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OCEANIC SURVEILLANCE AND NAVIGATION ANALYSIS, FY 72

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16. Abstract

This report summarizes the Oceanic Surveillance and Navigation Analysis performed, at or under the direction of, the Transportation Systems Center under PPA FA-204 for FY72. A methodology has been developed by Systems Control, Inc. for relating the safety (collision risk) of the North Atlantic organized Track System in the lateral dimension to the general characteristics of the on-board navigation system, the independent satellite surveillance system and the ATC procedures. The initiation of this effort by TSC was reported in TR DOT-TSC-FAA-71-13. The analysis and results are detailed herein. Extensions of this methodology to the latitude and vertical dimensions are also discussed and preliminary results are presented. A study has also been initiated to investigate and evaluate various configurations of aided inertial navigation system in the NAT region. The requirements, goals and contract award for this study are reviewed.

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PREFACE

The work reviewed in this document was directed here at TSC with the major study effort done under contract by System Control Inc. of Palo Alto, California. This program is sponsored by the Federal Aviation Administration and is designed to insure future airsafety in the heavily travelled North Atlantic.

Methods of approaching the problem of assessing air safety to airspace and air system parameters have been established. Parameter and tradeoff studies have been conducted and preliminary conclusions reached. The intent of the original effort was to assess lateral safety in the presence of satellite surveillance systems. This hasnnow been extended to both three dimensional safety analysis with satellite surveillance as well as safety considerations in the presence of hybrid inertials.

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1.1 OBJECTIVES

This report summarizes the results of the TSC's FY 72 effort in analyzing the safety/capacity problems associated with air traffic in the North Atlantic (NAT) region. The current high density of traffic coupled with both the projected increase in air traffic, and the economic penalties associated with non-optimum routes will lead to the eventual requirement of reducing the separation standards between nominal tracks. This will increase the number of tracks in the fixed airspace proximate to the minimum time track. Such a reduction, however, must not result in unacceptable levels of risk probability. The work conducted under PPA FA204 has been directed to the problem of analyzing navigation and/or surveillance systems capable of maintaining acceptable safety standards while increasing airspace capacity.

1.2 BACKGROUND

The North Atlantic Organized Track System is represented schematically in Figure 1-1. The system is established on a twice daily basis to account for both varying weather conditions and the diurnal flow of traffic, (e.g., the predominant flow in one twelve hour period peaking at approximately 8:00 pm EST is eastbound whereas the predominant flow during the other twelve hour period is westbound). The eastbound tracks are established by the Gander Center and the westbound routes by the Shanwick Center at Prestwick, Scotland. The basic concept of the Organized Track System is to establish a minimum time route and then provide a sufficient number of tracks on either side of this route, and at different flight levels, to accommodate the anticipated traffic. The origin and termination of the oceanic tracks are called coast-out and coast-in points, respectively. An example of the available flight levels for eastbound and westbound traffic on a typical day are shown in Figure 1-2. (The figure illustrates that the predominant flow of traffic (17 out of 19 tracks) at the monitored time was eastbound.)

as a broad cross-section of private industry both in the United States and abroad. These studies have resulted in:

a. A set of minimum system standards (Ref. 3),

b. Data on various system parameters (Ref. 3),

c. A number of modelling techniques (the most universally accepted being the Reich Collision Risk model (Ref. 6-8), described below),

d. Initial attempts to analyze the safety as a function of airspace, navigation, surveillance, and aircraft parameters.

The primary purpose of PPA FA204 during the last two fiscal years has been to conduct a technical program designed to develop a necessary methodology for relating separation standards to collision risk, and to assess the impact of satellite surveillance and inertial navigation (with and without external aids) on flight operations in the NAT region.

This report is organized into three principal parts. The first deals with the assessment of lateral collision risk in the presence of an independent satellite ATC/surveillance system and is discussed in detail in Section 3.0. An extention of this collision risk investigation to the general three dimensional case, the second area of investigation, is presented in Section 4.0. Section 5.0 addresses the third concern, namely the feasibility of using an aided-inertial system in the absence of independent surveillance.

2.0 PROJECT PLAN AGREEMENT

2.1 INTRODUCTION

The effort undertaken in FY 72 represents a direct extension of the work begun in FY 71 under PPA FA204. This work involved a continued study of the effects of satellite surveillance, air traffic control and inertial navigation on lateral collision risks for the routing structure in the North Atlantic region. The work agreement also provided for an independent investigation of aided-inertial navigation systems for the NAT region.

2.2 OBJECTIVES AND TASKS

The major objective of the FY 72 effort was to analyze the impact of air traffic control and satellite surveillance on lateral separation standards in the North Atlantic region. It was also recognized that while this study would shed some light on the relationship between lateral separation standards and collision risk in the NAT region, the full impact of surveillance/ATC on collision risk would not be assessed until the methodology was extended to a full three dimensional analysis including the effects of vertical as well as in-track position errors.

The following paragraphs from the Description of Work characterizes the intent of the PPA:

> A number of Air Traffic Control/Surveillance concepts will be modelled and analyzed. Their relative and absolute performances will be assessed in terms of their impact upon collision risk for the parallel lane systems found in the Oceanic Regions. A parametric study relating the sensitivity of the fix times, lane widths, alarm rates and surveillance accuracies to safety levels and on-board navigation capabilities will be performed. Operational procedures related to each concept will be defined. Optimum relationships in the surveillance process will be presented. This effort will continue to be directed towards providing answers to the questions associated with defining the achievable reduction in aircraft separation standards.

ing the safety level of NAT routes, the main thrust of the initial analysis was to study tradeoffs among the different surveillance parameters for the lateral dimension, and thereby, to assess the feasibility of reducing the lateral separation standard.

3.1.3 Study Objectives

The potential need for a truly independent oceanic surveillance system has been defined by the projected increase in air traffic over the oceanic routes, especially in the North Atlantic, and the desire to minimize the economic penalites of flying non-optimum routes by reducing the separation standards. However, before any type of independent surveillance system is placed in operation, and any of the separation standards reduced, an adequate safety level for the projected route-structure must be guaranteed through extensive quantitative analysis. This analysis must include both factors that cause mid-air collisions, such as navigation system errors, surveillance positioning errors, airline scheduling - and factors that help precent them - route structure, surveillance fix rate, and ATC procedures.

During TSC's initial study, the problems associated with the lateral dimension were isolated, a detailed model and computational technique were derived, and results were obtained that demonstrated the impact of a proposed satellite surveillance system on the oceanic ATC system.

The objectives of this study were twofold. First, it was desired to develop the methodology for relating the safety (collision risk) of oceanic routes to lane separation standards. The second objective was to obtain preliminary numerical results to show the impact of satellite surveillance and inertial navigation systems (INS) on both the safety and separation standards of oceanic routes. Furthermore, three guidelines were established to specify the direction of the work. These guidelines were (1) that this work be related to (and not depart from, wherever practical) previously accepted methods for assessing collision risk, (2) that emphasis be placed on determining the time-varying nature of aircraft position errors and collision risk, and (3) that the effort should concentrate on the lateral (cross-track) dimension.

To achieve the above objectives the following tasks were defined:

a. Develop an oceanic ATC surveillance model to relate lateral lane separations to collision risk. The model was to be sufficiently flexible to include different ATC system elements (navigation and surveillance systems and ATC procedures) and to be extendable to the three-dimensional case (as discussed in Section 4.0).

b. Develop a numerical procedure (computer simulation) to relate lateral oceanic separations to collision risk for an inertial navigation system (INS) and a satellite surveillance system.

c. Define a set of baseline parameters for the Oceanic ATC Surveillance System that would provide the desired lateral lane separation with a level of safety equal to, or greater than the present target level.

d. Perform a sensitivity study of the baseline parameters in order to specify those parameters of the Oceanic ATC Surveillance System which would have the most influence in determining collision risk.

e. Analyze the results of the lateral study and recommend future areas of investigation.

3.1.4 RFP and Award

A RFP was issued, and announced in Commerce Business Daily on March 4, 1971 with a contract code designation of TSC/PS-0029 (Ref. 11). Twenty-six companies requested copies of the RFP and 11 responded with technical proposals. Following a thorough evaluation of the submitted proposals, Systems Control, Inc., of Palo Alto was chosen to perform the study. The contract was awarded on June 15, 1971 and the 6 month effort was begun on July 2, 1971.

3.2 SURVEILLANCE MODEL AND COMPUTATIONAL TECHNIQUE

3.2.1 Basic Elements of SCI Surveillance/Collision Risk Model

The problem of quantitatively assessing the relationship between route spacing and safety requires modeling the effect of each of the Oceanic ATC Surveillance System elements on the aircraft position errors. The interrelationships of these system elements is schematically presented in Figure 3-1. The Oceanic ATC Surveillance System responds to a source of position errors (navigation system, pilot, and aircraft), interacts with a monitoring system of these errors (satellite surveillance), and corrects these errors (ATC procedures). These three systems determine how the aircraft position errors are generated, detected, and corrected so that each aircraft will stay within its allocated boundary (one-half the separation standard in the lateral, vertical and longitudinal directions). The position errors are related to collision risk (safety level) through such factors as exposure to other aircraft and flying time.

3.2.2 Separation of Collision Risk and Oceanic ATC Surveillance Models

The approach that SCI chose to follow in relating safety to route spacing is to separate the complete modeling function into a collision risk model and a surveillance model as shown in Figure 3-2. This approach has several advantages. The primary advantage is that the Reich Collision Risk Model (Refs. 6-8, 12), which has been accepted by NATSPG and is reviewed below, can be used directly. In addition, many of the variables in the Reich model have already been assigned values. Second, since the satellite surveillance system itself is the major unknown system element, by separating the modeling functions and concentrating on the Oceanic ATC Surveillance System model, the impact of this system on spacing and safety can be determined most efficiently. Separating the ATC Surveillance and collision risk models allows a more adaptable and accurate way of modeling the aircraft position errors applicable to a surveillance mode of operation; and finally, the results of

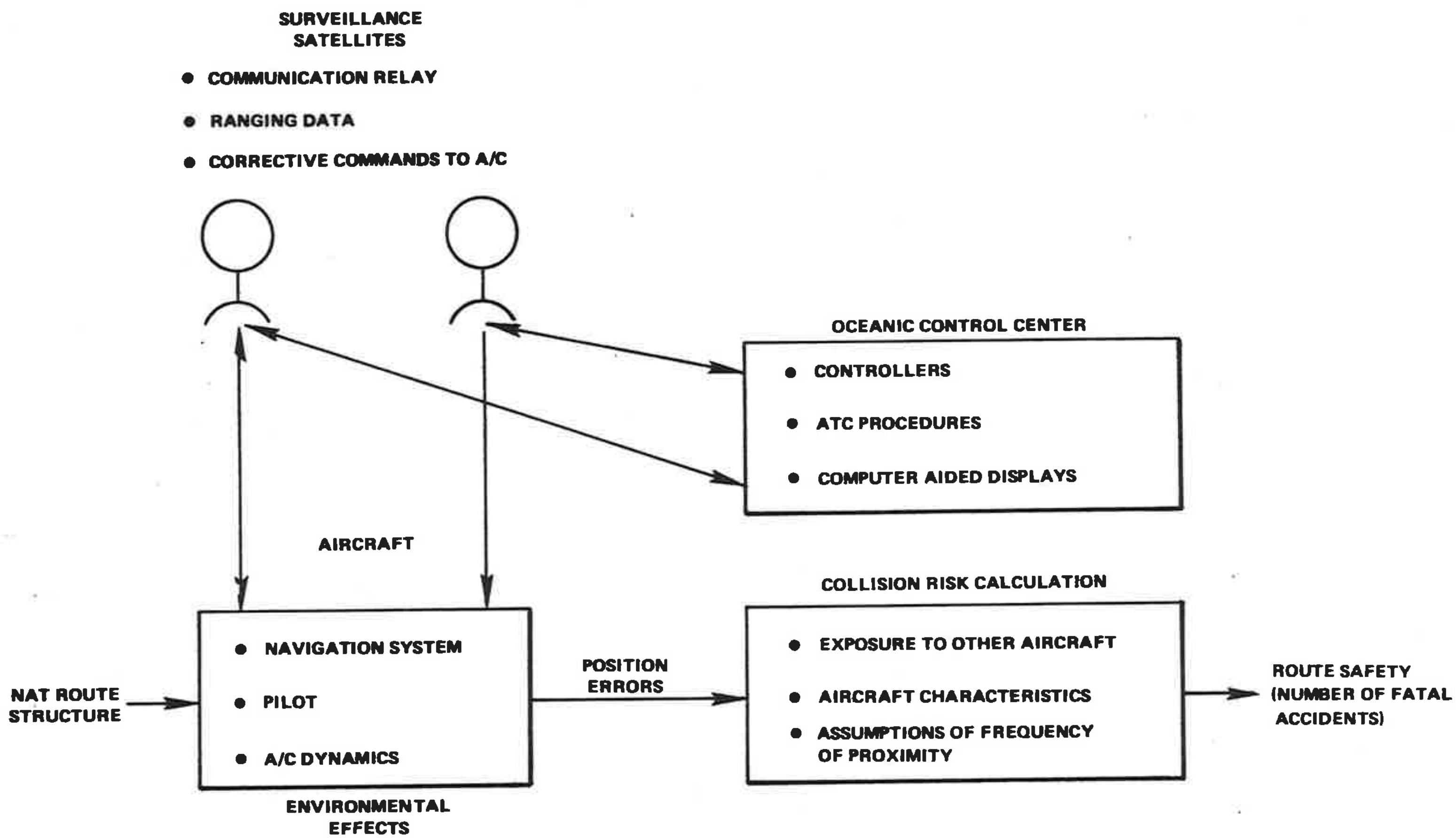


Figure 3-1. Elements of Oceanic Surveillance System

the first step (the distribution of position errors about one track and the probability of overlap for adjacent parallel tracks) are extremely useful in and of themselves.

