSS ERROR AT 200 NM RPV RANGE

Control Aircraft	Along-track (1σ)	Cross-track (1σ)
AHRS-equipped DC-130	1283 ft	32,980 ft
INS-equipped DC-130	1283 ft	10,813 ft

(From Ref 8:12)

errors and along-track errors are a result of linear measurement errors.

On the basis of the information in Tables I and II and interviews with the authors of the error analysis (Ref 11; Ref 14), a linear relationship is assumed in the model between total RSS RCO cross-track perception error and RPV range for the interval from 50 to 200 NM RPV range. Furthermore, the relatively small along-track error is assumed to be negligible in the model given the insignificant effect on total corridor saturation of individual vehicle along-track errors of approximately a thousand feet.

For this model, DC-130 heading error has been factored from the total RSS cross-track error listed in Table I. This removes the largest source of RCO perception error from further consideration in the simulation and provides a standardized model for representing RPV flight controlled with either AHRS-equipped or INS-equipped DC-130 aircraft. The separate treatment of the effect of DC-130 heading error at the beginning obviates the need to consider differences between the actual desired chaff corridor position and the RCO's perception of that position as a result of DC-130 heading error.

During the simulation, RCO control inputs are initiated as necessary to fly each vehicle to the perceived chaff corridor position which, after DC-130 heading error is removed, simulates the actual corridor position. Consequently, as will be illustrated in the example in Chapter IV of this paper, the simulation output is in two parts: the difference between the RCO's perceived corridor position and the actual desired corridor position, and the number of RPV's required to saturate that percieved chaff corridor. Figure 4 illustrates the RCO's perception error due to DC-130 heading error.

Explicit treatment of the effect of DC-130 heading error allows direct analysis of the importance of that error source to any given chaff dispensing mission. Assuming a linear relationship between the effect of DC-130 heading error and RPV range, the nominal RSS error values of AHRS-equipped and INS-equipped aircraft result in two different normally distributed corridor cross-track perception errors, each with a mean of zero and a standard deviation given by

$$\sigma = E \times D \qquad (3)$$

where σ is the standard deviation in NM, E is a DC-130 heading error coefficient for each type of aircraft system, and D is the distance from the DC-130 to the desired corridor

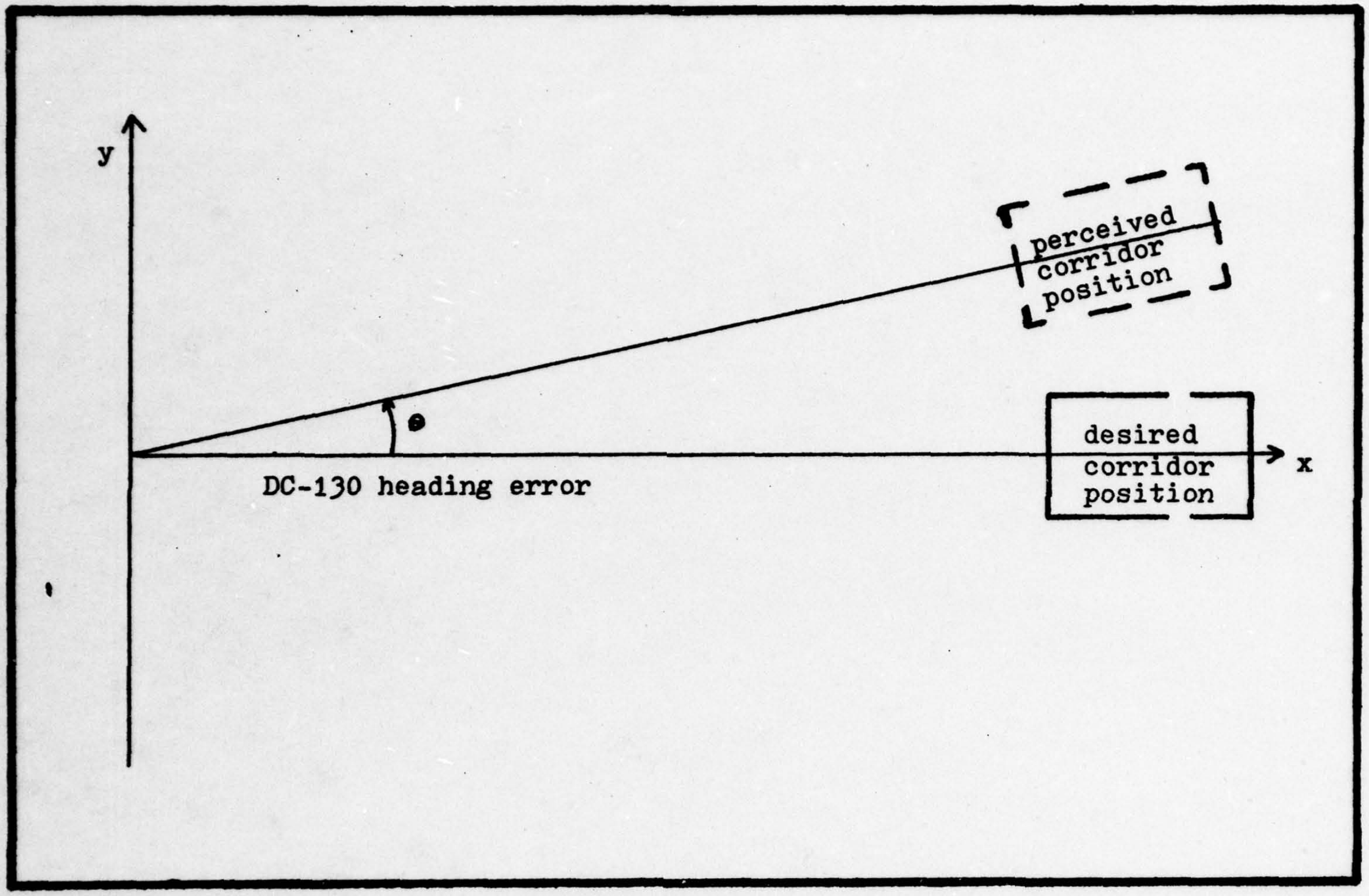

Figure 4. DC-130 Heading Error Effect on RCO Perception

position in NM. The values of E are .0261 for the AHRS-equipped aircraft and .00523 for the INS-equipped aircraft.

Since RCO corridor cross-track perception error will be greater than the values given by Eq (3) approximately 32% of the time, and since the RCO initiates control inputs based on his perception of corridor position as well as his perception of vehicle location, the importance of DC-130 heading error is apparent. When the given mission requires accurate positioning of the chaff corridor due to such factors as location of enemy defenses, follow-on aircraft target locations, or terrain obstacles in the objective area, consideration might be given to improving DC-130 heading accuracy to reduce the resulting RCO corridor cross-track perception error.

In this model, RCO corridor cross-track perception error is represented by two random variates, one for AHRS-equipped aircraft and one for INS-equipped aircraft. The populations from which these variates are generated are normally distributed with means equal to zero and standard deviations given by Eq (3) with appropriate substitutions for E.

<u>RPV Flight</u>

With the RCO corridor perception error due to DC-130 heading error explicitly treated at the start of simulation, the process of chaff corridor saturation is represented by the stochastic simulation of the flight of individual RPV's until saturation is achieved. The flight portion of the simulation model is an iterative algorithm that begins with the generation of two random variates which define two vectors.

The first vector represents the actual flight path of the vehicle while the second represents the RCO's perception of that flight path.

At this point in the simulation, a comparison of perceived and desired RPV flight paths is made. If the difference is less that the RCO control threshold value, the flight algorithm stops, and simulation of the effect of the vehicle in achieving corridor saturation begins. If the difference between the perceived and desired RPV flight paths is equal to or greater than the threshold value, RCO control action is simulated. With the termination of RCO control, another pair of random variates is generated to define two new flight vectors, one actual and one perceived. This iterative algorithm continues until the perceived RPV flight path does not violate the RCO control initiation threshold at the entrance to the chaff corridor.

This flight algorithm is repeated for each subsequent vehicle until the chaff corridor has been saturated. The relevant result of a simulation is the number of vehicles required to saturate the corridor. Figure 5 is a flow diagram of the flight algorithm.

There are two key assumptions underlying the representation of the flight segment of the chaff mission. The first is that autonomous flight is approximately linear, and the second is that cross-track navigational error can be approximated with Gaussian probability distribution functions.

As described in the preceding overview, all flight

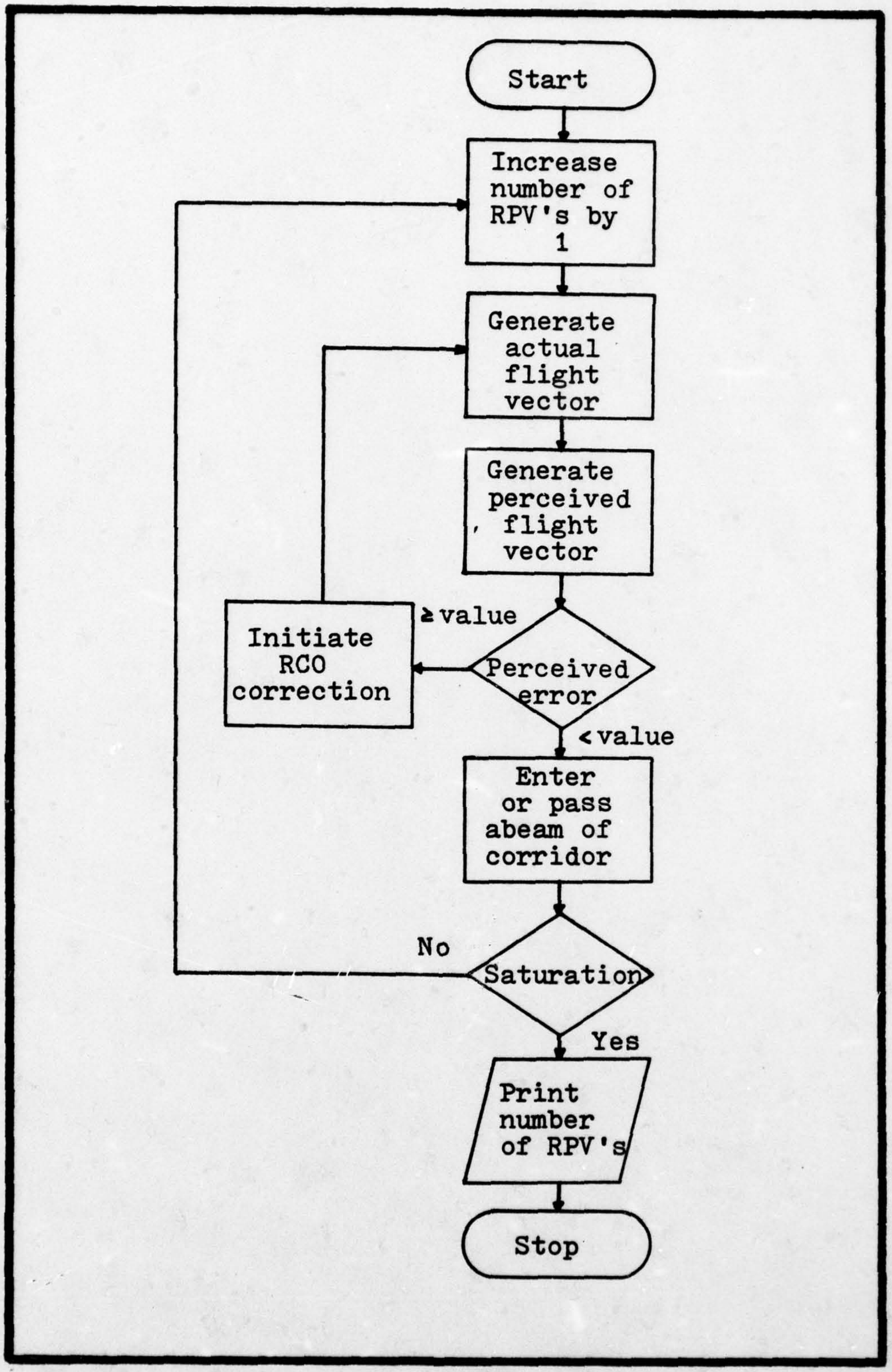

Figure 5. Flight Algorithm Flow Diagram

segments are represented by vectors in this simulation. The assumption that autonomous flight can be accurately represented by a straight line is based on an interview with the chief engineer responsible for flight test of the only dead-reckoning TEWS RPV to undergo testing to date, the AQM-34V. The interivew revealed that the greatest source of cross-track error encountered in flight test was heading gyro precession, and, even though brief transient random errors occurred, their aggregate long-term effect approximated a straight flight path (Ref 12).

As previously discussed in Chapter II, the cross-track navigational error for all TEWS RPV's not possessing an operable LORAN is symmetric about the desired flight path because left or right error is equally probable. In addition, because navigational errors are persistent and the flight path is linear, total error from the desired flight path is a function of the distance flown. On this basis, any symmetric distribution could be used to generate flight vectors, and, as the model is designed, any symmetric probability distribution can be readily accommodated. For lack of other evidence, and because of the alleged central limit properties of probability distribution functions, analyses to date have assumed that the cross-track errors of these RPV's are normally distributed (Ref 18). For these same reasons, all cross-track error probability distributions in this thesis will be assumed normal.

Given this brief overview and two assumptions, the portion of the model representing RPV flight is now addressed in greater detail with a discussion of the random variates and equations used to simulate the flight path of each vehicle. The discussion is divided into three parts: autonomous flight, RCO control policy, and RCO controlled flight.

Autonomous Flight. As described in the overview of the flight algorithm, the autonomous flight of each vehicle is represented in this model by two flight vectors: one actual and one perceived. The magnitude of the vector representing the actual flight path of a vehicle is equal to the along-track distance from the point at which the autonomous flight segment begins to the leading edge of the chaff corridor. The y component of this vector represents the cross-track error accumulated during flight and is determined by the generation of a random variate from the navigational error probability distribution describing the unique cross-track error statistic associated with each kind of vehicle. This distribution is assumed normal as previously discussed, has a mean equal to the y component of the point at which the autonomous flight segment begins (launch or termination of RCO controlled flight), and has a standard deviation which is a function of the magnitude of the vector and the navigational capability of the specific kind of vehicle being modeled.

Similarly, the y component of the vector simulating the flight path as perceived by the RCO represents the perceived cross-track error accumulated during flight and is determined by the generation of a random variate from the perception error probability distribution. This distribution is normal, has a mean equal to the random variate which gives the y component of the vector representing the actual flight path, and possesses a standard deviation given by the magnitude of the actual flight vector times the total RSS value of the error sources remaining in Table I after DC-130 heading error has been factored out. Because the along-track perception error of the RCO is negligible and assumed zero as discussed in the previous section entitled RCO Perception, the along-track (x component) distance of the perceived vector is equal to the along-track distance of the vector representing the actual flight path.

Figure 6 illustrates these two vectors. $\overline{OA}$ represents the actual flight path of a vehicle from the launch point, and $\overline{OP}$ represents the flight path as perceived by the RCO. The importance of the vector representing the perceived flight path of a vehicle will now be explained.

RCO Control Policy. A decision policy representing the size of the perceived position error at which RCO control will be initiated and the magnitude of the control input must be assumed for this model. Because no formal studies have been conducted to formulate optimal RCO policy, interviews were conducted with experienced RCO's to determine realistic parameters for use in the model. These interviews confirmed that the point at which a RCO initiates a control input in a given situation and the magnitude of that input vary considerably

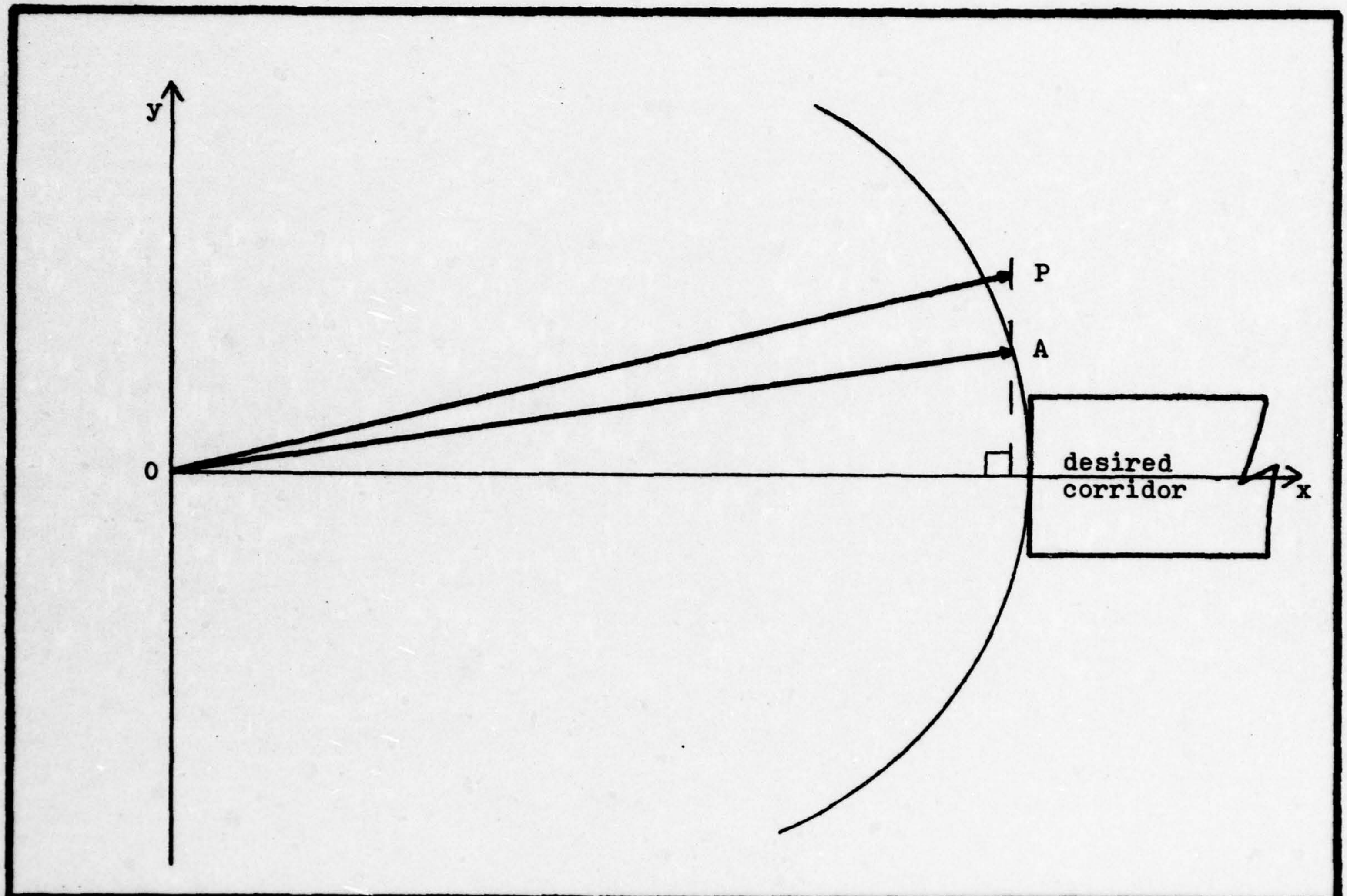

Figure 6. Stochastic Flight Vectors Representing RPV Flight Segments

among RCO's. Because of anticipated perception error and transient cross-track position errors due to gyro precession, however, it was generally agreed that heading trim inputs would seldom be initiated before a vehicle was perceived to be at least two NM off of desired track (Ref 13; Ref 20).

