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FACILITY FORM 602

N 69-21094

(ACCESSION NUMBER)

154

(THRU)

1

(PAGES)

WASA-CR # 86130

(NASA CR OR TMX OR AD NUMBER)

(CODE)

21

(CATEGORY)

EXPERIMENTAL L-BAND SST SATELLITE COMMUNICATIONS/SURVEILLANCE TERMINAL STUDY

1

VOLUME II

OPERATIONAL REQUIREMENTS STUDY

By

James T. Burghart

November 1968

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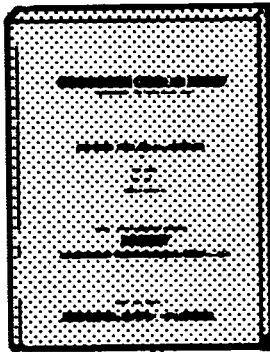
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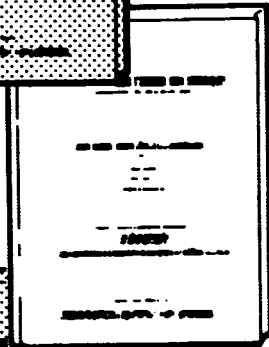
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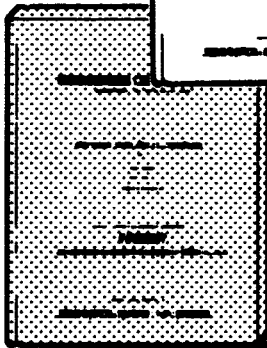
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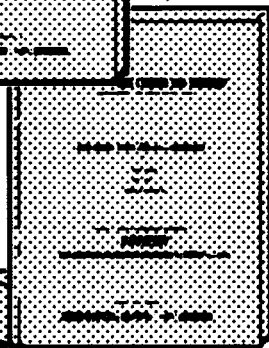
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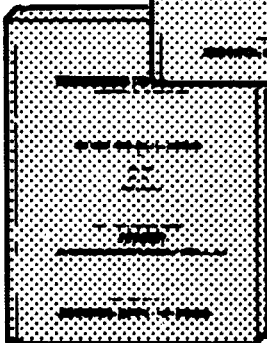
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EXPERIMENTAL L-BAND SST SATELLITE COMMUNICATIONS/SURVEILLANCE TERMINAL STUDY

VOLUME II: OPERATIONAL REQUIREMENTS STUDY

**By James T. Burghart
The Boeing Company**

SUMMARY

The development of the operational requirements performed as part of NASA/ERC contract NAS 12-621 is presented for an L-band satellite system performing air traffic control (ATC) in the North Atlantic air lanes. The current oceanic ATC procedures and traffic are considered and the increased benefits are given for extended ATC capabilities to a satellite system for handling the expected airplane and passenger traffic growth through 1980. The requirements for the ATC satellite system are developed for traffic in the open oceanic area between latitudes 40°N and 60°N and longitudes 10°W and 50°W. Using the traffic forecasts, specific surveillance and communications requirements are developed for use in the aircraft terminal design.

The results of the surveillance requirements analysis show the potential reduction in separation standards that can be achieved in terms of required aircraft position accuracies, surveillance fix rate, and onboard navigation capability. The analysis was carried out using results of surveillance and collision-risk mathematical models. It is concluded that a system satisfying the derived requirements (including a 1-n.mi. surveillance accuracy) would permit reduction of the current 120-n.mi. lane-separation standards to a goal of 30 n.mi. for INS-equipped SST's and to a goal of 60 n.mi. for present-day subsonic jet aircraft without an INS.

The results of the communications requirements analysis show that a system providing six voice channels is adequate for the expected message loads associated with the peak-hour busy-season traffic through 1980 for the North Atlantic area. The suggested implementation is five channels for normal message interchange with moderate delay characteristics and a zero-access-delay channel reserved for emergency transmissions.

1.0 INTRODUCTION

The operational requirements are those system characteristics that are specified from considerations of the needs of the system users as distinguished from the characteristics that arise from the system design parameters. The study was limited to the needs of the air traffic users. The degree to which the system meets or exceeds the requirements is a measurement of the usefulness of the system. The most important specifications for a North Atlantic air traffic control (ATC) system are the communications capacity, the position reporting accuracy, and the position reporting rate.

The study was performed as outlined in fig. 1. The details of each of the identified analyses (airplane traffic, communications, and surveillance) are contained in the following three sections. In addition, the impact of advanced technology such as the Automatic Flight Management (AFM) program on these requirements is considered (Sec. 5.0). As a background, a discussion of today's North Atlantic ATC system is included as app. A. The mathematical details of the requirements analyses are contained in the other appendixes.

A strong team effort was involved in conducting the overall study effort. The operational requirements study reported in this volume is the result of significant contributions by the following personnel:

Technical Direction	R. L. Erwin—Supervisor J. T. Burghart
Airplane Traffic Analysis	W. H. Litzenberger
Passenger Crossings Forecasts	Y. Aureille
Communications Analysis	S. R. Shah
Surveillance Analysis	D. M. Goodfellow
Collision Risk Analysis	J. T. Burghart
Computer Programming	J. M. Bedregal H. F. Lee J. Steigman

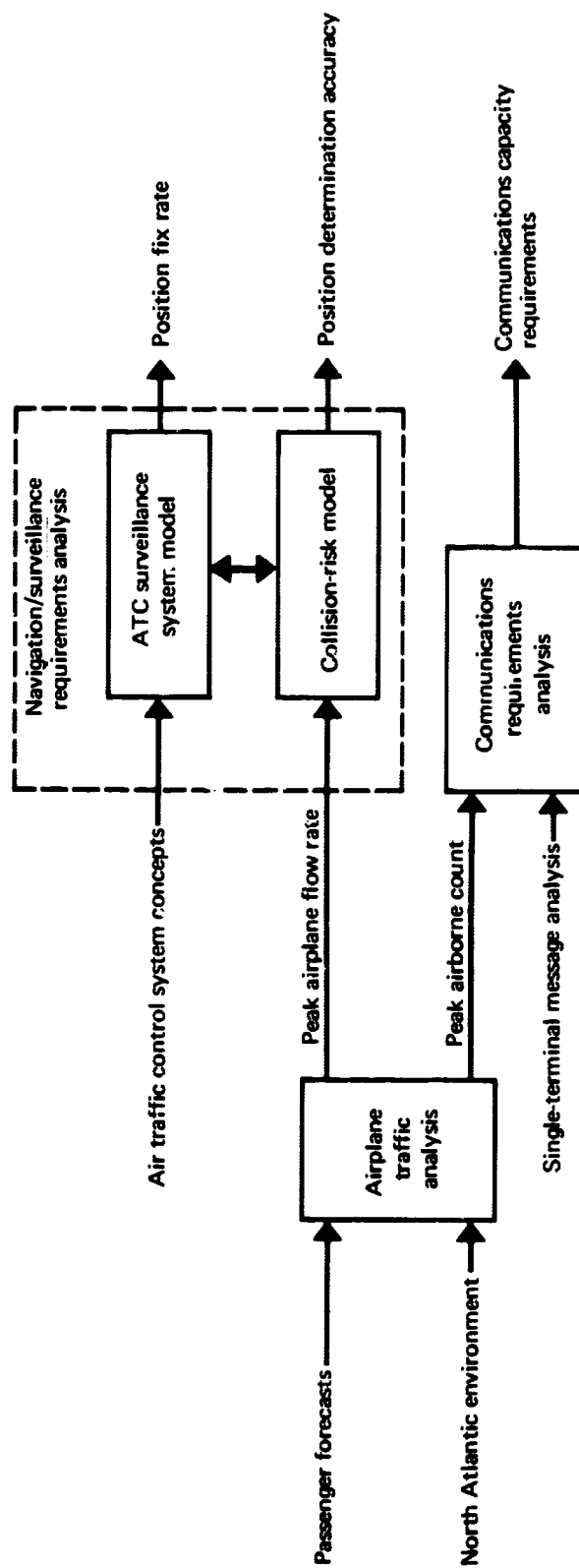


FIGURE 1.— OPERATIONAL REQUIREMENTS STUDY OUTLINE

2.0 AIRPLANE TRAFFIC ANALYSIS

For purposes of this study, the peak instantaneous airborne count and the busy-hour flow rate of airplanes into the system are the critical airplane traffic characteristics to be determined. The peak instantaneous airborne count (IAC) influences the communications capacity requirement. The flow rate determines the required separation standards that are set by the position reporting accuracy and rate.

2.1 Coverage Area

The area of primary interest is the North Atlantic region bounded approximately by latitudes 40°N and 60°N. The communications and navigation/surveillance problem areas in this route are between the 10°W and 50°W meridians.

This North Atlantic region contains about 50% of the overocean traffic in the world. Figures 2 and 3 are presented for comparative purposes. They show the weekly total of scheduled flights for all except North Atlantic (NAT) overocean flights. The NAT total is approximately 2,000 flights. Two other heavily traveled routes shown are the U.S. West Coast to Hawaii routes (19%) and the U.S. to Puerto Rico routes (15%). All other overocean routes total approximately 16% of the overocean traffic.

2.2 Passenger Crossing Projections

To calculate traffic output, it is necessary to determine the number of flights of the various types of aircraft and their spatial distribution for peak conditions. To obtain this for the 1975-1980 period, a prediction of passenger crossings is required. The passenger demand is then converted to flight data using known and postulated rules about airplane load factors, passenger preferences (both for departure hours and airplane types), airplane delivery schedules and seating capacities, and cargo flights. The procedure is illustrated in fig. 4. A computer program has been developed to perform this calculation and is described in app. B.

The greatest variation in the approach arises from the passenger projection input. Predictions of future North Atlantic travel demand are subject to large uncertainties. The usual approach is to examine past travel growth rates and postulate the future demand based on these. A typical projection (from FAA data, ref. 1) is shown in table 1, the first column.

The set of data shown in the other column is a more conservative traffic projection based on a correlation of passenger flow and gross national product (GNP) between North Atlantic country pairs. Gross national product growth has been more predictable in the past, and for that reason is a useful basis for projection.

2.3 North Atlantic Flight Projections

Because of the variable factors described, an attempt was made at determining the possible spread of traffic obtainable. The high passenger input was combined with a large supersonic preference factor to yield a maximum value. The minimum value was obtained by using the lower passenger input with an optimistic jumbo-jet estimate. The