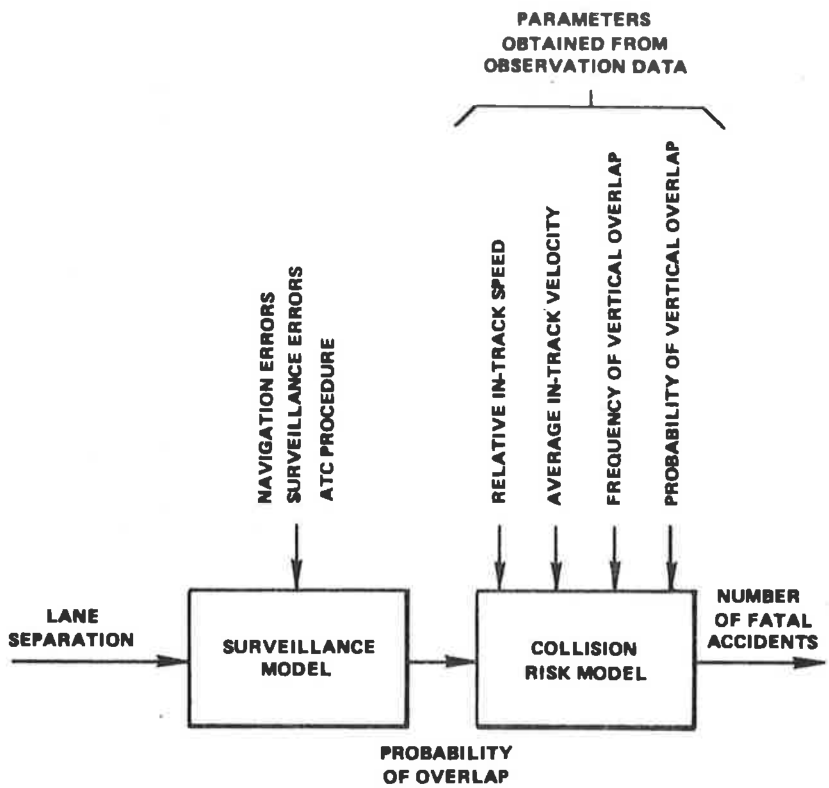


Figure 3-2. Separation of Surveillance and Collision Risk Models

3.2.3 Reich Collision Risk Model

Although the Oceanic ATC Surveillance model was of primary importance in the initial study, an understanding of the assumptions, required parameters, and validity of the Reich Collision Risk Model is important and is briefly discussed below.

3.2.3.1 Assumption to Risk Model - The Reich Collision Risk Model relates the expected number of accidents in 10 million hours of flying to aircraft characteristics, separation standards, and the frequency of aircraft position errors. The task of relating the expected collision rate to the probability of overlap in three dimensions is extremely difficult. To simplify this relationship, the Reich model contains three key assumptions.

1. Potential collisions can only occur between proximate aircraft (i.e., aircraft flying adjacent nominal positions).
2. Aircraft position errors in the three dimensions are independent.
3. Position errors of neighboring aircraft are independent.

These assumptions permit the lateral collision risk to be related directly to the probability of lateral overlap, the vertical collision risk to be related to the probability of vertical overlap, and so on. Furthermore, the lateral separation standard will only affect the calculation of the lateral collision risk; this holds for the vertical and longtidunal separation standards and the vertical and longitudinal collision risk, respectively. It is then possible to consider the separation standard/collision risk relationship in each of the three dimensions. The key parameter in the lateral collision risk equation is the probability of overlap between two laterally proximate aircraft. Therefore, the values for vertical and longitudinal overlap have been assigned nominal values.

As pointed out by Reich, the effect of each of the three assumptions listed above should be to make the final values of the Oceanic ATC Surveillance System parameters conservative. Assumption (1) and (3) have been shown to be fairly conservative on the basis of data gathered from actual flights. The conservative nature of assumption (2), however, is in serious doubt since even simple models of navigation errors demonstrate a correlation between the errors in the lateral and longitudinal dimensions. In any case, the basis for the assumption of independent position errors is completely invalid when considering composite separation standards (i.e., a collision under these track conditions requires large simultaneous errors in at least two dimensions). In addition, the lateral and longitudinal position errors in an INS system are known to be correlated, thus further invalidating this assumption. (The effect of this optimistic assumption is discussed in Section 4.0 which reviews the second phase of the SCI effort.)

3.2.3.2 Modeling Technique - A collision can occur only when two aircraft also coincide in altitude and in-track position. This coincidence depends on traffic (density as well as type of proximity - vertical or longitudinal), aircraft dimensions, and altitude and in-track aircraft position error statistics at nominally zero relative separation. Therefore, the Reich Collision Risk Model in each dimension is divided into two parts. The first consists of determining the "exposure to risk:. This is the period of time that pairs of aircraft, which are supposedly following different nominal flight plans, are actually proximate, (that is, within one separation standard of each other in each of the three dimensions). The second part consists of determining the number of collisions per unit of proximity time (collision rate) of these proximate aircraft. The expected number of collisions in 10^7 hours, can be expressed as:

$$\left\{\begin{array}{l}\text{Expected}\\\text{No. of}\\\text{Collision}\\\text{in } 10^7 \text{ hours}\end{array}\right\} = \left(\text{Const.}\right) \cdot \left(\frac{\text{Prob (collision)}}{\text{Duration of Proximity}}\right) \cdot \left(\begin{array}{c}\text{No. of}\\\text{proximities}\\\text{per hour}\end{array}\right) \cdot 10^7$$

namely, the product of the exposure frequency (hours of proximity per flying hours) and the collision rate.

The lateral collision risk, defined as the number of accidents occuring because of a loss of lateral separation, is mathematically expressed as a function of such parameters as:

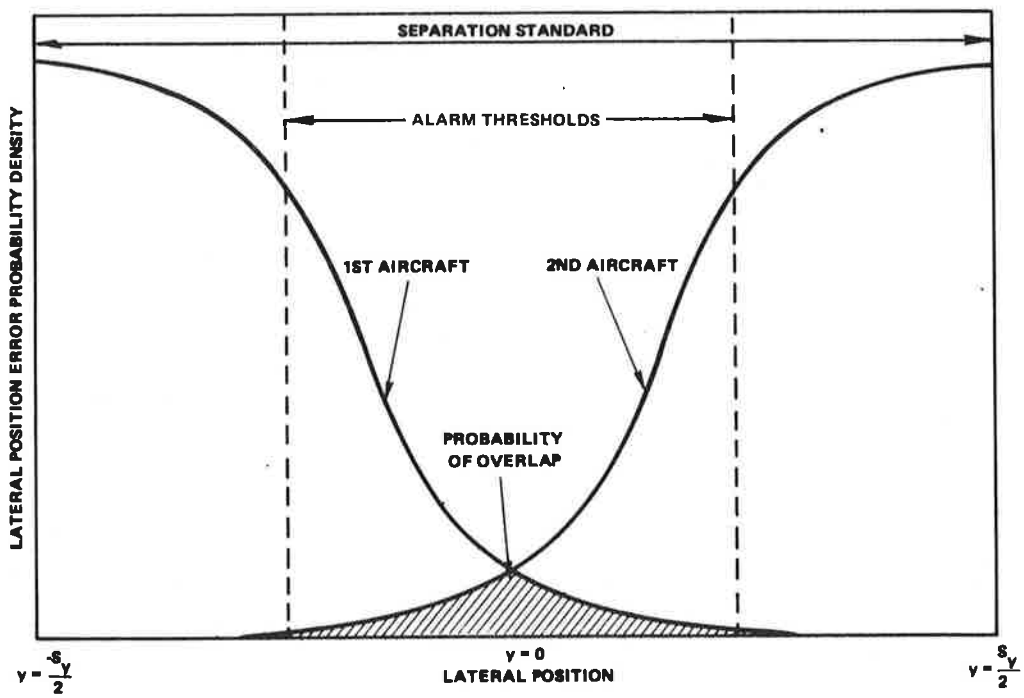
a. The percentage of time in which two aircraft are laterally proximate.

b. The frequency of vertical overlap between proximate aircraft.

c. The longitudinal and lateral aircraft dimensions, average aircraft speed, and relative cross-track velocity.

d. The probability that two aircraft, nominally separated by the lateral separation standard, overlap in the lateral dimension. [This is precisely the output of the surveillance model. (See Figure 3-2)].

3.2.3.3 <u>Position Error Density and Overlap Probability</u> - The lateral overlap probability is graphically represented in Figure 3-4 on the following page, where the two aircraft considered are assumed to be at the same vertical and longitudinal position and are flying on adjacent lanes whose center lines (i.e., the aircrafts' nominal lateral positions) are located at ± $S_y/2$.



nominal lateral position of aircraft #1

nominal lateral position of aircraft #2

Figure 3-3. Probability of Lateral Overlap

(It is important to note that since the probability of lateral overlap is a function of time the total collision risk will also be a function of time.)

As stated by Reich "... (I)t is the large, rare errors (rather than those of moderate size which forms the bulk of observations) that mainly determines the risk of collision" (Ref. 7). This can be readily gleaned by considering Figure 3-3. The more moderate (and hence more probable) the position errors of one aircraft, the smaller its effect is weighed in calculating the overlap probability. (For example, if one aircraft is close to its center line, a collision can occur between it and an adjacent aircraft only of the adjacent aircraft has suffered an extremely large - and extremely improbable positioning error - which places it in the vicinity of its lateral neighbor's nominal position) (Ref. 7).

A major finding of the recent NATSPG data collection exercise (Ref. 3) was that the tails of the distribution of lateral position errors was neither Gaussian nor exponential, but rather somewhere in between. Human blunders are one contributing factor to the larger occurence of gross blunders above the Gaussian level. These blunders include such errors as programming mistakes, miscalculations, and inefficiency or unawareness on the part of the crew. However, such factors are extremely difficult to model, which is unfortunate since they may be a major contributor to the collision risk value. A simplified, preliminary blunder model is included in the SCI model (and is discussed in more detail in Appendix F of reference 9). The program is in modular form and is capable of exercising more detailed blunder models.

SCIs computational techniques take full account of the requirement for accurately modeling the area and shape of the tails of the position error density. (This aspect is discussed briefly in the next section.)

3.2.3.4 <u>Parameters</u> - A number of parameters (including those listed on page 12) are required imputs to the Reich model. NATSPG has discussed the values of the various collision risk model parameters. These parameters were generally derived by either obsefving actual flights or hypothesizing aircraft behavior, and their results are thoroughly summarized in References 12 and 13. Many of these values were obtained during the data collection exercise undertaken by NATSPG in conjunction with its fourth meeting (Ref. 3), but some parameter values are still only rough estimates. Most of these values have not been updated for this study, although INS equipped aircraft were considered in deriving the cross-track velocity terms (Ref. 10). These parameters are listed in Section 3.3. Of these parameters, only the probability of overlap will be supplied by the Oceanic ATC Surveillance System model. At present, the other parameters have been assigned values based on observed data. (Note, a similar set of parameters is required for the vertical dimension and a somewhat different set for the longitudinal dimension.)

3.2.3.5 References - The reader is refered to the references for a more detailed and thorough analysis of the Reich Collision Risk. Model: its derivation and assumptions (Refs. 6-8, 12) its limitations (Ref. 9), its consequences, and some preliminary results obtained in its exercise (Refs. 3, 10, 14).

3.2.4 Oceanic ATC Surveillance System Model

3.2.4.1 Overview - The purpose of the surveillance model is to describe the relationship between the lane separation and the probability of overlap as a function of all the Oceanic ATC Surveillance System parameters. The general approach is applicable for determining the probability of overlap in each of the three dimensions although this section describes its application to the lateral dimension only.

The elements of the Oceanic ATC System considered in the SCI model include (1) the route structure, (2) the navigation system, (3) the surveillance system, and (4) ATC procedures. The model incorporates mathematical models of the navigation and surveillance system errors and the ATC control procedures in a computationally efficient algorithm to derive a closed form, probabilistic, time-dependent description of aircraft position errors. The mathematical development of the algorithm is included in Appendix A of Reference 9. This expression for the overlap probability can then be used as an input to the Reich Collision Risk model to obtain the safety level of the NAT routes.

One of the principal features of the SCI approach is to include time dependence in the analysis. This is considered imperative since the navigation and surveillance system error sources, the environmental effects, and the aircraft behavior itself, all vary with time. If this feature were to be eliminated, worst-case errors would have to be used, thereby resulting in needlessly conservative estimates of collision risk. The overlap probability, and therefore the collision risk itself, is calculated as functions of time into flight (or alternately as functions of longitudinal position over the North Atlantic).

Another major advantage to the SCI approach is that its computational technique is designed to produce closed-form expressions for position errors since previous studies have shown that Monte Carlo methods and even computer simulations of aircraft behavior are either impractical and/or in-sufficiently accurate or flexible.

The Oceanic ATC Surveillance System model essentially consists of two basic subsections as indicated in Figure 3-4.

a. The separate navigation, surveillance, and ATC control system models.

b. The computational algorithm for combining the above models to obtain a time-varying description of aircraft position errors and from this, the probability of overlap.

The purpose of each of the models in a is either to relate the appropriate error sources to a position error or to describe the aircraft's nominal behavior. The navigation system model which is developed in Appendix B of Reference 9 relates such error sources as gyro drift and human blunders.* to lateral aircraft position error. The surveillance system model, which is developed in Appendix C of Reference 9 is used to relate such error sources as ranging errors and geometric effects to the surveillance system positioning errors. In both cases, the model used consisted of simple one-dimensional descriptions relating the major error sources and the distribution of aircraft lateral position errors.

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*Human blunders, which may be an important source of errors, have been treated to only a very limited extent.