Based on this consensus of opinion, this model assumes the following RCO control policy: RCO heading trim inputs will be initiated whenever the cross-track error (y component) of a perceived flight vector is at least two NM, and the magnitude of the control input will be sufficient to reestablish the perceived position of the vehicle on the desired track (the x-axis) at a point equal to half the remaining along-track distance to the desired corridor leading edge. Furthermore, given the relatively high accuracy of along-track RCO perception, the ease with which programmer pulse advance and inhibit commands can be activated, and the insignificant effect on corridor saturation of along-track errors even if permitted to occur, the actual along-track position of each vehicle will be assumed accurate throughout the simulation. Hence, subsequent discussion of RCO controlled flight refers to flight controlled with the RCO's heading trim capability to correct cross-track errors. It is assumed that programmer pulse controls will be activated as necessary to correct along-track errors.

RCO Controlled Flight. All of the equations presented in this subsection use the previously stated assumption that along-track perception error is zero. Given that assumption, the along-track distance measured from the origin to any point along the actual flight vector representing a position at an instant in time is equal to the along-track distance measured from the origin to a point along the perceived vector representing the same instant in time. Simply stated, the position of an RPV at any instant is represented on both flight vectors by points having the same along-track distance to the origin.

Once RCO control has been determined necessary, the point of control initiation must be identified. This point is the position along the actual flight vector which corresponds to the location on the perceived flight vector at which the cross-track error is exactly two NM.

To illustrate this point at which RCO control is initiated, two figures are provided. Figure 7 depicts two hypothetical flight vectors ($\overline{A_0A_1}$ and $\overline{P_0P_1}$) representing actual and perceived autonomous flight from the launch point (origin). Figure 8 shows these same vectors representing autonomous flight which begins following termination of a period of RCO controlled flight. The position at which RCO control would be initiated for each situation is shown by point A_R. Note that this would be the second time RCO control had been used to correct the flight path in Figure 8.

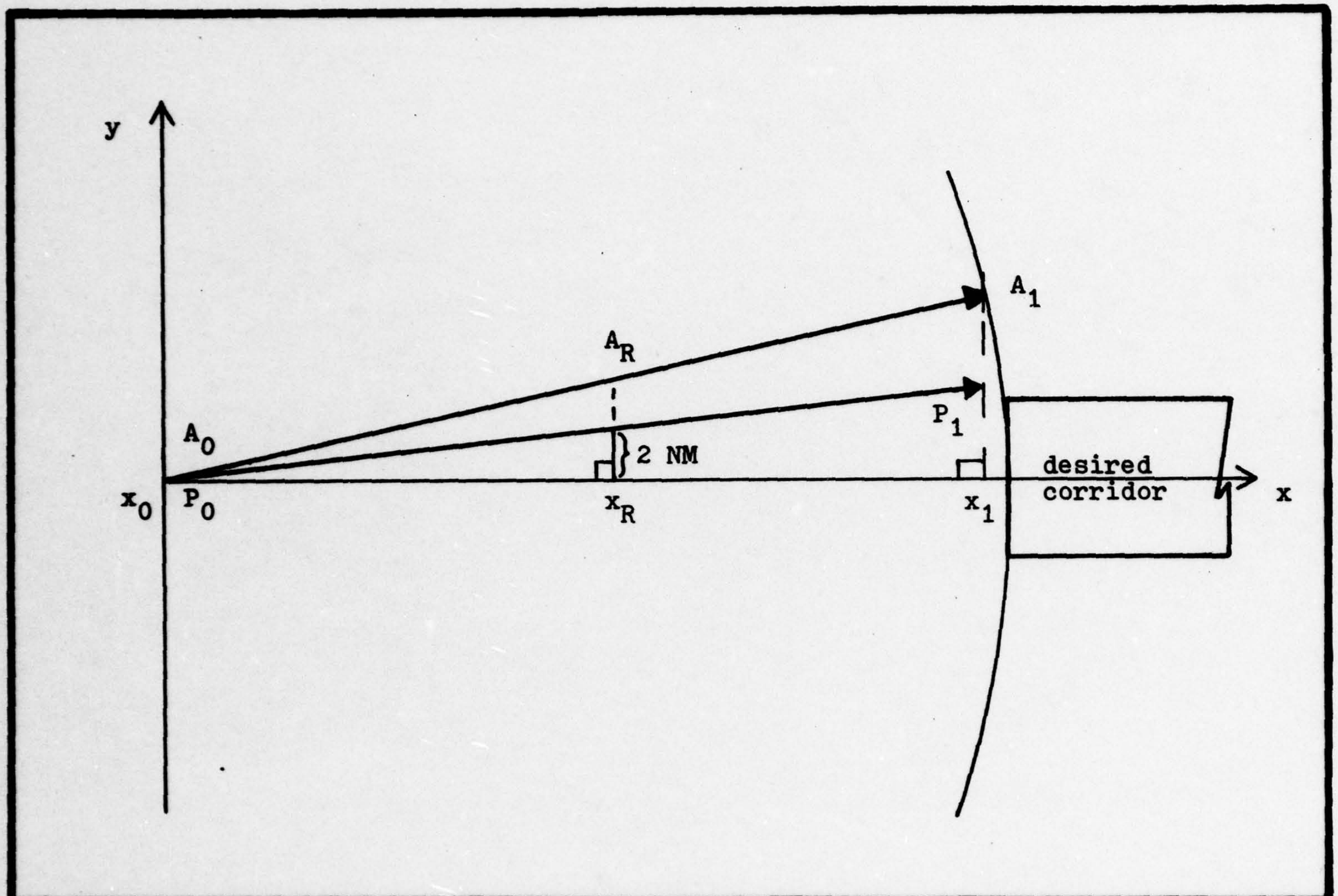

Figure 7. Autonomous Flight Vectors From the Launch Point

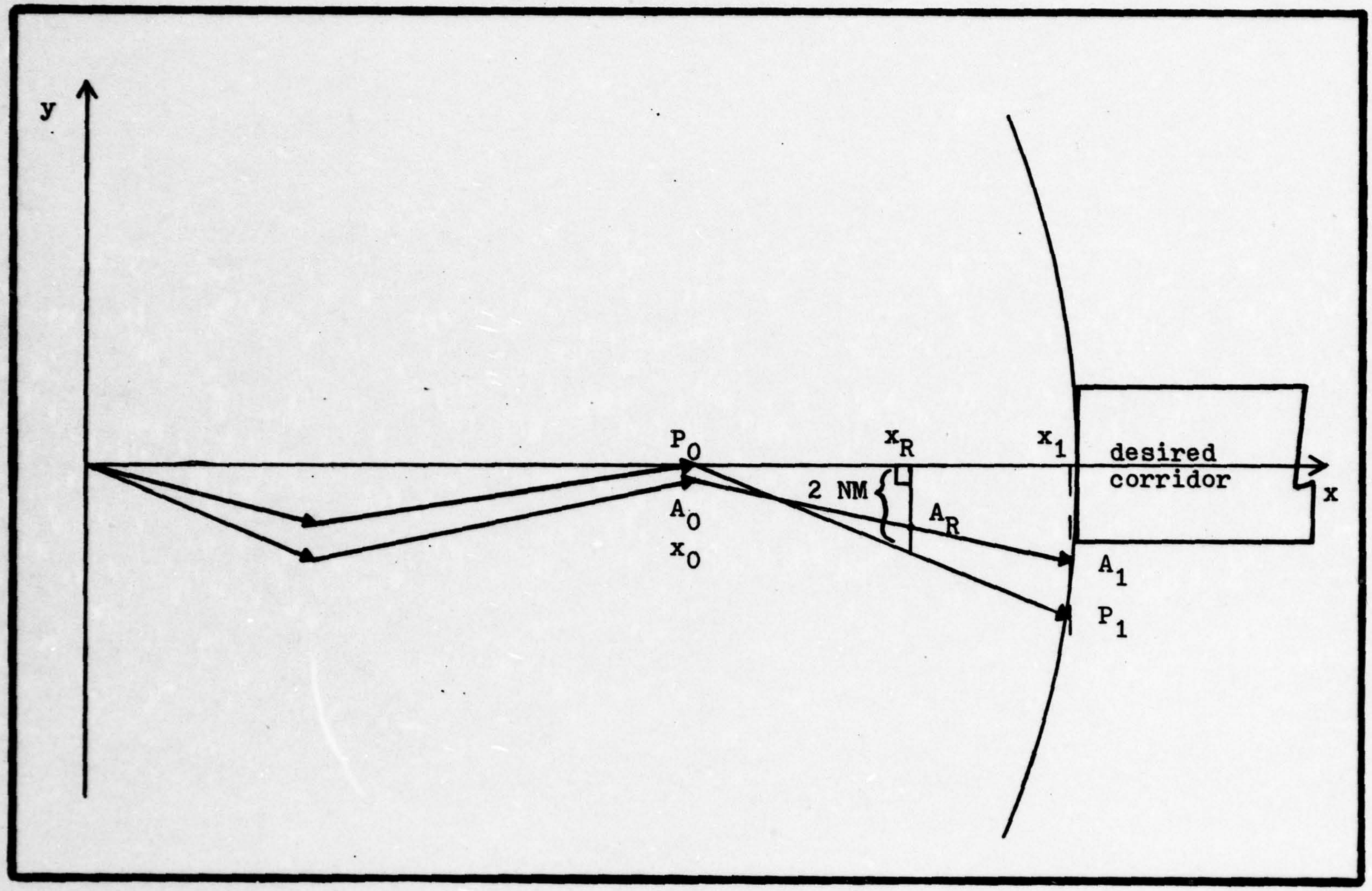

Figure 8. Autonomous Flight Vectors Following Termination of RCO Controlled Flight

In the model, the point at which RCO control is initiated is determined with three equations. The first provides the along-track distance from the origin to the end of both flight vectors. Then, that distance is used in the next equation to determine the along-track distance to the point at which RCO control is initiated. The third equation yields the cross-track distance (distance from the x-axis) of that point on the actual flight vector. While the first equation uses the Pythagorean relation, the second and third equations use properties of similar triangles.

Preserving the notation from Figures 7 and 8, these equations are written as follows:

$$X_1 = X_0 + [(X_2 - X_0)^2 - (YA_1 - YA_0)^2]^{1/2} \quad (4)$$

$$X_R = |2(X_1 - X_0)/YP_1| + X_0 \quad (5)$$

$$YA_R = YA_1(X_R - X_0)/(X_1 - X_0) \quad (6)$$

where X_1 is the along-track distance from the origin to the end of both flight vectors,

X_0 is the along-track distance from the origin to the start of both flight vectors,

X_2 is the along-track distance from the origin to the leading edge of the desired chaff corridor,

YA_1 is the cross-track distance to the end of the actual flight vector,

YA_0 is the cross-track distance to the beginning of the actual flight vector,

X_R is the along-track distance from the origin to the point at which RCO control is initiated,

YP_1 is the cross-track distance to the end of the perceived flight vector, and

YA_R is the cross-track distance to the actual point at which RCO control is initiated.

Note that when RCO control is initiated from autonomous flight vectors which start at the origin, X_0 and YA_0 are equal to zero. These two terms are included to allow the iterative use of Eqs (4), (5) and (6) for subsequent RCO control periods as required in the flight algorithm and as illustrated in Figure 8.

With the point of RCO control initiation determined, the along-track distance from the origin to the termination of RCO control (the point at which the vehicle is perceived to be located on the extended corridor longitudinal centerline) is given by

$$X_0 = X_R + (X_2 - X_R)/2 \qquad (7)$$

where X_0 is the along-track distance from the origin to the point of RCO control termination, X_R is the along-track distance from the origin to the point at which RCO control was initiated, and X_2 is the along-track distance from the origin to the leading edge of the desired chaff corridor. Note that the term X_0 is defined differently from its use in Eqs (4), (5), and (6). As defined in Eq (7), X_0 now becomes the along-track distance from the origin to the start of new actual and perceived flight vectors to be stochastically generated to represent the flight path of the vehicle after it resumes autonomous flight. This redefinition of X_0 provides the model with the capability to iterate autonomous and RCO controlled flight phases as necessary to accurately represent actual RPV flight. Figure 9 illustrates the terms used in Eq (7) and shows the redefinition of X_0.

The line joining the position on the perceived flight vector at which RCO control was initiated (where cross-track error was exactly two NM) and the point on the x-axis at which RCO controlled flight terminated can be considered a vector representing the perceived flight path of a vehicle during RCO controlled flight. This conceptualized flight vector is illustrated by $\overline{P_R P_0}$ in Figure 9. In accordance with the assumed RCO control policy discussed in the last subsection, this vector represents the termination of RCO controlled flight at a perceived position along the longitudinal centerline of the corridor.

Given this vector, a vector is needed to represent the actual flight path of the vehicle during RCO controlled flight, and the end point of that vector represents the actual cross-track error which exists at the termination of RCO controlled flight. In effect, this situation is the reverse of that during autonomous flight, where a perceived cross-track error is generated from the actual cross-track error. Here, an actual cross-track error is generated from the perceived cross-track error.

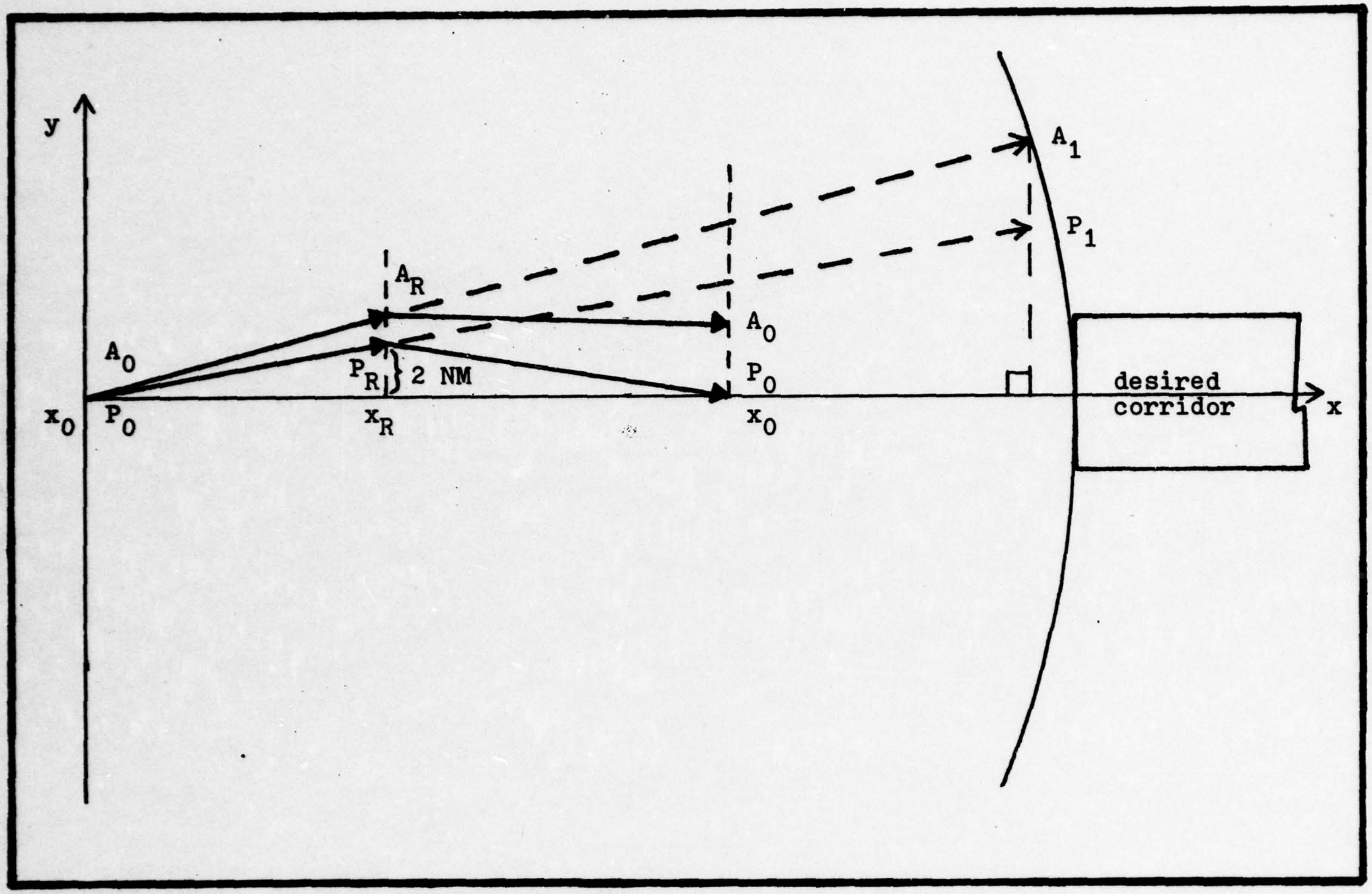

Figure. 9. Autcnomous and RCO Controlled Flight Vectors

In this model, the actual cross-track error which exists at the termination of RCO controlled flight is determined by the generation of a random variate. The mean of the normal probability distribution from which the variate is generated is equal to the difference between the cross-track distance to the actual point at which RCO control was initiated and the the cross-track distance to the perceived point at which RCO control is initiated (which is two NM according to the assumed RCO control policy). This mean is used so that the expected value of the perception error which will exist at the termination of RCO controlled flight is equal to the perception error which existed at the beginning of RCO controlled flight. The standard deviation of the probability distribution is equal to the along-track distance from control initiation to control termination multiplied by a coefficient that accounts for the total RSS value of the error sources remaining in Table I after DC-130 heading error has been factored out.