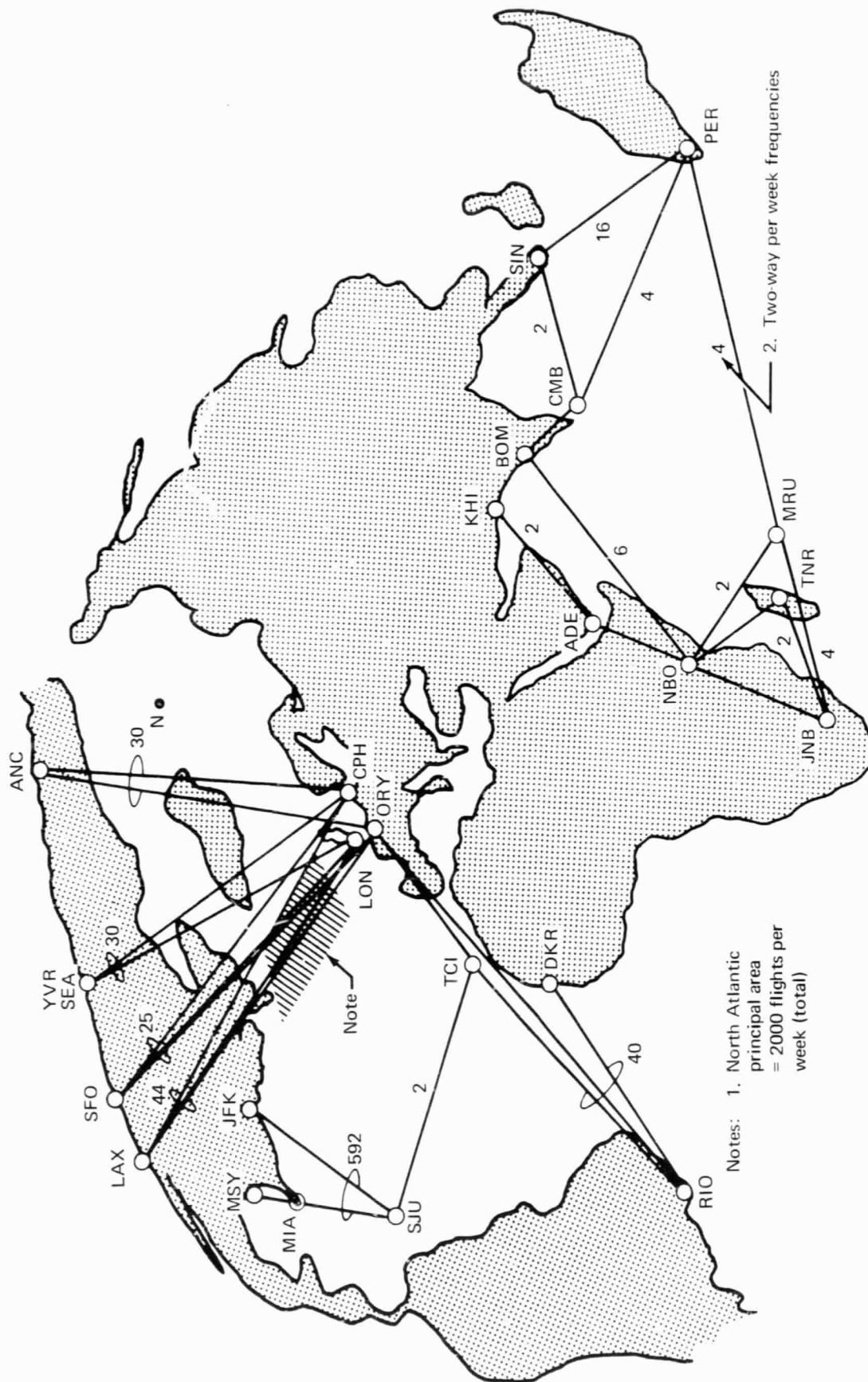


FIGURE 2.— INTERCONTINENTAL TRUNK ROUTES—ATLANTIC

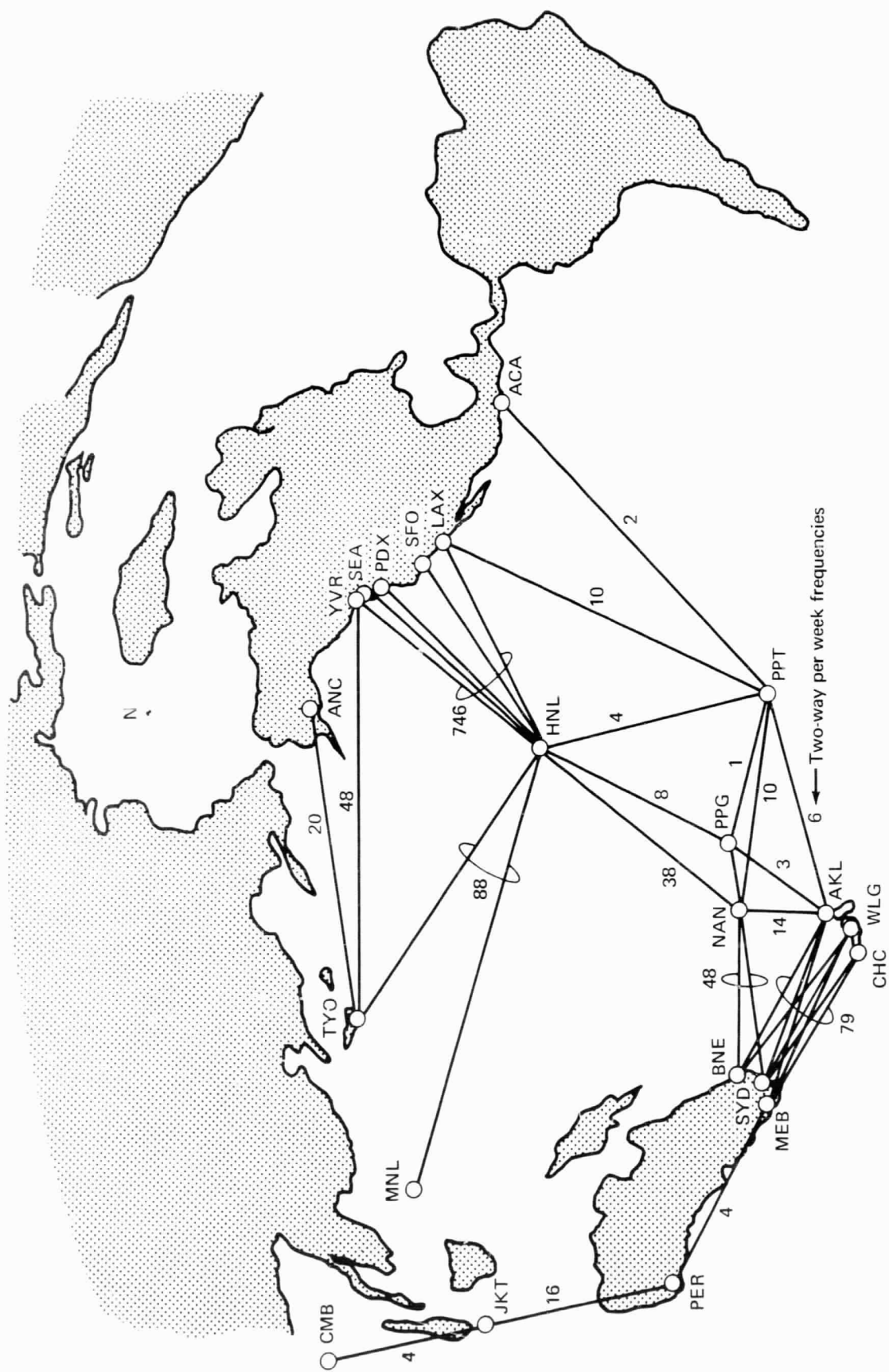


FIGURE 3.— INTERCONTINENTAL TRUNK ROUTES—PACIFIC

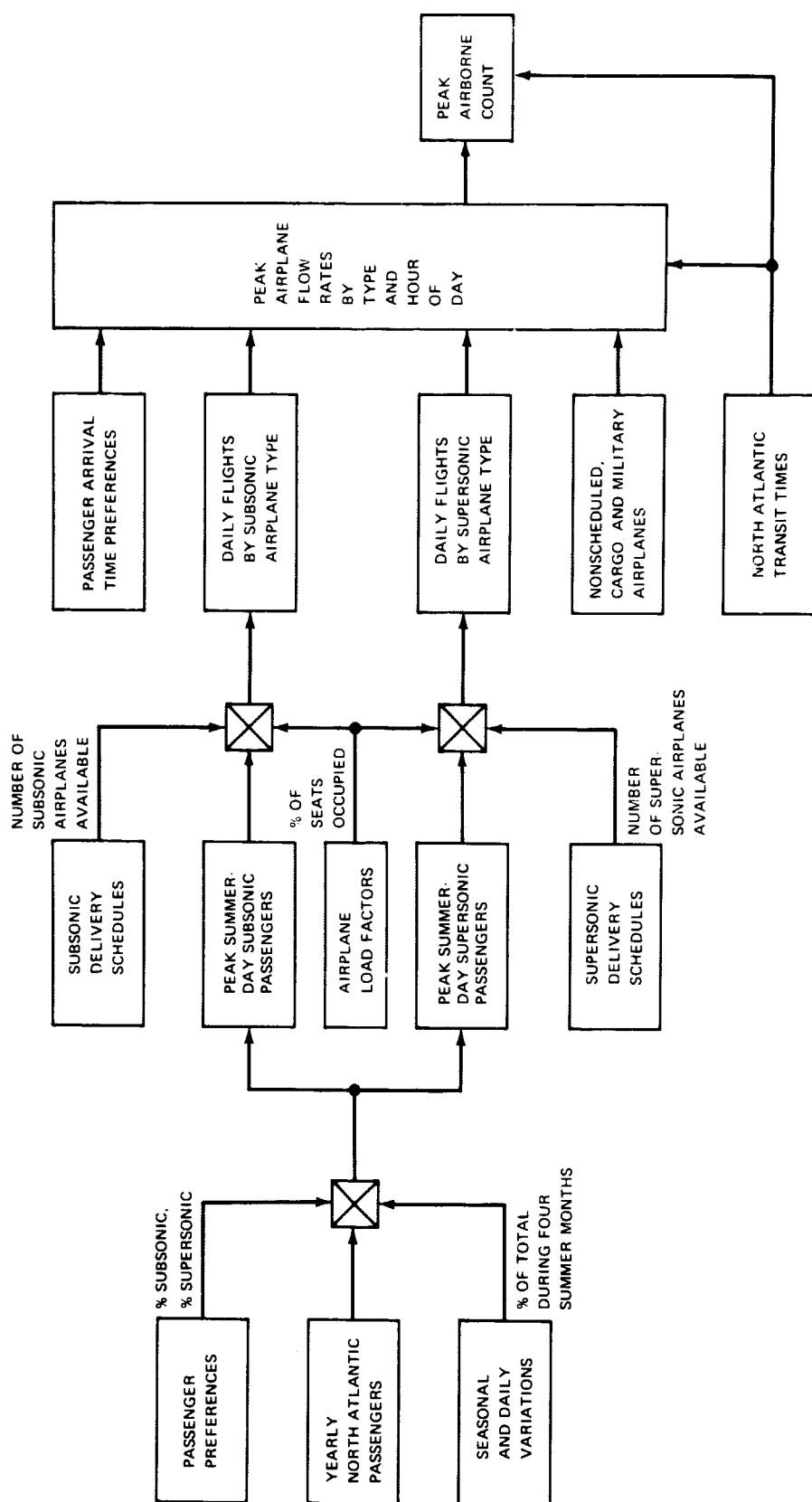


TABLE 1.— PROJECTED NORTH ATLANTIC PASSENGER CROSSINGS

Year	Typical forecast (a)	Conservative forecast
1975	14 024 000	8 454 000
1976	16 045 000	8 978 000
1977	18 371 000	9 515 000
1978	21 100 000	10 061 000
1979	24 000 000	10 621 000
1980	27 300 000	11 243 000

^a1978-1980 data were extrapolated from 1968-1977 forecast.

difference in passenger-carrying capacity between the supersonics and the jumbo jets, combined with the different peaking characteristics of the traffic schedules, produces a peak instantaneous airborne count variation that is not simply a function of the passenger total.

Figure 5 shows the results of this variation on the total daily flights. The assumptions used in obtaining these curves are detailed in app. B.

For the purpose of sizing the requirements of an ATC satellite, the 1980 estimates were selected. Between the two estimates, a variation in the 1980 peak instantaneous airborne count in the communications gap (longitude 10°W to 50°W) of the following was obtained:

Subsonic	55 to 68
Supersonic	21 to 63
Total	76 to 131

For purposes of the communications analysis, the higher IAC values were chosen. This choice is in line with a conservative design philosophy. However, an analysis was also performed for a minimum capability based on a low traffic estimate. The details of this analysis are given in Sec. 3.0. The spatial distribution of the IAC is shown in table 2. A preferred communications capability in the North Atlantic communications gap would accommodate 131 airplanes.

The peak hourly subsonic and SST flow rate is used in the navigation analysis. By calculating the high traffic estimates as in the previous IAC analysis, the peak flow rates of table 3 were determined for 1980. These numbers formed the basis for the navigation analysis input.

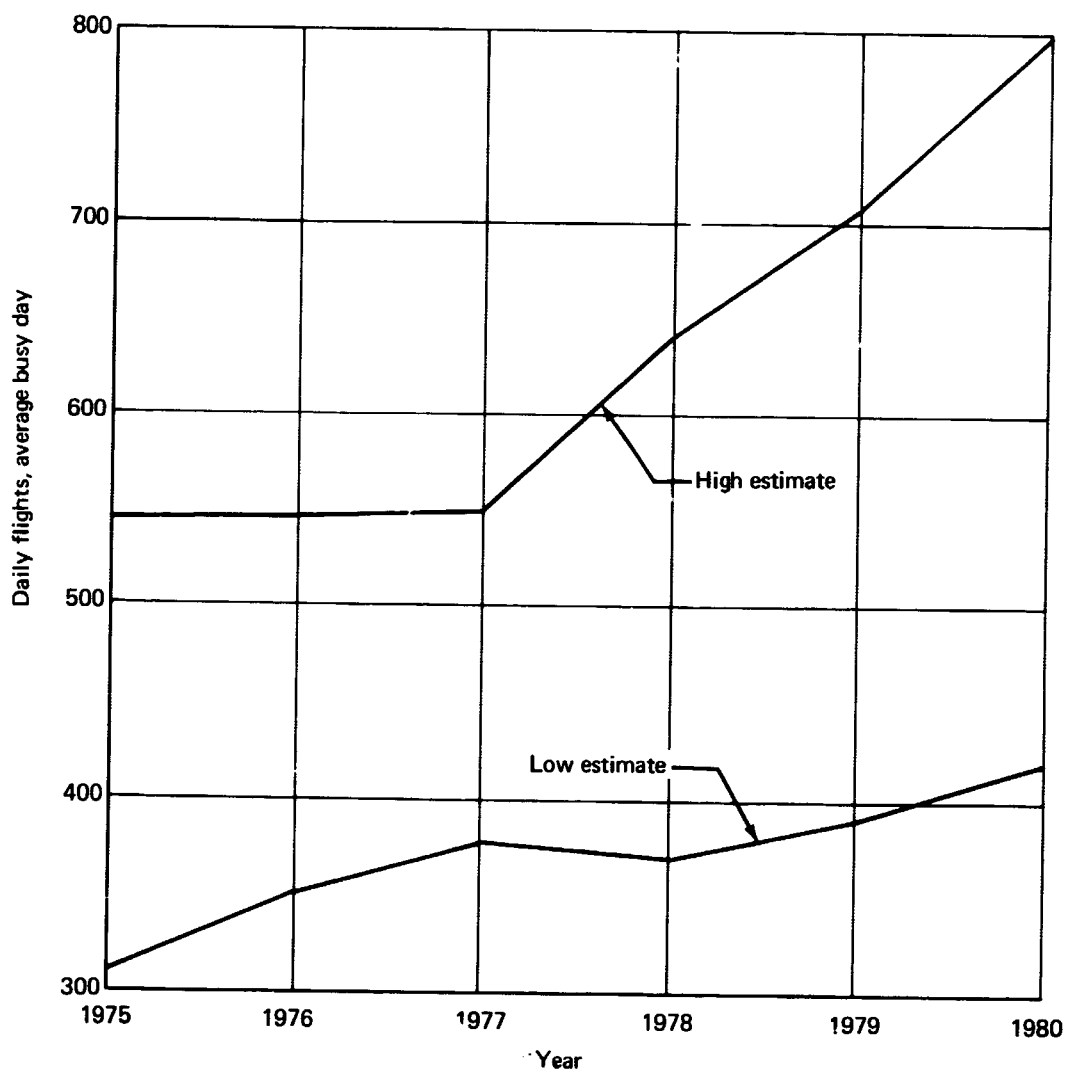


FIGURE 5.— DAILY NORTH ATLANTIC FLIGHTS

TABLE 2. – NORTH ATLANTIC TRAFFIC SPATIAL DISTRIBUTION

Region	Longitude	Number of airplanes (a)		
		Subsonic	Supersonic	Total
Polar (60°N to 90°N)	----	10	4	14
Principal area (40°N to 60°N)	0°W to 10°W	12	19	31
	10°W to 20°W	20	16	36
	20°W to 30°W	16	15	31
	30°W to 40°W	16	16	32
	40°W to 50°W	16	16	32
	50°W to 60°W	14	37	51
	60°W to 70°W	10	35	45
Other (0° to 40°N)	----	26	9	35
TOTAL		140	167	307

131
Aircraft

^aFor 1980; transoceanic traffic; peak busy summer day; instantaneous count

TABLE 3. – PEAK NORTH ATLANTIC FLOW RATES

Airplane type	Peak flow (a)
U.S. supersonic	36
Concorde	9
Subsonic	19
TOTAL	64

^aFor peak flow hour, busy summer day (both ways)

3.0 COMMUNICATIONS REQUIREMENTS ANALYSIS

To determine the satellite communications capacity requirements, the airplane traffic load postulated in Sec. 2.0 is combined with the single-terminal message load. The method chosen to accomplish this combination is a queueing-type computer simulation model. The model generates message traffic based on peak-hour airplane loading and postulated message-type distributions. The output is the message delay statistics by category. The details of the model can be found in app. C.

3.1 Single-Terminal Messages

Determination of North Atlantic single-terminal message characteristics for the 1980's is made by extrapolation of the present environment into a 1980 environment that includes an ATC satellite capability. Single-terminal messages are those exchanged between one aircraft and one ground terminal. Several operational concepts have been analyzed. The following alternate concepts form the basis of the analysis:

- (1) Present ATC procedures and voice transmission
- (2) Position reporting rate increased from every 10° to every 5° of longitude
- (3) Digital position reporting (one automatic report every 3 minutes)
- (4) Ail-digital system with typical U.S. message load
- (5) Surveillance capability added and present oceanic voice message load
- (6) Surveillance capability added and typical U.S. voice message load

All concepts were analyzed for the high-traffic estimate, except the present ATC procedures concept that was analyzed for both the high and low estimates.

From an operational viewpoint, the last concept is preferred. However, cost-benefit considerations might dictate selection of a lesser capability. A cost-benefit study is not within the scope of this analysis, but preliminary results from a North Atlantic economics model being developed at Boeing indicate that by 1980 the cost penalty paid by the air carriers due to deviations from optimum tracks will support the preferred concept. The results shown in ref. 2 are indicative of the trends.

The quantity and the type of messages currently transmitted in the North Atlantic are limited by the communications capability. To project the communications load to the 1980's, a method of determining the effect of improved capability on the load is required. The method chosen is to assume that the U.S. communications environment is representative of a future goal in the North Atlantic. Using this criterion, the following list of message types was used as a base:

- (1) First-Priority
(category 1) Emergency

Conflict resolution

Other
- (2) Air Traffic Control
(category 2) Position reports

Clearance control

Vectoring
- (3) Advisory
(category 3) Aircraft traffic advisories

Airport status

Weather
- (4) Unclassified
(category 4) Miscellaneous

Non-ATC

This list is ordered by importance to the ATC system. The messages fall naturally into the four categories indicated. The queueing model described in app. C was developed to include a priority scheme that selects the highest priority message awaiting transmission and permits it access to the system first. The delay statistics as a function of these four categories are the outputs of the model.

Table 4 presents a summary of the communications traffic model selected for analysis. The numbers were determined as follows:

- (1) Average Duration of Contact -- This parameter is defined as the total time required to complete two-way voice transmission of the information contained in each message. The format specifications of the International Civil Aviation Organization (ICAO) were used. An average talking rate of 2.5 words per second was used. This is based on an analysis of U.S. domestic ATC communications systems (ref. 3). Acknowledgments, access time, and pause in transmission are included in the total time. For example, a typical position report as specified for use in the North Atlantic compulsory 10° reporting procedures would contain 75 to 80 words. This would occupy 30 to 32 seconds. To account for pauses, acknowledgments, and access procedures, 45 seconds was selected as an average message time.
- (2) Information Bits -- The information bit content of the message is defined as the number of digital bits required to transmit the information in the message, exclusive of redundancy and error correction bits. Seven bits per alphanumeric character were used. Two categories of messages were assumed.

TABLE 4. — COMMUNICATIONS REQUIREMENTS

Message category	Message type	Average duration of contact, seconds	Information bits (a)	Number of messages, peak-hour loading	
				Present procedures (b)	Comm/surv satellite system (c)
First priority	Emergency	30	900	10	10
	Conflict resolution	30	600	35	70
	Other	30	750	---	60
ATC messages	Position report	45	225	300	---
	Clearance control	15	60	100	100
	Vectoring messages	10	60	---	100
Advisory messages	Aircraft traffic	10	250	---	30
	Airport status	5	100	---	5
	Weather advisory	10	200	50	100
Unclassified	Non-ATC	20	600	50	200
	Miscellaneous	20	500	60	70

^aATC message formatted; other messages transmitted with elimination of voice redundancy

^b1980 traffic with 10⁰ position reports (present-day North Atlantic message load)

^c1980 traffic with 20-position samples per hour and typical U.S. message load

The ATC messages (for example, the position report) are of a nature that allows a standardized format to be adopted. This permitted considerable reduction over a straight alphanumeric transmission. The other messages were judged to be unpredictable in content and to require a straight character transmission. However in these cases, a 50% to 60% reduction was used based on eliminating some of the voice redundancy.

- (3) Number of Messages – This value was determined from the peak-hour instantaneous airplane count given in Sec. 2.3. The heavy traffic count was used to derive the numbers in table 4 for two environments. The first is the present-day environment where the requirement is to report a position every 10° of longitude. In the traffic model used (table 2), there are 131 airplanes in the area of interest (longitude 10°W to 50°W) – 68 subsonic and 63 supersonic. The supersonic airplanes each generate three position reports per hour; the subsonic, slightly more than one per hour. Therefore, a total of 300 reports per hour was used. In addition, the requirement exists to report when passing from the Gander control area (CTA) to the Shanwick CTA; each supersonic airplane would do this once in the busy hour. About one-third of the subsonic airplanes would pass from one control area to the other.