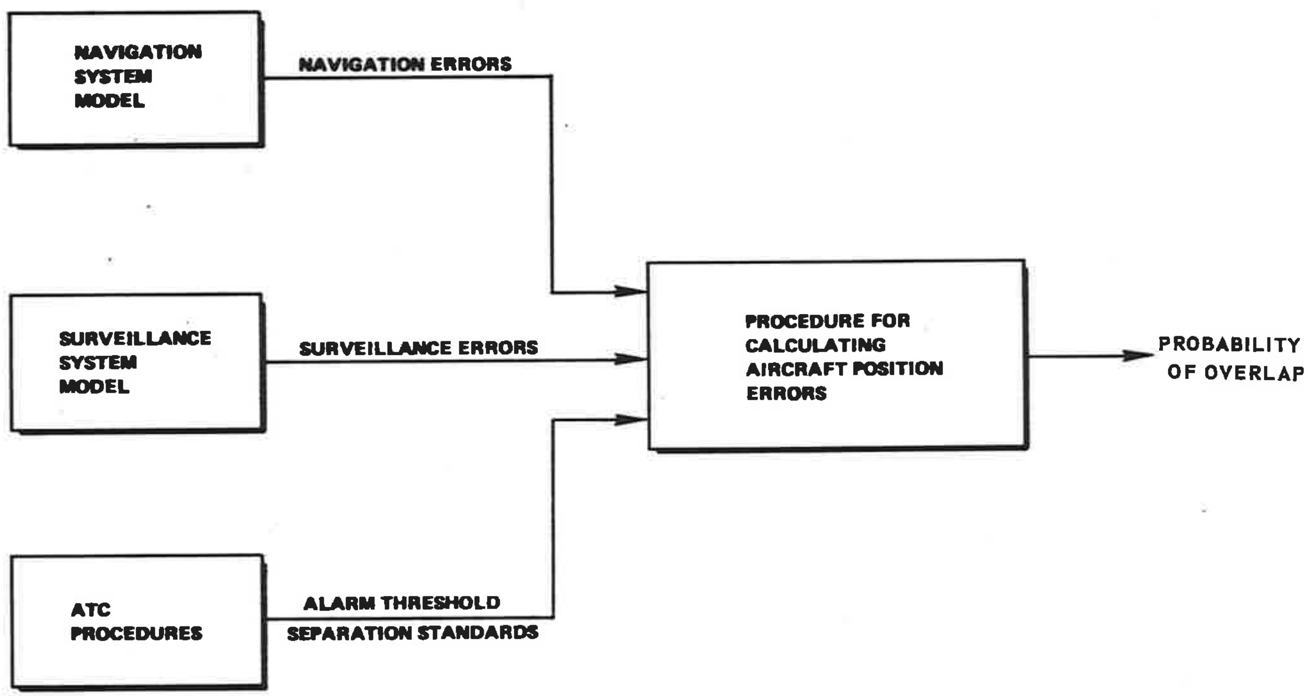

Figure 3-4. ATC Surveillance System Model

The ATC procedures describe the controller functions (issuing return commands after a surveillance alarm), the control philosophy that is used (tactical, strategic, time threshold, or position threshold), and the various ATC surveillance parameters (e.g., surveillance fix rate, alarm threshold). These factors will determine when and how often a surveillance alarm is to be sent.

Each of these models and computational algorithm are separately described in the following subsections.

3.2.4.2 Navigation System Model - The required output of the navigation system model is a time history of the distribution of position errors caused by the navigation system. In general, any type of navigation system such as Doppler, INS, Doppler updated by Loran, INS updated by OMEGA, etc., could be simulated to generate this required output.

The specific systems used in the study were present day inertial systems. There are two methods available for modeling these inertial errors. The first is to formulate empirical equations or tables that describe the distribution of lateral position errors as a function of time and flight direction. The second method is to derive an analytical model of the position errors of a typical INS. Complete descriptions of empirical and analytical models of the Litton LTN-51 and Delco Electronics Carousel navigators are to be found in Appendix B of Reference 9.

For this study, empirical models of navigation position errors of typical inertial navigators were used, since the primary concern was to analyze the effect of the navigation errors rather than the cause of these errors. The empirical results were based on actual navigation error data collected by airlines in tests and operational flights. Gaussian, lateral position errors were constant or assumed, the standard deviation growth with time being modelled either as a linearly increasing function. (Other potential time variations, such as with t^2 and $\sqrt{t}$, have been considered and can be treated with the Oceanic ATC Surveillance model.)

3.2.4.3 Satellite Surveillance System Error Model - Two prime candidate systems have been proposed for maintaining the safety level of NAT route structure with reduced lane separations. One such system is a hybrid inertial navigation system which uses external position information (i.e., Omega or satellite navigation) to update desired on-board inertial position. The hybrid system is discussed in some detail in Section 5.0. The other is an independent satellite surveillance system, namely one which determines the aircraft position independently from the aircraft's on-board navigation system. The independent character of such a system results in a number of advantages over dependent systems such as hybrid-INS. This independent satellite surveillance system was analyzed and used in both of the Systems Control Inc's studies (detailed in this and the following section).

Various systems have been proposed for satellite surveillance. However, the most likely system to exist and the one that is under consideration for the preoperational Aerosat program, is the two-satellite ranging scheme. As indicated in Figure 3-5 below, a

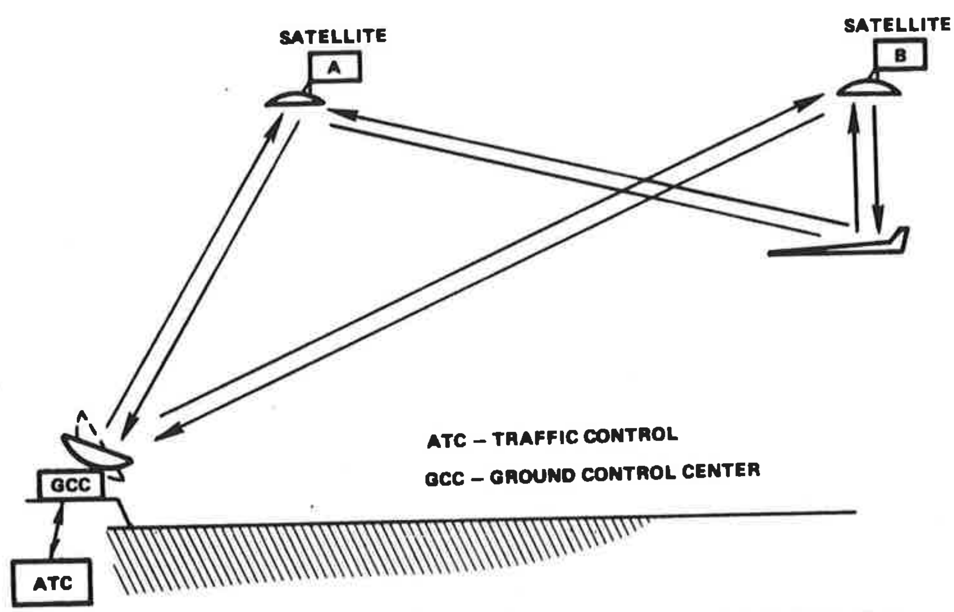

Figure 3-5. Two Satellite Surveillance Ranging Concept

signal is sent from the ground station to the aircraft by way of both satellites. A transponder on the aircraft returns the two received signals through the satellites to the oceanic control center. The timing of the signal to go out and return by two paths produces two range measurements. The aircraft's altitude, measured by an onboard barometric or radar altimeter, is also transmitted back to the ground station, so the aircraft's position can be determined by triangulation.

A model has been developed to relate the basic surveillance error sources in timing, satellite ephimeris, and the like to surveillance errors in latitude and longitude. The effect of each of these error sources on position fix error is strongly influenced by the geometry between the ground station, the satellite location, and the aircraft location. Therefore, the flight path of the aircraft must be known to produce the time history of the surveillance errors. The geometric effects resulting from the changing relative position of the aircraft and the satellites have also been included. The error model of the satellite surveillance system is presented in full detail in Appendix C of Reference 9.

3.2.4.4 <u>ATC Procedures</u> - ATC procedures describe the type of control philosoply that is employed and the type of corrective maneuvers sent to an aircraft after a surveillance alarm. These factors influence the aircraft position error distribution, first by determining when and how often surveillance alarms are to be sent and, second, by altering the intended heading of the aircraft producing an intended velocity component in the crosstrack dimension.

The control philosoply chosen for the current safety/lane separation tradeoff studies is strategic (independent of traffic conditions) and employs a position threshold. This means that, at each surveillance fix time, if an aircraft appears to have crossed the alarm threshold - i.e., an intermediate boundary between the intended track and the half-standard - the aircraft is given a surveillance alarm. (See Figure 3-6.)

The surveillance fix rate may be constant or may vary with aircraft position coordinates. (A constant rate was assumed in the analyses but variable fix rates are easily included in the Oceanic ATC Surveillance Model.)

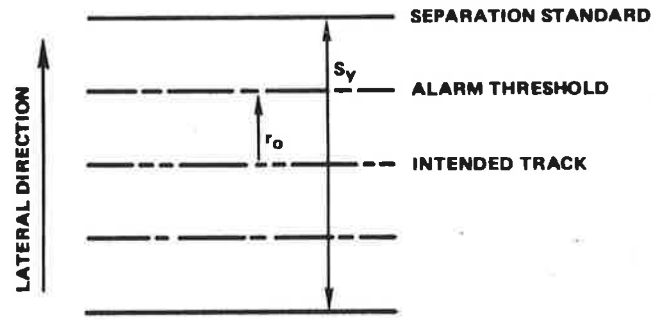

Figure 3-6 Location of Lateral Alarm Threshold

With a position threshold, the operation of the Oceanic ATC Surveillance System in the lateral dimension is assumed to proceed as follows:

a. The aircraft enter the surveillance region with some initial distribution of lateral position errors.

b. The aircraft are allowed to proceed unhindered as long as their positions do not appear to violate the alarm threshold.

c. When an aircraft appears to the surveillance system to have violated the threshold, its present position is updated with the surveillance system's estimate of its position and a return heading and velocity command is issued.

3.2.4.5 Computational Algorithm - The computational algorithm incorporates the outputs from the navigation and surveillance system models and the ATC procedures to calculate the probability of lateral overlap between aircraft on adjacent lanes. At the heart of this algorithm is a procedure for calculating the probability that an aircraft has a given lateral position error at a specified time, based on its specific past behavior. (See Figure 3-4.)

The computational procedure that makes use of the SCI Oceanic ATC Surveillance System model and that has been implemented for the lateral case includes the following steps:

a. Calculation of navigation and surveillance errors. Time histories (along a nominal route) of (1) the distribution of lateral position errors from the INS model and (2) the distribution of positioning errors from the surveillance model are calculated and stored.

b. Calculation of the time-dependent distribution of aircraft position errors about a single track. The time histories from step (a) are used to generate the time-varying distribution of cross-track position errors.

c. Calculation of the probability of lateral overlap. The probability of overlap is computed from the distribution of position errors step (b) for two adjacent routes. The distributions may be for two aircraft going either in the same or opposite directions.

d. Calculation of collision risk. The collision risk for two adjacent routes is computed by using the time-varying probabilities of overlap from step (c) and additional terms in the Reich model.

The required inputs to the computational algorithm, therefore, are:

a. The Oceanic ATC Surveillance System parameters (fix rate and alarm threshold).

b. The time-dependent probability density function for the navigation error.

c. The time dependent probability density function for the surveillance positioning error (which will vary as a function of an aircraft's position coordinates).

d. The ATC control procedures (NAT route structure, type of control philosophy, and separation standards).

e. The initial distribution of aircraft about the intended track.

f. The percentage of aircraft affected by human blunders and the range of such errors (e.g., ±10° in heading angle).

g. The maximum number of surveillance fix intervals it takes for an aircraft to fly a return trajectory (due to an ATC Surveillance system command) assuming no intervening surveillance alarms.

The steps by which the computational algorithm determines the probability of overlap from the information given by the inputs are as follows:

a. With the distribution of position errors specified at the first surveillance fix time, the position error probability density function is evaluated at the second surveillance fix time at N (nominally 20) values of possible (positive)* errors. (If the distribution is desired at any intermediate time, the same procedure is followed; however, only the initial distribution is used to propagate the distribution throughout the first interval.)

b. An interpolation routine (for the N points) is used to describe the position error probability density function at the second surveillance fix time.

c. The resulting interpolation is used (together with the initial distribution) to generate the probability density function of position errors at the N points for any time up to and including the third surveillance fix time.

d. The interpolation routine is used again, and the process repeated. In general, as many past surveillance fix time position error density functions will be required to describe the density function during the next interval as the maximum number of surveillance fix intervals it takes an aircraft to return to the intended track after a surveillance alarm.

e. The resulting time-dependent distribution of lateral position errors for aircraft about a single track is multiplied (convolved) with a second distribution of

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*The sensity of position errors is assumed symmetric; relative negative errors are the mirror image of the positive errors.

aircraft errors about an adjacent track (one separation standard away) at each point along the route. The end result is a time-dependent description of the probability of lateral overlap.

The calculation of the probability of a signle lateral position error at a given time (steps 1-4) is the keystone of the Oceanic ATC Surveillance model. The computation of this probability is described in detail in Appendix A of Reference 9. The computation of the probability of overlap from the two position error distributions is described in detail in Appendix D of Reference 9.

There is one key feature of the SCI Oceanic ATC Surveillance model that makes possible a closed-form solution for the complete position error probability density function. That is, that the "form" of the integral relationships which describe the probability of being at a certain point at a desired time (as a function of the position error distributions at previous fix times) is independent of the particular fix interval being considered. The only factors that change are the parameters describing the navigation and surveillance accuracy (as a function of time). The form of the expressions that incorporates the several models is invariant. This feature is also further described in Referance 9.

3.3 RESULTS

3.3.1 Baseline Parameter Values for Collision Risk Assessmemt

The first step in determining the impact of INS and satellite surveillance on the lane separation standards was to select a baseline set of values for the several parameters in the Oceanic ATC Surveillance System and Reich Collision Risk models. The collision risk for these parameter values was then determined, and a sensitivity study of the effect on collision risk of variation in these values was performed.

The baseline set of parameter values for the Oceanic ATC Surveillance System model were based either on experimental results (such as INS drift rates) or are considered to be easily attainable with projected technology (such as surveillance positioning accuracy). Two laterally adjacent paths that lie along the route given in the center lane of Figure 1-1 were also chosen. The surveillance errors were generated using an analytical model of the 1σ position error ellipsoid assuming the satellites were in synchronous, equatorial orbits at 10° and 70° W longitude. The surveillance system lateral positioning error is a function of position along the route.

The baseline values chosen are indicated in Table 3-1 below.