With the flight vector representing the actual flight path during the period of RCO control determined, the entire effect of RCO control has been modeled. Figure 9 illustrates the perceived and actual flight vectors representing the flight path of a hypothetical vehicle from launch until termination of RCO control. Vectors $\overline{A_0A_R}$ and $\overline{P_0P_R}$ depict, respectively, the actual and perceived flight vectors from launch to the point at which RCO control is initiated. Vectors $\overline{A_RA_0}$ and $\overline{P_RP_0}$ illustrate the vectors from the point of RCO control initiation to the point of RCO control termination.

With the RCO controlled portion of flight modeled, the simulation of autonomous flight begins again with the generation of two new autonomous flight vectors, one representing the actual flight path and one representing the perceived flight path. The method used to generate these vectors is the same as that used to generate the original autonomous flight vectors.

Thus, the flight algorithm simulates RPV flight with the iteration of autonomous flight vectors and RCO controlled flight vectors until a vehicle reaches a position with a cross-track error of less than two NM on an arc whose length is the along-track distance from the origin to the leading edge of the chaff corridor. From this point, the representation of the effect of that vehicle on chaff corridor saturation begins.

Chaff Corridor Saturation

This model uses a stochastic simulation of the flight of each vehicle to establish a distribution of vehicles entering the chaff corridor. The effect of that distribution of vehicles in achieving saturation of the desired chaff corridor assumes that RCO control will not be initiated to correct vehicle cross-track errors after the vehicle passes through or abeam of the leading edge of the chaff corridor. Thus, with the last autonomous flight vectors generated prior to reaching the chaff corridor leading edge, this portion of the simulation model is deterministic.

As previously stated, little appears to be known of the actual dispersion of the chaff dipole cloud dispensed by each vehicle and the relationship of that cloud to the saturation of the chaff corridor. In addition, little is known of the actual width of the corridor produced by chaff dispensing vehicles after the chaff dipoles reach equilibrium in the atmosphere. To date, the only criterion used to measure chaff corridor effectiveness has been the success of the corridor in screening follow-on aircraft from detection by enemy radar, and that success depends on the specific enemy radar employed, display console resolution, operator ability, and physical characteristics of the chaff corridor (Ref 15).

As a result of this uncertainty, the following method of representing the effect of RPV's inside the chaff corridor was deemed sufficient for this model. The chaff corridor area is divided into small rectangular sections hereafter called boxes. A line of boxes parallel to the x-axix is called a string. The autonomous flight vector representing the actual flight path of each vehicle is extended through the length of the corridor and each box penetrated by a vehicle is recorded. If the flight of individual RPV's is simulated until all boxes have been penetrated at least once, then total saturation of the chaff corridor is represented.

An advantage of this representation of corridor saturation is the flexibility provided for analysis. Both the number of vehicles required to achieve any degree or percentage of saturation and the density of saturation in any given area of the corridor can be determined at any point in the simulation. From this data, various launch and employment scenarios can be evaluated with modifications of the flight parameters of the model.

Because little is known of the actual width of a chaff corridor after chaff dipoles reach equilibrium in the atmosphere, and because the corridor width appears to be dependent upon the dispersion of the chaff dipole cloud produced by each vehicle, the model design for this simulation was developed with a fixed number of strings per corridor. Thus, as the width of the strings is increased, the width of the entire corridor increases. This representation appears to capture the actual relationship between the chaff corridor and the individual dipole clouds dispensed from each vehicle.

The number of strings per corridor was set at eight to conform with empirical data indicating the width and dipole density of several chaff corridors laid by dispensing formations consisting of four manned aircraft. The manned formations dispensed a chaff cloud considered operationally sufficient. With that data as a basis, eight strings per corridor allow representation of the chaff dispensing formation since aircraft wing-tip spacing can be represented by the width of strings in the model.

While this portion of the model has been developed, because of the absence of other information, for compatibility with the empirical data measured immediately after chaff dispensing, it is apparent that the true criterion of vehicle chaff effectiveness should be the chaff corridor which has reached equilibrium in the atmosphere. It is this corridor which determines the degree of protection provided to follow-on aircraft. Before this true criterion of chaff corridor effectiveness can be modeled, however, more data is needed in the area of chaff dynamics and steady-state dipole characteristics.

Vehicle Chaff Effectiveness. The representation of the chaff effectiveness of each vehicle begins with the extension of the actual autonomous flight vector through or abeam of the chaff corridor. This is accomplished with the calculation of the cross-track error of the vehicle when it is located at or abeam of the leading edge of the chaff corridor and the calculation of the slope of the actual autonomous flight vector. These are given by

$$YA_2 = (YA_1 - YA_0)(X_2 - X_0)/(X_1 - X_0) + YA_0 \quad (8)$$

and $$DY/DX = (YA_1 - YA_0)/(X_1 - X_0) \quad (9)$$

where YA_2 is the cross-track distance to the vehicle when the vehicle is located at or abeam of the corridor leading edge,

YA_1 is the cross-track distance to the end of the actual flight vector,

YA_0 is the cross-track distance to the beginning of the actual flight vector,

X_2 is the along-track distance from the origin to the leading edge of the chaff corridor,

X_0 is the along-track distance from the origin to the start of both flight vectors,

X_1 is the along-track distance from the origin to the end of both flight vectors, and

DY/DX is the slope of the actual autonomous flight vector. Figure 10 illustrates the autonomous flight vectors, the distance YA_2, and the slope of the actual vector extended through the chaff corridor.

Following the calculation of these two values, a comparison is made between the absolute value of the cross-track distance to the vehicle when on or abeam of the leading edge of the chaff corridor (YA_2 in Figure 10) and half of the width of the corridor (CW/2). If $|YA_2|$ is greater than CW/2, the vehicle misses the chaff corridor completely and the simulation of the flight of that vehicle ends. If $|YA_2|$ is less than CW/2, the vehicle enters the corridor and its effect on corridor saturation is simulated.

Essentially, the simulation of vehicle performance in the chaff corridor consists of an iterative algorithm which uses the present vehicle position and the flight vector slope given by Eq (9) to determine the starting and ending horizontal box numbers in which the vehicle is located aa it enters and exits each vertical string. Figure 11 illustrates the vertical string and horizontal box numbering systems used for this model. The algorithm is iterated for each subsequent string number until the vehicle exits the corridor through either of the lateral boundaries or the corridor trailing edge. Hence, by using present vehicle position and slope to determine

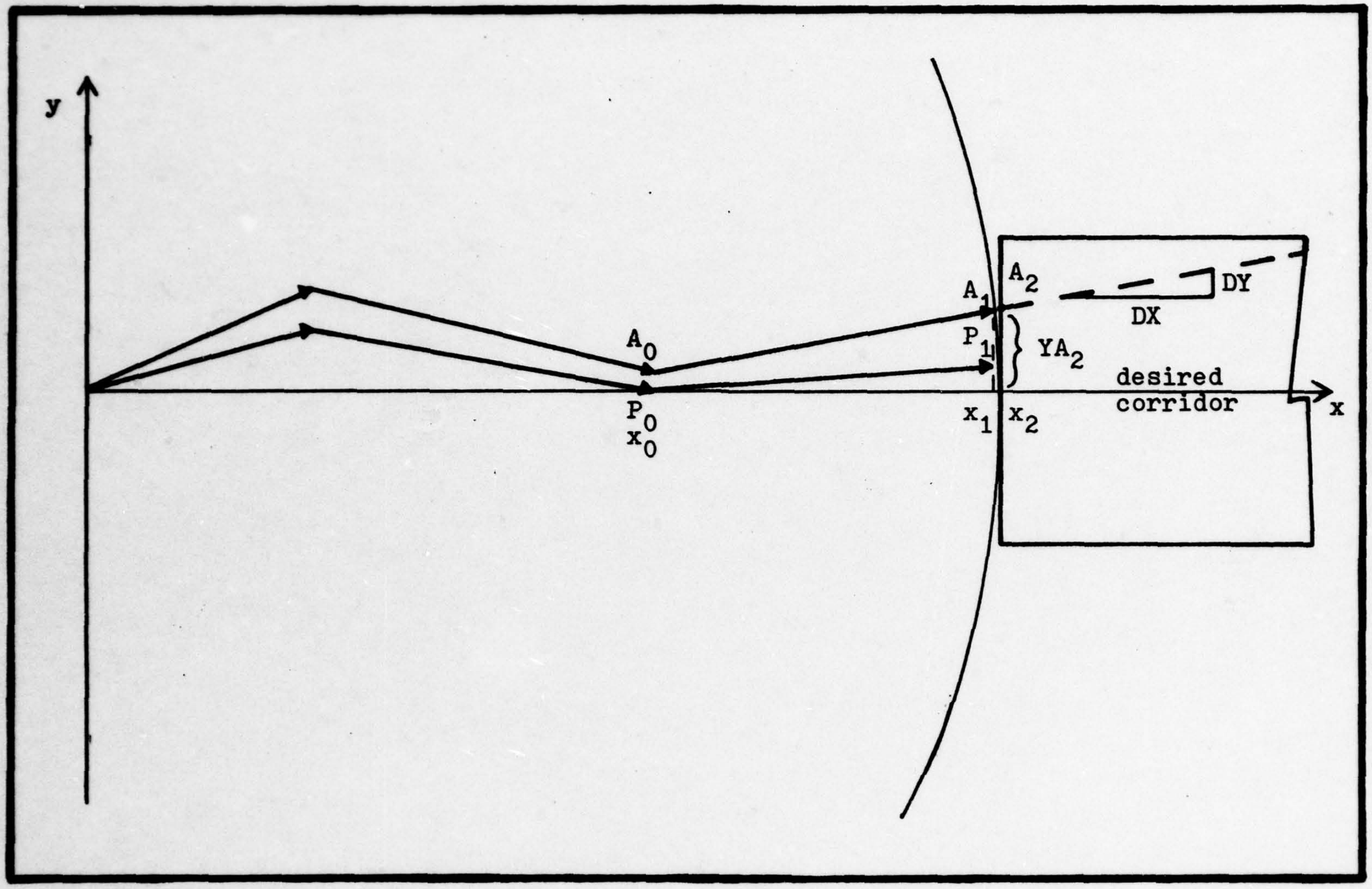

Figure 10. The Extension of Flight Vector $\overline{A_0A_1}$ Through the Chaff Corridor

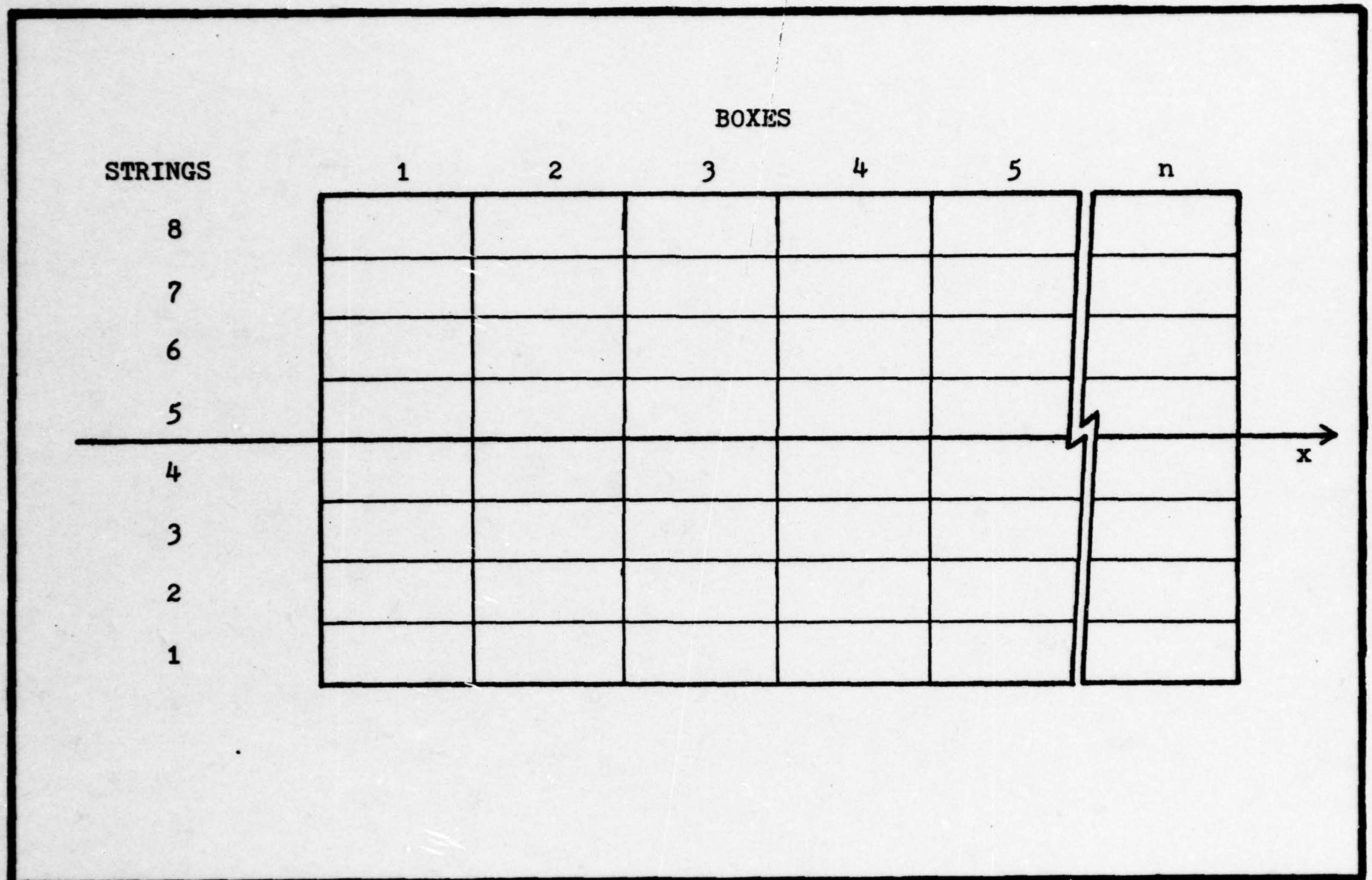

Figure 11. ·The Vertical String and Horizontal Box Numbering Systems

vehicle location at subsequent key points (the string boundaries), the algorithm eliminates the necessity of tracking vehicle position from box to box.

The first requirement for each new vehicle entering the chaff corridor is a calculation to determine in which string the vehicle is positioned when located on the corridor leading edge. This string number is given by

$$S = (YA_2 + CW/2)/SW + 1 \qquad (10)$$

where S is the string number in which the vehicle is located as it enters the corridor,

YA_2 is the cross-track distance to the vehicle when located on the corridor leading edge,

CW is the corridor width, and

SW is the width of each corridor string.

The proper calculation for the cross-track distance to the vehicle when it reaches the boundary of the next string is determined by the slope of the flight vector given by Eq (9). If the slope is near zero, the vehicle remains in the present string until reaching the trailing edge of the corridor. Otherwise, the new cross-track distance to the vehicle is given by one of the following, depending on the sign of the slope:

if slope is positive, $$Y_2 = (S - 4)SW \qquad (11)$$

if slope is negative, $$Y_2 = (S - 5)SW \qquad (12)$$

where Y_2 is the new cross-track distance, S is the present string number given by Eq (10), and SW is the string width.

With Y_2 determined, tha along-track distance from the leading edge of the corridor to the location of the vehicle when on the boundary of the next string is given by

$$X_2 = X_1 + (Y_2 - Y_1)/(DY/DX) \tag{13}$$

where X_2 is the along-track distance at the next string boundary,

X_1 is the along-track distance from the leading edge of the corridor to the position at which the vehicle entered the present string,

Y_2 is the cross-track distance given by Eq (11) or (12),

Y_1 is the cross-track distance to the vehicle at the point at which it entered the present string, and

DY/DX is the slope given by Eq (9).

For the first iteration of this algorithm as the vehicle enters the corridor, X_1 is zero and Y_1 equals YA_2. For subsequent iterations, X_1 is the value of X_2 from the previous iteration, and Y_1 is the value of Y_2 from the previous iteration.

Given X_2, the horizontal box in which the vehicle is located as it exits the present string is determined by

$$B_2 = INT[(X_2/L) + 1] \tag{14}$$

where B_2 is the ending box number as the vehicle exits the present string,

INT is the greatest integer function,

X_2 is the along-track distance given by Eq (13), and

L is the horizontal length of the boxes in the corridor. Since B_1, the box in which the vehicle is located when it enters the present string, is set at one in the first iteration and has the value of B_2 from the previous iteration in subsequent iterations of this algorithm, the starting and ending horizontal box numbers can be determined for each vertical string of the corridor penetrated by the vehicle. The algorithm is iterated until the vehicle exits either lateral boundary of the corridor or reaches the corridor trailing edge. At that point, simulation of the effect of that vehicle is terminated. With the beginning and ending boxes for each string determined, all boxes which are penetrated by the vehicle during flight within each string can be recorded.