In the present environment, studies have shown that position-report messages constitute 50% to 60% of the North Atlantic communications traffic.

To postulate the communications load in a future environment having more reliable communications, a different approach is required. The position-report messages were determined in the same manner as that for the present messages except the rate was increased from every 10° to every 5° and then to an automatic report every 3 minutes. This was done to permit reduction of separation standards as discussed in Sec. 4.

The other message quantities were determined using analyses performed of typical U.S. message traffic. It was assumed that a future satellite system will provide a similar capability and environment.

3.2 Communications Capacity Requirements

The next step followed in the analysis was to combine the requirements in table 4 with various operational concepts. This identifies the needed computer runs used to specify the communications system requirements. The indicated runs are shown in table 5.

The specified loads were run with various numbers of channels and for digital transmission bit rates. The detailed results of each run can be found in app. C. A summary of the results for the selected channel requirements is in table 6.

The number of channels was selected based on both the average delay per message and the worst-case delay within each category of message.

An all-voice system (including voice position reports every 5°) was investigated. This concept using the same delay criteria required nine channels. A minimum capability all-voice system required four channels.

TABLE 5. — MESSAGE FREQUENCIES

Operational concept		Run number	Peak hour— number of voice messages by category				Peak hour— digital bits by category			
			1	2	3	4	1	2	3	4
All voice (present procedures) ^a	Minimum capability	1a	40	120	40	80	----	----	----	----
	Preferred capability	1b	45	400	50	110	----	----	----	----
All voice (increased position reporting) ^b		2	45	600	50	110	----	----	----	----
Automatic digital position reporting ^c		3	45	100	50	110	----	562 x 10 ³	----	----
All-digital system— U.S. ATC message load		4	----	----	----	----	96 x 10 ³	574 x 10 ³	32 x 10 ³	124 x 10 ³
Surveillance function added (present procedures) ^d		5	45	100	50	110	----	----	----	----
Surveillance function added—U.S. ATC message load ^d		6	140	200	135	270	----	----	----	----

^aBased on: position reports every 10° of longitude —low traffic estimate for minimum capability; high traffic estimate for preferred capability

^bPosition reports every 5° of longitude

^cDigital position report transmitted every 3 minutes

^dSurveillance function assumed to eliminate need for position reports

TABLE 6. — SUMMARY OF CHANNEL REQUIREMENTS

Operational concepts	Channel requirements				Average delay by message category, seconds				Maximum delay, seconds (b)
	Voice		Digital (a)						
	Number of channels	Channel utilization, percent	Number of channels	Channel utilization, percent	1	2	3	4	
All voice—minimum capability	4	56	---	---	0.6	1.4	3.0	5.1	10.6
All voice—preferred capability	7	77	---	---	0.5	3.5	14.5	24.9	9.3
All voice—increased position reports	9	86.6	---	---	0.3	4.6	27.0	46.2	7.5
Automatic digital position reports	3	46	3	52.7	---	^c 2.9	---	---	---
					^d 0.2	^d 0.6	^d 1.1	^d 2.3	^d 6.0
All-digital system—U.S. message load	1	Emergency only	4	75	^c 0.4	^c 1.6	^c 3.6	^c 5.2	^c 6.9
Surveillance function added—present procedures	3	46	---	---	0.2	0.6	1.1	2.3	6.0
Surveillance function added—U.S. ATC message load	5	77.7	---	---	0.2	0.7	1.8	6.3	9.6

^a100 bit/sec data rate^bMaximum delay is the average delay for the worst delayed message of each run (100 or more runs).^cFor digital messages^dFor voice messages

An approach having features of both the all-voice system and a surveillance system was also analyzed. This consisted of automatic position reports on a digital channel with the remaining messages voice transmitted. This approach required three voice and three digital (100-bits per second) channels. The digital concepts were run for increased data rates also. It is obvious that the amount of information transmission required could easily be sent over one high-bit-rate channel (1000 to 1200 bits per second). The three-channel requirement was selected, however, to supply redundancy to the system.

The preferred operational concept requires a surveillance-satellite system with a voice communications capability. This concept requires five voice channels to give a weighted average delay of 2.8 seconds for all messages. The maximum delay for a first-priority message (including emergencies) was 9.6 seconds. The concept assumes that a priority scheme can be implemented to permit access to the first open channel for an emergency message. Without a priority scheme, an open channel would be added to the required five for emergency use only. Channel utilization during the busy hour is 77.7%.

4.0 POSITION FIXING REQUIREMENTS

The objective of implementing an ATC satellite capability in the North Atlantic is to permit an increasing flow of airplanes in this region to operate with safety equal to or better than today's. The safety record currently being experienced in spite of unreliable communications and relatively poor navigation accuracy (compared to domestic operations) is kept within acceptable bounds by maintaining large, planned separations between airplanes. With an increasing flow rate of aircraft, however, this separation causes increasing economic penalties to airplanes that must deviate from an optimum track. Reduction of these penalties by decreasing airplane separation is the incentive used to justify the cost of improved ATC capability. The detailed evaluation of this cost-benefit tradeoff was not within the scope of the analysis presented here. However, studies previously performed and currently underway at Boeing indicate that the growing traffic in the North Atlantic will in the 1975-1980 period justify the cost of both improved airborne navigation equipment and ATC surveillance systems.

These studies have justified the inclusion of inertial navigation systems (INS) in both airplane types (the U.S. SST and the Boeing 747) that Boeing customers will be operating during this time period. The use of an adequately monitored inertial system (assuming all airplanes equipped) should permit a reduction in lateral separation from 120 to 60 nautical miles (ref. 2). The addition of a surveillance capability overlaid on this track-keeping ability will permit a further reduction in separation standards. This will also permit (to a yet to be determined degree) the operation of less precisely navigated airplanes within the system with similar separations.

The analysis presented here is aimed at specifying the performance requirements of the ATC surveillance system based on safety and separation criteria. The mathematical details of the models used in this analysis are contained in app. D.

The theoretical results given can be used as a basis for determining the requirements, but the actual reduction of separation standards is usually accomplished through observation of the operational system long enough to validate the predicted operational characteristics. The models then should be modified to account for these characteristics. Then, the separation standards suited to the acceptable safety level can be implemented.

4.1 General Description

A collision risk model and an ATC surveillance model are used. Briefly, the procedure is as follows: (The mathematical derivations are included in app. D.)

The collision risk model (based on work done by the Royal Aircraft Establishment, ref. 4) is used to determine an acceptable probability of overlap. Certain limitations are recognized; for instance, the model does not include the ability of the pilot or a collision avoidance system to reduce collision risk. However, the surveillance parameters are conservative and are suitable for developing terminal requirements. Probability of overlap is defined as the probability that two aircraft (with planned separation in one dimension only) are actually in conflict in that dimension. This is not the collision risk but is related to the collision risk by the parameters of the model (traffic, airplane dimensions, probability of conflict in the other dimensions, etc.). The "acceptable" collision risk is an input to the model.

The acceptable probability of overlap is an input to the ATC surveillance model that brings in the airplane navigation and surveillance accuracies, the position reporting rates, and the separation standards. These are the design parameters of most interest to the study.

4.2 Analytic Description

This section outlines a qualitative description of the analyses leading to the models used. It enables an evaluation to be made of the assumptions and approximations used in Sec. 4.3, "Results."

4.2.1 Collision risk model.— In evaluating the effectiveness of a navigation system in an enroute environment, such as the North Atlantic oceanic area, the breakdown of a planned lateral (across-track) separation is the key factor. A collision can occur, however, only when the two airplanes also coincide in altitude and along-track position. This coincidence depends on the traffic situation (probability of another airplane being present), airplane dimensions, and altitude and along-track distribution of airplanes at nominally zero separation.

The lateral collision risk C_y is mathematically expressed as a function of the following parameters:

- (1) The total time during which the aircraft are laterally proximate. The time is included for same-direction traffic T_{ys} and opposite-direction traffic T_{yo} .
- (2) The probability of vertical overlap of proximate aircraft P_{zo} and the frequency with which vertical overlap occurs N_{zo} .
- (3) The along-track separation standard S_x .
- (4) The aircraft parameters. The following terms are contained in the model:
 - (a) Average cruise speed $\bar{V}$
 - (b) Mean cruise speed difference for same-direction proximate pairs $\Delta\bar{V}$
 - (c) Aircraft dimensions λ_x and λ_y
 - (d) Relative across-track velocity $|\dot{y}|$
- (5) The probability of across-track overlap of laterally proximate aircraft P_y

The collision risk (C_y = number of collisions) as a function of this probability and using the preceding notation becomes

$$\frac{C_y}{P_y} = \frac{T_{ys}}{S_x} \left[\frac{\Delta\bar{V}}{2} P_{zo} + \lambda_x N_{zo} + \frac{\lambda_x P_{zo} |\dot{y}|}{2\lambda_y} \right] + \frac{T_{yo}}{S_x} \left[\bar{V} P_{zo} + \lambda_x N_{zo} + \frac{\lambda_x P_{zo} |\dot{y}|}{2\lambda_y} \right]$$

The detailed derivation of this equation is in app. D.

4.2.2 ATC surveillance model.— This model takes the overlap probability (calculated based on an acceptable collision risk) and specifies the ATC capabilities required to maintain this safety.

The model has been conservatively developed. This is desirable because of the safety aspects in the analysis. The aim is to avoid collisions completely. Since this requirement is not amenable to analysis, an “acceptable” safety level must be determined. Use of a conservative approach in the model tends to bias the answers obtained toward the zero-collision-risk goal.

An ATC surveillance system detects airplanes that represent a collision hazard and then guides these airplanes toward a safe position. This view identifies two surveillance parameters of special significance: alarm rate and the unfavorable alarm rate. Unfavorable alarms guide an airplane into a more hazardous position. This situation is illustrated in fig. 6. The airplane indicated is given an order to move to the right based on erroneous information received from surveillance. This movement takes the airplane from an actual location inside the nonalarm region to an actual position within the alarm region on the right side. The curves shown are exaggerated for clarity.

The ratio of unfavorable alarms to alarms is a key item to be specified. The value of one unfavorable alarm in a thousand used later in this volume ensures that unfavorable alarms have a negligible effect on the safety criterion (acceptable overlap probability). The small ratio, however, does force development of a more accurate surveillance system design than would a less conservative model.

4.3 Results

4.3.1 Probability of overlap.— The collision-risk model is used to determine an acceptable overlap probability. Table 7 shows the values used in the model. Because the proximity factors are the most critical to be estimated, their selection is discussed in detail in the following paragraphs.

The total time spent in lateral proximity (defined as a condition in which two airplanes are nominally separated from each other only in the across-track direction) is a function of the following:

- (1) Transit time
- (2) Total traffic
- (3) Scheduling
- (4) ATC procedures
- (5) Number of flight levels
- (6) Along-track separation
- (7) Pilot preferences

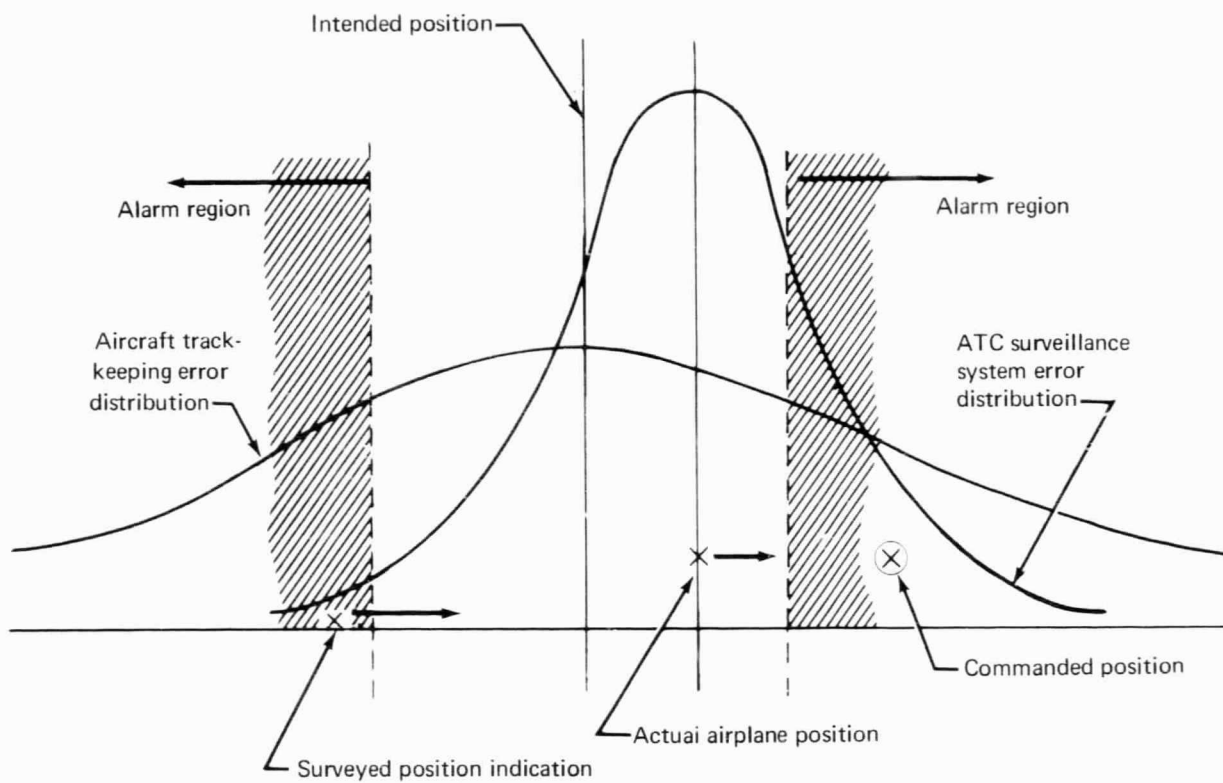


FIGURE 6.— "UNFAVORABLE" ALARMS

TABLE 7.— COLLISION RISK PARAMETERS

Parameter	Symbol	Dimensions	Value	
			Subsonic	SST
Proximity factor (same direction)	T_{ys}/S_x	hr/n.mi.	4×10^4	5×10^3
Average relative velocity (same direction)	$\Delta \bar{V}$	knots	13	40
Probability of vertical overlap	P_{zo}	----	0.25	0.25
Airplane length	λ_x	n.mi.	0.04	0.05
Number of vertical overlaps	N_{zo}	no./hr	50	50
Relative across- track velocity	$ \dot{y} $	knots	60	180
Proximity factor (opposite direction)	T_{yo}/S_x	hr/n.mi.	320	40
Airplane wingspan	λ_y	n.mi.	0.025	0.025
Average velocity	$\bar{V}$	knots	480	1500
Total flights ^a	F	----	780 000	380 000

^a1975-1980

The along-track separation standard S_X determines how many airplanes are considered to be in proximity. Airplanes in tracks adjacent to each other and at the same assigned altitude are proximate if they are also within two along-track separation standards of each other. Therefore, the total proximity time for all airplanes is a direct function of S_X .

The collision-risk equation as formulated requires the proximity times to be divided by S_X . This has the effect of canceling the along-track separation standard from the analysis. For this reason, a proximity factor (T_{ys}/S_X and T_{yo}/S_X) in dimensions of hours per nautical mile is estimated instead of the proximity time in hours.

The model requires an evaluation of both same-direction and opposite-direction proximity. The same-direction value has a much greater effect on the final result than the opposite-direction case (at least 80% of the total risk). This results from the longer time spent in proximity by two aircraft flying in adjacent tracks in the same direction. For this reason, emphasis was placed on determining the same-direction time more precisely.

The assumption is made that subsonic airplanes, the SST, and the Concorde will be separated from each other in the enroute area by virtue of their differing flight level preferences (fig. 7). This permits each type of aircraft to be considered separately by model.

The total SST traffic for the 1975-1980 period is estimated at 380 000 flights. Each SST is assumed to make 1.5 round-trip flights per day. The enroute SST transit time for the North Atlantic is approximately 1 hour (from longitude 10°W to 50°W).

The effects of scheduling and ATC procedures on proximity time can be easily seen by considering that the available SST's could readily be spaced throughout the day so that no two aircraft could ever come close to each other. However, the peaking characteristics of passenger demand preclude this being done.

Figure 8 shows a postulated distribution of flight times for SST's across the North Atlantic. It was assumed further that the SST flights would all occupy one flight level. Using these two assumptions combined with the total traffic flow mentioned in Sec. 2.0, an estimate of 5000 hours per nautical mile was made for the same-direction proximity time as a function of the along-track separation standard T_{ys}/S_X . The value of the opposite-direction proximity factor is estimated at 40 hours per nautical mile.