TABLE 3-1. SET OF NOMINAL OCEANIC ATC SURVEILLANCE SYSTEM PARAMETER VALUES

NAME	VALUE
Surveillance Fix Interval	10 minutes
Alarm Threshold	10 nmi
Lateral Separation Standard	30 nmi
Stand Deviation of Navigation System Drift Error	1 knot
Standard Deviation of Surveillance Positioning Error*	≅2 nmi
Standard Deviation of Initial Aircraft Position Error Distribution	3 nmi
Return Heading Angle	20°
Return Velocity	180 knots

*Surveillance positioning accuracy actually varies with position along the route. The figure given is the mid-range value for satellites located at 10° and 70° longitude.

The lateral collision risk, or number of accidents due to a loss of lateral separation, is mathematically expressed as a function of the following Reich collision Risk parameters:

a. The percentage of time in which two aircraft are laterally proximate. The time is included for same-direction traffic, both eastward and westward, E_y^e (same) and E_y^w (same) respectively, and opposite direction aircraft E_y (opp). These proximity times are functions of both the traffic density and route structure.

b. The frequency of vertical overlap of laterally proximate aircraft, $P_z(0)$, and the frequency with which such vertical overlap occurs, $N_z(0)$.

c. The along-track separation standard, S_x.

d. The following aircraft parameters:

   1. Average aircraft speed, $\bar{V}$;

   2. Average difference in along-track speed between two aircraft in adjacent lanes, $\overline{\Delta V}$;

   3. Lateral and longitudinal aircraft dimensions, λ_x and λ_y;

   4. Relative cross-track velocity. This is included for same direction aircraft, both eastward and westward, $\dot{y}^e$ (same) and $\dot{y}^w$ (same), and opposite direction aircraft, $\dot{y}$ (opp)

   5. The probability that two aircraft, norminally separated by the lateral separation standard, S_y, overlap in the lateral dimension. This is an outout of the Oceanic ACT Surveillance System model, is a function of time, and is included for same direction aircraft, both eastward and westward, P_y^e (same) and P_y^w (same), and opposite direction aircraft, P_y (opp).

The Reich Collision Risk equation for the lateral dimension, along with a detailed derivation of this equation from the basic assumptions, is given in References 6-8 and reviewed in References 3, 9 and 12.

The values for the different parameters (except for P_y) are given in Table 3-2 below, along with the sources from which these values were obtained. Although some of the parameter values are accurate with respect to current or projected technology (such as cross-track velocity and aircraft dimensions), several of them are based on outdated data and may therefore be optimistic. It was been determined however, that, for the expected range of parameter variations, changes in any single parameter, except those which directly affect the probability of overlap, we have relatively little effect on the collision risk level.[9]

TABLE 3-2. PARAMETER VALUES FOR REICH COLLISION RISK MODEL

PARAMETER	SYMBOL	DIMENSION	VALUE
Proximity Time	E_y(opp)	Percentage	.014*
	E_y^e(same)		.417*
	E_y^w(Same		.417*
Longitudinal Separation Standard	S_x	nmi.	120
Frequency and Probability of Vertical Overlap	$N_z(0)$	Cycles/hr.	20'
	$P_z(0)$	Probability	.25'
Aircraft Speeds	V	Knots	475
	ΔV	Knots	15
Aircraft Dimensions	λx	nmi.	.033[10]
	λy	nmi.	.033[10]
Relative Cross-Track Velocities (1σ errors)	$\dot{y}^e$(same	Knots	4.44+
	$\dot{y}^w$(same	Knots	2.96+
	$\dot{y}$(opp	Knots	3.7+

NOTES:

+ The 1 sigma relative cross-track error velocities were derived by averaging the velocity errors discussed in Reference 10.

*The proximity time was derived using an average number of daily NAT flights of 389. This forecast included a projected SST population end is therefore subject to revision. Experimental curves derived by Scott[16] were used to relate occupancy to average number of flights. A track structure similar to that shown in Figure 3-2 was assumed.

The probability of lateral overlap is not the only time-dependent term in the Reich model. Several others, principally the probability of vertical overlap and the relative cross-track velocities, are also functions of time. A full consideration of the time-dependence of these terms is included in the second phase of the SCI study (Section 4.0). Average values, taken from time histories of relative cross-track velocities, were used in the initial study.

3.3.2 Probability of Overlap

The probability of overlap, and hence the collision risk, is not only dependent upon the distribution of position errors about each track, but also is dependent on the direction of travel along each of the routes (east-east, east-west, etc.). There are three relative orientations two aircraft can have when they are laterally proximate. They can be both headed eastward, both headed westward, (flying side-by-side in both cases, since they are assumed to have the same nominal velocity) or one headed eastward and the other westward. If the two aircraft are headed in the same direction, the probability of overlap is found by using the same distribution of cross-track errors for both aircraft. The probability of overlap between the two aircraft is then a function of how long it has been since they left the coast-out points, or equivalently, their position along the route.

For aircraft which are headed in opposite directions, the probability of overlap is found by first specifying a position along the route and then determining what the position error distribution functions are for both an eastbound and westbound flight passing that point. In each case the overlap probability is derived by convolving the appropriate position density as indicated in Figure 3-3. The probability that there are two aircraft opposite each other at that point along the route is contained in the exposure factor of the collision risk equation.

Figure 3-7 shows the probability of overlap as a function of time into flight, both with and without (INS only) satellite surveillance. Both eastbound and westbound flights are included.

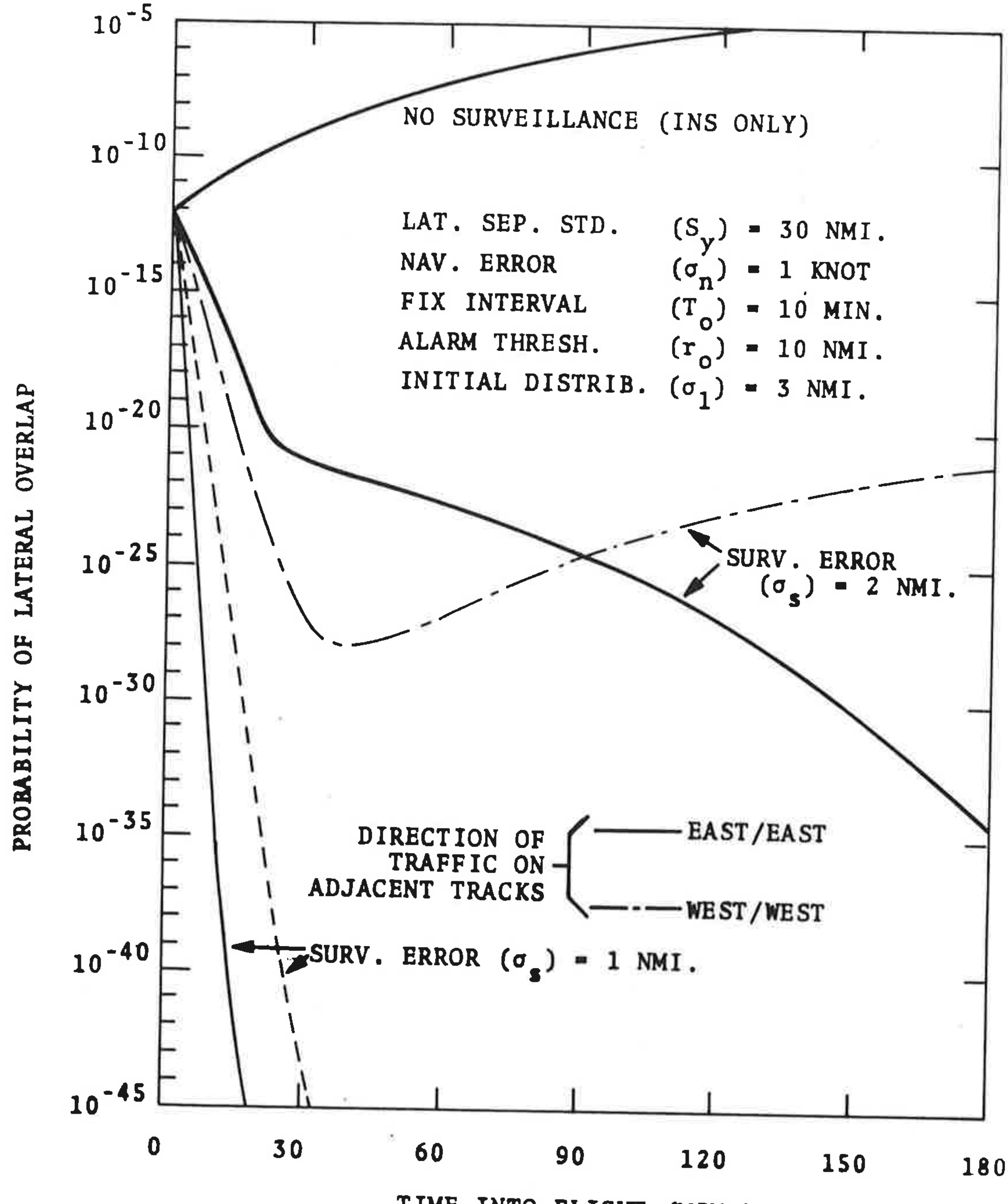

Figure 3-7. Probability of Overlap as a Function of Time for Eastbound and Westbound Flights

The aircraft are assumed to be in adjacent lanes and traveling in the same direction). The first point to note from this curve is the significant difference in the probability of overlap between (1) the case where INS only is assumed (no satellite surveillance), and (2) the cases where satellite surveillance is assumed. The lower values of overlap probability for the surveillance cases clearly results in a significantly lower collision risk (as is shown in the following section).

The second point to note from Figure 3-7 is the difference in the probability of overlap for the eastbound and westbound flights. This difference results almost entirely from geometric effects (i.e., the relative location of the satellites and the aircraft). The satellites are located in equatorial, synchronous orbit at 20° W and 70°W longitude. The aircraft are flying great circle routes. The cross-track surveillance errors are complicated functions of position related to the orientation of the error ellipsoids as a function of position along the variable latitude flight path. (Note therefore, that the lateral errors are not North errors and further that, the intrack errors experience opposite effects). The probability of overlap experiences on initial decrease because of the initial effectivenees of the surveillance system in identifying and correcting those aircraft beyond the threshold. This initial decrease is more pronounced in the case of westbound flights than eastbound flights because of the higher surveillance accuracy for the westbound flights at the beginning of its transoceanic flight. As the respective flights continue, however, the satellite surveillance error decreases as a function of time for eastbound, and increases as a function of time for westbound flights. If the satellite surveillance error were constant along the flight path, the effects would be suppressed. (Only a very small increase with time in both directions would be expected as a result of navigation system error build-up.)

The third point to note from Figure 3-7 is the dramatic decrease in probability of overlap that occurs when the satellite surveillance error is decreased from 2 nmi., to 1 nmi. This is a strong indication of the dominant role that is played by the satellite surveillance system as compared to the navigation system, in decreasing collision risk.

Figure 3-8 illustrates the variation in the probability of overlap as a function of both "position" and aircraft orientation (i.e., whether the two aircraft are both headed eastward, westward or in opposite directions). Note the similarity between Figure 3-7 and 3-8. For σ_s = 2 nmi. (nominal), the east/east cases are identical, but for the abscissa scale change from time into flight to degrees longitude. The west/west case in Figure 3-8 represents mirror image of the same case in Figure 3-7.

The decrease in the probability of overlap in the 45° to 20°W longitude region, as noted earlier, is due to the fact that the 1σ surveillance positioning error decreases when going from west to east, and increases from east to west. The "opposite direction" probability of overlap lies in between the eastward and westward curves since it is derived from one eastward and one westward position error distribution. The collision risk equation involves all three probabilities of overlap with each one being multiplied by a different (unequal) weighting factor.

3.3.3 Parameter Tradeoff Study

3.3.3.1 Nominal Collision Risk Function - The collision risk is obtained by combining the time-varying probabilities of overlap (Figure 3-8) with the Reich model parameters (in Table 3-2). For the baseline system parameter presented in Table 3-1, the collision risk is shown in Figure 3-9.

Because collision risk has been shown to be a function of position along the route, a problem arises when attempting to provide tradeoffs among the important ATC Surveillance System parameters. Simply stated, the problem is: At what point along the route should the position dependence be fixed and the tradeoffs performed with the associated value of collision risk? One approach would be to perform the tradeoff analysis where the collision risk is at a maximum, which is the most conservative solution. The results show that this maximum occurs at the end points.