Aggregate Chaff Effectiveness. At the conclusion of the simulation of the effect of the vehicle in the chaff corridor, a tally is made of the total number of boxes penetrated by all vehicles. If the total number of boxes penetrated is less than the number of boxes in the chaff corridor, another vehicle launch is simulated and the entire process described to this point is repeated. When the total number of boxes penetrated equals the number of boxes in the chaff corridor, total corridor saturation as defined in this model has been achieved, and simulation of that corridor terminates.

THE COMPUTER PROGRAM

The computer program constructed for the simulation model presented in the previous section of this chapter is coded in FORTRAN IV programming language. FORTRAN IV was selected because of its structural flexibility, universal familiarity, and accessibility. While specialized simulation languages such as SAINT and DYNAMO were considered for this programming problem, their limited familiarity and inaccessibility to potential users of the program outweighed their apparent suitability. The program was built and run on the Control Data Corporation (CDC) 6600 computer of the Aeronautical Systems Division, Air Force Systems Command.

This section consists of two subsections. The first briefly explains the computer program and its components whilc the second presents specific references to program information which can be found in the appendices to this paper.

Program Components

The computer program consists of a main program and seven subroutines.

The Main Program. The main program controls the simulation and calls the subroutines as required. Each time the simulation program is run, statements in the main program read-in and set the random number seed for the pseudo-random number generator used to generate random variates.

With the present main program control structure, multiple simulation experiments can be performed during one run of the simulation program. Input parameters for each of these simulation experiments are read-in with a READ statement in the main program. The following nine input parameters are read each time the READ statement is executed:

1. CORBEG, the distance from the launch point to the leading edge of the chaff corridor;

2. COREND, the distance from the launch point to the trailing edge of the chaff corridor;

3. NUMRUN, the number of times the simulation experiment is to be replicated with the given set of input parameter values;

4. DELX, the length of each horizontal box in the chaff corridor;

5. DELY, the width of each vertical string in the chaff corridor;

6. LIMRPV. the maximum number of RPV's that can be simulated in one replication before simulation of that replication is terminated with a warning message;

7. ERRNAV, the coefficient which when multiplied by distance flown gives the standard deviation of the navigational error probability distribution for the kind of vehicle simulated;

8. ERRRCO, the coefficient which when multiplied by distance flown gives the standard deviation of the RCO perception error probability distribution; and

9. POLICY, the distance representing the size of the cross-track error at which the RCO will initiate heading trim control.

In addition, with the exception of RCO corridor perception error due to DC-130 heading error and end of simulation statistics, the main program contains all output statements executed in the simulation program.

Subroutine HEADERR. This subroutine, when called by the main program at the beginning of each simulation replication, prints out and returns two RCO cross-track corridor perception errors, one for AHRS-equipped DC-130 aircraft and one for INS-equipped DC-130 aircraft. Each of these errors is generated with a separate call to Subroutine RNORMAL. Subroutine HEADERR treats the RCO perception error due to DC-130 heading error explicitly so that it can be dropped from consideration for the remainder of the simulation.

Subroutine FLIGHT. This subroutine, when called by the main program, returns the vehicle position when located on or abeam of the leading edge of the chaff corridor and actual flight vector slope for each vehicle simulated. Subroutine FLIGHT generates the actual and perceived autonomous flight vectors for each vehicle with a call to Subroutine RNORMAL. When RCO control is necessary, Subroutine FLIGHT calls Subroutine RCO.

Subroutine RCO. This subroutine, when called by Subroutine FLIGHT, returns the cross-track and along-track distances defining the positions from which new, corrected autonomous flight vectors begin.

Subroutine CORIDOR. This subroutine, when called by the main program, returns an array listing the chaff corridor boxes penetrated by vehicles to that point in the simulation.

Subroutine TALLY. This subroutine, when called by the main program, returns the total number of chaff corridor boxes which have been penetrated to that point in the simulation.

Subroutine RNORMAL. This subroutine, when called by Subroutines HEADERR, FLIGHT, OR RCO, returns a normal random variate from a population whose mean and standard deviation are provided as arguments by the calling subroutine. The normal random variate is constructed from a pseudo-random number which is generated from the intrinsic function RANF, the CDC system random number generator. Subroutine RNORMAL uses the Marsaglia and Bray transformation for generating normally distributed pseudo-random numbers (Ref 4:361).

Subroutine STAT. This subroutine, when called by the main program at the end of each simulation run, prints out means and standard deviations based on the number of replications in the run. Statistics are calculated and printed for the RCO corridor cross-track perception errors for both AHRS and INS-equipped DC-130 aircraft and for the number of RPV's required to achieve 50%, 90%, 95%, and 100% chaff corridor saturation.

Detailed Program Information

The preceding discussion of the computer program components provides a general description of the basic program.

More detailed information is located in the appendices to this paper. Appendix A is a list of variable definitions. Appendix B presents the program flow chart. Appendix C is a program listing, and Appendix D is sample output.

IV. Experiments

This chapter describes experiments performed with the simulation model presented in Chapter III. The chapter is divided into three sections, each addressing one of the categories of simulation testing defined by Fishman and Kiviat: (1) verification, which insures that the model behaves as intended; (2) validation, which tests the agreement between the behavior of the model and the real world; and (3) problem analysis, which draws statistically significant inferences from the data generated by the simulation (Ref 5:232). It is intended that this chapter serve as a basis for the conduct of more extensive simulation testing with this model by the RPV SPO.

VERIFICATION

Verification of the simulation model developed in this thesis consisted of extensive desk checking of the model design and computer program. The verification process was accomplished in two parts. First, the model design and computer program were carefully compared for consistency be inspection. Then, the algorithms of the program were tested for several combinations of input parameters by substituting from a table of random normal numbers and following the program sequence by hand computation.

The only difference in procedure between the hand checked algorithm and the computer algorithm is the method of random variate generation. For the computer program, the pseudorandom number stream is provided by the CDC intrinsic function RANF, and normal random variates are generated from a subroutine employing the Marsaglia and Bray transformation (Ref 4:361-362).

To ensure random sampling and provide the capability for correlated sampling, the CDC system subroutines RANSET and RANGET were included in the computer program. At the start of each program run, a random number seed is read in and set using the RANSET subroutine. At the end of the program run, the ending seed is obtained with the RANGET subroutine and recorded. Thus, when random sampling is desired, the end seed from the previous run can be used as the initial seed for the current run. If, instead, correlated sampling is desired, the same initial seed can be used for both runs.

VALIDATION

Validation is defined as the process of developing an acceptable level of confidence that the inferences drawn from the results of a model are correct and applicable to the real world. To achieve an acceptable level of confidence in a model, Naylor and Finger suggest a three stage approach:

(1) Construct a set of hypotheses about the manner in which the model elements interact. These hypotheses should be based on all available information including observations, previous research, relevant theory, and intuition.

(2) Attempt to verify the hypotheses of the model whenever possible using statistical testing.

(3) Compare the input-output transformations of the model to those of the real system (Ref 4:217).

The discussion of model validation presented in this section is oriented toward this three stage approach.

Naylor and Finger's Stage (1) was, in practice, performed during the design and construction of the simulation model developed in this thesis. The data collection process during the course of model development was directed toward constructing a set of hypotheses, and these hypotheses are manifested in the model design.

Stage (3), on the other hand, cannot be performed at the present time because no empirical data currently exists concerning RPV effectiveness in a chaff dispensing mission. Thus, this last and most crucial test of model validity must await real world developments. Given the status of Stages (1) and (3), the validation process at present is limited to the development of Stage (2) of Naylor and Finger's three stage approach, and this stage is the subject of the remainder of this section.

The two validation experiments conducted with the simulation model developed in this thesis have addressed the effects of certain input variables or parameters, called factors, on the response variable, which is defined as the number of RPV's required to achieve chaff corridor saturation. The experiments were conducted separately because one represents an analysis of the RPV flight portion of the model, while the other represents an analysis of the chaff corridor portion of the model. Both of these experiments used full factorial designs and employed analysis of variance (ANOVA) techniques to determine statistical significance.

RPV Flight Model Validation

Four factors were selected for analysis of the flight portion of the model because these parameters were initially believed to have a strong influence on the response variable. The four variables were

(1) ERRNAV, the coefficient which, when multiplied by distance flown, gives the standard deviation of the navigational error probability distribution;

(2) CORBEG, the distance fom the launch point to the leading edge of the chaff corridor;

(3) CORLEN, the length of the chaff corridor; and

(4) POLICY, the cross-track error threshold beyond which the RCO is assumed to initiate heading trim control.

While each of these is a quantitative factor, only linear effects were of interest in this initial test. Therefore, a full factorial experiment was performed with each of the factors varied at two levels representing the extreme points of the range of interest. The resulting orthogonal design consists of 16 (2^4) treatments or cells. Each cell was replicated 30 times, and 480 data points or cases resulted. Table III illustrates the experimental design for the RPV flight portion of the model.

Table III

EXPERIMENTAL DESIGN FOR THE FLIGHT PORTION OF THE MODEL

		$ERRNAV_1$		$ERRNAV_2$	
		$CORLEN_1$	$CORLEN_2$	$CORLEN_1$	$CORLEN_2$
$CORBEG_1$	$POLICY_1$	30	30	30	30
	$POLICY_2$	30	30	30	30
$CORBEG_2$	$POLICY_1$	30	30	30	30
	$POLICY_2$	30	30	30	30

The data collected from the experiment were analyzed with a four-way analysis of variance (ANOVA) technique using the Statistical Packages for the Social Sciences ANOVA computer routine (Ref 3). The ANOVA table and cell means and standard deviations are provided in Appendix E. Of the main effects, only CORBEG was statistically insignificant. While the three-way and four-way interactions were not significant, the two-way interactions between the three significant factors (CORBEG, ERRNAV, and POLICY) were also statistically significant, and further analysis of the effects of these three factors is warranted.

The results of the experiment provided the following observations:

(1) The longer the chaff corridor, the more RPV's required to achieve saturation,

(2) The greater the value of ERRNAV, the more RPV's required to achieve saturation, and

(3) The greater the value of POLICY, the more RPV's required to achieve saturation.

These observations, made by comparisons of the means of each experiment cell, coincide with real world expectations and thus provide confidence in the validity of the model.

Chaff Corridor Validation

The second validation experiment addresses the chaff corridor portion of the model. Because very little actual data exists to support any particular chaff corridor design, an analysis of the effects of the two corridor dimensions on the number of RPV's required to achieve chaff corridor saturation is essential before establishing any degree of confidence in the validity of the simulation model. The two box dimension factors considered are DELX, the length of each box, and DELY, the width of each string in the chaff corridor.

To test the effects of these factors on the response variable, a full factorial experiment was designed with each of the factors varied at two levels. The resulting orthogonal design consists of four (2^2) cells and 120 cases since each cell was replicated 30 times. Table IV illustrates the experimental design.

The data collected from the experiment were analyzed with a two-way ANOVA, and the ANOVA table and cell means and stand-and deviations are provided in Appendix E. Of the two main effects and one two-way interaction, only the effect of DELY was statistically significant. In fact, a comparison of the cell mean values presented in Table V shows that a three-fold

Table IV

EXPERIMENTAL DESIGN FOR THE CORRIDOR PORTION OF THE MODEL

	$DELY_1$	$DELY_2$
$DELX_1$	30	30
$DELX_2$	30	30

Table V

CELL MEANS FOR THE CORRIDOR EXPERIMENTAL DESIGN

	DELY = 250 ft	DELY = 750 ft
DELX = .5 NM	832.8	189.4
DELX = 2 NM	731.3	185.6

increase in the width of the corridor strings results in a four-fold decrease in the number of RPV's required to achieve corridor saturation, even though an increase in string width implies a concomitant increase in corridor width. Fewer vehicles are required to achieve saturation when the width of the strings is increased because, in the model, the penetration of any portion of a box by the extended flight vector of a vehicle is interpreted as chaff saturation of that box. This sensitivity to values of DELY coincides with real world expectations, in that, as the value of the lateral dipole dispersion diameter of the chaff cloud for each vehicle increases, the number of vehicles required to perform the mission decreases.

While this portion of the model is designed with as much detail as known information will allow, the awareness of model sensitivity to lateral dipole dispersion diameters conditions the use of the model. Because of the sensitivity, any corridor mission simulation must assume a lateral dipole diameter (value of DELY), and any inferences from the results of the experiment must be drawn with reference to that assumption.

PROBLEM ANALYSIS

Problem analysis is the last of Fishman and Kiviat's simulation testing categories. This category of testing represents the culmination of the modeling process to date, and it is during this period of analysis that the model is exercised to obtain the information for which the model was originally developed. Problem analysis does not mark the termination of the modeling process, however. Rather, the problem analysis category of simulation testing begins an iterative process of model refinement and modification.

This section first presents an application of the model developed in this thesis to establish the chaff mission effectiveness of two postulated RPV's possessing different operating parameters. Then, the simulation model will be used to demonstrate the potential mission effectiveness of one of the postulated vehicles as a result of certain system improvements.

Mission Effectiveness of Two Postulated RPV's

To demonstrate the application of the chaff effectiveness model, two portulated RPV's will be evaluated. The first vehicle uses a dead-reckoning navigational system while the second vehicle possesses both LORAN C/D and doppler capability.

The Dead-Reckoning Vehicle. The evaluation of the dead-reckoning vehicle begins with the simulation of vehicle performance using the model presented in Chapter III. Input parameters for the simulation are set as follows:

1. CORBEG = 100 NM (A midrange distance for anticipated employment scenarios);

2. COREND = 150 NM (A midrange distance giving a corridor length of 50 NM);

3. NUMRUN = 30 (Provides 30 replications of the experiment);

4. DELX = 1 NM (Selected arbitrarily since validation experiments indicated this parameter has no significant effect in the range .5 NM to 2 NM);

5. DELY = .25 NM (Assumes a lateral dipole dispersion diameter of .5 NM per vehicle to ensure saturation if vehicles penetrate adjacent corridor strings at opposite lateral limits of the strings);

6. LIMRPV = 1000 (Prevents excessive execution time if total saturation is not achieved);

7. ERRNAV = .03 (The navigational error coefficient of the postulated vehicle);

8. ERRRCO = .00722 (The RCO perception error coefficient for the DC-130 aircraft and MDCC system);

9. POLICY = 2 NM (The assumed RCO control threshold).

Statistics for the 30 replications of the simulation are

Table VI

SIMULATION RESULTS

	MEAN	STD DEV
Cross-track perception error due to DC-130 heading error		
AHRS-equipped aircraft	.101 NM left	2.588 NM
INS-equipped aircraft	.001 NM left	.653 NM
Number of vehicles required to achieve the following levels of saturation		
50%	11.7	3.300
90%	36.7	10.452
95%	49.5	15.813
100%	89.9	33.568

presented in Table VI. The standard deviations of the RCO corridor cross-track perception errors due to DC-130 heading error are 2.588 NM and .653 NM for the AHRS and INS-equipped aircraft, respectively. Consequently, the subsequent statistics presented in Table VI refer to a chaff corridor which is expected to be located at least 2.588 NM left or right of the desired corridor position 32% of the time if AHRS-equipped aircraft are used to control the vehicles and at least .653 NM left or right of the desired corridor position 32% of the time if INS-equipped aircraft are used. The importance of this error depends on the specific mission scenario under analysis.

Given that the number of vehicles required to achieve a stated level of corridor saturation in each simulation replication is an independent random variable having the same distribution, and since the experiment is replicated 30 times, the Central Limit Theorem can be applied. Thus, the sample mean of the number of vehicles required for each saturation level approximates a normally distributed random variable (Ref 1:206).

Consequently, the following relationship can be used to determine a confidence interval for the number of vehicles required to achieve each level of corridor saturation (Ref 1:272):

$$\bar{x} - Z_{\alpha/2}(\sigma/\sqrt{n}) < \mu < \bar{x} + Z_{\alpha/2}(\sigma/\sqrt{n}) \qquad (15)$$

where $\bar{x}$ is the sample mean, $Z_{\alpha/2}$ is the value such that the integral of the standard normal density from $Z_{\alpha/2}$ to ∞ equals $\alpha/2$, σ is the population standard deviation (estimated by the sample standard deviation since $n = 30$), n is the sample size, and μ is the population mean.

Using Eq (15), the following are 95% confidence intervals for the mean number of vehicles required to achieve the following levels of corridor saturation:

50% saturation	$10.5 < \mu < 12.9$
90% saturation	$33.0 < \mu < 40.4$
95% saturation	$43.8 < \mu < 55.2$
100% saturation	$77.9 < \mu < 101.9$

To obtain confidence intervals for the total number of vehicles which must be available to achieve the desired level of corridor saturation, the confidence limits given by Eq (15) must be divided by the mission completion success probability, (MCSP). For example, given a MCSP of .6 for the vehicle under consideration, 100% corridor saturation would require the availability of between 130 and 170 vehicles in 95 of 100 saturation attempts.

The LORAN-Equipped Vehicle. Assuming the LORAN remains functional, the evaluation of a LORAN-equipped vehicle can be accomplished analytically. Given a cross-track navigational accuracy of within 300 feet of desired track at any point during flight, and assuming a lateral dipole displacement diameter of .5 NM per vehicle as used in the evaluation of the dead-reckoning vehicle, four vehicles would be required to achieve total saturation of a two NM wide chaff corridor. With an accuracy of within 300 feet, each vehicle would be programmed to fly down the centerline of two of the strings defined in the simulation of the dead-reckoning vehicle.

To determine the number of vehicles which must be available to achieve corridor saturation, the number of vehicles which must fly the mission is divided by the MCSP. Assuming a MCSP of .5, corridor saturation would require the availability of eight LORAN-equipped vehicles. Should LORAN capability be lost at any point, the simulation model developed in this thesis could be used to obtain statistics on the number of vehicles required to fly the mission to achieve any desired level of corridor saturation.