In the subsonic case of approximately 780 000 flights and a 3-hour transit time, the present-day peaking characteristics were assumed. This resulted in estimates of 40 000 and 320 hours per nautical mile. Since the collision risk is a direct function of these terms, the subsonic case is more critical than the supersonic in this parameter. This is a result of the fewer flights and the lower exposure time (1 hour versus 3 hours) for the supersonic case.

The other parameters required by the model are either fixed by the physical description of the airplane or have been determined by a less detailed analysis because of their smaller effect on the final result.

The safety value selected is a fatal accident rate of 0.1 per 10 million flying hours. This is based on the levels suggested by the North Atlantic Systems Planning group, which is responsible for analyzing separation standards in the North Atlantic. This figure ensures that North Atlantic collision accidents account for a negligible amount of the total flying risk.

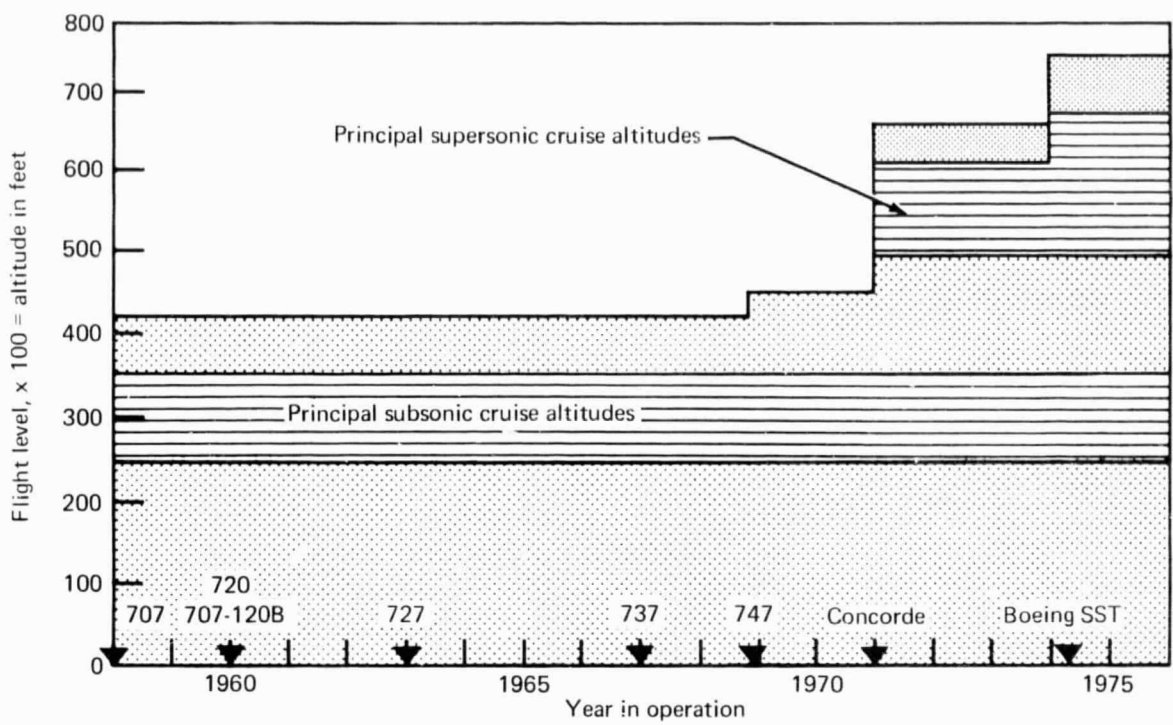


FIGURE 7.—JET LINER ENROUTE ALTITUDES

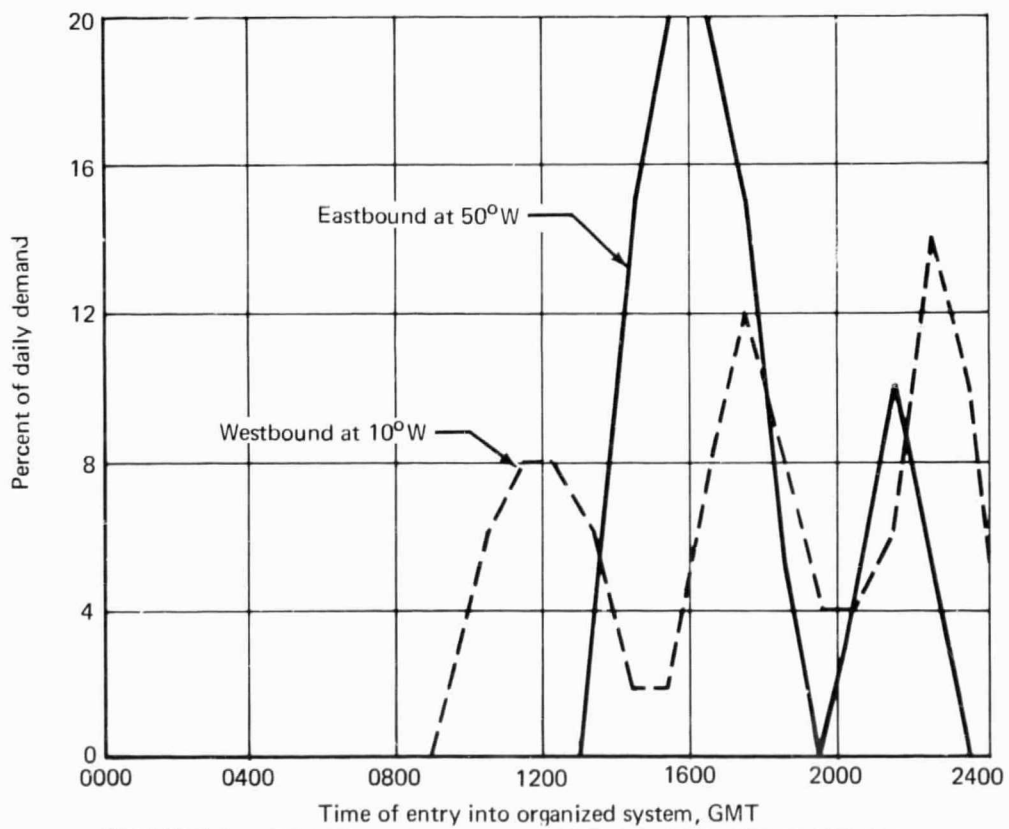


FIGURE 8.—NORTH ATLANTIC SST FLIGHT DISTRIBUTION

The number of collisions C_y for the 1975-1980 period is determined as follows:
collisions = (fatal accident rate) x (total number of flights) x (flight time) x (collisions per fatal accident). For the SST, $C_y = (1/10^8) (380\,000)(1)(\frac{1}{2}) = 1.9 \times 10^{-3}$. For subsonic airplanes, $C_y = (1/10^8)(780\,000)(3)(\frac{1}{2}) = 1.17 \times 10^{-2}$. These results assume two fatal accidents per collision and 1-hour and 3-hour enroute flight times.

Finally, using these numbers in the model specifies an acceptable overlap probability of 6.8×10^{-9} for the SST and 1.75×10^{-8} for subsonic airplanes.

4.3.2 Surveillance system results.— This part of the analysis establishes the position-fixing requirements. Surveillance accuracy and position fix rate are the most critical values. The analysis has been performed for a typical supersonic-inertial configuration and a subsonic configuration using present-day navigation techniques. These choices should bracket the capabilities expected for the 1975-1980 period.

4.3.2.1 Supersonic-inertial results: The following values are assumed for the SST with inertial navigation:

$$\sigma_r = 5 \text{ n.mi. (overall accuracy/trip)}$$

$$\sigma_r' = 2 \text{ knots (drift rate—one sigma value)}$$

$$S_r = 30 \text{ n.mi. (separation standard)}$$

$$N = 150 \text{ aircraft}$$

Navigation-system parameters σ_r and σ_r' are representative of an aircraft equipped with inertial navigation equipment. The traffic figure is from Sec. 2.0 The separation standard is chosen to reflect a requirement based on preliminary cost-benefit considerations.

The ratio of unfavorable to favorable alarms is set at $\bar{P}_A/P_A = 10^{-3}$. This value ensures that unfavorable alarms have a negligible affect on the safety criterion.

The alarm rate selected is $A_f = 3$ alarms per hour. This value is selected to produce a reasonable workload on the air traffic control facility and also fits in well with the other parameters already selected, as an examination of fig. 9 will show.

Finally, the acceptable probability of overlap is selected as $P_f = 6.8 \times 10^{-9}$ from Sec. 4.3.1.

Based on these values, a set of curves (derived from the curves in App. D) is shown in fig. 9.

For an alarm rate of 3 alarms per hour, fig. 9(a) shows that the required alarm threshold (r_0) is approximately 10 n.mi. For convenience, assume

$$r_0 = 10 \text{ n.mi.}$$

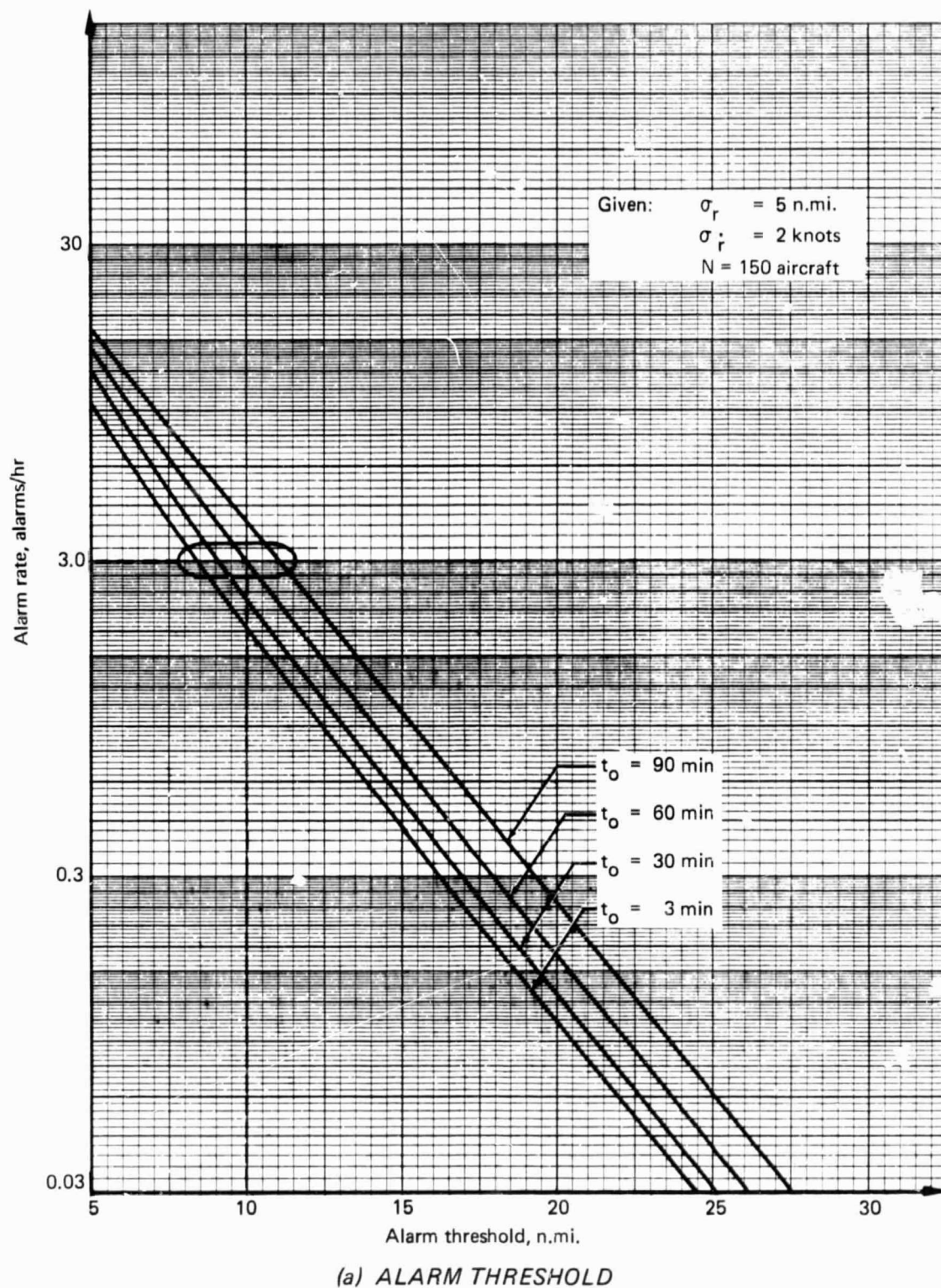
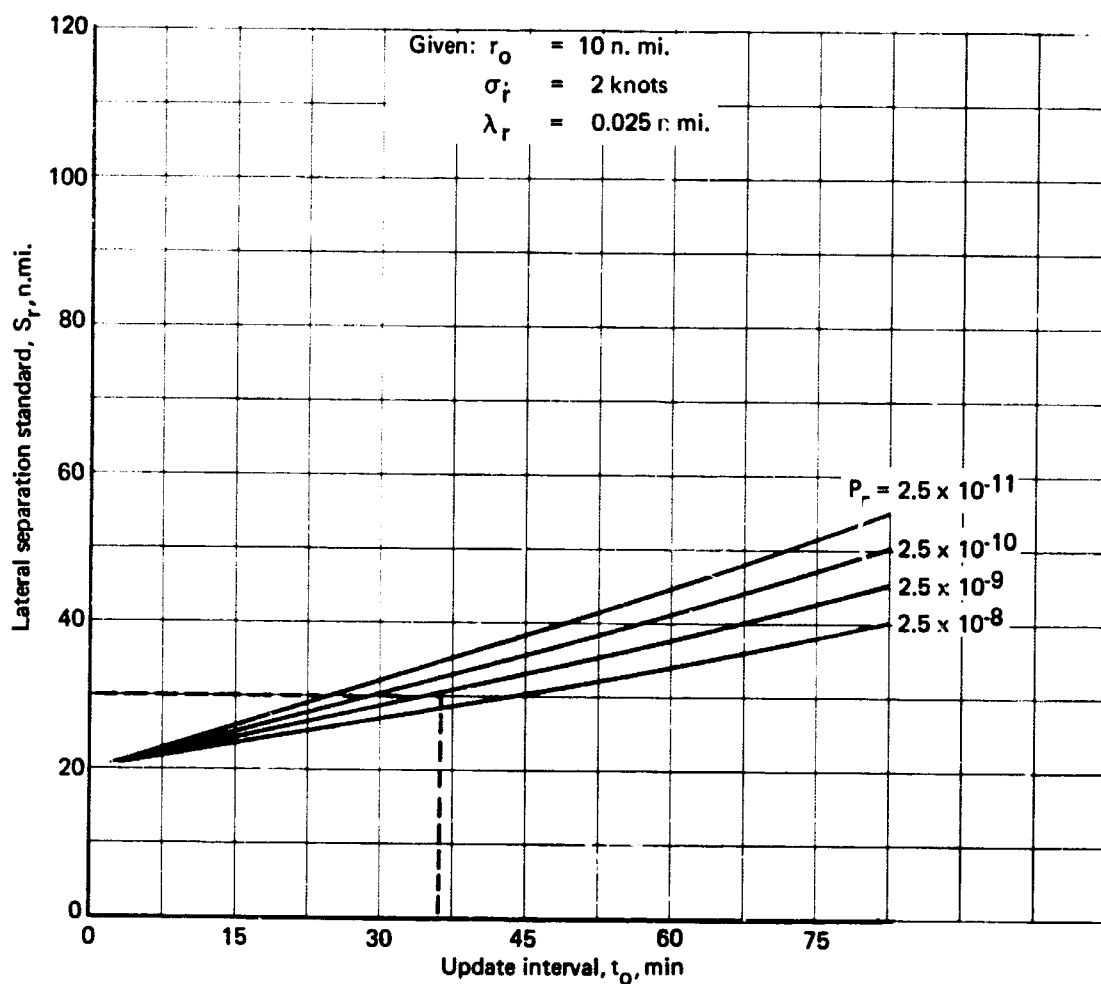
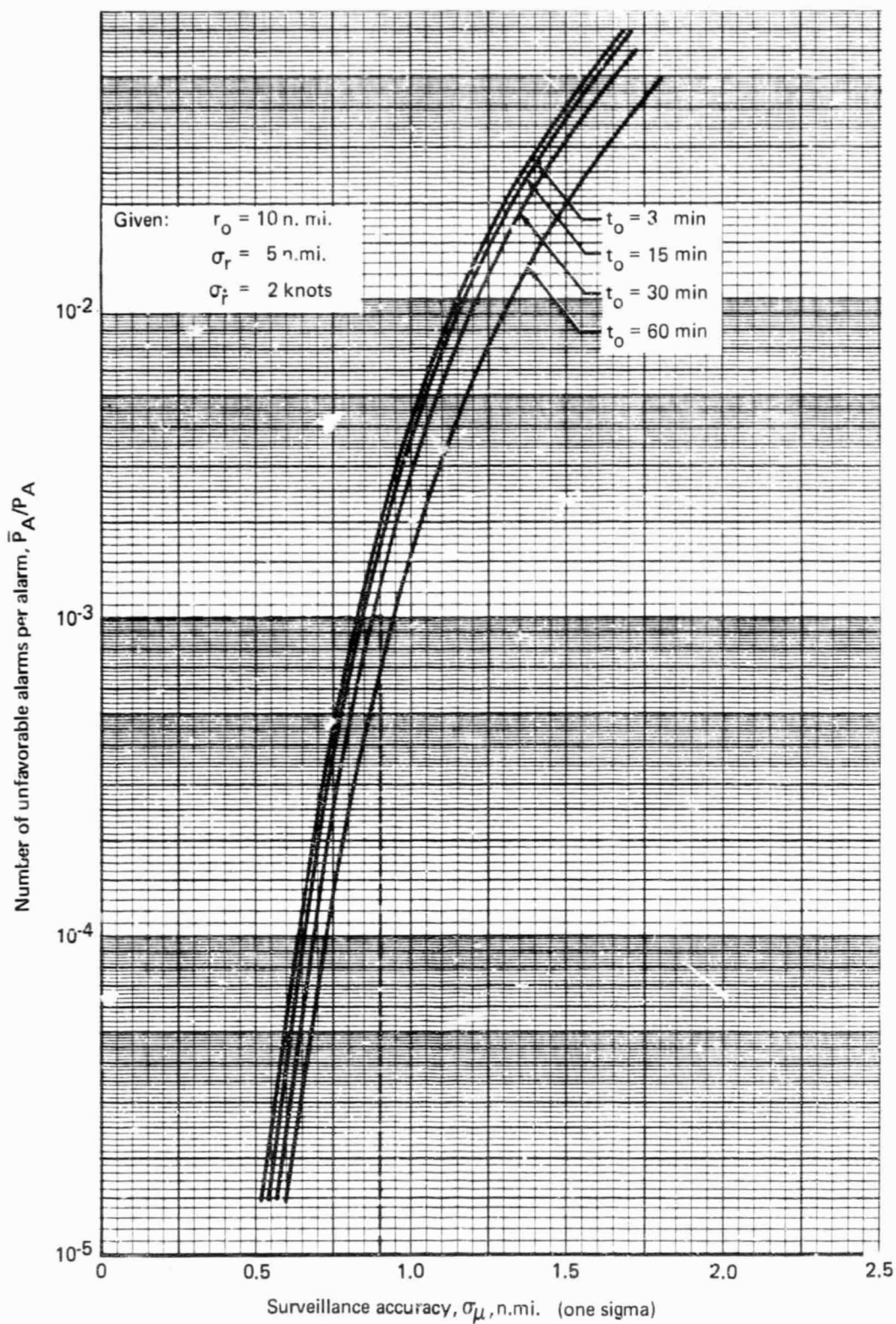