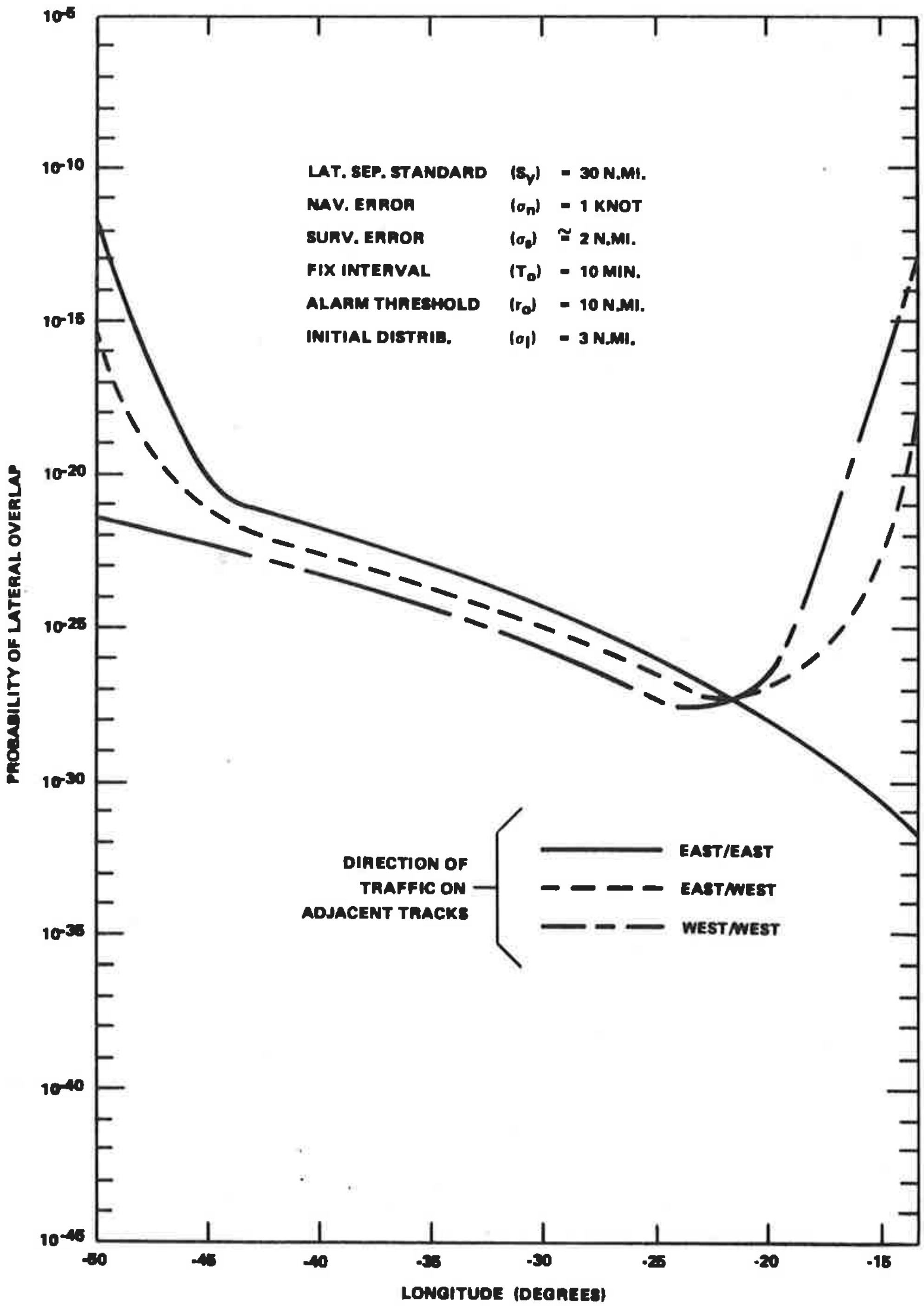

Figure 3-8. Probability of Overlap as a Function of Position

However, since (1) the initial distributions of position errors are not well-known, and (2) collision risk changes rapidly at these points, these points were not used. Instead, a point at 35° W longitude was used where the transient behavior of the collision

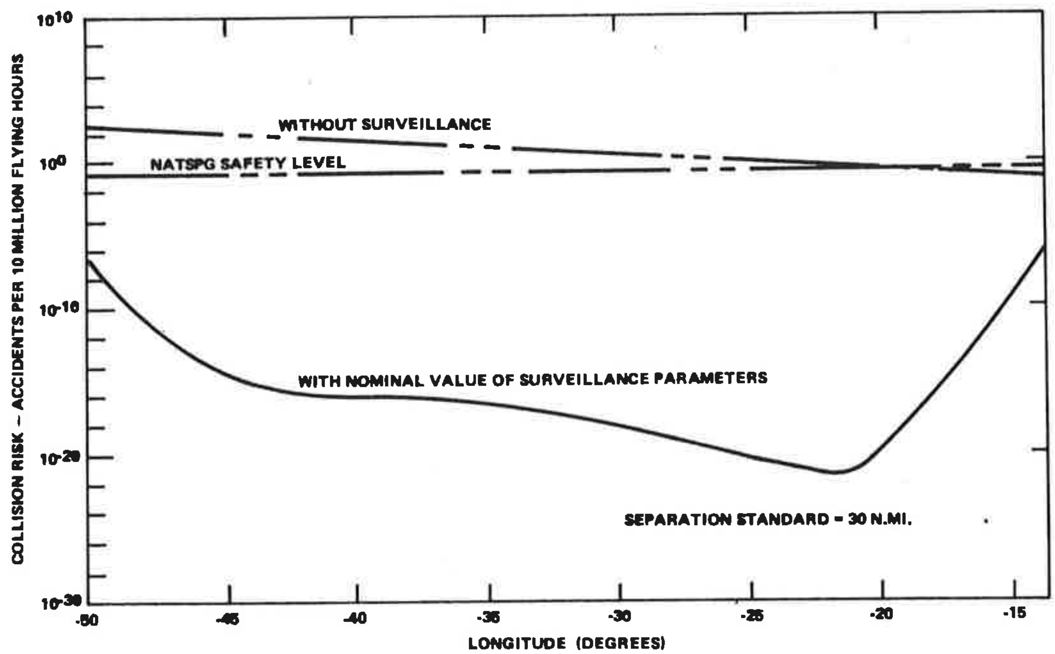

Figure 3-9. Collision Risk of Nominal Set of Surveillance Parameter Values

risk is less pronounced and the system appears to have reached some steady state. Therefore the collision risk parameter sensitivity can be investigated in the absence of transient, non-system effects; however, the actual tradeoff values will change if a different position is chosen (although this change can be shown to be of an absolute rather than relative nature).

This section will demonstrate the effect and relative importance of several ATC Surveillance parameters on collision risk. The data is presented in two ways: (1) parametric families of collision risk curves and (2) direct sensitivity tradeoffs among given parameters at 35° W longitude.

3.3.3.2 <u>Effect of Surveillance Error and Fix Interval on Collision Risk</u> - Figure 3-10 shows (1) the variation in collision risk with changes in the surveillance error (σ_s) and fix interval (T_o), (2) the present NATSPG target level of safety (.15), and (3) the collision risk with no surveillance (INS only). For all values of surveillance error (2, 1.5 and 1 nmi.) and fix interval (10, 7.5 and 5 min.) the collision risk for a 30 nmi. lateral separation is far below the NATSPG traget level. However, the collision risk with no surveillance (INS only) exceeds the target level of safety.

Several observations can be made from the curves in Figure 3-10 concerning the effects of the parameter variation. First, it is clear that the surveillance error has a relatively significant effect on collision risk while the surveillance fix interval does not. Although the fix interval has more effect when the surveillance error is smaller (1 nmi.), it is still relatively small. The reason for this weak dependence of collision risk on the fix interval is that because of the small navigation error drift rate (1 nmi./hr.), there is very little change in the aircraft position errors in 5 to 10 minutes.

The reason for the strong dependence of collision risk on surveillance error is simply that an increase in the surveillance error will result in a higher percentage of large position errors, in excess of the alarm threshold, being detected. This directly affects the tails of the distribution of position errors about the nominal track, the probability of overlap between aircraft on adjacent routes, and, therefore, collision risk.

An additional observation to be noted from Figure 3-10 is that regardless of the values of the surveillance error (σ_s) or fix interval (T_o), the values of the collision risk at both ends of the route are the same. This is because, with the 1σ initial positioning error taken as 3 nmi., the incidence of large cross-track errors is highest during the first stages of an eastbound or westbound flight. Therefore, in calculating collision risk at either end of the route, this "same direction" term dominates the rest, and since the initial distribution is assumed that the same

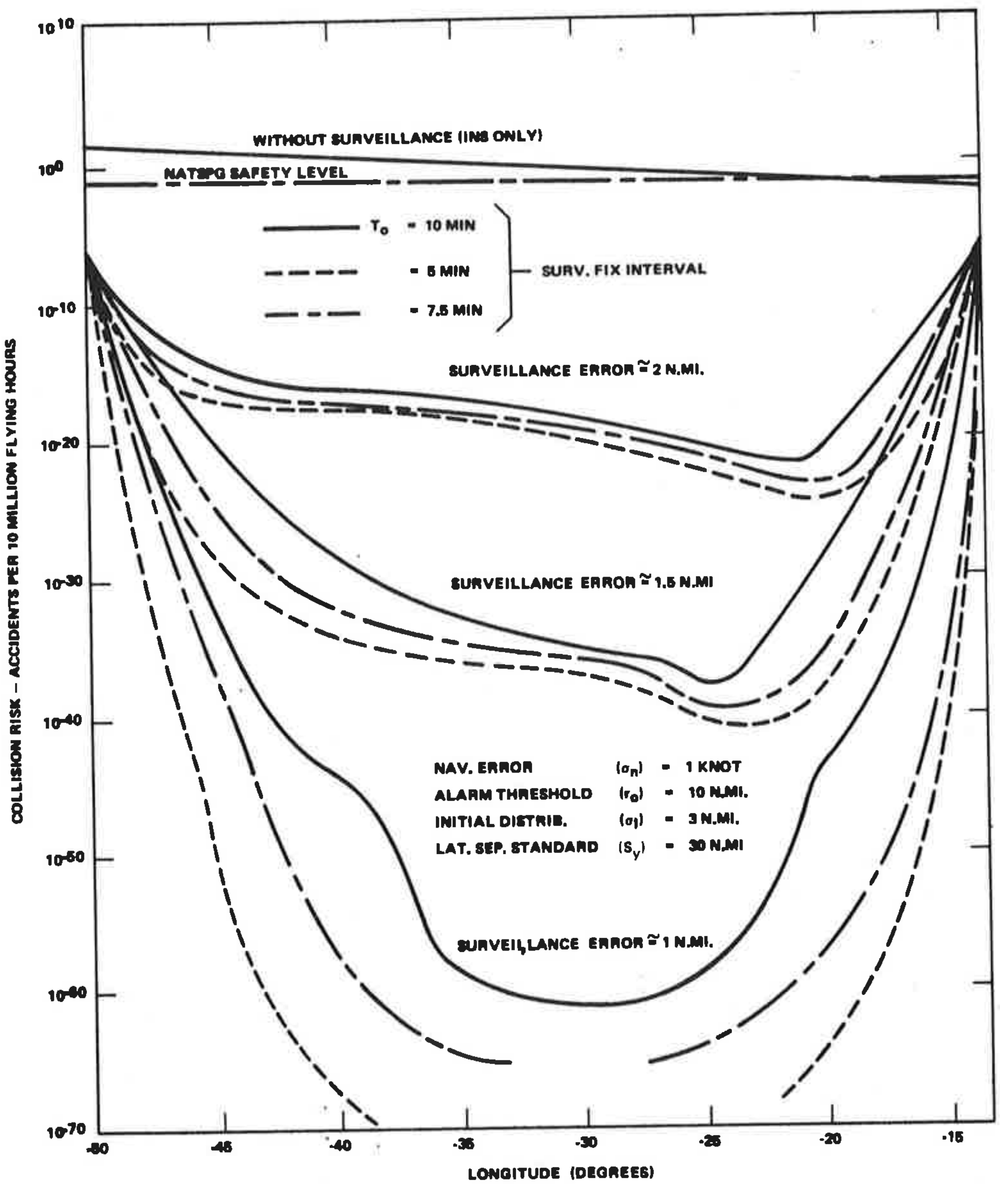

Figure 3-10. Collision Risk Vs. Position for Varying Surveillance Errors and Fix Interval

for all the cases (except when it is the object of the sensitivity study), the end points are fixed.

Other methods of presenting information of the effects of surveillance errors is to perform sensitivity analyses at a constant longitude (here, 35° W). The results of such procedures are shown below in Figure 3-11 and 3-12.

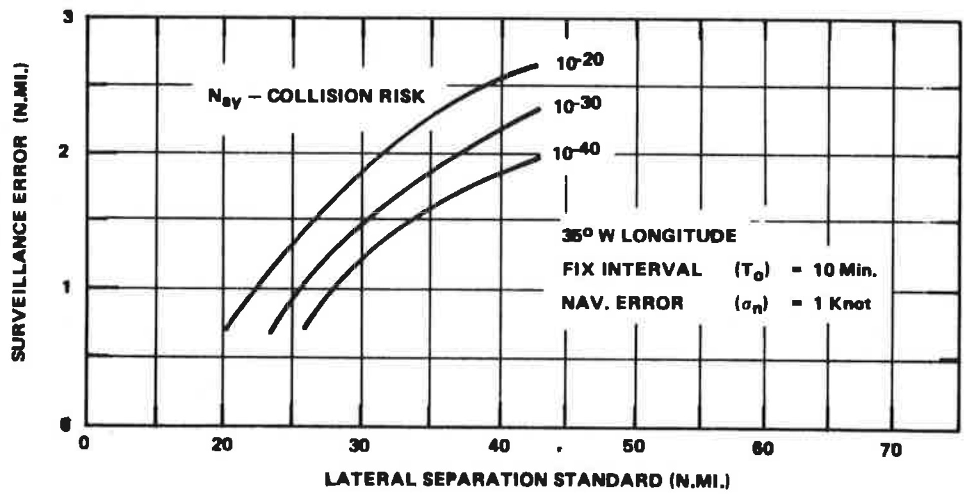

Figure 3-11. Surveillance Error as a Function of Separation Standard for Varying Collision Risk

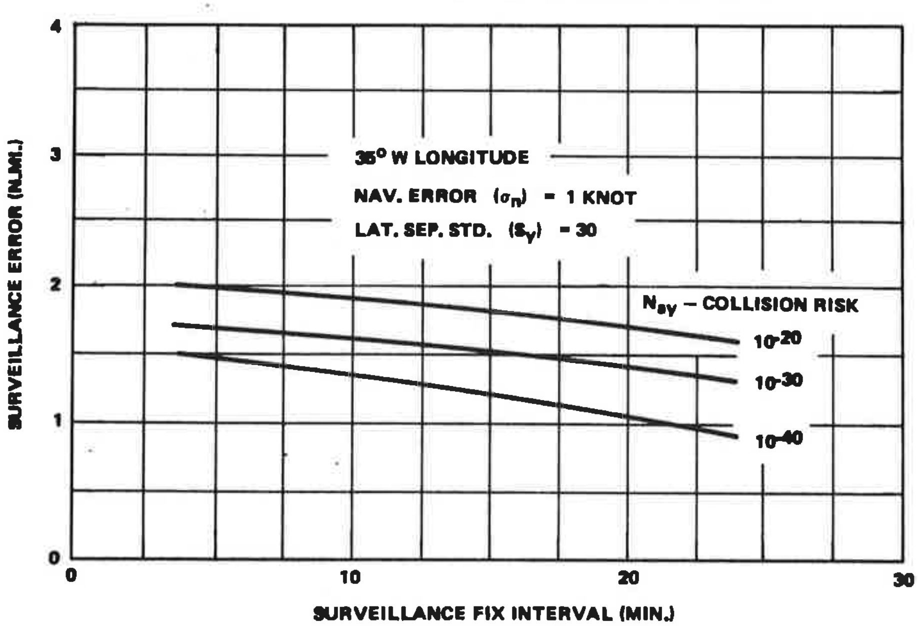

Figure 3-12. Surveillance Error as a Function of Surveillance Fix Interval

From Figure 3-11 it can be seen that a factor of two change in the surveillance error will have a drastic effect on the collision risk. It is possible to conclude, therefore, that a safe separation standard is much more sensitive to the surveillance positioning error than to the surveillance fix interval. This conclusion is further illustrated in Figure 3-12 which shows that for a separation standard of 30 nmi., the curve relating surveillance positioning error to surveillance fix interval is almost horizontal.