Potential Vehicle Effectiveness Improvements

The simulation experiment discussed in the preceding subsection revealed that a large quantity of dead-reckoning vehicles are required to achieve total chaff corridor saturation, even assuming a large lateral dipole dispersion diameter (.5 NM) reflected in the width of the corridor strings (DELY = .25 NM). With current employment concepts based on only

30 TEWS RPV sorties per day (Ref 7), and given the input parameters of the preceding simulation, only one chaff corridor mission could be flown each day, and that mission would result in a corridor saturation level of less than 90% in 95 of 100 attempts.

Consequently, simulation experiments were conducted to demonstrate the ability of the simulation model to provide information on the potential improvements in vehicle effectiveness derived from changes in the dead-reckoning system. The experiments assumed the retention of the dead-reckoning system, but autonomous vehicle navigational capability and RCO perception were improved.

Table VII presents the increased effectiveness derived from these improvements. The means listed in Table VII result from a simulation run which replicated each experiment 30 times. DELY was set equal to .25 NM for all experiments.

Table VII

VEHICLES REQUIRED FOR GIVEN LEVELS OF CORRIDOR SATURATION

INPUT PARAMETERS			MEAN NUMBER OF VEHICLES				
ERRNAV	ERRRCO	POLICY	50%	90%	95%	100%	MISSES
.03	.00721	2.0	11.7	36.7	49.5	89.9	29.1
.01	.00721	2.0	9.6	35.8	56.1	213.2	53.0
.03	.00361	1.0	8.3	23.4	32.4	60.8	2.6
.01	.00361	1.0	6.7	26.5	35.7	72.9	4.1
.03	.00180	0.5	6.5	27.2	44.5	825.4	0
.01	.00180	0.5	7.7	63.3	172.4	593.3	0

Note in Table VII that POLICY decreases with each decrease in ERRRCO. This reflects the relationship between the RCO's perception ability and his willingness to take corrective action. The more accurate his perception of the actual vehicle position, the more quickly he will take corrective action when he perceives a position error.

Note also that the mean number of vehicles required to achieve a stated level of corridor saturation increases with the final improvements in input parameters. While this would appear to indicate a decrease in vehicle effectiveness, the last column of the table, presenting the mean number of vehicles which miss the corridor completely, decreases for improvement in ERRRCO and POLICY. This increase in mean number of vehicles required implies an inconsistent saturation density where many vehicles are redundently seeding the same corridor area while other areas remain unseeded.

Consequently, at some point during the process of improving vehicle input parameters, the current simulation scenario of launching each vehicle from the extended corridor centerline and returning that vehicle to the perceived centerline during subsequent RCO control must be revised. At that point, a more sophisticated employment scenario must be assumed in which vehicles are launched with predetermined latéral spacing and are subsequently corrected to provide lateral spacing during RCO control. The simulation model developed in this thesis has the capability to represent such an employment scenario and evaluate its effectiveness.

V. SUMMARY

The objectives of this thesis were to design and construct a model to determine the quantity of RPV's required to perform a chaff dispensing mission and to demonstrate the use of the model by establishing the chaff mission effectiveness of two postulated RPV's. To accomplish the first objective, a model to evaluate chaff mission effectiveness was developed using vehicle navigational accuracy and mission completion success probability as the relevant operating parameters of each vehicle. The second objective was accomplished when the model was used to evaluate the effectiveness of two postulated vehicles, one possessing a dead-reckoning navigational system and one navigating with LORAN C/D and doppler.

CONCLUSIONS

A model to determine the quantity of RPV's which must be available to perform a given chaff dispensing mission has been developed. While the system reliability measurements for all vehicles and the navigational accuracy of LORAN-equipped vehicles can be represented deterministically, the navigational accuracy of vehicles not equipped with functioning LORAN is described stochastically, and a simulation model seems appropriate for that portion of the overall effectiveness model.

A search performed during the development of the stochastic simulation model for a method to represent the contribution made by each vehicle toward achieving saturation of the chaff corridor revealed that very little is known about the nature of chaff clouds. In addition, little is known of the width of actual chaff corridors after the dipoles reach equilibrium in the atmosphere. Since the simulation model developed in this thesis reflects real world sensitivity to these unknown parameters, any inferences drawn from the results of experiments performed with the model must be based on an assumed lateral chaff dispersion diameter. Greater confidence in the results of experiments could be achieved if more empirical data concerning chaff dispersion were available. Further model validation must await a clearer understanding of chaff dynamics and steady-state dipole characteristics.

Beyond providing statistical results given certain vehicle parameters and assumptions of the chaff corridor characteristics, the model appears to have application in two areas. The first is evaluating the increased mission effectiveness derived from improvements in navigational accuracy and/or RCO perception. This evaluation is necessary for the allocation of resources to research alternatives offering the highest return in overall mission effectiveness. The second application is evaluating alternative launch and employment scenarios including DC-130 positioning at launch and RCO vehicle correction policies.

RECOMMENDATIONS FOR FUTURE WORK

Research is under way to determine such chaff corridor characteristics as required corridor width and the lateral dimensions of the dipole cloud produced by each seeding vehicle.

As information becomes available, it should be used to determine realistic parameters for the chaff corridor portion of the simulation model.

The last two recommendations for future refinement of the model pertain to the sensitivity of the simulation portion of the overall model. The simulation model currently assumes that cross-track errors are normally distributed. To determine the sensitivity of this assumption, other symmetric probability distributions with the same location and scale parameter values might be substituted for the normal distribution in the model. If the normality assumption proves sensitive, further investigation of actual flight test data to ensure the accuracy of the distribution function selected for the model is warranted.

Finally, the number of vehicles required to achieve mission completion is highly sensitive to the percentage of chaff corridor saturation desired. Consequently, any saturation level less that 100% requires significantly fewer vehicles to achieve, and an investigation of the actual degree of corridor saturation deemed sufficient for mission success would provide valuable information for future applications of the model.

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Appendix A

Variable Definitions

Appendix A

Variable Definitions

Subroutines

CORIDOR - returns an array containing the number of vehicles which have penetrated each corridor box to that point in the simulation.

FLIGHT - returns the vehicle position when located on or abeam of the leading edge of the chaff corridor and the actual flight vector slope.

HEADERR - returns two RCO cross-track corridor perception error values due to DC-130 heading error.

RANGET - a CDC intrinsic function, returns the current RANF seed for future use.

RANSET - a CDC intrinsic function, sets the seed in the RANF generator.

RCO - returns the cross-track and along-track distances defining the position from which new, corrected autonomous flight vectors begin.

RNORMAL - returns normal random variates given distribution parameters as arguments.

STAT - computes and prints the response variable statistics for each simulation experiment.

TALLY - returns the total number of chaff corridor boxes which have been penetrated to that point in the simulation.

Main Program Variables

CORBEG - an input parameter, distance from launch to the leading edge of the desired chaff corridor.

COREND - an input parameter, distance from launch to the trailing edge of the desired chaff corridor.

CORW - width of the desired chaff corridor.

CRIT - an array containing the saturation level values for which response variable statistics are to be calculated.

CURSEED - value of the ending RANF seed obtained by RANGET.

DELX - length of the corridor boxes, an input parameter.

DELY - width of the corridor strings, an input parameter.

ERR1 - the value of the RCO cross-track corridor perception error due to AHRS-equipped DC-130 heading error.

ERR2 - the value of the RCO cross-track corridor perception error due to INS-equipped DC-130 heading error.

ERRNAV - the coefficient describing the navigational error probability distribution for the vehicle simulated.

ERRRCO - the coefficient describing the RCO perception error probability distribution.

HOLD - an array storing all response variable values until needed for statistical calculations.

ICOR - an array listing the number of vehicles which have penetrated each corridor box to that point in the simulation.

ICOREND - the number of boxes in one string of the chaff corridor.

ICOUNT - total number of boxes penetrated by RPV's to that point.

LIMRPV - the maximum number of RPV's that can be simulated in one replication before simulation of that replication terminates.

NUMISS - number of RPV's that have missed the perceived corridor completely to that point in the replication.

NUMRPV - the response variable, number of RPV's launched and flown to that point in the replication.

NUMRUN - the number of replications to be simulated with one set of input parameters.

NUMTOT - total number of boxes in the chaff corridor.

POLICY - RCO control initiation threshold, an input parameter.

SEED - value of the beginning RANF seed, set by RANSET.

YCOR - the cross-track distance to the vehicle when located on or abeam of the leading edge of the chaff corridor.

Subroutine CORIDOR Variables

CORBEG4 - distance from launch to the leading edge of the desired chaff corridor.

COREND4 - distance from launch to the trailing edge of the desired chaff corridor.

CORW - width of the chaff corridor.

DELX4 - length of the corridor boxes.

DELY4 - width of the corridor strings.

DX - along-track distance traveled by a vehicle while remaining within one string.

DYDX4 - the slope of the actual flight vector.

IBOXBEG - the horizontal box number in which a vehicle enters a new string.

IBOXEND - the horizontal box number in which a vehicle exits a string.

ICOR4 - an array listing the number of vehicles which have penetrated each corridor box to that point in the simulation.

ICOREN4 - the number of boxes in one string of the corridor.

ISTRING - the number of the string in which a vehicle is located.

XNEW - along-track distance fom the leading edge of the corridor to the point at which a vehicle exits a string.

XOLD - along-track distance from the leading edge of the corridor to the point at which a vehicle enters a new string.

YCOR4 - cross-track distance to the vehicle when located on or abeam of the leading edge of the corridor.

YNEW - cross-track distance to the point at which a vehicle exits a corridor string.

YOLD - cross-track distance to the point at which a vehicle enters a new corridor string.

Subroutine FLIGHT Variables

AYBEG - cross-track distance to the beginning of the actual flight vector.

AYEND - cross-track distance to the end of the actual flight vector.

CORBEG2 - distance from the launch point to the leading edge of the corridor.

DYDX2 - slope of the actual flight vector.

ERRNAV2 - the coefficient describing the navigational error probability distribution for the vehicle simulated.

ERRRCO2 - the coefficient describing the RCO perception error probability distribution.

EXA - the mean of the actual flight vector cross-track error probability distribution.

EXP - the mean of the perceived flight vector cross-track error probability distribution.

POLICY2 - RCO control initiation threshold.

PYBEG - cross-track distance to the beginning of the perceived flight vector.

PYEND - cross-track distance to the end of the perceived flight vector.

STDA - standard deviation of the actual flight vector cross-track error probability distribution.

STDP - standard deviation of the perceived flight vector cross-track error probability distribution.

XBEG - along-track distance from the origin to the start of both flight vectors.

XEND - along-track distance from the origin to the end of both flight vectors.

YCOR2 - cross-track distance to the vehicle when located on or abeam of the leading edge of the corridor.

Subroutine HEADERR Variables

A = Hollerith format specification for output.

CORBEG1 - distance from the launch point to the leading edge of the corridor.

ERR1 - the value of the RCO cross-track corridor perception error due to AHRS-equipped DC-130 heading error.

ERR2 - the value of the RCO cross-track corridor perception error due to INS-equipped DC-130 heading error.

EX1 - the mean of the RCO cross-track corridor perception error probability distribution due to AHRS-equipped DC-130 heading error.

EX2 - the mean of the RCO cross-track corridor perception error probability distribution due to INS-equipped DC-130 heading error.

I - Hollerith format specification for output.

L - Hollerith format specification for output.

R - Hollerith format specification for output.

STD1 - the standard deviation of the RCO cross-track corridor perception error probability distribution due to AHRS-equipped DC-130 heading error.

STD2 - the standard deviation of the RCO cross-track corridor perception error probability distribution due to INS-equipped DC-130 heading error.

Subroutine RCO Variables

AYBEG3 - cross-track distance to the beginning of the actual flight vector.

AYEND3 - cross-track distance to the end of the actual flight vector.

AYRCO - cross-track distance to the actual point at which RCO control is initiated.

CORBEG3 - distance from the launch point to the leading edge of the corridor.

ERRRCO3 - the coefficient describing the RCO perception error probability distribution.

EX3 - the mean of the probability distribution describing AYBEG3.

POLICY3 - RCO control initiation threshold.

PYBEG3 - cross-track distance to the beginning of the perceived flight vector.

PYEND3 - cross-track distance to the end of the perceived flight vector.

PYRCO- cross-track distance to the point at which RCO control is perceived to begin.

STD3 - the standard deviation of the probability distribution describing AYBEG3.

XBEG3 - along-track distance from the origin to the start of both flight vectors.

XEND3 - along-track distance from the origin to the end of both flight vectors.

XFIX - along-track distance from the point at which RCO control begins to the point at which RCO control ends.

XRCO - along-track distance from the origin to the point at which RCO control is initiated.

Subroutine RNORMAL Variables

All variables are components of the Marsaglia and Bray normal random variate transformation (Ref 4:361-362).

Subroutine STAT Variables

AVG - an array which stores the mean values of the response variables until printed.

DEV - an array which stores the standard deviations of the response variables until printed.

DIF - an array which stores the sum of the difference between individual response variable values and the mean value.

HOLD7 - an array which stores all response variable values until needed for statistical calculations.

NUMRUN7 - the number of replications to be simulated with one set of input parameters.

SUM - an array which holds the sum of all the individual response variable values.

Subroutine TALLY Variables

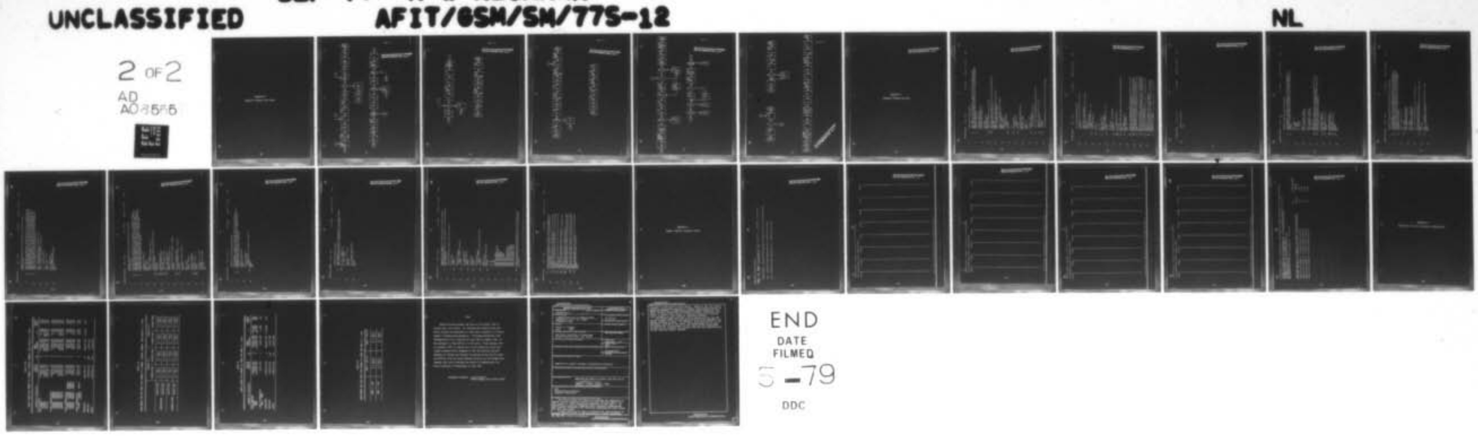
ICOR5 - an array listing the number of vehicles which have penetrated each corridor box to that point in the simulation.

ICOREN5 - the number of boxes in one string of the chaff corridor.

ICOUNT5 - total number of boxes penetrated by RPV's to that point.

AD-A065 557 AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OHIO SCH--ETC F/G 17/4
A METHODOLOGY FOR AN EFFECTIVENESS ANALYSIS OF RPV'S IN A CHAFF--ETC(U)
SEP 77 R W NEUMANN
UNCLASSIFIED AFIT/GSM/SM/77S-12 NL