FIGURE 9.— SST SURVEILLANCE CURVES - Continued



(b) UPDATE INTERVAL
 FIGURE 9.— Continued



(c) SURVEILLANCE ACCURACY

FIGURE 9.— Concluded

For $r_O = 10$, $S_r = 30$, $P_r = 7 \times 10^{-9}$, fig. 9(b) shows that the update interval t_O is approximately 36 minutes.

Returning to fig. 9(a), with $t_O = 36$ minutes, the exact alarm rate is determined to be

$$A_i = 2.4 \text{ alarms/hr}$$

which is acceptable.

Entering fig. 9(c) with $\sigma_r = 5$, $\bar{P}_A/P_A = 10^{-3}$, $r_O = 10$, and $t_O = 36$ minutes.

$$\sigma_\mu = 0.9 \text{ n.mi.}$$

Thus, the required accuracy and reporting rate are

$$\sigma_\mu = 0.9 \text{ n.mi.}$$

$$t_O = 36 \text{ min}$$

4.3.2.2 Subsonic present-day results: The following values are selected:

$$\sigma_r = 12 \text{ n.mi.}$$

$$\sigma_i = 20 \text{ knots (lateral velocity error rate)}$$

$$S_r = 30 \text{ n.mi.}$$

$$N = 50 \text{ aircraft}$$

$$\left. \begin{array}{l} A_i = 3 \text{ alarms/hr} \\ \bar{P}_A/P_A = 10^{-3} \end{array} \right\} \text{ as selected in the first case}$$

$$P_r = 1.75 \times 10^{-8} \text{ (from Sec. 4.3.1)}$$

Figure 10 was constructed for these values.

In fig. 10(a) at $A_i = 3$, $r_O \approx 25$ n.mi.

Figure 10(b) shows that a separation standard of 30 n.mi. is not feasible. Possible alternatives are:

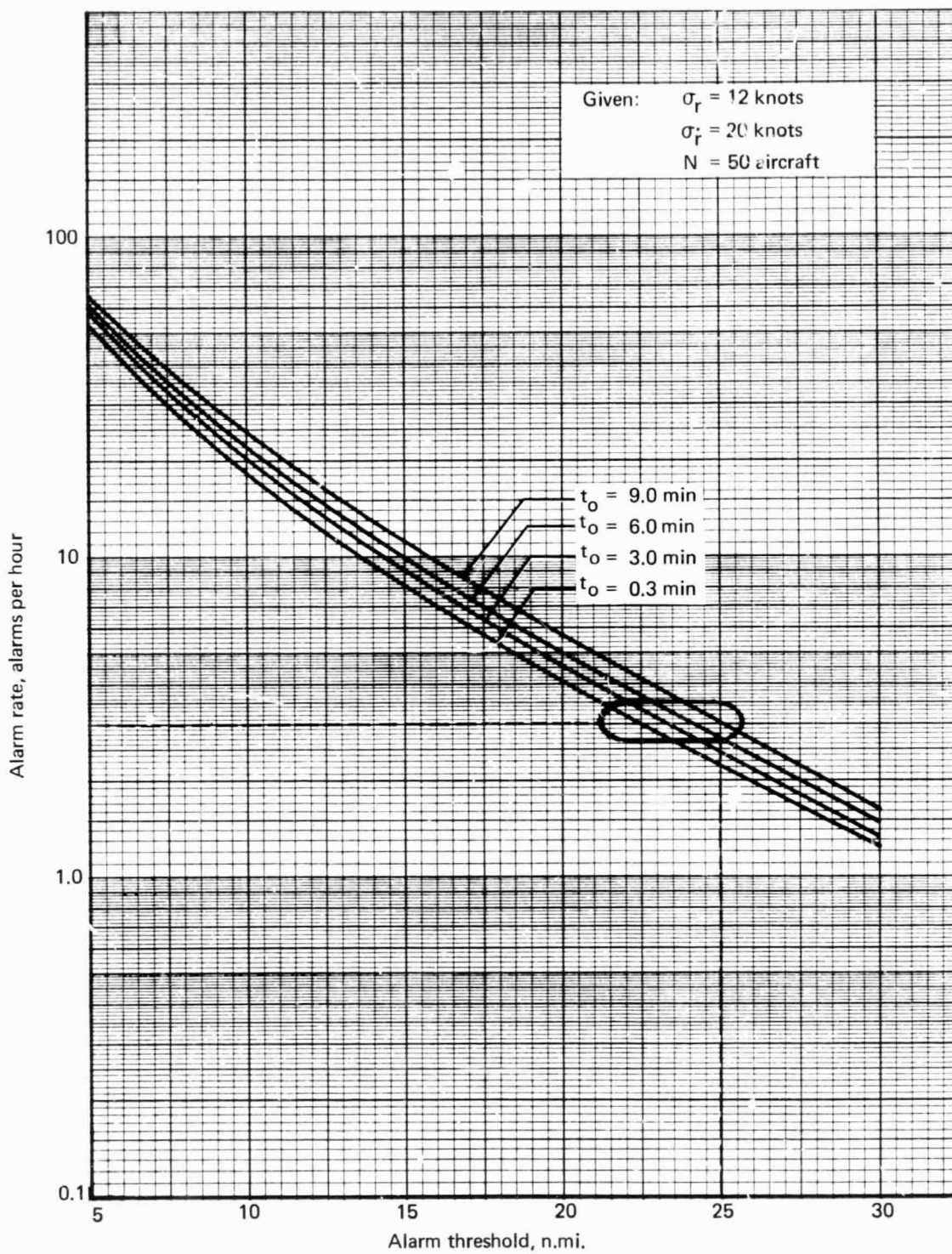
- (1) Raise the separation standard
- (2) Lower the alarm threshold (thus raising the alarm rate)
- (3) Accept a lower level of safety P_r

Assume that the separation standard is allowed to be increased to 60 n.mi. then, fig. 10(b) shows that $t_O = 4.6$ minutes at $P_r = 1.8 \times 10^{-8}$.

Returning to fig. 10(a), the alarm rate

$$A_i = 2.7 \text{ alarms/hr}$$

is acceptable.



(a) ALARM THRESHOLD

FIGURE 10.— SUBSONIC SURVEILLANCE CURVES - Continued

Figure 10(c) shows, with $\sigma_r = 12$, $\bar{P}_A/P_A = 10^{-3}$, $r_0 = 25$, and $t_0 = 4.6$, that

$$\sigma_\mu = 2.4 \text{ n.mi.}$$

Thus,

$$\sigma_\mu = 2.4 \text{ n.mi.}$$

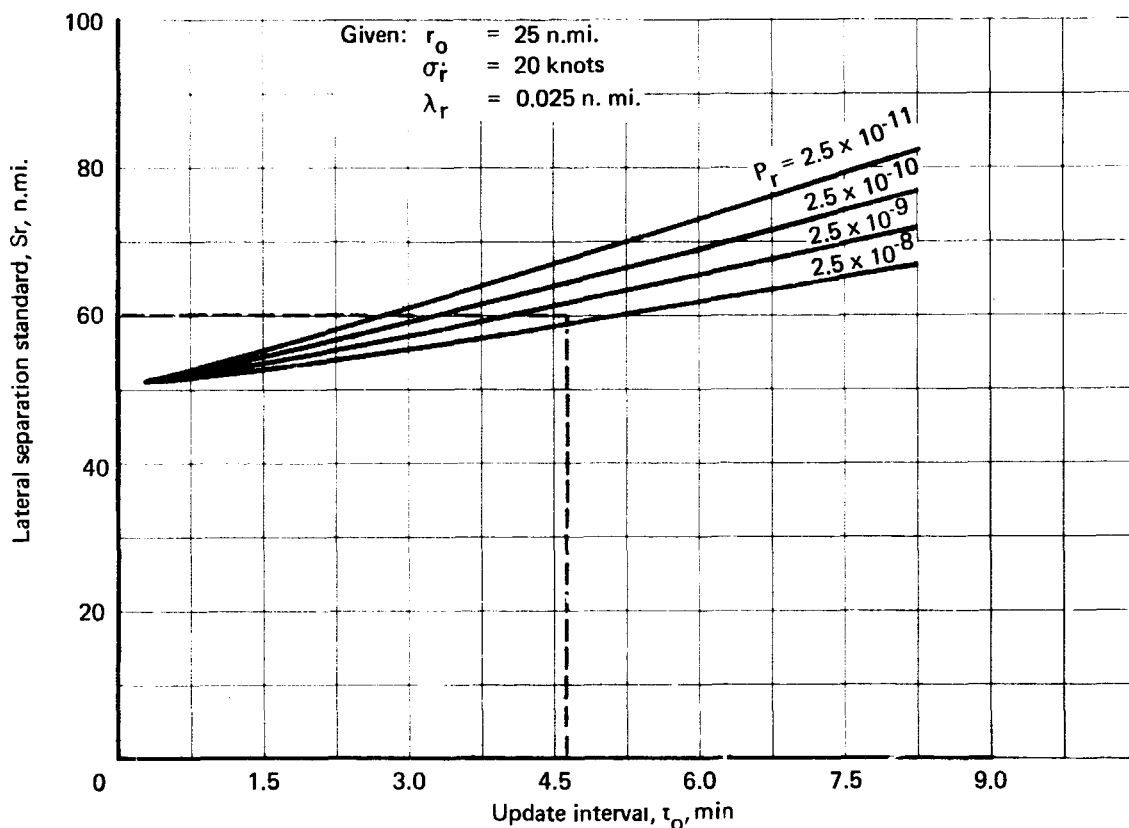
$$t_0 = 4.6 \text{ min}$$

The two examples considered above are intended to be realistic estimates of what might be expected in the 1980's. It is quite obvious that optimum utilization of the air-space might require different separation standards and different surveillance requirements for different type aircraft. If this happens, it might be possible to allow aircraft with less stringent surveillance accuracy requirements to use simpler, less expensive airborne equipment, whereas high-accuracy users would employ more sophisticated gear to obtain the required accuracy. The basic surveillance system (independently of the airborne equipment) must be able to meet the most stringent requirements placed on it by any user vehicle. If the more stringent requirements on both accuracy and reporting rate are taken from each of the two exercises considered above,

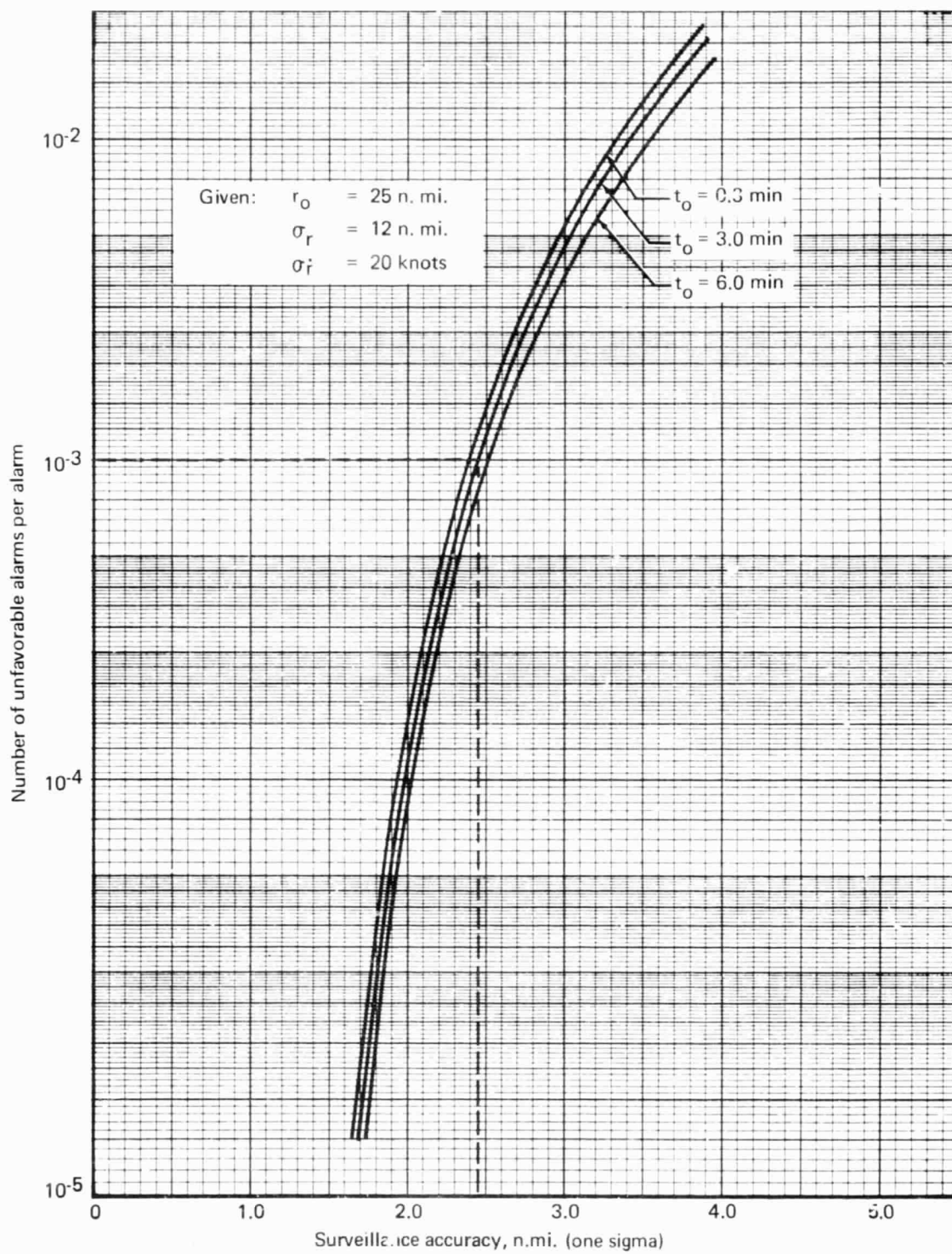
$$\sigma_\mu = 1 \text{ n.mi.}$$

$$t_0 = 4 \text{ min}$$

A surveillance system that meets these requirements will provide adequate ATC surveillance service over the North Atlantic in the 1980's.