In Figure 3-13 surveillance positioning error is determined as a function of the surveillance fix interval for several values of lateral separation. With a 30 nmi. lateral separation standard, the value of fix interval that is chosen is not critical as long as surveillance positioning error of approximately 1.5 - 2.0 nmi. can be obtained. However, the influence of the fix interval on the required separation standard does increase as the value of the

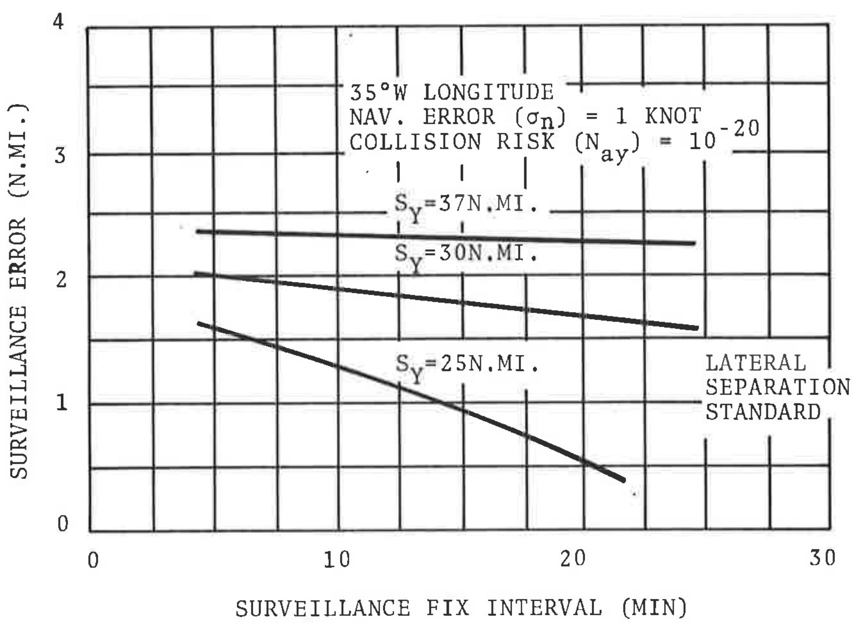

Figure 3-13. Surveillance Error as a Function of Surveillance Fix Interval for Varying Separation Standard

separation standard decreases, as shown by the changing slope of the curves. For example, a separation standard of 25 nmi. can be maintained by a twofold decrease in the surveillance fix interval (20 to 10 min.) and slightly over a twofold increase in surveillance positioning error (.6 to 1.4 nmi.) with the same safety level. Therefore, although the positioning error is the most critical parameter, the surveillance fix interval becomes more sensitive for small separation standards.

3.3.3.3 Effect of Separation Standard and Surveillance Fix Interval of Collision Risk - Figure 3-12 shows the time-varying collision risk for lateral spacings of 25, 30, and 45 nmi. as compared to the NATSPG target level of safety. The general effect of increasing the lane spacing is to decrease collision risk, as would be expected. Since the frequency (or probability) of the lateral position errors must decrease with increasing distance from the intended track, the larger the lane separations, the smaller the overlapping area under the tails of the error distributions about adjacent tracks. (See Figure 3-3.)

The numerical values of collision risk shown in Figure 3-14 indicate that a 25 nmi. lateral spacing is about the minimum value that could be supported without exceeding the NATSPG target safety level. A 30 nmi. spacing appears to be quite safe (3 to 20 orders of magnitude below the NATSPG level), and a 45 nmi. level is extremely safe (20 to 60 orders of magnitude below the NATSPG level).

Figure 3-14 also shows the weak dependence of surveillance fix interval on collision risk for the three lane separations that were considered. (This tendency was recognized above in Figures 3-12 and 3-13.) Parametric tradeoffs of surveillance fix versus lateral separation are shown below for the cases of (1) constant surveillance error and a parametric family of collision risks (Figure 3-15) and (2) constant risk for specific surveillance accuracies (Figure 3-16).

From Figure 3-15, it can be seen that, for a given separation standard, even a factor of two changes in the surveillance fix interval results in only a (relatively) minor change in collision risk. In Figure 3-16, the value of the surveillance fix interval is varied against the separation standard for two values of surveillance positioning error. Again we see that it is principally the

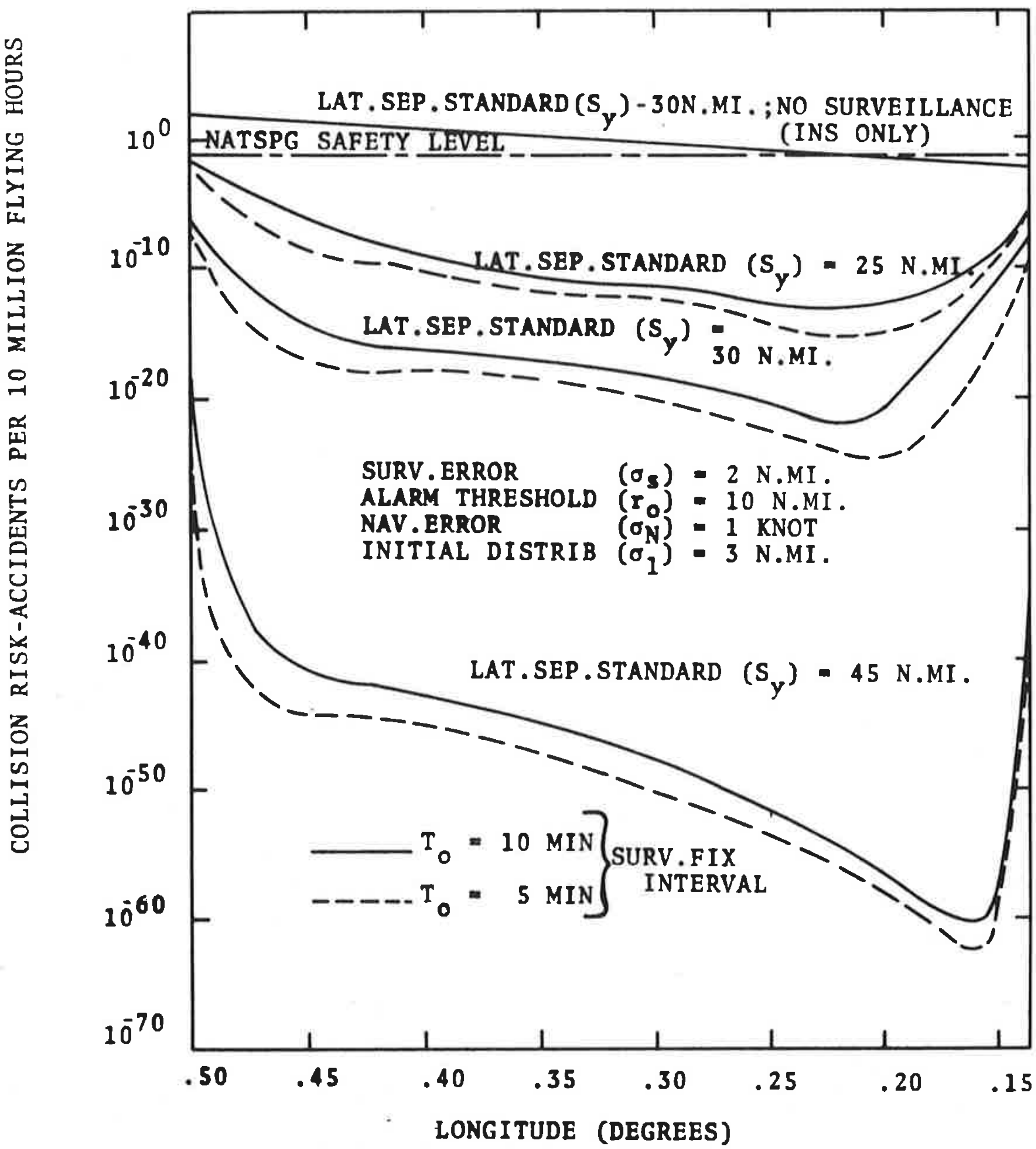

Figure 3-14. Collision Risk as a Function of Separation Standard and Fix Rate Interval

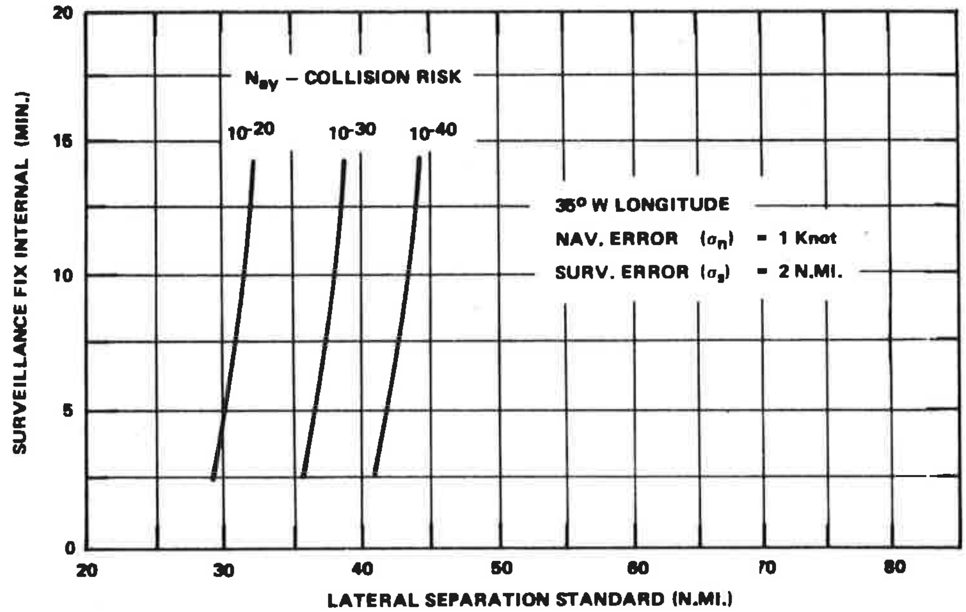

Figure 3-15. Surveillance Fix Interval as a Function of Separation Standard for Varying Collision Risks

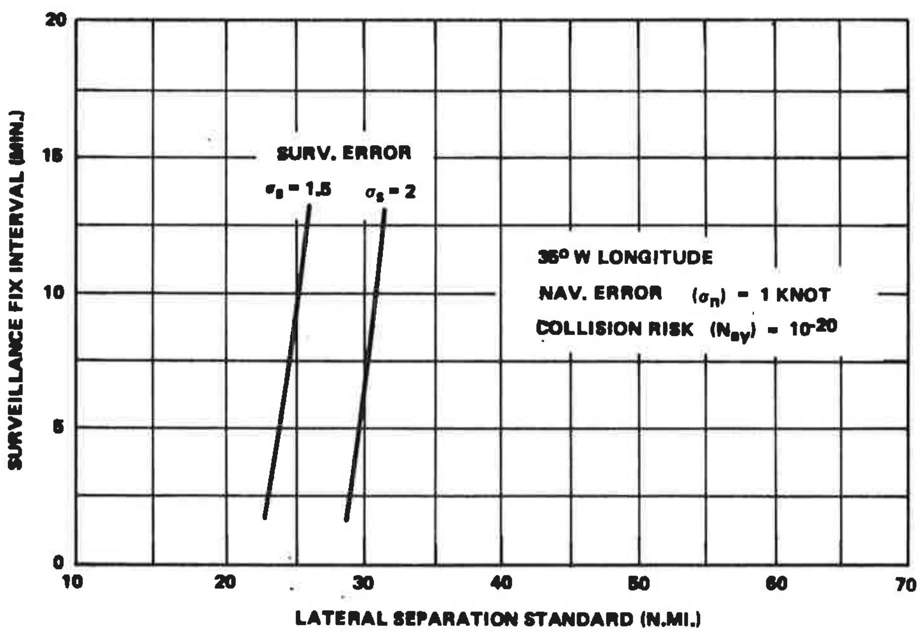

Figure 3-16. Surveillance Fix Interval as a Function of Separation Standard for Varying Surveillance Error

value of the surveillance positioning error that established a safe lateral separation standard. A 33% increase in the surveillance positioning error requires an increase of 5 nmi. in the separation standard to maintain the same collision risk level. However, the same increase in separation standard would allow much more than a threefold increase in the fix interval.

3.3.3.4 Effect of Initial Aircraft Position Errors - As shown in the preceding figures, the collision risk is highest for the initial and final portions of an oceanic flight. This suggests a strong dependence of initial position errors on collision risk, which is confirmed by the results in Figure 3-17. A change in the standard deviation of the initial position error distribution from 3 nmi. to 1 nmi. completely changes the initial and final collision risks. (Note: Because of the strong dependence of oceanic collision risk on initial position errors, the data analysis that is being undertaken by the British Board of Trade to determine statistics on the initial errors for westbound Atlantic flights will be of great value for future assessments of oceanic collision risk.[17].) It is also interesting to note that the collision risk level between the longitudes of approximately 40° W and 22° W is independent of the initial position errors. This seems to suggest that there is a steady-state behavior for collision risk, at least with respect to this set of surveillance errors.

3.3.3.5 Effect of INS Error on Collision Risk - The effect of varying the INS drift rate error (σ_n of 3 nmi./hr., 2 nmi./hr., and 1 nmi./hr.) on collision risk for INS only and INS with satellite surveillance is shown in Figure 3-18. (Note the translation in the vertical scale as compared to some earlier collision risk curves.) These results indicate the significance of INS errors on collision risk without satellite surveillance. However, with satellite surveillance even a threefold increase in the navigation error does not have a significant effect on collision risk.