2 OF 2
AD
A065557



END
DATE
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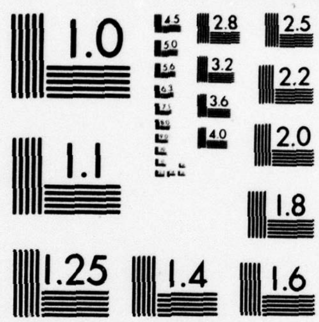
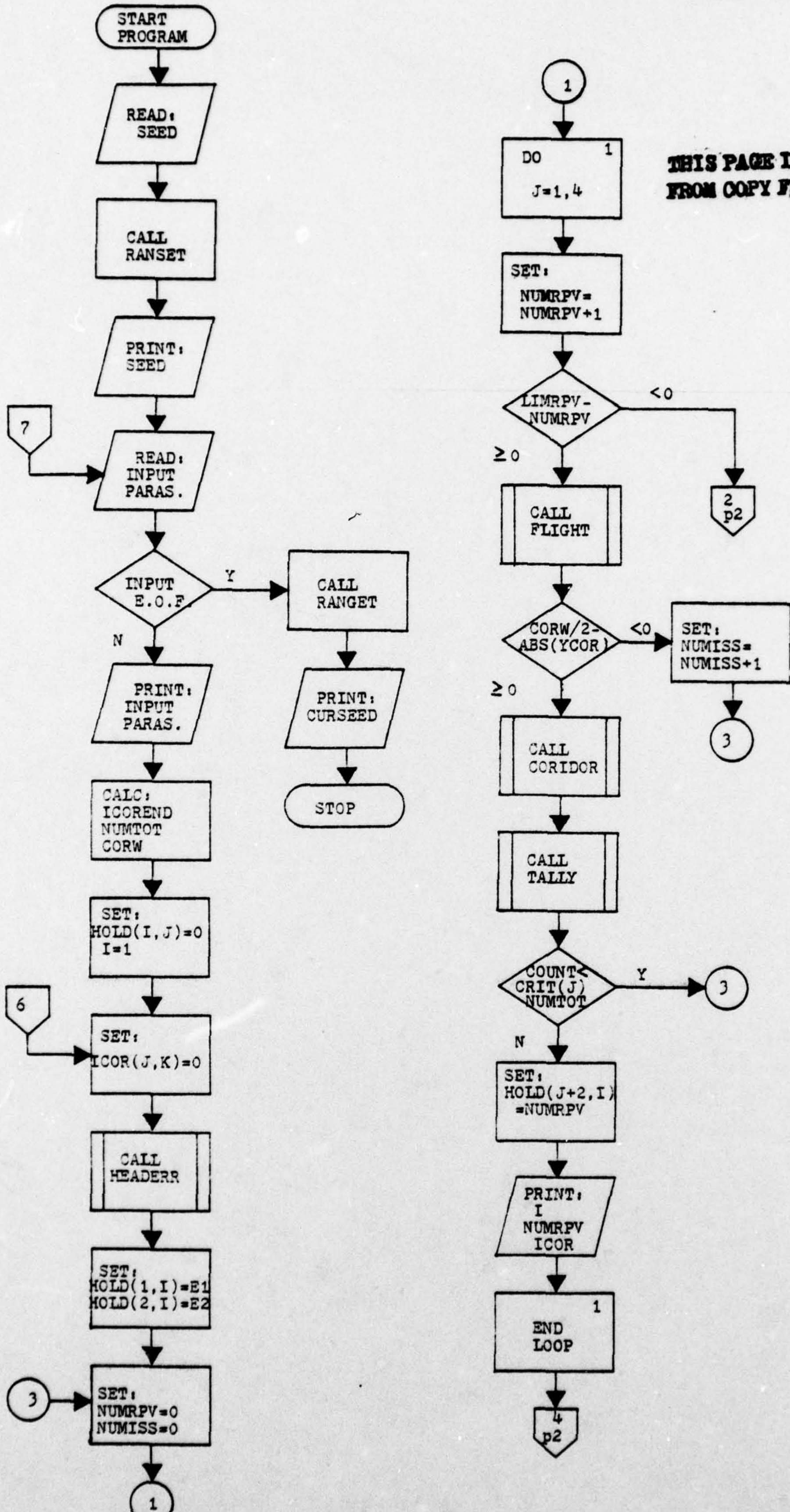
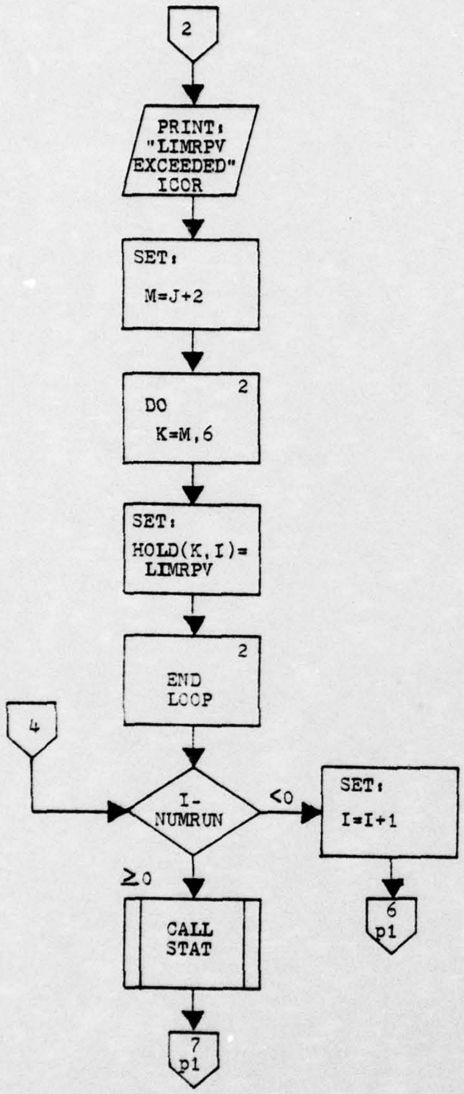


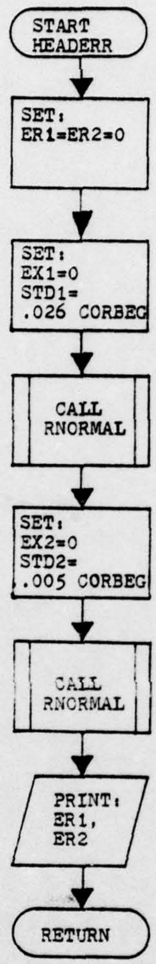
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

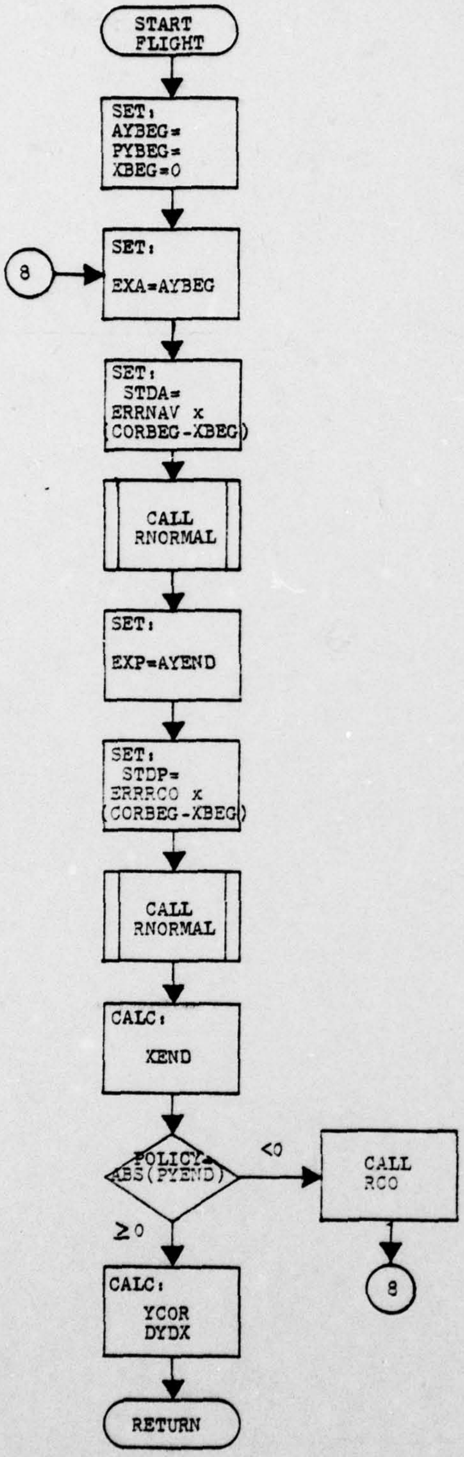
Appendix B

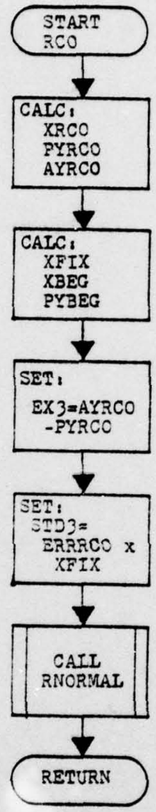
Computer Program Flow Chart

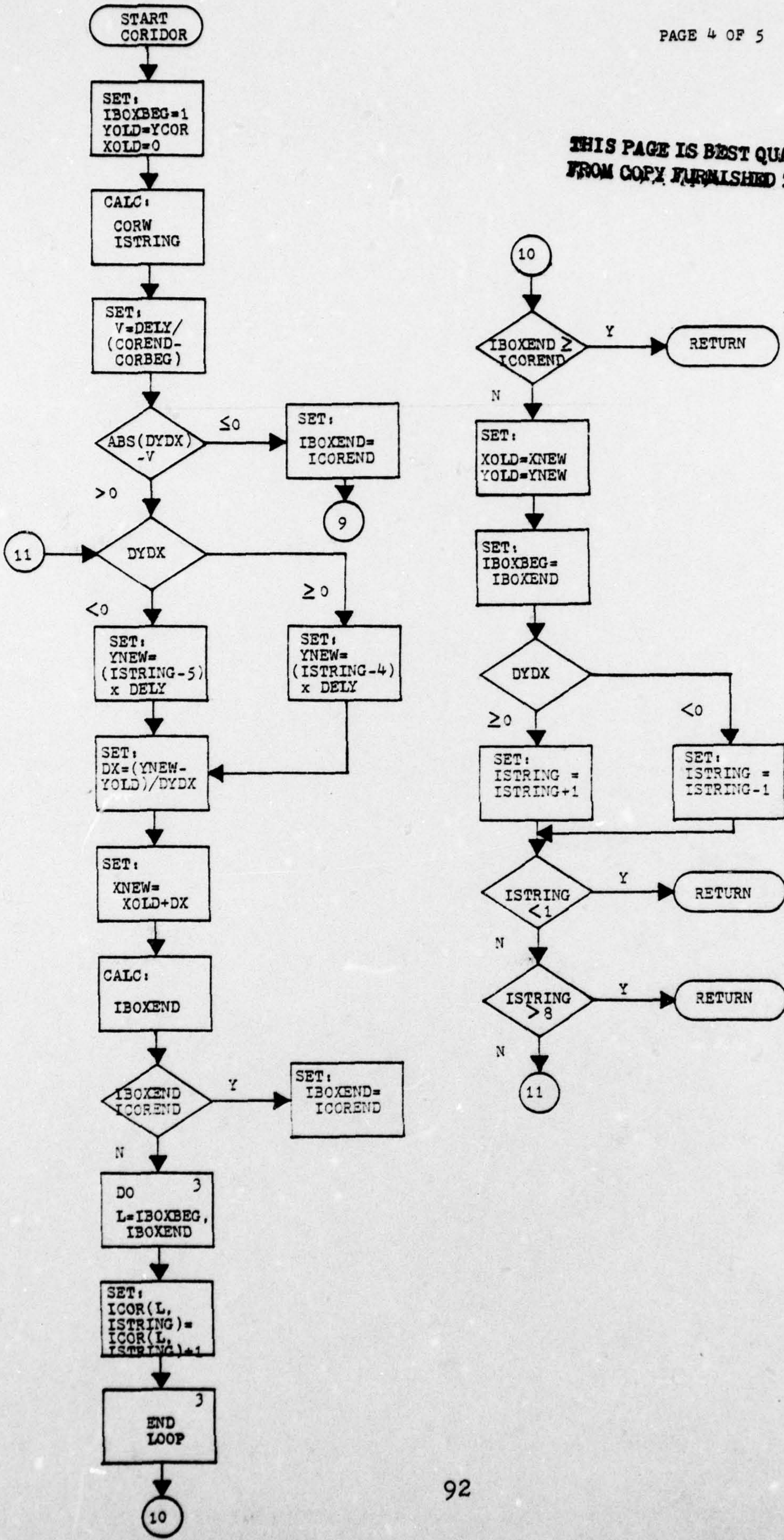

START PROGRAM
READ: SEED
CALL RANSET
PRINT: SEED
7
READ: INPUT PARAS.
INPUT E.O.F.
Y
CALL RANGET
PRINT: CURSEED
STOP
N
PRINT: INPUT PARAS.
CALC: ICOREND NUMTOT CORW
SET: HOLD(I,J)=0 I=1
6
SET: ICOR(J,K)=0
CALL HEADERR
SET: HOLD(1,I)=E1 HOLD(2,I)=E2
3
SET: NUMRPV=0 NUMISS=0
1
1
DO 1 J=1,4
SET: NUMRPV= NUMRPV+1
LIMRPV- NUMRPV
<0
2 p2
≥0
CALL FLIGHT
CORW/2- ABS(YCOR)
<0
SET: NUMISS= NUMISS+1
3
≥0
CALL CORIDOR
CALL TALLY
COUNT< CRIT(J) NUMTOT
Y
3
N
SET: HOLD(J+2,I) =NUMRPV
PRINT: I NUMRPV ICOR
END LOOP 1
4 p2

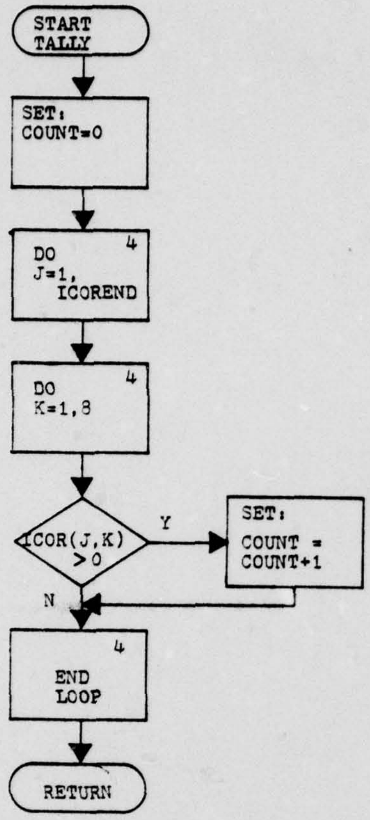

2
PRINT: "LIMRPV EXCEEDED" ICOR
SET: M=J+2
2
DO K=M,6
SET: HOLD(K,I)= LIMRPV
2
END LOOP
4
I-NUMRUN
<0
SET: I=I+1
6 p1
≥0
CALL STAT
7 p1

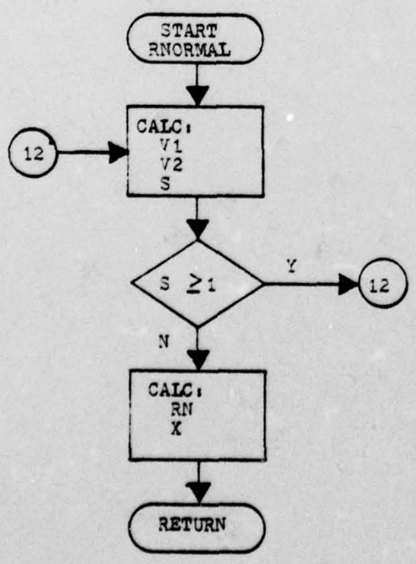

START HEADERR
SET: ER1=ER2=0
SET: EX1=0 STD1= .026 CORBEG
CALL RNORMAL
SET: EX2=0 STD2= .005 CORBEG
CALL RNORMAL
PRINT: ER1, ER2
RETURN

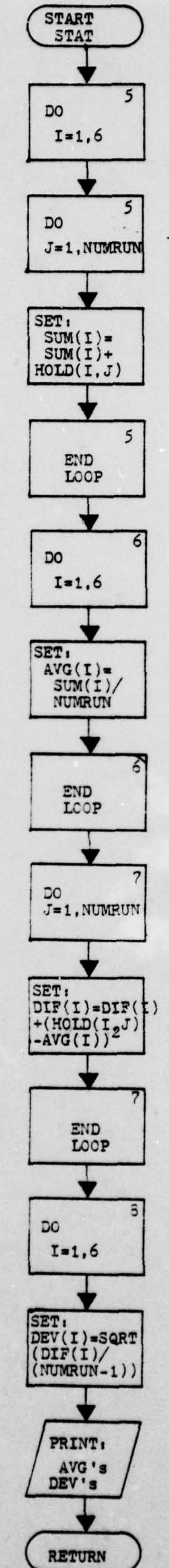

START FLIGHT
SET: AYBEG= PYBEG= XBEG=0
8
SET: EXA=AYBEG
SET: STDA= ERRNAV x (CORBEG-XBEG)
CALL RNORMAL
SET: EXP=AYEND
SET: STDP= ERRRCO x (CORBEG-XBEG)
CALL RNORMAL
CALC: XEND
POLICY- ABS(PYEND)
<0
CALL RCO
8
≥0
CALC: YCOR DYDX
RETURN


START RCO
CALC: XRCO PYRCO AYRCO
CALC: XFIX XBEG PYBEG
SET: EX3=AYRCO -PYRCO
SET: STD3= ERRRCO x XFIX
CALL RNORMAL
RETURN


START CORIDOR
SET: IBOXBEG=1 YOLD=YCOR XOLD=0
CALC: CORW ISTRING
SET: V=DELY/ (COREND- CORBEG)
ABS(DYDX) -V
≤0
SET: IBOXEND= ICOREND
9
>0
11
DYDX
<0
≥0
SET: YNEW= (ISTRING-5) x DELY
SET: YNEW= (ISTRING-4) x DELY
SET: DX=(YNEW- YOLD)/DYDX
SET: XNEW= XOLD+DX
CALC: IBOXEND
IBOXEND ICOREND
Y
SET: IBOXEND= ICOREND
N
DO 3 L=IBOXBEG, IBOXEND
SET: ICOR(L, ISTRING)= ICOR(L, ISTRING)+1
3 END LOOP
10
10
IBOXEND ≥ ICOREND
Y
RETURN
N
SET: XOLD=XNEW YOLD=YNEW
SET: IBOXBEG= IBOXEND
DYDX
≥0
<0
SET: ISTRING = ISTRING+1
SET: ISTRING = ISTRING-1
ISTRING <1
Y
RETURN
N
ISTRING >8
Y
RETURN
N
11


START TALLY
SET: COUNT=0
DO J=1, ICOREND
4
DO K=1,8
4
ICOR(J,K) > 0
Y
N
SET: COUNT = COUNT+1
END LOOP
4
RETURN


START RNORMAL
CALC: V1 V2 S
12
S ≥ 1
Y
N
12
CALC: RN X
RETURN


START STAT
DO I=1,6
5
DO J=1,NUMRUN
5
SET: SUM(I)= SUM(I)+ HOLD(I,J)
END LOOP
5
DO I=1,6
6
SET: AVG(I)= SUM(I)/ NUMRUN
END LOOP
6
DO J=1,NUMRUN
7
SET: DIF(I)=DIF(I) +(HOLD(I,J) -AVG(I))2
END LOOP
7
DO I=1,6
8
SET: DEV(I)=SQRT (DIF(I)/ (NUMRUN-1))
PRINT: AVG's DEV's
RETURN