(b) UPDATE INTERVAL
 FIGURE 10.— Continued



(c) SURVEILLANCE ACCURACY

FIGURE 10.— Concluded

5.0 IMPACT OF TECHNOLOGY ADVANCES

The preceding sections have been confined to a discussion of the requirements based on a limited extrapolation of the present operational environment over the North Atlantic. The operational changes postulated are those that can be predicted to occur if the proposed ATC satellite becomes operational. For example, the communications load has been increased over that presently experienced by assuming that the increased availability of communications obtainable from a satellite system will lead to an environment more like the present-day U.S. environment.

In this section, we will consider the possible effect of implementation of other proposed systems. Those considered most likely in the 1970's are the Aircraft Integrated Data System (AIDS), Automatic Flight Management (AFM), Collision Avoidance System (CAS), and Pilot Warning Indicators (PWI). The implementation of any or all of these systems is still not certain and depends on indeterminant factors. Also, the extent of implementation is a key missing piece of information. Since no central authority exists to enforce uniformity of operation in the North Atlantic, there is a low likelihood of any estimates being correct. However, in spite of these limitations, enough is known about the operation of these systems to enable an assessment of the impact of each on a satellite ATC system. This is not the case for other possible systems. Therefore, only the identified systems will be examined.

5.1 Aircraft Integrated Data System (AIDS)

An AIDS capability on an airplane would permit inflight fault detection and engine and flight performance monitoring. The data collected would either be stored onboard the airplane for later analysis or analyzed onboard and data-linked digitally to a ground terminal. The possible data-link loading is of importance to a communications satellite design.

To determine this loading, the following information must be available:

- (1) Identification of parameters to be monitored
- (2) Monitoring frequency
- (3) Information content of parameters monitored
- (4) Criteria for data-linking specified parameters
- (5) Required availability of data (continuous or sampled)

This information is incomplete and not wholly available. Also, each user specifies his own requirements. For example, some airlines would store all data onboard for later analysis, whereas others would perform sufficient analysis onboard to data-link replacement instructions to the ground; some items of airplane operational information could be continuously transmitted in real time. Obviously, the data-link loading would vary from zero to a full-time dedicated channel for each airplane.

However, considering the cost of a satellite digital data link, it is estimated that at most only failure information requiring replacement would be data-linked in flight on a North Atlantic crossing. Assuming about 100 items to be monitored with one failure indication per flight and 25 12-bit words for identifying the failure, only 300 bits per flight are required to be transmitted. If all 150 airplanes in flight would require a failure indication during a peak hour, then 45 000 bits per hour might be required. One 1200-bit-per-second channel would have approximately 100 times this capacity. Therefore, at the most, it appears that two 1200-bit-per-second channels could handle any likely AIDS requirement.

5.2 Automatic Flight Management (AFM)

The AFM system is a concept being developed at Boeing to improve safety and economy in airline operations through: increased precision and reliability in control, guidance, and navigation; improved data display and extensions to flight-deck automation to reduce pilot workload; and automation of maintenance data collection and assessment to reduce aircraft down-time. Use of an airborne digital computer is envisioned to optimally filter sampled navigational data from several different sensors, compute position and guidance errors relative to a stored flight plan, and automatically control the flightpath including all-weather automatic landing and sequence and control electronic display instruments and other automatic functions. This capability could have an influence on a future North Atlantic ATC satellite system. Again, indeterminant factors will affect the extent of this influence. The following factors are most important:

- (1) Number of AFM-equipped aircraft
- (2) Compatibility of ground ATC environment with AFM
- (3) Implementation of alternative approaches to ATC problems

The AFM airborne system design goals that may have a significant bearing on the character and operation of overocean air traffic control in the future are as follows:

- (1) ± 300 -foot horizontal position error enroute (U.S. domestic airspace)
- (2) Prestorage of standard flightpaths (automatic path guidance)
- (3) Reduced enroute separation

Quantitatively, AFM will provide continuous position (including altitude) measurement to an accuracy of from 100 to 300 feet (2σ) in U.S. domestic airspace, depending upon (1) the navigation aids available and (2) control of the airplane to continuously achieve a desired position as a function of time within an accuracy of 5 to 10 seconds relative to the flight plan.

Normal flight will be based on the clearance stored in the AFM computer in terms of the desired airplane position as a function of time. This would be compared to the existing airplane position (and velocity) and error signals generated for any required velocity or direction change. These error signals are displayed to the pilot; he may use them either to fly the aircraft manually or to monitor system operation in the automatic mode.

Thus, the aircraft will be maintained continuously on the cleared flight plan or, if this requires changes that exceed the airplane's performance, a changed flight plan that can be quickly originated and approved.

Conceptually, this capability would permit the following operational ATC procedures. The precise path to be followed enroute will be assigned by ATC in accordance with a standard route procedure. (In some cases, a time schedule for key way-points is chosen by the pilot).

The assignment will be entered in a ground computer system.

The AFM aircraft will be responsible for staying on this assigned track. If it is necessary to deviate from the assigned track, ATC will be alerted. Otherwise, the airplane proceeds on its assigned track, occasionally checked by ATC radar. The radar data enters the ATC computer, which checks the assigned track, and any discrepancy is flagged to alert the controller.

Notice that:

- (1) The aircraft position as computed onboard is not transmitted to the ground, and
- (2) No direct command information is normally sent from the ground to the aircraft.

This eliminates the necessity for the high-volume data link, and yet all parties know the aircraft status. When exceptions arise, the voice link is used.

Areas of no radar coverage, such as the North Atlantic, present no special problems. The newer aircraft occupy higher altitude strata. AFM lateral precision path control using LORAN-Inertial (automatically combined) would allow use of smaller horizontal separation standards than those used by non-AFM-equipped aircraft.

It would seem that nothing would be gained by transmitting position data derived onboard an AFM aircraft to the traffic control center. If the airborne equipment is working, the airplane will be exactly where it is supposed to be, which is known before takeoff and is already in the ground computer. If its equipment is faulty, it could not transmit useful data anyway. If any trouble is encountered in keeping on the assigned path and schedule, the standard procedure might be to contact ATC for a new clearance and descend to an altitude level at which traffic density is much less (non-AFM separation standards).

It should be remembered that the preceding is strictly conceptual at the present time. No analysis of the concept for feasibility or cost benefit has been attempted. However, conclusions based on the above qualitative description would tend to minimize the need for the satellite surveillance/navigation requirement for aircraft equipped with AFM.

The communications requirement in an AFM-ATC system would assume even greater importance. The capacity requirement would probably be less due to elimination of some portion of the voice load now assumed. However, a digital data link would be required. This link would be similar to that required for an AIDS-type operation. In the preceding section, we saw that two 1200-bit-per-second channels would probably be sufficient for any conceivable situation.

5.3 Collision Avoidance Systems (CAS) and Pilot Warning Indicators (PWI)

A collision avoidance system performs the following functions:

- (1) Detect potentially dangerous intruders
- (2) Evaluate the hazards presented by the detected aircraft
- (3) Determine if a maneuver is required
- (4) Indicate the evasive maneuver required to provide safe separation

The CAS is *not* intended to replace the ground-based air traffic control (ATC) system nor should ATC rely on the CAS for providing safe separation for aircraft. The role of the airborne CAS is to provide safe separation of aircraft independent of ATC when, for any reason, the ATC system fails to fulfill its intended role.

For this reason, the effect on a satellite ATC system is expected to be minimal; however, if all aircraft are equipped with CAS, it might be possible to reduce North Atlantic separation standards. This follows from considering the collision-risk equation discussed in Sec. 4.0. One of the assumptions in development of the model was that no evasive action would be taken by colliding aircraft. A CAS would obviously change this assumption. The model would have to be changed by some factor that would depend on the operational and equipment characteristics of the implemented CAS.

Depending on the amount of possible separation reduction, the requirements placed on the satellite position-fixing requirements would be lessened.

A quantitative analysis of this concept has not been attempted. Such a study would involve detailed analyses of the several proposed CAS designs and modification of the collision risk model based on these analyses.

A Pilot Warning Instrument (PWI) is a device that aids visual detection. Such devices merely warn the pilot of the presence of other aircraft. Though they may provide information on an intruder's location, they do not evaluate the nature of the situation nor indicate appropriate maneuvers.

This can be analyzed in the same manner as the CAS. In this case, it is obvious that a less effective system results because safe evasive maneuvering is not provided by the system; further analysis is required to quantitatively determine the degree of benefit.

In either case, the lack of firm data about implementation plans and system specifications precludes meaningful analysis at this time.

6.0 RECOMMENDED SYSTEM REQUIREMENTS

In the previous sections of this report, analyses were presented to show the effects of the communications and navigation/surveillance system operational specifications on the ATC operational environment. For example, the effects of the surveillance satellite accuracy and position reporting rate on the separation standards and the collision risk were analyzed in Sec. 4.0. Also, the effect of communications channel capacity on the message transmission delays was analyzed in Sec. 3.0. In this section, these analyses are used in specifying the requirements of a preferred system. The choice of a preferred system configuration depends on both this type of analysis and on other considerations. Cost-benefit considerations play a significant role. Also operational constraints must be examined for their effect on the selected system. Growth potential should also be factored into a selection. In this section, an attempt is made to incorporate all of these factors into a system configuration that meets all requirements.

6.1 General Considerations

The purpose of providing a satellite capability for air traffic control is to allow separation standards for reduced lateral and longitudinal spacings over the North Atlantic. These standards will decrease the frequency and magnitude of economic penalty associated with deviations from the optimum track that occur during peak traffic periods.

The system concept and requirements must be chosen to provide the maximum benefit-to-cost ratio, where the benefit is the reduction in airplane flight costs and cost is the system investment and operational costs. Two mitigating factors in defining this optimum operational concept are:

- (1) Separation standards are chosen for some minimum acceptable collision risk that, in turn, depends upon the frequency of occurrence of large navigation errors. Because these large errors are rare events, they are not amenable to calculation; they are typically derived from operational experience.
- (2) Division of control responsibility due to ATC operational considerations and the international political aspects of the control system may place constraints on the operational concept.

These factors are considered in developing the recommended system requirements.

6.2 Navigation/Surveillance Requirements

These requirements are considered first because they significantly affect communications requirements.

A surveillance capability provides airplane positional data to ATC using a separate system from that for navigation. The advantage of surveillance is that errors in ATC and airplane navigation positional data are not correlated. Thus, when a navigation error occurs, the difference in airplane and ATC positional data provides evidence of the situation. This type of operation is epitomized by the U.S. domestic airspace system, in which

the aircraft are navigated using the VOR/DME ground-based system while ATC monitors progress with primary and secondary radars.

The decision to use the ATC satellite capability for navigation or surveillance depends fundamentally upon which approach will support the smaller separation standards.

Separation standards are chosen to provide an "acceptably" low probability of collision. Since the probability of collision must be kept extremely small, North Atlantic navigational errors greater than half the present separation standard are "rare events". Navigational errors of this magnitude are generally referred to as "blunder errors". This term is applied because large navigational errors are generally caused by equipment or human failures rather than by equipment performance tolerances.

Present separation standards over the North Atlantic are 120 n.mi. laterally (across track) and 15 minutes or more of flight time longitudinally (along track). During peak traffic, the magnitude of these separations produces undesirably large deviations from the most economical flightpath. Commercial aircraft operators would like to see the standards provide for a reduction in separation of about an order of magnitude (e.g. 12 to 15 n.mi. and 3 to 5 minutes).

A reduction in the lateral separation requires a significant improvement in track-keeping accuracy. This can be accomplished either by improving the navigation accuracy, by providing a surveillance capability, or by a combination of both. The system effectiveness criterion is the probability of an unpredictable blunder error occurring. Because of this unpredictability (especially before a system is used), the selection of a best approach is a matter of controversy and is not easily analyzed.

Inertial navigation systems are expected to provide track-keeping accuracies through the NAT Oceanic Control Area (OCA) of 8 to 12 n.mi. (2σ). Without surveillance, this capability is expected to support a 60-n.mi. lateral separation. Addition of a satellite surveillance capability of 2 to 5 n.mi. (2σ) to this system could produce the desired 12- to 15-n.mi. separation. The use of inertial navigation systems (INS) will become prevalent in the 1970-1980 period. The Boeing 747, American SST, and Concorde are planned with INS's, whereas at least one air carrier (AAL) is seeking to retrofit its B707 aircraft. Most commercial operations prefer a self-contained navigation system, because it allows worldwide operation and is independent of failures in the external environment.

Thus, in summary, the best argument for surveillance is probably that because our capability to predict blunder rate is very poor, we should devise separate standards to achieve an order-of-magnitude reduction in spacings by splitting the risk between the airplane navigation system and an ATC satellite surveillance system.

Quantitatively, based on the analysis in sec. 4.0, the following requirements are selected for the preferred surveillance system:

System accuracy	1.0 n.mi. (1σ)
Reporting rate	20 position reports/hour/airplane
Separation standard	30 n.mi. (lower if operational experience permits)
Alarm rate	3/hr
Alarm threshold	10 n.mi.

The reporting rate specified above is 20 reports per hour per airplane or an updating period of 3 minutes. The analysis in Sec. 4.0 indicated updating periods of 4.6 minutes for conventionally equipped subsonic airplanes and 36 minutes for inertially equipped supersonic airplanes. The more stringent requirement specified above is chosen to reflect a system designed to accommodate safely the lesser-equipped airplanes and also to permit a possible reduction in longitudinal (along-track) separation requirements.

The present position reports of every 10⁰ (about 45 minutes) support a longitudinal separation of 15 minutes. This is sufficient separation to ensure a low probability of a front-to-rear collision of two airplanes nominally separated in only the along-track dimension. Such a collision could occur because of inaccuracies in airplane velocity measurements. The lateral-collision risk evaluated in Sec. 4.0 involved errors in the across-track position accuracy.

A detailed analysis of the along-track collision situation has not been performed in this study. However, the update period of 3 minutes was selected based on similar analyses performed by other groups (ref. 5).

6.3 Communications Requirements

The NAT OCA principal area is presently divided into four flight information regions (FIR's):

- (1) Gander FIR - controlled from Gander, Canada
- (2) New York FIR - controlled from New York
- (3) Sharnwick FIR - controlled from Prestwick, Scotland
- (4) Lisbon FIR - controlled from Lisbon, Portugal

With the introduction of supersonic aircraft, control is expected to be divided by altitude with low-altitude sectors for flights below FL (flight level) 180, high-altitude sectors between FL 180 and FL 420, and ultra-high-altitude sectors above FL 420. Most commercial traffic will use the two upper levels whereby subsonic jets are in the high sectors and supersonic aircraft are in the ultrahigh sectors.

Real-time reliable communications and more frequent and accurate aircraft-position data will allow ATC operation in which short-term clearances are feasible. This will contribute to more economical and comfortable flight operations.

Reliable, minimum delay, ATC communications in this region will require that the U.S. message load specified in table 4 be handled. Since a surveillance system is also specified, position reports can be eliminated. Five voice channels will be required to implement this system. Ideally, all five channels should be time-shared among the four oceanic areas handling traffic. The details of the ground terminals need further study to determine the feasibility of this time sharing. A priority message-handling technique is recommended. If this is not feasible, an emergency channel should be allocated.

Quantitatively, the following requirements are specified:

Number of busy-hour messages	745
Required number of voice channels	5
Channel utilization	less than 80%
Average delay (all messages)	less than 20 sec
Average delay (first-priority messages)	less than 1 sec
Worst-case delay (first-priority messages)	less than 10 sec

6.4 Recommended Operational Concept

The operational concept requirements are:

- (1) Aircraft position, altitude, and identity should be automatically transmitted to the appropriate control facility by a surveillance capability.
- (2) The ATC satellite position data should be used to provide ATC surveillance. The choice of an active or passive system should be based on cost/benefit considerations.
- (3) Direct pilot-to-controller communications will be used. This is the functional equivalent of a channel for use between each controller and those aircraft under his jurisdiction. The mixture of voice and data link will depend upon ATC development of facilities to use data-link messages.

APPENDIX A BACKGROUND ON NORTH ATLANTIC AIR TRAFFIC CONTROL

A1.0 TRAFFIC CHARACTERISTICS

The North Atlantic ATC system has developed to accommodate the flow and flight characteristics of international aviation.