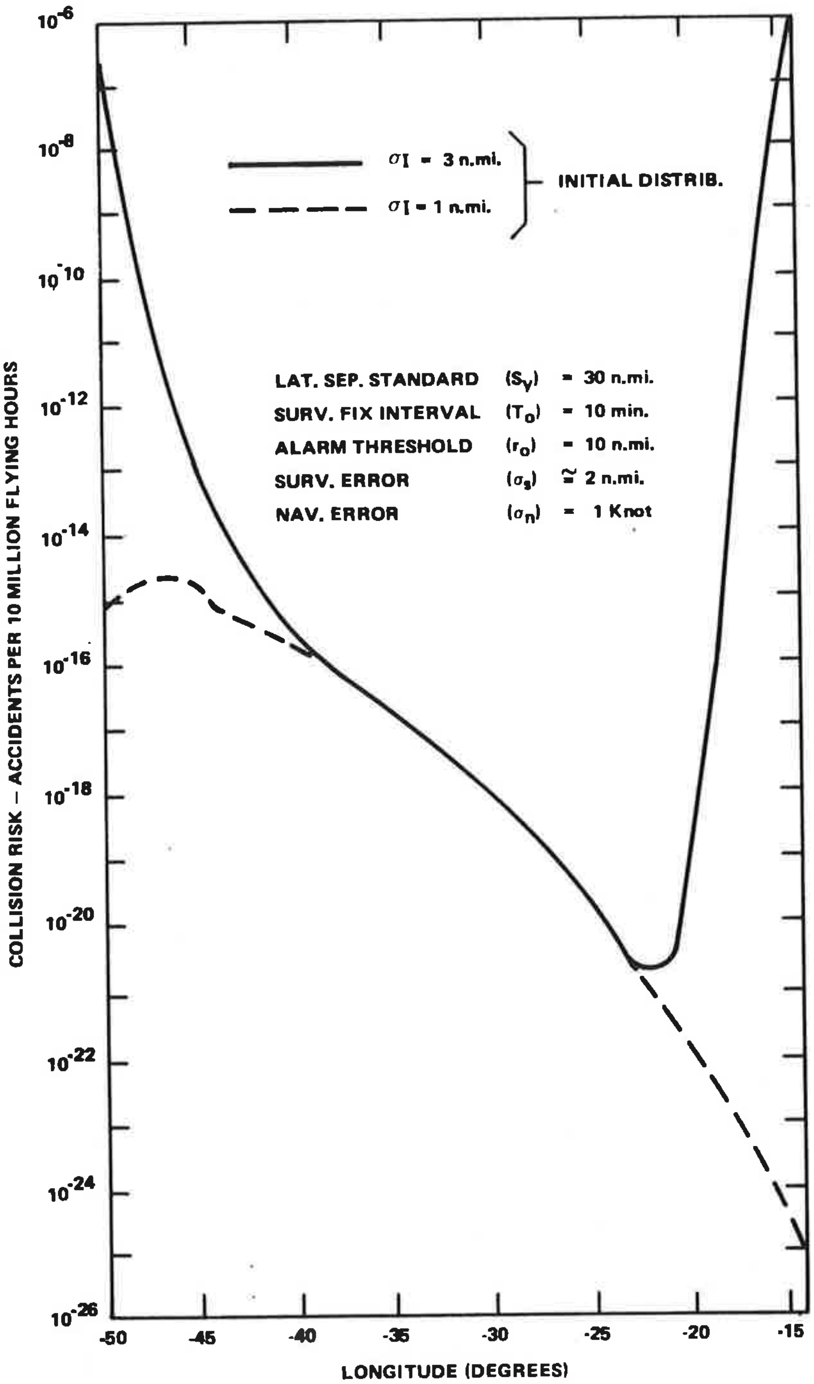

Figure 3-17. Effect of Change in Initial Error Distribution On Collision Risk

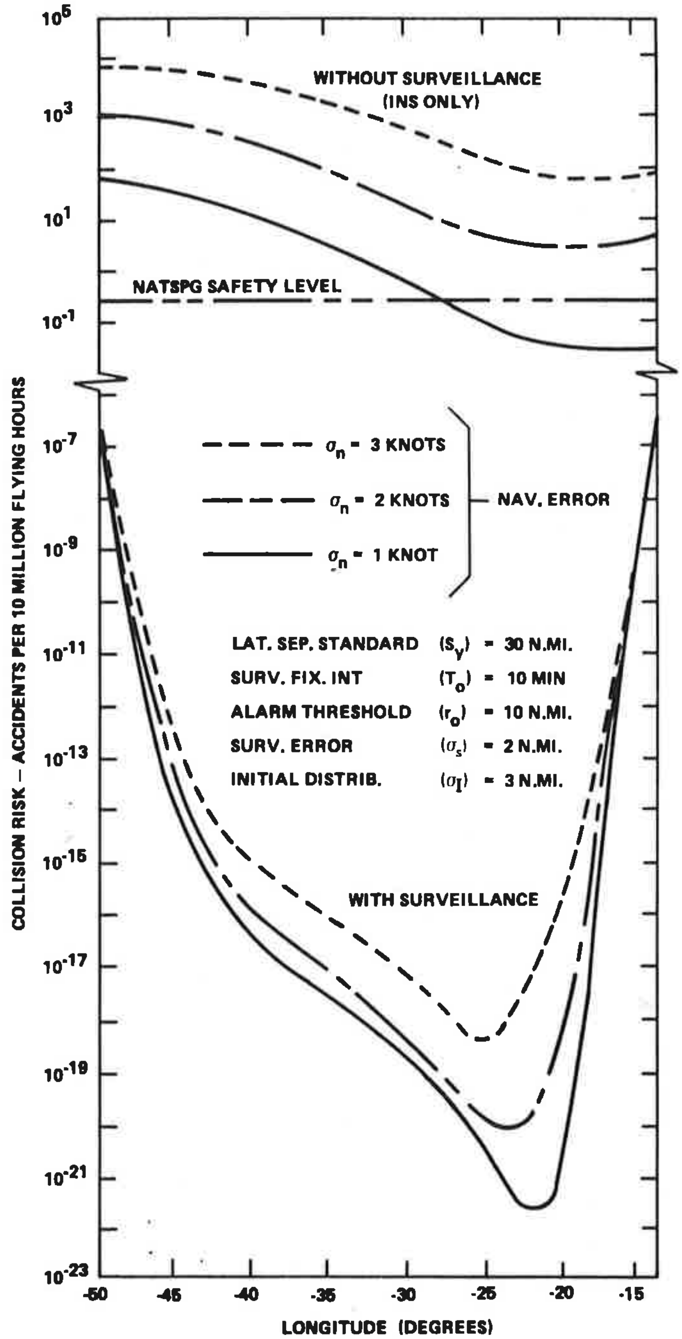

Figure 3-18. Effect of Change in Navigation Error on Collision Risk

The importance of the interaction between the navigation system and the surveillance system, and the relative errors between these systems should be mentioned. With a nominal surveillance error of 2 nmi. or less, a surveillance fix interval of 10 min. or less, and an INS drift rate of 2 nmi./hr. or less: (1) the drift rate between fix intervals is very small, and (2) a very small percentage of aircraft exceed the threshold (because of the surveillance error). With large navigation errors, more aircraft would approach the threshold boundary, and thus, the fix interval would be a more significant parameter. Also, it has been assumed that some means of updating the INS after a surveillance fix would be implemented. This means that the accuracy with which an aircraft can return to the assigned track is limited by the surveillance error (plus whatever INS drift occurs subsequent to updating).

3.3.3.6 Result Summary - It is possible to determine the expected safety, in the lateral dimension, of any parallel route structure with aircraft position errors being monitored by an independent surveillance system by using the Oceanic ATC Surveillance model developed by SCI. In particular, it has been shown that a satellite surveillance system, with a positioning error of 2 nmi. or less can safely support a lateral separation standard between parallel routes of 30 nmi. for aircraft equipped with INS with a 1σ position error drift of one knot. It has also been shown, through various tradeoff curves, that the surveillance positioning error is the most critical Oceanic ATC System parameter (for fixed separation standard) and that the collision risk is not particularly sensitive to the surveillance fix interval.

A more complete set of results can be found in the System Control, Inc. Interim Report of February 1972.[9]

3.4 CONCLUSIONS

a. The general approach that has been followed and the model that has been developed provide a useful means of relating the elements of an Oceanic ATC System (navigation, surveillance, and ATC procedures) to collision risk and the separation standard between parallel adjacent airway tracks.

b. Based on the assumptions of the model and the extent to which it has been exercised, the set of nominal Oceanic ATC Surveillance System parameters, which includes a satellite surveillance error of 2 nmi. or less, a fix interval of 10 minutes or less, and an INS drift rate of 1 nmi./hr. or less (all of which are considered to be highly conservative values), will support a lateral separation of 30 nmi. based on the present NATSPG target level of safety.

c. The level of collision risk for a fixed lane separation (or vice versa) is most strongly dependent on surveillance error, and less dependent on navigation error and surveillance fix rate.

d. Collision risk is time-dependent along typical NAT routes and very sensitive to initial position errors. For the distribution of initial aircraft poistion errors assumed in this study, collision risk was highest at the beginning and end of the oceanic route.

3.5 RECOMMENDATIONS

a. The model that has been developed should be used to determine the sensitivity of collision risk for a more complete range of Oceanic ATC System parameters.

b. The Oceanic ATC Surveillance model (including the ATC system elements) and the computational procedure should be extended to obtain probability of overlap in the in-track and vertical dimensions.

c. The Reich Collision Risk model should be extended and/or modified in conjunction with the Oceanic ATC Surveillance model to more accurately assess the complete three-dimensional collision risk.

d. A complete assessment of collision risk and its dependence on both the separation standards in each of the three-dimensions and the ATC parameters should be made using the models recommended in (2) and (3) above.

e. Statistics for the aircraft position errors at the origin of the oceanic routes should be compiled and used in the model.

f. Models of the ATC System should be expanded where required to provide a more accurate description of collision risk. This would include (1) more complete navigation system models, (2) different types of navigation system models that are in use or will be in use in the NAT region, (3) a model that more accurately described the surveillance error, including the oceanic tracking procedure, (4) different types of alarm threshold schemes and ATC procedures, and (5) more complete models of human blunders.

g. Studies should be made of aided inertial systems such as Omega-INS. Comparisons should be made between these hybrid-inertial systems and the independent satellite surveillance system proposed and analyzed in this study on the basis of safety, stability, convenience and cost.

Many of the first six recommendations are incorporated into the second phase of the SCI study, discussed in Section 4.0. The seventh recommendation is discussed in detail in Section 5.0.

4.0 OCEANIC ATC SURVEILLANCE SYSTEMS STUDY: EXTENSION TO LONGITUDINAL AND VERTICAL DIMENSIONS

4.1 INTRODUCTION

SCIs original analysis of Air Traffic Control and Surveillance in the North Atlantic (as presented in the previous chapter) was restricted to the lateral dimension. As an initial effort, it was successful in isolating the problems associated with oceanic surveillance and it fully demonstrated the impact of a proposed Satellite Surveillance System on the Oceanic ATC System. The methodology developed proved to be a valuable building clock for the ultimate goal of relating route structure to safety in complete three-dimensional generality.

This section describes preliminary results obtained by Systems Control, Inc. on Phase II of their Oceanic ATC Surveillance Systems Study. The follow up effect, funded under an extension to their original study contract, DOT-TSC-260 was negotiated on February 17, 1972 and was directed at extending the methodology developed during the first phase for the lateral dimension to the longitudinal and vertical dimensions. The Phase II study objectives, the task definitions and schedules, model extensions and preliminary results will be described in the sections to follow. A more complete review of this effort will be available after contract completion in September, 1972. This report review is preliminary and, therefore, somewhat cursory.

4.2 STUDY OBJECTIVES

The objectives were:

a. To extend and improve the Inertial Navigation System Model, the ATC/Surveillance Model and the Reich Collision Risk Model so as to reflect the three-dimensional character of the NAT route structure.