Appendix C

Computer Program Listing

```
      PROGRAM RPVSIM(INPUT,OUTPUT)

C     THIS PROGRAM IS A SIMULATION MODEL WHICH DETERMINES THE NUMBER OF RPV,S
C     WHICH MUST BE FLOWN TO ACHIEVE A STATED LEVEL OF CHAFF CORRIDOR SATURATION
C     USING THE NAVIGATIONAL CAPABILITY OF EACH KIND OF VEHICLE AS THE RELEVANT
C     OPERATING PARAMETER.

      DIMENSION ICOR(100,8)
      DIMENSION CRIT(4),HOLD(6,100)
      DATA CRIT/.50,.90,.95,1./

      READ*,SEED
      CALL RANSET(SEED)
      PRINT 100,SEED
100   FORMAT(1H ,T10,*SEED =*,T17,F15.13)

103   READ*,CORBEG,COREND,NUMRUN,DELX,DELY,LIMRPV,ERRNAV,ERRRCO,POLICY
      IF(EOF(5LINPUT).NE.0.)GO TO 399
      PRINT 197
      PRINT 198,CORBEG,COREND,NUMRUN,DELX,DELY,LIMRPV
      PRINT 199,ERRNAV,ERRRCO,POLICY

      ICOREND = INT((COREND-CORBEG+.1)/DELX)
      NUMTOT = ICOREND * 8
      CORW = 8.*DELY
      DO 104 J=1,6
        DO 104 K=1,100
          HOLD(J,K) = 0.
104   CONTINUE

      I = 1

105   DO 110 J=1,100
        DO 110 K = 1,8
          ICOR(J,K) = 0
110   CONTINUE

      CALL HEADERR(I,CORBEG,ER1,ER2)
      HOLD(1,I) = ER1
      HOLD(2,I) = ER2

      NUMRPV = 0
      NUMISS = 0

      DO 150 J = 1,4
120     NUMRPV = NUMRPV + 1
        IF(LIMRPV-NUMRPV)153,130,130

130     CALL FLIGHT(CORBEG,ERRNAV,ERRRCO,POLICY,YCOR,DYDX)

        IF(CORW/2. - ABS(YCOR))133,134,134
133     NUMISS = NUMISS + 1
        GO TO 120
134     CONTINUE

        CALL CORIDOR(YCOR,CORBEG,COREND,DYDX,DELY,DELX,ICOREND,ICOR)
```

```
                 CALL TALLY(ICOR,ICOREND,ICOUNT)

                 IF(ICOUNT.LT.INT(CRIT(J)*NUMTOT)) GO TO 120
                 CONTINUE

                 HOLD(J+2,I) = FLOAT(NUMRPV)
                 PRINT 190,I,NUMRPV,INT(100.*(CRIT(J)+.005))
                 PRINT 191
                 PRINT 192
                 DO 140 K=1,ICOREND
                   PRINT 193,(ICOR(K,L),L = 1,8)
      140        CONTINUE
                 PRINT 195,NUMISS,I

      150     CONTINUE

              GO TO 160

      153     PRINT 194,LIMRPV,I
              PRINT 192
              DO 155 K=1,ICOREND
                PRINT 193,(ICOR(K,L),L = 1,8)
      155     CONTINUE

              M = J+2
              DO 157 K=M,6
                HOLD(K,I) = FLOAT(LIMRPV)
      157     CONTINUE

      160     IF(I-NUMRUN)170,180,180
      170     I = I + 1
              GO TO 105
      180     CALL STAT(NUMRUN,HOLD,CORBEG,COREND,DELX,DELY,ERRNAV,ERRRCO,POLICY
             1,SEED)
              GO TO 103
      999     CALL RANGET(CURSEED)
              PRINT 196,CURSEED
              STOP

      190     FORMAT(1H-,T10,*CORRIDOR NUMBER*,T26,I2,T29,*REQUIRED*,T38,I3,T42,
             1*RPV'S FOR*,T52,I3,T56,*PERCENT SATURATION*)
      191     FORMAT(1H0,T10,*THE FOLLOWING ARRAY DEPICTS SATURATION DENSITY*)
      192     FORMAT(1H0,T10,*STRING1*,T25,*STRING2*,T40,*STRING3*,T55,*STRING4*
             1,T70,*STRING5*,T85,*STRING6*,T100,*STRING7*,T115,*STRING8*)
      193     FORMAT(1H ,T14,I3,T29,I3,T44,I3,T59,I3,T74,I3,T89,I3,T104,I3,T119,
             1I3)
      194     FORMAT(1H-,T10,*WARNING - RPV LIMIT OF*,T33,I4,T38,*VEHICLES HAS B
             1EEN EXCEEDED FOR CORRIDOR NUMBER*,T85,I2,T88,* - MISSION ABORTED*)
      195     FORMAT(1H-,T10,I4,T15,*RPV'S MISSED THE CORRIDOR COMPLETELY UP TO
             1THIS POINT IN CORRIDOR*,T81,I2)
      196     FORMAT(1H-,T15,*RANDOM NUMBER SEED AT END OF SIMULATION IS*,T58,
             1T58,F15.13)
      197     FORMAT(1H1,T5,*PARAMETERS ARE SET AS FOLLOWS:*)
      198     FORMAT(1H0,T5,*CORBEG =*,T14,F4.0,T20,*COREND =*,T29,F4.0,T35,
             1*NUMRUN =*,T44,I2,T48,*DELX =*,T55,F5.3,T62,*DELY =*,T69,F11.9,
             1T83,*LIMRPV =*,T92,I4)
      199     FORMAT(1H ,T5,*ERRNAV =*,T14,F4.2,T20,*ERRRCO =*,T29,F9.7,T39,
```

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```
115           1*POLICY =*,T48,F4.1)
               END
```

```
      SUBROUTINE HEADERR(I1,CORREG1,ERR1,ERR2)
C     THIS SUBROUTINE IS GIVEN THE DISTANCE FROM  THE DC-130 POSITION TO THE
C     LEADING EDGE OF THE DESIRED CHAFF CORRIDOR POSITION AND RETURNS RCO
C     CROSS-TRACK CORRIDOR PERCEPTION ERROR DUE TO AHRS AND INS-EQUIPPED DC-130
C     AIRCRAFT
      ERR1 = ERR2 = 0.
      A = 4HAHRS
      I = 3HINS
      L = 4HLEFT
      R = 5HRIGHT
      EX1 = 0.
      STD1 = .026168 * CORREG1
      CALL RNORMAL(EX1,STD1,ERR1)
      EX2 = 0.
      STD2 = .0052336 * CORREG1
      CALL RNORMAL(EX2,STD2,ERR2)
      PRINT 200,I1
  200 FORMAT(1H-,T10,*CORRIDOR NUMBER*,T26,I2,T29,*WOULD HAVE THE FOLLOW
     1ING CROSS-TRACK ERROR DUE TO DC-130 HEADING ERROR*)
  205 FORMAT(1H-,T10,F5.3,T17,*NM*,T20,A10,T26,*OF DESIRED LOCATION WITH
     1*,T51,A10,T56,*-EQUIPPED DC-130 AIRCRAFT*)
      IF(ERR1)210,220,220
  210 PRINT 205,ABS(ERR1),R,A
      GO TO 230
  220 PRINT 205,ABS(ERR1),L,A
      CONTINUE
  230 IF(ERR2)240,250,250
  240 PRINT 205,ABS(ERR2),R,I
      GO TO 260
  250 PRINT 205,ABS(ERR2),L,I
      CONTINUE
  260 RETURN
      END
```

```
      SUBROUTINE FLIGHT(CORBEG2,ERRNAV2,ERRRCO2,POLICY2,YCOR2,DYDX2)
C     THIS SUBROUTINE IS GIVEN THE DISTANCE FROM LAUNCH TO THE LEADING EDGE OF
C     THE CHAFF CORRIDOR, THE NAVIGATIONAL ERROR COEFFICIENT FOR THE VEHICLE
C     SIMULATED,THE RCO PERCEPTION ERROR COEFFICIENT, AND THE CROSS-TRACK ERROR
C     AT WHICH RCO CONTROL WILL BE INITIATED AND RETURNS THE VEHICLE POSITION
C     ON OR ABEAM OF THE CORRIDOR LEADING EDGE AND THE SLOPE OF THE ACTUAL
C     AUTONOMOUS FLIGHT VECTOR

      AYBEG = PYBEG = XBEG = 0.

  300 EXA = AYBEG
      STDA = ERRNAV2*(CORBEG2-XBEG)
      CALL PNORMAL(EXA, STDA,AYEND)

      EXP = AYEND
      STDP = ERRRCO2 * (CORBEG2-XBEG)
      CALL PNORMAL(EXP,STDP,PYEND)

      XEND = XBEG + SQRT((CORBEG2-XBEG)**2 - (AYEND-AYBEG)**2)

      IF(POLICY2-ABS(PYEND))310,320,320
  310 CALL RCO(CORBEG2,AYEND,PYEND,XEND,ERRRCO2,POLICY2,AYBEG,PYBEG,
     1XBEG)
      GO TO 300

  320 YCOR2 = (AYEND-AYBEG) * (CORBEG2-XBEG)/(XEND-XBEG) + AYBEG
      DYDX2 = (AYEND-AYBEG)/(XEND-XBEG)
      RETURN
      END
```

```
      SUBROUTINE RCO(CORBEG3,AYEND3,PYEND3,XEND3,ERRRCO3,POLICY3,AYBEG3
     1,PYBEG3,XBEG3)
C
C     THIS SUBROUTINE IS GIVEN THE DISTANCE FROM LAUNCH TO THE CORRIDOR LEADING
C     EDGE, THE CROSS-TRACK DISTANCE TO THE END OF THE ACTUAL FLIGHT VECTOR, THE
C     CROSS-TRACK DISTANCE TO THE END OF THE PERCEIVED FLIGHT VECTOR, THE ALONG-
C     TRACK DISTANCE FROM LAUNCH TO THE END OF BOTH FLIGHT VECTORS, THE RCO
C     PERCEPTION ERROR COEFFICIENT, AND RETURNS THE CROSS-TRACK DISTANCE TO THE
C     START OF THE NEW ACTUAL FLIGHT VECTOR, THE CROSS-TRACK DISTANCE TO THE
C     START OF THE PERCEIVED FLIGHT VECTOR, AND THE ALONG-TRACK DISTANCE FROM
C     LAUNCH TO THE START OF THE NEW FLIGHT VECTORS

      XRCO = ABS((XEND3-XBEG3)*POLICY3/PYEND3) + XBEG3
      PYRCO = SIGN(POLICY3,PYEND3)
      AYRCO = AYEND3 * (XRCO-XBEG3)/(XEND3-XBEG3)

      XFIX = (CORBEG3-XRCO)/2.

      XBEG3 = XRCO + XFIX
      PYBEG3 = 0.

      EX3 = AYRCO-PYRCO
      STD3 = ERRRCO3 * XFIX
      CALL RNORMAL(EX3,STD3,AYBEG3)
      RETURN
      END
```

```
      SUBROUTINE CORIDOR(YCOR4,CORBEG4,COREND4,DYDX4,DELY4,DELX4,
     1ICOREN4,ICOR4)
C     THIS SUBROUTINE IS GIVEN THE VEHICLE POSITION ON THE CORRIDOR LEADING
C     EDGE, THE DISTANCE FROM LAUNCH TO THE CORRIDOR LEADING EDGE, THE DISTANCE
C     FROM LAUNCH TO THE CORRIDOR TRAILING EDGE, THE SLOPE OF THE ACTUAL
C     AUTONOMOUS FLIGHT VECTOR, THE WIDTH OF THE CORRIDOR STRINGS, THE LENGTH OF
C     THE CORRIDOR BOXES, AND THE NUMBER OF HORIZONTAL BOXES IN THE CORRIDOR AND
C     RETURNS THE ARRAY ICOR REPRESENTING THE NUMBER OF CORRIDOR BOXES
C     PENETRATED TO THAT POINT IN THE REPLICATION
      DIMENSION ICOR4(100,8)
      IBOXBEG = 1
      YOLD = YCOR4
      XOLD = 0.
      CORW = 8. * DELY4
      ISTRING = INT((YOLD+CORW/2.)/DELY4) + 1
      IF(ABS(DYDX4)-DELY4/(COREND4-CORBEG4))500,500,510
  500 IBOXEND = ICOREN4
      GO TO 560
  510 CONTINUE
  520 IF(DYDX4)530,540,540
  530 YNEW = (ISTRING-3)*DELY4
      GO TO 550
  540 YNEW = (ISTRING-4)*DELY4
  550 DX = (YNEW-YOLD)/DYDX4
      XNEW = XOLD + DX
      IBOXEND = INT(XNEW/DELX4) + 1
      IF(IBOXEND.GT.ICOREN4) IBOXEND = ICOREN4
      CONTINUE
  560 DO 570 L=IBOXBEG,IBOXEND
        ICOR4(L,ISTRING) = ICOR4(L,ISTRING) + 1
  570 CONTINUE
      IF(IBOXEND.GE.ICOREN4) RETURN
      CONTINUE
      XOLD = XNEW
      YOLD = YNEW
      IBOXBEG = IBOXEND
      IF(DYDX4)580,590,590
  580 ISTRING = ISTRING - 1
      GO TO 600
  590 ISTRING = ISTRING + 1
  600 CONTINUE
      IF(ISTRING.LT.1) RETURN
      CONTINUE
      IF(ISTRING.GT.8) RETURN
      GO TO 520
      END
```

```
      SUBROUTINE TALLY(ICOR5,ICOREN5,ICOUNT5)
C     THIS SUBROUTINE IS GIVEN THE ARRAY ICOR REPRESENTING THE NUMBER OF
C     CORRIDOR BOXES PENETRATED TO THAT POINT IN THE REPLICATION, THE NUMBER OF
C     HORIZONTAL BOXES IN THE CORRIDOR AND RETURNS THE NUMBER OF BOXES
C     PENETRATED TO THAT POINT IN THE REPLICATION
      DIMENSION ICOR5(100,8)
      ICOUNT5 = 0
      DO 700 J=1,ICOREN5
        DO 700 K = 1,8
          IF(ICOR5(J,K).GT.0) ICOUNT5 = ICOUNT5 + 1
  700 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE RNORMAL(EX,STD,X)
C     THIS SUBROUTINE IS GIVEN A MEAN AND STANDARD DEVIATION AND RETURNS A
C     NORMAL RANDOM VARIATE USING THE MARSAGLIA AND BRAY METHOD
800   V1 = 2.0 * RANF(A) - 1.
      V2 = 2.0 * RANF(A) - 1.
      S = V1**2 + V2**2
      IF(S.GE.1.) GO TO 800
      CONTINUE
      RN = V1*SQRT(-2.0*ALOG(S)/S)
      X = EX + RN * STD
      RETURN
      END
```

```
      SUBROUTINE STAT(NUMRUN7,HOLD7,CORBEG7,COREND7,DELX7,DELY7,ERRNAV7,
     1ERRRCO7,POLICY7,SEED7)
C     THIS SUBROUTINE IS GIVEN ALL INPUT PARAMETERS FOR EACH REPLICATION AND
C     PRINTS STATISTICS

      DIMENSION HOLD7(5,100),SUM(5),AVG(6),DIF(6),DEV(6)

      DO 905 I=1,6
        SUM(I) = 0.
  905 CONTINUE

      DO 910 I=1,6
        DO 910 J=1,NUMRUN7
          SUM(I) = SUM(I) + HOLD7(I,J)
  910 CONTINUE

      F = FLOAT(NUMRUN7)
      DO 920 I=1,6
        AVG(I) = SUM(I)/F
  920 CONTINUE

      DO 930 I=1,6
        DIF(I) = 0.
  930 CONTINUE

      DO 940 I=1,6
        DO 940 J=1,NUMRUN7
          DIF(I) = DIF(I) + (HOLD7(I,J)-AVG(I))**2
  940 CONTINUE

      FLESS = F - 1.
      DO 950 I=1,6
      DEV(I) = SQRT(DIF(I)/FLESS)
  950 CONTINUE

      I = 50
      J = 90
      K = 95
      L = 100
      PRINT 960,NUMRUN7
      PRINT 970,CORBEG7,COREND7
      PRINT 975,DELX7,DELY7
      PRINT 976,ERRNAV7
      PRINT 977,ERRRCO7
      PRINT 978,POLICY7
      PRINT 979,SEED7
      PRINT 980
      PRINT 990,AVG(1),DEV(1)
      PRINT 1000,AVG(2),DEV(2)
      PRINT 1010,I,AVG(3),DEV(3)
      PRINT 1010,J,AVG(4),DEV(4)
      PRINT 1010,K,AVG(5),DEV(5)
      PRINT 1010,L,AVG(6),DEV(6)

  960 FORMAT(1H1,T10,*THE FOLLOWING STATISTICS ARE CALCULATED FROM*,T55,
     1I3,T59,*REPLICATIONS OF CORRIDOR SATURATION WITH THE FOLLOWING PAR
     1AMETERS:*)
```

```
 970  FORMAT(1H0,T10,*DISTANCE FROM LAUNCH TO CORRIDOR BEGINNING:*,T53,
     1F4.0,T58,*NM*,T64,*DISTANCE FROM LAUNCH TO CORRIDOR END:*,T102,
     1F4.0,T107,*NM*)
 975  FORMAT(1H ,T10,*DIMENSION OF CORRIDOR "BOXES":*,T42,F5.3,T48,*NM H
     1ORIZONTALLY BY*,T57,F11.9,T70,*NM VERTICALLY*)
 976  FORMAT(1H ,T10,*NAV ERROR STD DEV IS*,T31,F4.2,T36,*TIMES DISTANCE
     1 FLOWN*)
 977  FORMAT(1H ,T10,*RCO PERCEPTION STD DEV IS*,T36,F9.7,T46,*TIMES DIS
     1TANCE FLOWN*)
 978  FORMAT(1H ,T10,*RCO DECISION POLICY IS*,T33,F4.1)
 979  FORMAT(1H ,T10,*RANDOM NUMBER SEED AT BEGINNING OF SIMULATION IS*,
     1T59,F15.13)
 980  FORMAT(1H-,T100,*MEAN*,T115,*STANDARD DEVIATION*)
 990  FORMAT(1H0,T10,*CROSS-TRACK ERROR DUE TO AHRS-EQUIPPED DC-130 HEAD
     1ING ERROR(POS=LEFT,NEG=RIGHT)*,T100,F5.3,T106,*NM*,T115,F7.3,T123,
     1*NM*)
1000  FORMAT(1H ,T10,*CROSS-TRACK ERROR DUE TO INS-EQUIPPED DC-130 HEADI
     1ING ERROR(POS=LEFT,NEG=RIGHT)*,T100,F5.3,T106,*NM*,T115,F7.3,T123,
     1*NM*)
1010  FORMAT(1H0,T10,*NUMBER OF RPV'S REQUIRED FOR*,T39,I3,T43,*PERCENT
     1CORRIDOR SATURATION*,T100,F6.1,T115,F7.3)
      RETURN
      END
```

Appendix D

Sample Computer Program Output