A1.1 Routes

Approximately 50% of the Free World scheduled air carrier flights are conducted between North America and Europe over the North Atlantic (NAT). The cities that generate the majority of this traffic are listed in table A1.

TABLE A1. – PRINCIPAL NORTH ATLANTIC TRAFFIC-GENERATING CITIES

North America	Europe
New York	London
Montreal	Paris
Toronto	Frankfurt
Boston	Rome
Chicago	Amsterdam

Great-circle routes connecting these cities fall within a latitude band of about 8° over the North Atlantic (fig. A1). The optimum track between any city pair is a minimum time track (MTT) that considers the existing wind velocities. Since prevailing winds are from west to east, eastbound MTT's tend to lie along the latitude of maximum wind velocity, whereas westbound MTT's skirt this latitude. Thus, at any one time, the MTT's between various city pairs are usually more concentrated than the great-circle paths.

A1.2 Demand

The flights over the North Atlantic vary both with time of day and season. Most eastbound passengers prefer to leave North America in the evening and arrive in Europe the next morning. Most westbound passengers prefer to leave Europe in the morning and arrive in North America the same day. The resulting diurnal variation in flights is shown in fig. A2. The seasonal variation is characterized by the summer peak, which is generally attributed to tourists. Approximately 40% of the annual passenger traffic occurs during the busy months of June, July, August, and September.

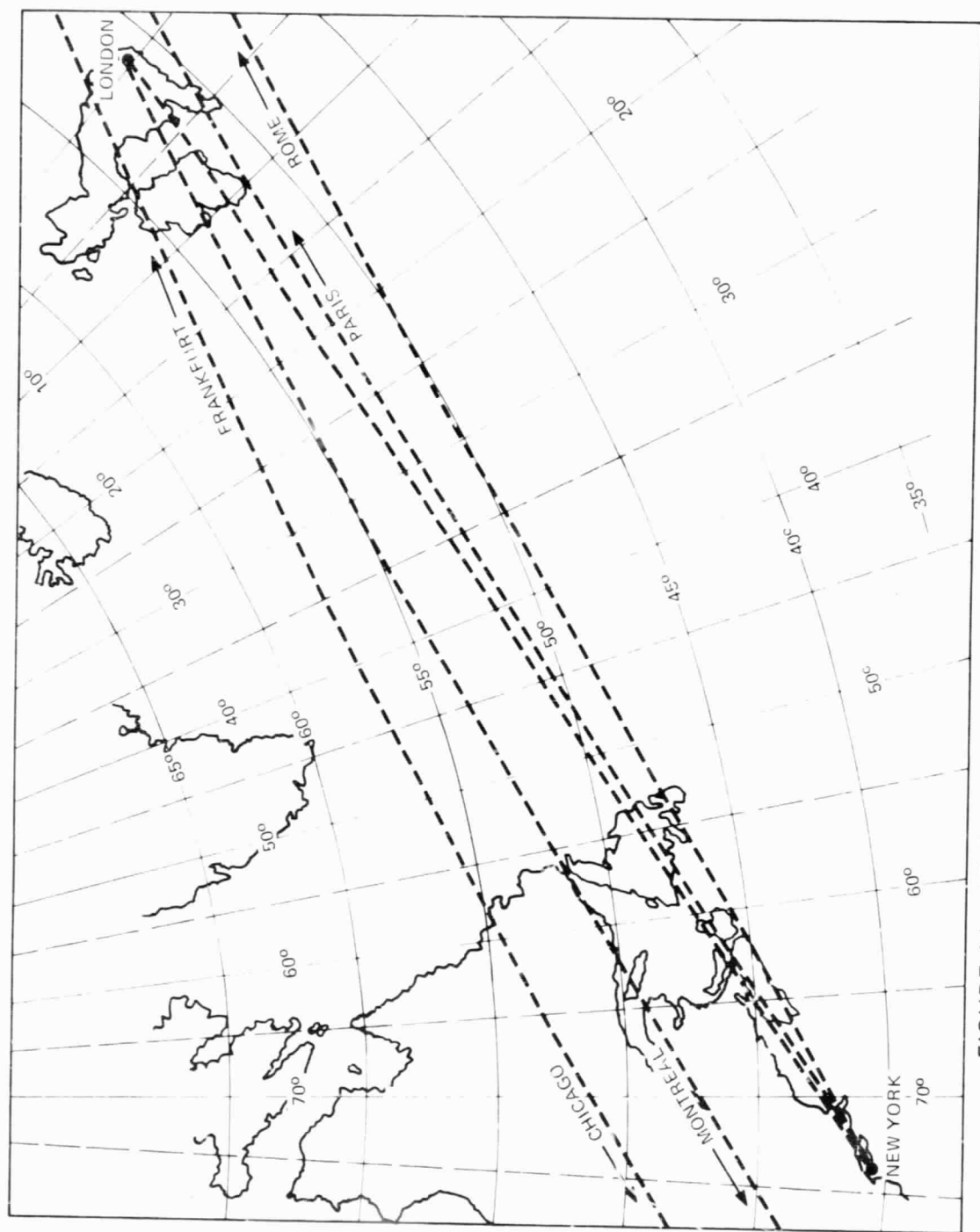


FIGURE A1.—SELECTED NORTH ATLANTIC GREAT-CIRCLE ROUTES

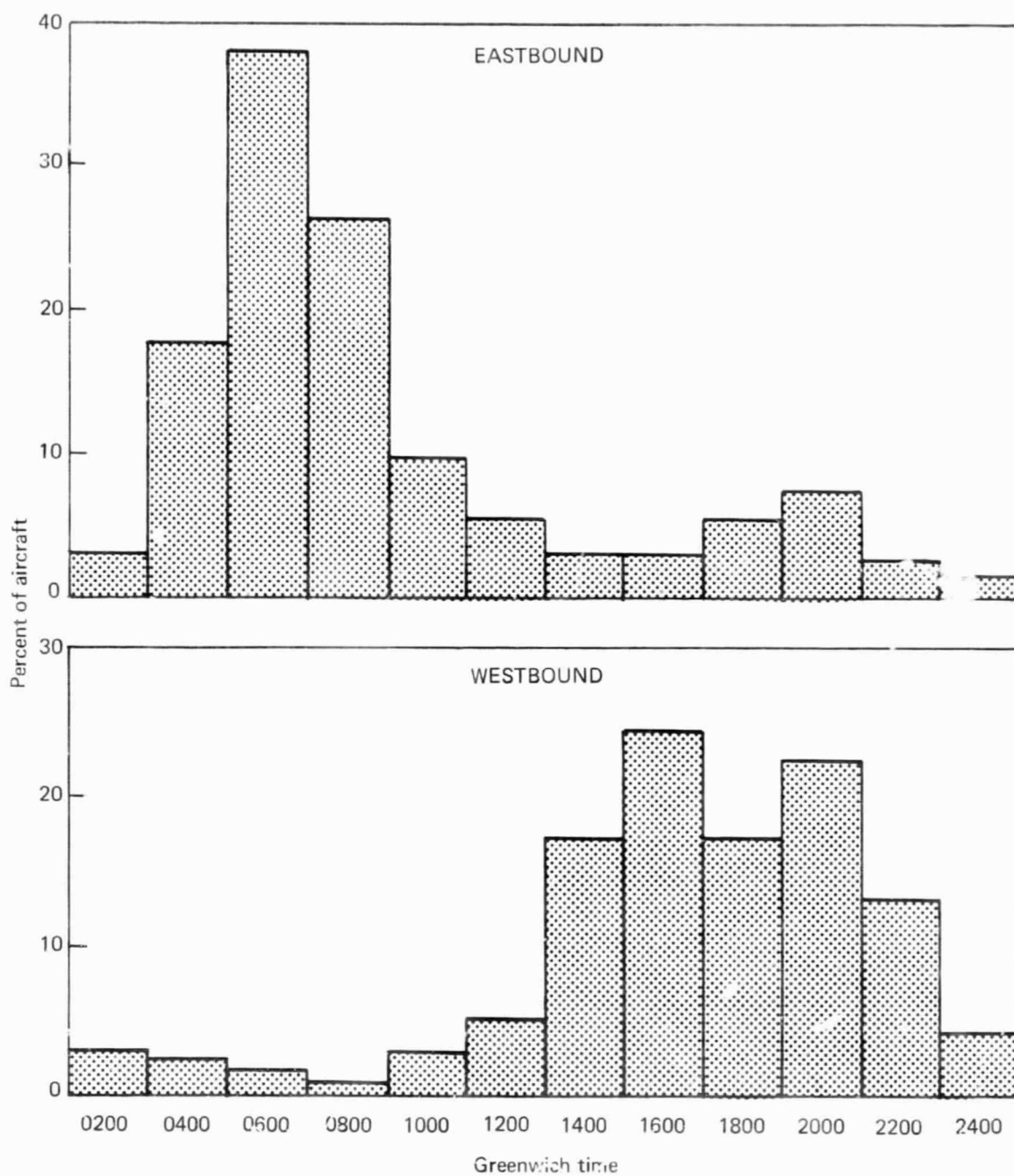


FIGURE A2. - TIME DISTRIBUTION OF CIVIL JETS CROSSING 30° W MERIDIAN

A1.3 Aircraft

Most scheduled air carriers fly subsonic jet aircraft. The principal types are the B-707, DC-8, and VC-10. These aircraft have similar speed and altitude capabilities. Thus, the flight plans are usually similar with the desired altitude differing principally due to the aircraft weight and pilot-company operating techniques. Figure A3 shows the actual altitude usage for a 24-hour period and displays the congregation of aircraft in flights levels 310 to 370.

A2.0 PRESENT ENVIRONMENT

The International Civil Aviation Organization (ICAO) publishes a plan for the provision of facilities and services for air navigation in the North Atlantic (ref. 6). These facilities are provided by the contracting states. The principal facilities of interest are air traffic services, communication, and navigation aids. This discussion is confined to those facilities serving the principal North Atlantic area through which the majority of traffic between North America and Europe normally moves.

A2.1 Air Traffic Services

The North Atlantic Region is subdivided into control areas (CTA) as delineated in fig. A4. The principal area consists of the New York, Lisbon, Gander, and Shanwick Oceanic CTA's. The significant facilities are the area control centers (ACC) and the ocean station vessels.

2.1.1 Air control centers (ACC).— Area control service is provided by an area control center for each control area. Control centers* for the principal area are located at:

- (1) Ronkonkoma, New York (New York Oceanic CTA)
- (2) Gander, Newfoundland (Gander Oceanic CTA)
- (3) Prestwick, Scotland (Shanwick Oceanic CTA)
- (4) Santa Maria, Azores* (Lisbon Oceanic CTA)

Surveillance radar, VHF communications, and VOR navigation aids, which are the basis for ATC over land, all have line-of-sight limited coverage. Generally these facilities are located along the seacoast such that service for jet aircraft at cruise altitudes is available out to about 200 n.mi. (fig. A5). It is partially because of this that oceanic boundaries begin offshore approximately where the land-based ATC system becomes ineffective.

Since radar surveillance is not available, oceanic controllers use flight progress strips, flight plans, and position reports to plan initial clearances through the area and to monitor flight progress. This "strategic" mode of control is employed wherein clearances are granted for the entire flight through the CTA's.

*Lisbon ACC is planned.

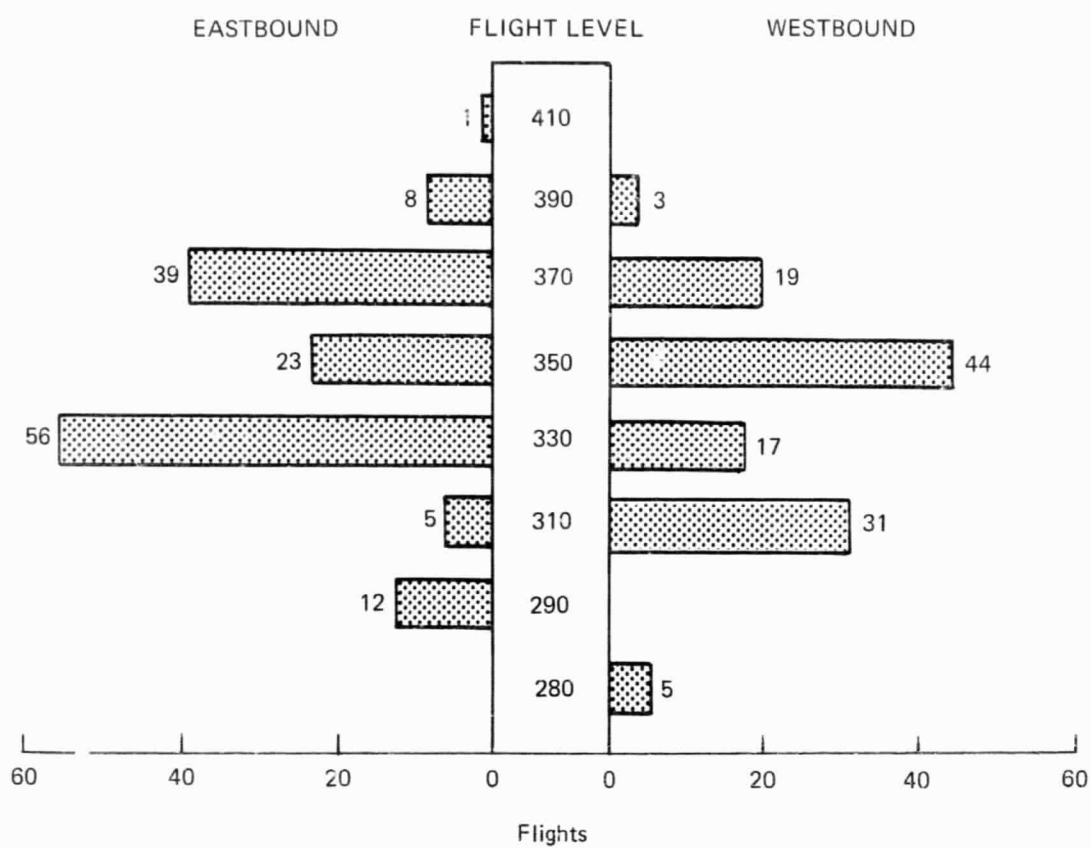


FIGURE A3.— GANDER-AREA TURBOJET ALTITUDES (SEPTEMBER 29, 1967)

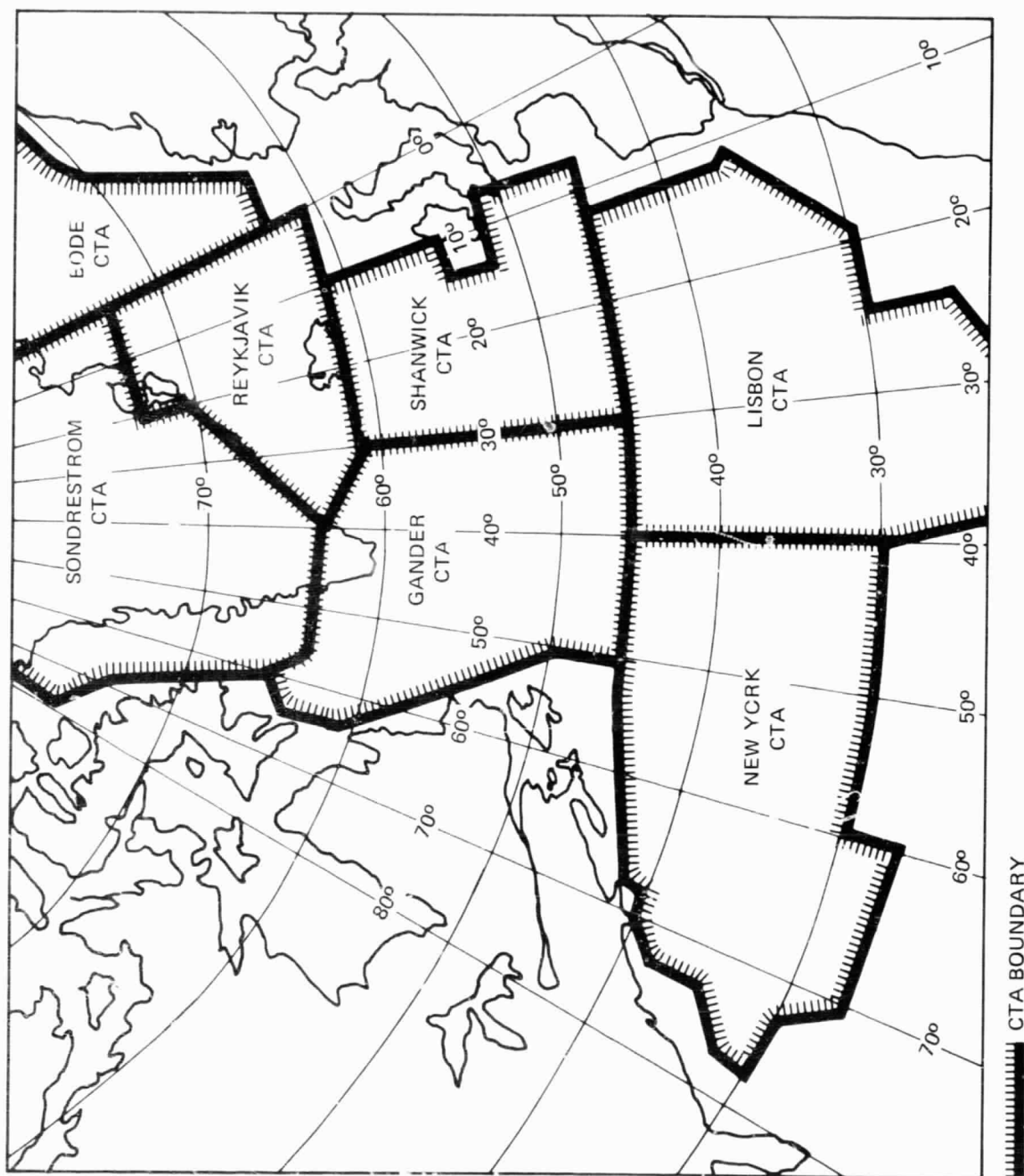


FIGURE A4. – NORTH ATLANTIC CONTROL AREAS (CTA)