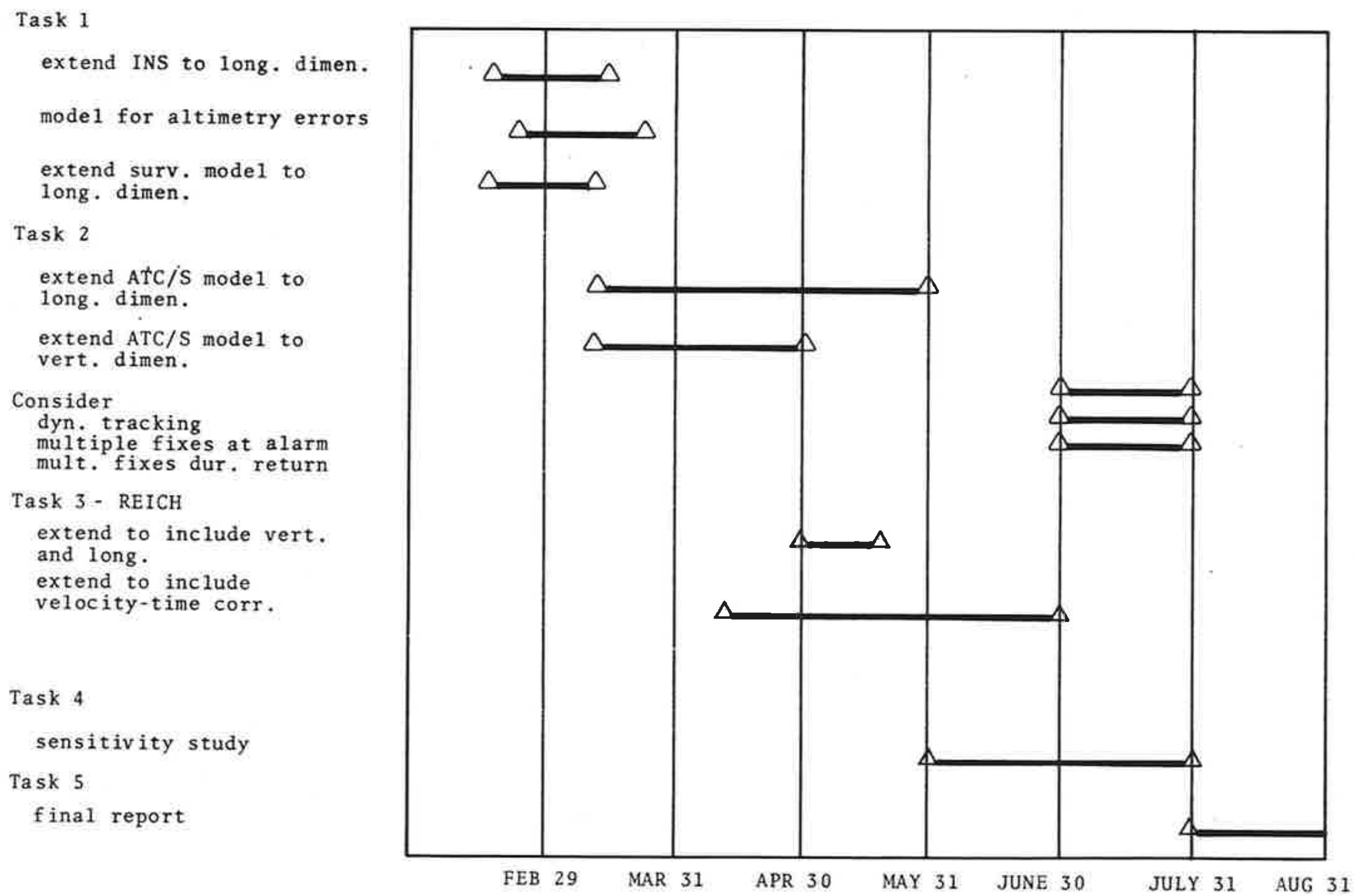

Figure 4-1. Extension on Contract DOT-TSC-260 Milestone Chart

error sources it has been found that the distribution of a single aircraft's vertical position errors can be represented by an initial Gaussian distribution with mean 0 and a standard deviation of 200 ft. and a random fluctuation with Gaussian statistics of (0, 75 ft.). This fluctuation is caused by the flight technical errors which are the only stochastic errors. This is shown schematically below in Figure 4-2.

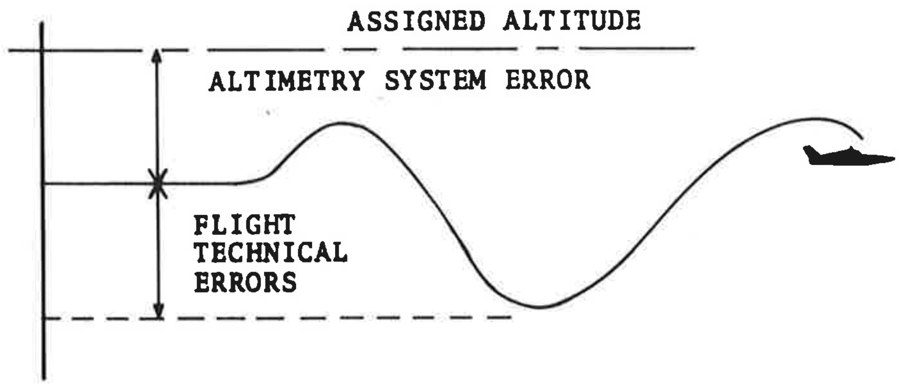

Figure 4-2. Vertical Model

The relative vertical speed between two aircraft can be expressed in terms of the phugoid frequency and amplitude as discussed by NATSPG in its fourth annual meeting.[3] Information on phugoid frequencies and amplitude obtained from the Boeing Corporation indicate the mean relative vertical speed is 2.05 knots.

4.4.2 ATC/Surveillance Model in Longitudinal Dimension

There are several problems specially related to longitudinal control such as (1) the coast-out queueing problem, (2) the economic penalties associated with indiscriminate speed changes - as differentiated from multiple heading changes in the lateral case - and (3) the built in tactical, domino relationship between all the aircraft in a queue track.

After some preliminary investigation of operating procedures in the North Atlantic, it was decided the following assumptions could reasonably be made:

a. Upon receipt of an ATC command, aircraft will either slow down or speed up to the extent of .02 MACH.

b. Once an aircraft has modified its velocity, it maintains that velocity for the remainder of the flight unless given a subsequent ATC longitudinal command. (Note that to recover 60 nmi. at .02 MACH will take over four hours).

In addition to these operational assumptions, it was decided to deal with pairs of aircraft in a tactical mode as opposed to single aircraft in a strategic mode. The control action that was assumed is that if the surveillance system detects that two aircraft are within half a separation standard of each other, it will order the one with the larger apparent position error (relative to its nominal longitudinal position) to modify its velocity.

The computer simulation program has to date been developed to the extent that the following operational conditions for two aircraft can be treated:

a. Different longitudinal velocities;

b. Different navigation systems;

c. Random initial separation (other than minimum allowable separation).

It is therefore possible to simulate the fast-following-slow situation or the accurate navigation system vs. the inaccurate navigation system situation.

4.4.3 Cross-Track Velocity

An analytical model has been developed for deriving the two dimensional distribution of relative cross-track position error and velocity. Under investigation at present is whether this distribution should be used for directly computing the frequency of lateral overlap, N_y, and thereby simplifying the Reich equations, or whether it should be used to compute the mean relative absolute cross-track velocity, and maintain the present Reich formulation. In any case, the logic for the cross-track case will be extended to the longitudinal case, as well.

4.4.4 Dynamic Tracking (Trend Analysis)

After preliminary discussions on possible controller - ATC System interfaces SCI is now analyzing an ATC procedure more sophisticated than the one fix, static control decision process modelled in their phase I effort. A tactical method is being investigated whereby a controller makes use of previous fixes in investigating trends away from nominal positions. The initial analysis has been concerned with the problem of trends of one aircraft away from the centerline of its nominal path (the lateral case). Later analyses will include the longitudinal case, namely using the trend of the separation distance between aircraft to adjust the longitudinal separation.

Referring to Figure 4-3 (given for the lateral case) the following assumptions were made:

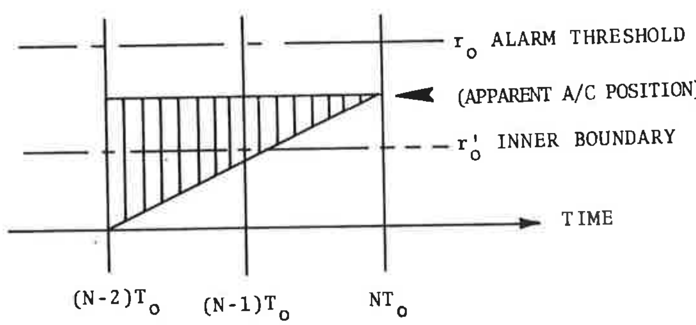

Figure 4-3. Dynamic Tracking Model

1. An inner boundary r_o' is designated such that if an aircraft appears to be between r_o' and the alarm threshold, r_o, its past performance is scrutinized.
2. If that aircraft appeared to be anywhere within region A during the past two surveillance fixes, it is considered to be drifting away from its intended track and is issued a return command.

The analytical work implementing these operational assumptions has begun, although, it is not to the point of computer programming. An analysis of how the logic for this implementation is to be incorporated into the ATC/Surveillance system model has not yet been completed and will not be included in this report. The results of this work will be included in SCIs final report due in August, 1972.

4.4.5 Baseline Parameters

Several computer runs were performed to investigate the sensitivity of the longitudinal probability of overlap to changes in several of the important parameters in the extended ATC Surveillance Model. These sample runs with the ATC/Surveillance longitudinal model were made with constant values for the navigation drift rate and the surveillance positioning accuracy. (Although the parameter values obviously vary with time and position, these dependencies were initially neglected.)

The set of baseline parameter values chosen are presented in Table 4-1.

TABLE 4-1. BASELINE PARAMETER VALUES (LONGITUDINAL CASE)

Longitudinal Separation Standard	S_x = 5 minutes (≈45 nmi.)
Surveillance Fix Interval	T_o = 10 minutes
Standard Deviation of Navigation System Drift Error	σ_n = 1 knot
Standard Deviation of Surveillance Positioning Error	σ_s = 2 nmi.
Standard Deviation of Initial Aircraft Position Error Distribution	σ_I = 0.5 minutes
Return Velocity	10 knots

4.4.6 Preliminary Results

The results of the four different runs are shown in Figure 4-4 along with the results, under similar conditions, for the lateral dimension, with a nominal separation of 30 nmi.

As can be seen the probability of longitudinal overlap for baseline parameter values is well below the NATSPG safety level*. A doubling of the nominal longitudinal separation further reduces the longitudinal risk by a factor of close to 10^{30}. As contrasted with the sensitivity of lateral risk, the dominant parameter in the longitudinal case appears to be the navigation drift rate, rather then the surveillance positioning accuracy. This is due to the tactical nature of the along track model. This is because the model is tactical and it is not until the aircraft have large position errors that an alarm is received. In the lateral dimension model (which was strategic) the alarm threshold acted as a boundary for large aircraft position errors. The transient behavior from an initial distribution of 10 sec. (1σ) (instead of 30 secs. (1σ)) again looks very different but appears to converging to the baseline results after two hours.

*The safety level is .15 collisions due to collapse of longitudinal separation in 10^7 flying hours.[1]

5.2 SIMULATION APPROACH

For the type of analysis anticipated with this program, it appears that an ensemble error analysis approach is the only feasible method. One ensemble simulation can provide the equavalent of a large number of Monte Carlo simulations which are costly and time consuming.

The error analysis will be performed by assuming a flight path and processing the resultant acceleration profile in a computer mathematical model of the navigation system. In the model, system errors are mathematically described by a covariance matrix and the purpose of the simulation is to determine how the covariance matrix changes with time while the maneuvering aircraft takes fixes with its several sensors. The required output of the navigation system model is a time history of the distribution of position errors caused by the navigation system.

It was expected that the simulation program accepted would make use of ensemble linear covariance analysis methods for calculating error time histories. Alternative proposed methods were considered, however, when sufficient justification is presented.

5.3 TASK DEFINITION

The work to be accomplished consists of the following items:[19]

a. Develop analysis techniques capable of evaluating aided inertial navigation systems utilizing external position measurements from the following candidate sources:

   (1) Doppler
   (2) Air Data
   (3) OMEGA
   (4) Satellite Surveillance (2 satellite ranging)

   Develop appropriate error models for each of the listed navigational aids. This development effort will emphasize the use of error models that accurately characterize currently available hardware or that which will become available in the near future.

b. Develop a navigation error analysis digital computer program which can be used to analyze various inertial aircraft navigation systems utilizing external position measurements from the candidate sources listed in Item 1. Mathematical models of the inertial system and candidate aids must be reviewed and approved by the TSC Technical Monitor prior to implementation. Special program requirements and technical specifications were also called for. They are reviewed in the next section.

c. Demonstrate the operation of the computer program by analyzing the performance of a navigation/guidance system to be specified by the TSC Technical Monitor. Document the results in the Final Report.

d. Implement the computer simulation program on a CDC 3800 to be designated by the TSC Technical Monitor. The contractor may propose development of the simulation program for an alternate computer if compelling technical reasons are presented. The contractor will provide program documentation and user instruction manuals as specified. (See next section.)

5.4 PROCUREMENT REQUIREMENTS

5.4.1 Navigation System Simulation

The computer simulation program will be coded in a modularized form to facilitate the evaluation of desired system configurations. This form will allow the user greater freedom in specifying particular subsystem components and also allow the use of alternative estimation algorithms. In addition, the following factors will be considered and accounted for in the simulation:[19]

a. Incomplete measurements

b. Intermittently available radio fixes

c. Effects of on-board computer size, accuracy, speed

d. Means for evaluating the sensitivity of the estimation

e. Effects of suboptimal filtering

d. Discuss feasible navigation system configurations and indicate the most likely system to be implemented.

2. Technical Approach

a. Model Selection - Indicate the mathematical models you intend to employ in analyzing the performance of aided inertial navigation systems. Indicate the degree of complexity of the position estimation algorithm you intend to use.

b. Solution method - Indicate the general techniques you envision, as necessary, to solve the problem at hand. Specify the advantages of your techniques over other possible approaches. (For example: Do you favor a probabilistic or deterministic approach? Will a hybrid approach be necessary?).

c. Indicate the range of essential parameter values needed to perform the required trade-off analyses.

3. Technical Team Qualifications

a. Team background must correlate with the technical approach chosen. For example, a highly theoretical mathematic approach may call for an expert in Kalman Filtering or random processes, whereas a "common-sense" deterministic approach may call for a systems and operationally-oriented individual, perhaps with flying experience. This matching of approach to individual should be indicated.

b. The contract manager must have the time to become actively involved in the project.

4. Company Qualifications

a. Indicate the support and guidance which can be provided to the technical team when required.

b. Briefly describe the general configuration of the digital computer you intend to use.

As a guide to contractors responding with proposals the following remarks on evaluating policy were offered:

1. The proposal will be expected to contain specific details in regard to the points raised above under "Evaluation Criteria". Unduly long proposals that do not primarily address themselves to the specific problems discussed in this RFP are discouraged.

2. In his proposal, the prospective contractor is at liberty to comment on the general scope of the contract as well as on the specific tasks indicated. Carefully considered deviations from the approach specified will be given full consideration.

3. The purpose of this contract is to obtain a digital computer simulation program which can be used at TSC as a tool to evaluate the performance of various alternative navigation systems and the implementation of these systems in commerical aircraft operating in the NAT region.

4. The output of the navigation system model will be used in conjunction with models of ATC procedures to determine collision risk. The result of these parametric trade-off studies will be revised specifications for navigation equipment, ATC procedures and separation standards for the NAT region.

5. The foregoing criteria are weighted in the following manner. Three-fourths (3/4) of all weight is almost equally split between criteria 1 and 2. The remaining weight is almost equally split between criteria 3 and 4.

Aerospace Systems, Inc. (ASI) of Burlington, Mass., was awarded the contract on June 30, 1972 at an estimated cost of $60,000.

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