```
PARAMETERS ARE SET AS FOLLOWS:

CORBEG = 100.   COREND = 150.   NUMRUN = 30   DELX = 1.000   DELY =   .250000000    LIMPPV = 1000
ERRNAV =   .03   ERRRCO =   .0072168 POLICY =    2.0

     CORRIDOR NUMBER   1 WOULD HAVE THE FOLLOWING CROSS-TRACK ERROR DUE TO DC-130 HEADING ERROR

     3.244   NM RIGHT OF DESIRED LOCATION WITH AHRS  -EQUIPPED DC-130 AIRCRAFT

     1.199   NM RIGHT OF DESIRED LOCATION WITH INS   -EQUIPPED DC-130 AIRCRAFT
```

COPPIDO? NUMBER 1 REQUIRED 15 RPV'S FOR 50 PERCENT SATURATION

THE FOLLOWING ARRAY DEPICTS SATURATION DENSITY

STRING1	STRING2	STRING3	STRING4	STRING5	STRING6	STRING7	STRING8
1	1	3	1	0	0	1	1
1	1	3	1	0	0	1	1
1	1	3	1	0	0	1	1
1	1	3	1	0	0	1	0
1	1	3	1	0	0	1	0
1	1	3	1	0	0	1	0
0	1	3	1	0	0	1	0
0	1	3	1	0	0	1	0
1	1	3	1	0	0	1	0
1	1	3	1	0	0	1	0
1	1	2	1	1	0	1	0
1	1	2	0	1	0	1	0
1	2	2	0	1	0	1	0
1	2	1	0	1	0	1	0
1	2	1	0	1	0	1	0
1	2	1	0	1	0	1	0
1	2	1	0	1	0	1	0
0	2	1	0	1	0	1	0
0	2	1	0	1	0	1	0
0	2	1	0	1	0	1	0
0	2	1	0	1	0	1	0
0	2	1	0	1	1	1	0
0	2	1	0	0	1	1	1
0	2	1	0	0	1	0	1
1	2	1	0	0	1	0	1
1	1	1	0	0	1	0	1
1	1	1	0	0	1	0	1
1	1	1	0	0	1	0	1
1	1	1	0	0	1	0	1
1	1	1	0	0	1	0	1
1	1	1	0	0	1	0	1
1	1	1	0	0	1	0	1
1	1	1	0	0	1	0	1
1	1	1	0	0	1	1	1
1	1	1	0	0	0	1	1
1	1	1	0	0	0	1	1
1	1	1	0	0	0	1	1
1	1	1	0	0	0	1	1
1	1	1	0	0	0	1	1
0	1	1	0	0	0	1	1
0	1	1	0	0	0	1	1
0	1	1	0	0	0	1	1
0	1	1	0	0	0	1	1
0	1	1	0	0	0	1	1
0	1	1	0	0	0	1	2
1	1	1	0	0	0	0	2
1	0	1	0	0	0	0	2
1	0	1	0	0	0	0	2
1	0	1	0	0	0	0	1
1	0	1	0	0	0	0	1

7 RPV'S MISSED THE CORRIDOR COMPLETELY UP TO THIS POINT IN CORRIDOR 1

CORRIDOR NUMBER 1 REQUIRED 31 RPV'S FOR 90 PERCENT SATURATION

THE FOLLOWING ARRAY DEPICTS SATURATION DENSITY

STRING1	STRING2	STRING3	STRING4	STRING5	STRING6	STRING7	STRING8
2	1	4	3	3	2	2	1
2	1	4	2	3	2	2	1
2	1	4	2	3	2	2	1
2	1	4	2	3	2	3	0
2	1	4	2	3	1	3	0
2	1	4	2	3	1	3	0
1	1	4	2	3	1	3	0
1	1	4	2	3	1	3	0
2	1	4	2	3	1	3	2
2	1	4	2	3	1	1	2
2	1	3	2	4	1	1	2
2	1	3	1	4	1	1	2
2	2	3	1	4	1	1	2
2	2	2	1	4	1	1	2
2	2	2	1	4	1	1	2
2	2	2	1	4	2	1	1
2	2	2	1	3	2	1	1
1	2	2	1	3	2	1	1
1	2	2	1	3	2	1	1
0	2	2	1	3	2	1	1
0	2	2	1	3	2	1	1
0	2	2	1	3	3	1	1
0	2	2	1	2	3	1	2
0	2	2	1	2	3	0	2
1	2	2	1	2	3	0	2
1	1	2	1	2	3	0	2
1	1	2	1	2	3	0	2
1	1	2	1	2	3	0	2
1	1	2	1	2	3	0	2
1	1	2	1	2	3	0	2
1	1	2	1	2	3	0	1
1	1	2	1	2	3	1	1
1	1	2	1	2	2	1	1
1	1	2	1	2	2	2	1
1	1	2	1	2	1	2	1
1	1	2	1	2	1	2	1
1	1	2	1	2	1	2	1
1	1	2	1	2	1	2	1
1	1	2	1	2	1	2	1
0	1	2	1	2	1	2	1
0	1	2	1	2	1	2	1
0	1	2	1	2	1	2	1
0	1	2	1	2	1	2	1
0	1	2	1	2	1	2	1
0	1	2	1	2	1	2	2
1	1	2	1	2	1	1	2
1	0	2	1	2	1	1	2
1	0	2	1	2	1	1	3
1	0	2	1	2	1	0	2
1	0	2	1	2	1	0	2

14 RPV'S MISSED THE CORRIDOR COMPLETELY UP TO THIS POINT IN CORRIDOR 1

CORRIDOR NUMBER 1 REQUIRED 41 RPV'S FOR 93 PERCENT SATURATION

THE FOLLOWING ARRAY DEPICTS SATURATION DENSITY

STRING1	STRING2	STRING3	STRING4	STRING5	STRING6	STRING7	STRING8
4	3	5	6	3	2	3	1
4	3	5	5	3	2	3	1
4	3	5	5	3	2	3	1
3	3	5	5	3	2	4	0
3	3	5	5	3	1	4	0
2	3	5	5	3	1	4	0
1	3	5	5	3	1	4	0
1	3	5	5	3	1	4	0
2	3	5	5	3	1	4	2
2	3	5	5	3	1	2	2
2	3	4	5	4	1	2	2
2	3	4	4	4	1	2	2
3	5	4	4	4	1	2	2
3	4	2	4	4	1	2	3
3	4	2	4	4	1	1	3
3	4	2	4	4	2	1	2
3	4	2	4	3	2	1	2
2	4	2	4	3	2	1	2
2	4	2	4	3	2	1	2
1	4	2	4	3	2	1	2
1	4	2	4	3	2	1	2
1	4	2	4	3	3	1	2
1	4	2	4	2	3	1	3
1	4	2	4	2	3	0	3
2	4	2	4	2	3	0	3
2	3	2	4	2	3	0	3
2	3	2	4	2	3	0	3
2	3	3	4	2	3	0	3
2	2	3	4	2	3	0	3
2	2	3	4	2	3	0	3
2	2	3	4	2	3	0	2
2	2	3	4	2	3	1	2
2	2	3	4	2	2	1	2
2	2	3	4	2	2	2	2
2	2	3	4	2	1	2	1
2	2	3	4	2	1	2	1
2	2	3	4	2	1	2	1
3	2	3	4	2	1	2	1
3	1	3	4	2	1	2	1
2	1	3	4	2	1	2	1
2	1	3	4	2	1	2	1
2	1	3	4	2	1	2	1
2	1	3	4	2	1	2	1
2	1	3	4	2	1	2	1
2	1	3	4	2	1	2	2
3	1	3	4	2	1	1	2
3	0	3	4	2	1	1	2
3	0	3	4	2	1	1	3
3	0	3	4	2	1	0	2
3	0	3	4	2	1	0	2

15 RPV'S MISSED THE CORRIDOR COMPLETELY UP TO THIS POINT IN CORRIDOR 1

CORRIDO? NUMBER 1 REQUIRED 57 RPV'S FOR 100 PERCENT SATURATION

THE FOLLOWING ARRAY DEPICTS SATURATION DENSITY

STRING1	STRING2	STRING3	STRING4	STRING5	STRING6	STRING7	STRING8
7	3	7	8	5	4	3	3
7	3	8	7	5	4	3	3
7	3	8	6	5	4	3	3
6	3	8	6	5	4	4	2
6	3	8	6	5	3	4	2
5	3	8	6	5	3	4	2
4	3	8	6	5	3	4	1
3	3	8	6	5	3	4	1
4	3	8	6	5	3	4	3
4	3	8	6	5	3	2	3
4	3	7	6	6	3	2	3
4	3	7	5	6	3	2	3
5	5	7	5	6	3	2	2
5	5	6	5	6	3	2	3
5	5	5	4	6	3	1	3
5	5	5	4	6	4	1	2
5	5	5	5	5	4	2	2
4	5	5	5	4	3	2	2
4	5	5	5	4	3	2	2
3	5	5	5	4	3	2	2
3	5	5	6	4	3	2	2
2	5	5	6	3	4	2	2
2	5	5	6	2	4	2	3
2	5	5	6	2	4	1	3
4	5	5	6	2	4	1	3
3	3	5	6	2	4	1	3
3	3	5	6	2	4	1	3
3	4	6	6	2	4	1	3
3	3	5	6	2	4	1	3
3	3	5	6	2	4	1	3
3	3	5	6	2	4	1	2
3	3	5	6	2	4	2	2
3	3	5	6	2	3	2	2
3	3	5	6	2	3	3	3
3	3	5	6	2	2	2	2
3	3	5	6	2	2	2	2
3	4	5	6	2	2	2	2
3	4	4	6	2	2	2	2
3	3	4	6	2	2	2	2
2	3	4	6	2	2	2	2
2	3	4	6	2	2	2	2
3	3	5	6	2	2	2	2
3	2	5	5	2	2	2	2
3	2	6	5	2	2	2	2
3	2	6	4	2	2	2	3
4	2	6	4	2	2	1	3
4	1	6	4	2	2	2	3
4	1	6	4	2	1	2	4
4	1	6	4	2	1	1	3
4	1	6	4	2	1	1	3

18 RPV'S MISSED THE CORRIDOR COMPLETELY UP TO THIS POINT IN CORRIDOR 1

THE FOLLOWING STATISTICS ARE CALCULATED FROM 30 REPLICATIONS OF CORRIDOR SATURATION WITH THE FOLLOWING PARAMETERS:

DISTANCE FROM LAUNCH TO CORRIDOR BEGINNING:100. NM   DISTANCE FROM LAUNCH TO CORRIDOR END: 150. NM
DIMENSION OF CORRIDOR "BOXES": 1.000 NM HORIZONTALLY BY .250000000 NM VERTICALLY
NAV ERROR STD DEV IS .03 TIMES DISTANCE FLOWN
RCO PERCEPTION STD DEV IS .0072168 TIMES DISTANCE FLOWN
RCO DECISION POLICY IS 2.0
RANDOM NUMBER SEED AT BEGINNING OF SIMULATION IS .1234567890123

	MEAN	STANDARD DEVIATION
CROSS-TRACK ERROR DUE TO AHRS-EQUIPPED DC-130 HEADING ERROR(POS=LEFT,NEG=RIGHT)	.101 NM	2.586 NM
CROSS-TRACK ERROR DUE TO INS-EQUIPPED DC-130 HEADING ERROR(POS=LEFT,NEG=RIGHT)	.001 NM	.653 NM
NUMBER OF RPV'S REQUIRED FOR 50 PERCENT CORRIDOR SATURATION	11.7	3.300
NUMBER OF RPV'S REQUIRED FOR 90 PERCENT CORRIDOR SATURATION	36.7	10.452
NUMBER OF RPV'S REQUIRED FOR 95 PERCENT CORRIDOR SATURATION	49.5	15.813
NUMBER OF RPV'S REQUIRED FOR 100 PERCENT CORRIDOR SATURATION	89.9	33.568

Appendix E

Statistics from the Validation Experiments

Table VIII

ANOVA TABLE FOR NUMRPV BY CORBEG, CORLEN, ERRNAV, AND POLICY (n = 480)

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIGNIF OF F
MAIN EFFECTS	10858600.025	4	2714650.006	172.589	.001
CORBEG	15697.969	1	15697.969	.998	.318
CORLEN	4188242.852	1	4188242.852	266.276	.001
ERRNAV	3609321.102	1	3609321.102	229.470	.001
POLICY	3045338.102	1	3045338.102	193.614	.001
2-WAY INTERACTIONS	1628684.796	6	271447.466	17.258	.001
CORBEG CORLEN	20059.602	1	20059.602	1.275	.259
CORBEG ERRNAV	3270.852	1	3270.852	.208	.649
CORBEG POLICY	1829.102	1	1829.102	.116	.733
CORLEN ERRNAV	387319.219	1	387319.219	24.625	.001
CORLEN POLICY	573875.852	1	573875.852	36.485	.001
ERRNAV POLICY	642330.169	1	642330.169	40.837	.001
3-WAY INTERACTIONS	74347.992	4	18586.998	1.182	.318
CORBEG CORLEN ERRNAV	3915.919	1	3915.919	.249	.618
CORBEG CORLEN POLICY	5651.269	1	5651.269	.359	.549
CORBEG ERRNAV POLICY	32587.552	1	32587.552	2.072	.151
CORLEN ERRNAV POLICY	32193.252	1	32193.252	2.047	.153
4-WAY INTERACTION	41571.019	1	41571.019	2.643	.105
CORBEG CORLEN ERRNAV POLICY	41571.019	1	41571.019	2.643	.105
EXPLAINED	12603203.831	15	840213.589	53.418	.001
RESIDUAL	7298234.900	464	15728.955		
TOTAL	19901438.731	479	41547.889		

Table IX

CELL MEANS AND STD DEVS FOR NUMRPV BY CORBEG, CORLEN, ERRNAV, AND POLICY (n = 480)

		ERRNAV=.01		ERRNAV=.05	
		CORLEN=30NM	CORLEN=70NM	CORLEN=30NM	CORLEN=70NM
CORBEG=80NM	POLICY=1NM	$\bar{x}$ = 108.7 s = 47.6	$\bar{x}$ = 192.7 s = 90.1	$\bar{x}$ = 159.7 s = 47.6	$\bar{x}$ = 298.8 s = 121.0
	POLICY=3NM	$\bar{x}$ = 154.9 s = 50.8	$\bar{x}$ = 293.6 s = 210.7	$\bar{x}$ = 315.3 s = 138.9	$\bar{x}$ = 649.0 s = 221.8
CORBEG=120NM	POLICY=1NM	$\bar{x}$ = 86.3 s = 31.7	$\bar{x}$ = 156.7 s = 54.0	$\bar{x}$ = 154.9 s = 50.8	$\bar{x}$ = 332.0 s = 112.0
	POLICY=3NM	$\bar{x}$ = 106.7 s = 47.5	$\bar{x}$ = 333.6 s = 196.5	$\bar{x}$ = 293.2 s = 102.1	$\bar{x}$ = 617.8 s - 178.7

Table X

ANOVA TABLE FOR NUMRPV BY DELX AND DELY (n = 120)

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARES	F	SIGNIF OF F
MAIN EFFECTS	10688935.617	2	5344467.808	194.544	.001
DELX	83055.408	1	83055.408	3.023	.085
DELY	10605880.208	1	10605880.208	386.065	.001
2-WAY INTERACTION DELX DELY	71687.408	1	71687.408	2.609	.109
EXPLAINED	10760623.025	3	3586874.342	130.566	.001
RESIDUAL	3186722.767	116	27471.748		
TOTAL	13947345.792	119	117204.586		

Table XI

CELL MEANS AND STD DEVS FOR NUMRPV BY DELX AND DELY (n = 120)

	DELY = 250 ft	DELY = 750 ft
DELX = .5NM	$\bar{x}$ = 832.8 s = 211.5	$\bar{x}$ = 189.4 s = 67.3
DELX = 2 NM	$\bar{x}$ = 732.1 s = 233.2	$\bar{x}$ = 185.6 s = 79.2

VITA

Robert William Neumann was born on 22 October 1947 in Jersey City, New Jersey. He attended the United States Air Force Academy and graduated in 1969 with a Bachelor of Science degree in Engineering Mechanics. Following graduation from Undergraduate Pilot Training at Vance AFB in August 1970, he was assigned to Pope AFB as a C-130 pilot. From January 1973 to December 1974, he served as a C-130 instructor pilot and flight examiner while assigned to the 345 Tactical Airlift Squadron in Taiwan and Okinawa. He served as the Airlift Liaison Officer with the 82nd Airborne Division at Fort Bragg from Jauuary 1975 until entering the School of Engineering, Air Force Institute of Technology in June 1976.

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The United States Air Force will possess the capability to employ several different remotely piloted vehicles (RPV's) for the conduct of chaff dispensing operations in the 1980's. An effectiveness analysis comparing force structure alternatives will provide information for decisions regarding RPV force mixes for that time frame.

A model which can be used to evaluate the effectiveness of various kinds of RPV's in the performance of chaff dispensing

missions is developed in this thesis. Based on the two vehicle operating parameters expected to differ significantly among the kinds of vehicles, navigational accuracy and reliability, the model combines analytical and digital computer simulation techniques to predict the number of vehicles required to successfully complete a chaff corridor saturation mission.

The methodology developed in this thesis can aid the RPV System Program Office in performing effectiveness analyses comparing existing systems. In addition, with modification of the simulation portion of the model, the methodology can be used to analyze the effectiveness of RPV chaff mission employment options and to evaluate the benefits derived from modifications to the existing weapons systems.