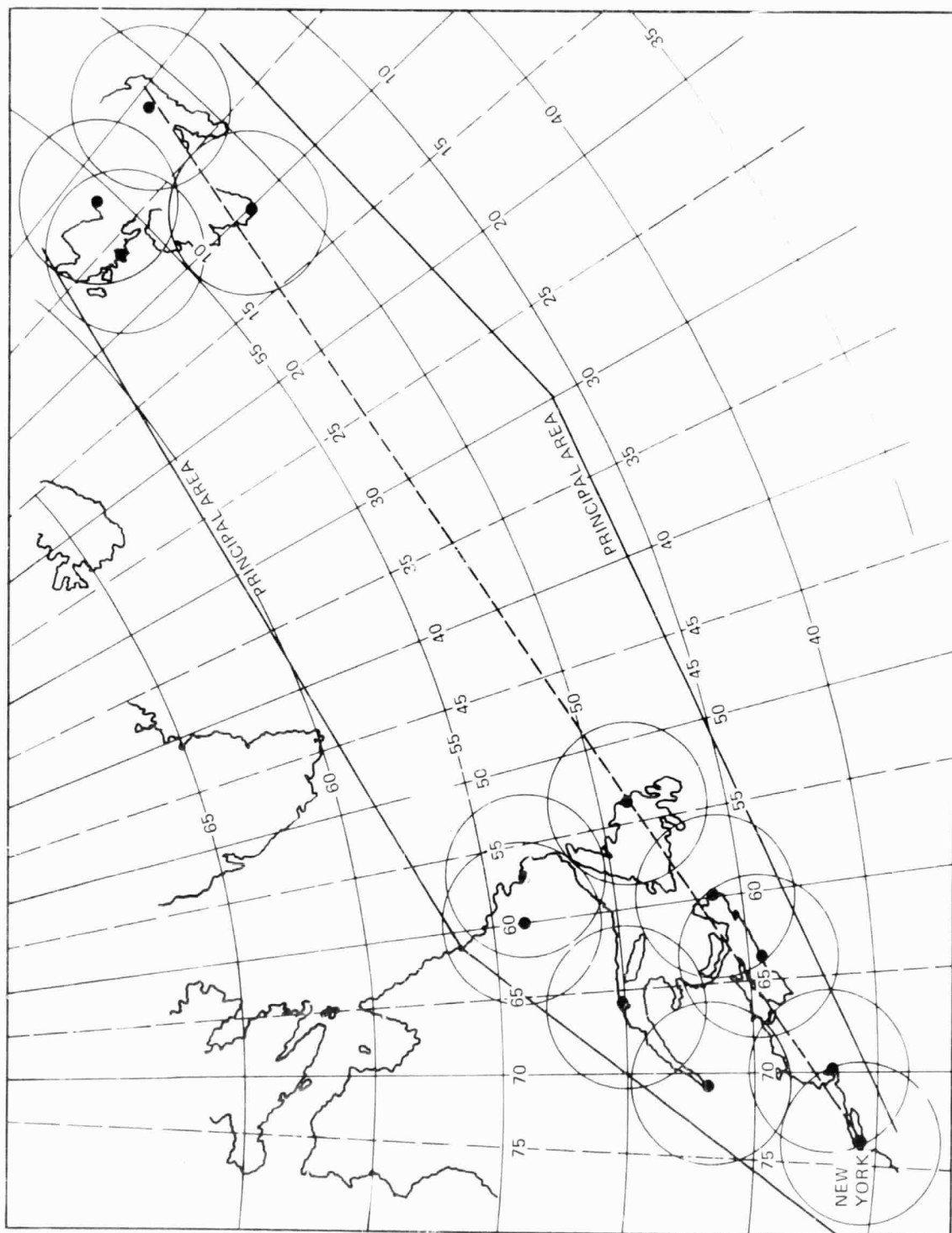


FIGURE A5.— SURVEILLANCE COVERAGE

Pilots are required to make periodic position reports (normally when crossing the 10° meridians). If a flight fails to achieve its cleared flight plan such that it may come within less than the separation standard of another flight, clearances are revised to ensure separation.

A2.1.2 Ocean station vessels (OSV). - Nine ships known as ocean station vessels are positioned in the North Atlantic. These vessels are supplied by the NAT contracting states. Their primary role is search and rescue while providing assistance to aircraft flying past their position. Each ship has radar and both VHF and HF communications facilities. Typically, they may provide position fixes to aircraft passing within line-of-sight and may be involved in relaying messages between aircraft and the control centers.

A2.2 Air-Ground Communications

VHF is used for enroute communications when an airplane is within VHF coverage of an aeronautical station. Generally this distance is within 200 n.mi. of land. Outside of VHF coverage, HF radio telephony is employed. A network of HF stations is located around the region and on ocean station vessels. The primary aeronautical stations are located at New York, Gander, Prins Christian Sund, Reykjavik, Lisbon, and Shannon.

However, due to the vagaries of HF propagation, messages must often be relayed through whatever station the aircraft can contact—sometimes via other aircraft.

In addition to air traffic service (ATS) communications facilities, Aeronautical Radio, Incorporated (ARINC) has facilities for airline management communications with an aircraft. These facilities are connected to the control centers via teletype and are often used for air-to-ground ATC communications.

ARINC has HF stations and extended-range (propagation beyond line-of-sight by tropospheric scatter) VHF stations. Figure A6 shows the ATS HF stations, ARINC extended-range 30 000-foot coverage, and OSV VHF 30 000-foot coverage.

A2.3 Navigation

The basic long-distance radio navigation aids for the North Atlantic region are LORAN and CONSOL supplemented by a number of nondirectional radio beacons (NDB). In addition, Dectra is available. Most commercial aircraft are navigated using LORAN A for position fixes, a gyro compass for directional guidance and either calculated wind vectors or a doppler radar for velocity determination. CONSOL and Dectra have limited use, and LORAN C to date has not been employed.

Figure A7 shows LORAN A coverage for the NAT principal area. LORAN A receivers allow the navigator to obtain readings from which he may calculate position. The receivers must be manually operated and allow obtaining of only periodic position data. (Continuous real-time position is *not* available).

CONSOL stations are located in Europe and one in the United States (CONSOLAN). They provide bearing to between 0.5° and 4.0° accuracy up to a range of approximately

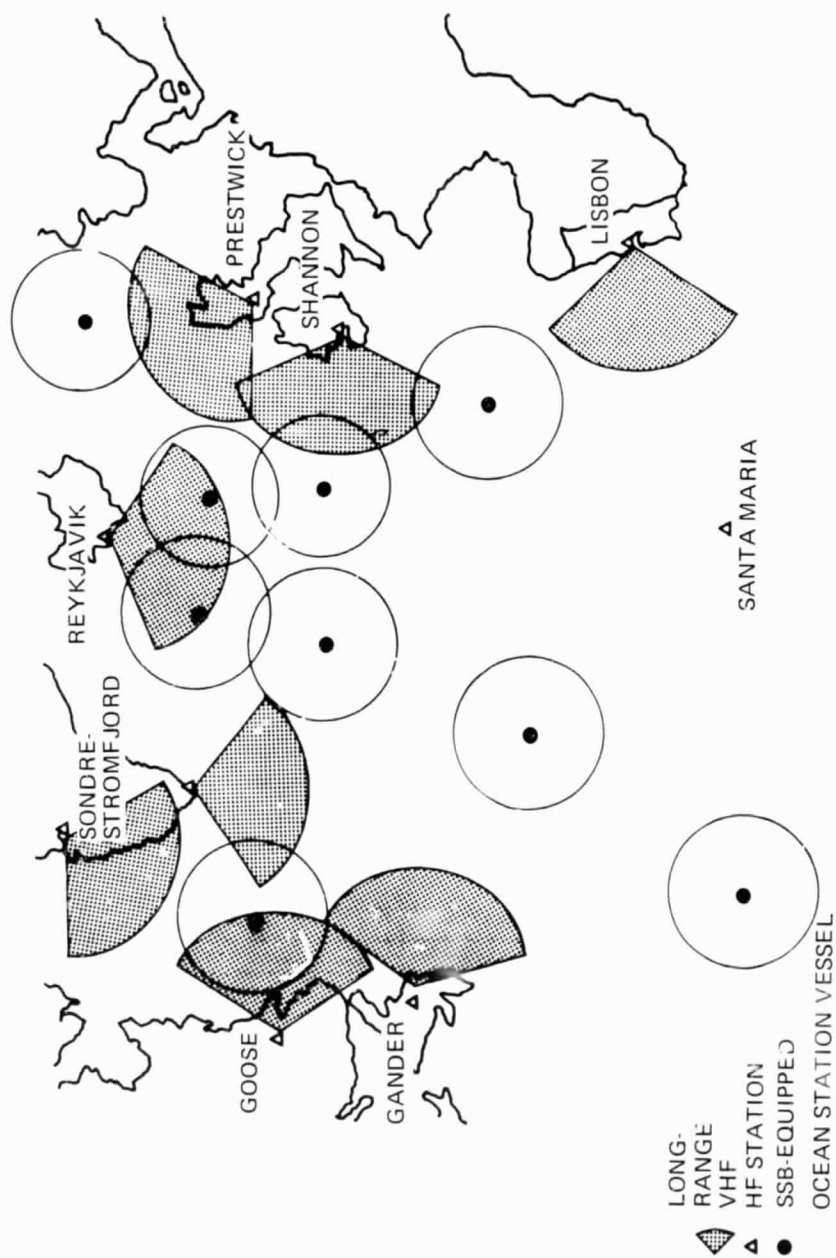


FIGURE A6.-- NORTH ATLANTIC COMMUNICATIONS FACILITIES

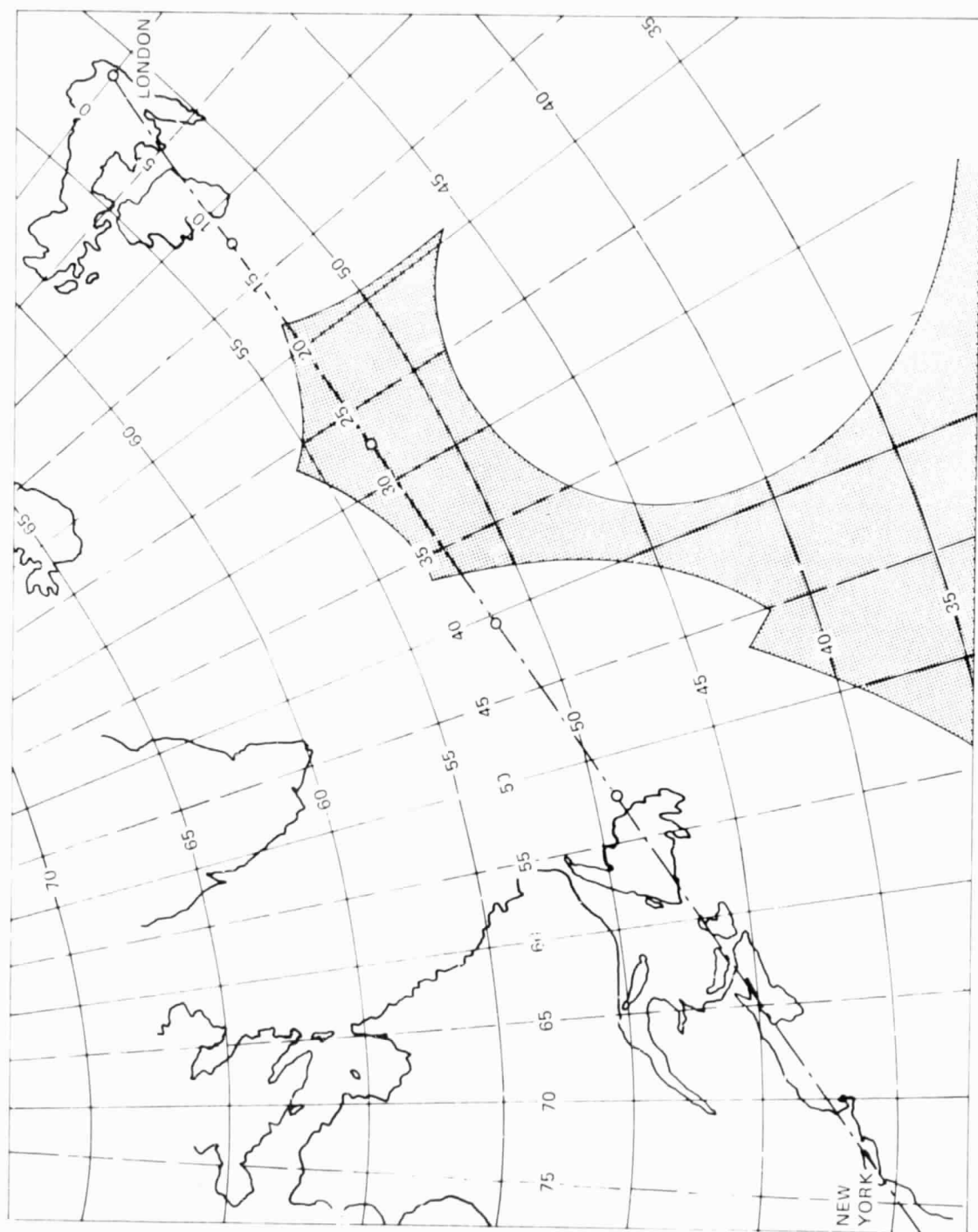


FIGURE A7.— NORTH ATLANTIC LOFANA

1000 nautical miles. Dectra II provides a 5-n.mi. position-fixing accuracy (67% confidence factor) over an elliptical region bounded by longitudes 5°W and 55°W and latitudes 45°N and 65°N.

Figure A8 shows the present LORAN C coverage in the NAT principal area. Although LORAN C receivers that provide continuous position data are available, they have not been employed by commercial air carriers, which is probably due to the high cost of the equipment.

A3.0 SYSTEM OPERATION

The basic oceanic ATC system is a "free" system in which pilots file for their desired track, speed, and altitude. ATC checks each flight plan against previous clearances for conflicts. (Conflict is where aircraft will come within less than the prescribed minimum separation distance.) If no conflict is involved, the clearance is granted. Otherwise, the clearance is revised to avoid conflicts.

A3.1 Separation Standards

The basic NAT separation standards (ref. 7) for subsonic jet aircraft are:

- (1) Vertical—1000 feet below 30 000 feet altitude and 2000 feet above 30 000 feet altitude.
- (2) Longitudinal—20 minutes of flying time except 15 minutes in the Gander Oceanic, Reykjavik, Shanwick Oceanic, and Sondrestrom (south of 70°N) control areas, provided the aircraft have reported over the same entry point into the oceanic controlled airspace and (a) follow the same track, or (b) follow diverging tracks until another form of separation is established. In practice, Gander ACC provides 15 minutes for aircraft on the same track, provided they fly the same constant Mach number. If a faster aircraft is following, they add 3 minutes for each Mach 0.01 difference.
- (3) Lateral—120 nautical miles minimum

A3.2 Organized Tracks

Most flights through the NAT principal area fly essentially parallel tracks. To make more efficient use of the available airspace during periods of peak traffic, ATC lays out a series of parallel organized tracks and aircraft are cleared only for flights along these tracks (or outside of the area where the tracks are established). These tracks are organized and operated as follows:

- (1) Gander ACC using expected eastbound traffic determines the hours in which an organized system is needed. Based on the forecast meteorological conditions, the minimum-time track (MTT) between New York and London is

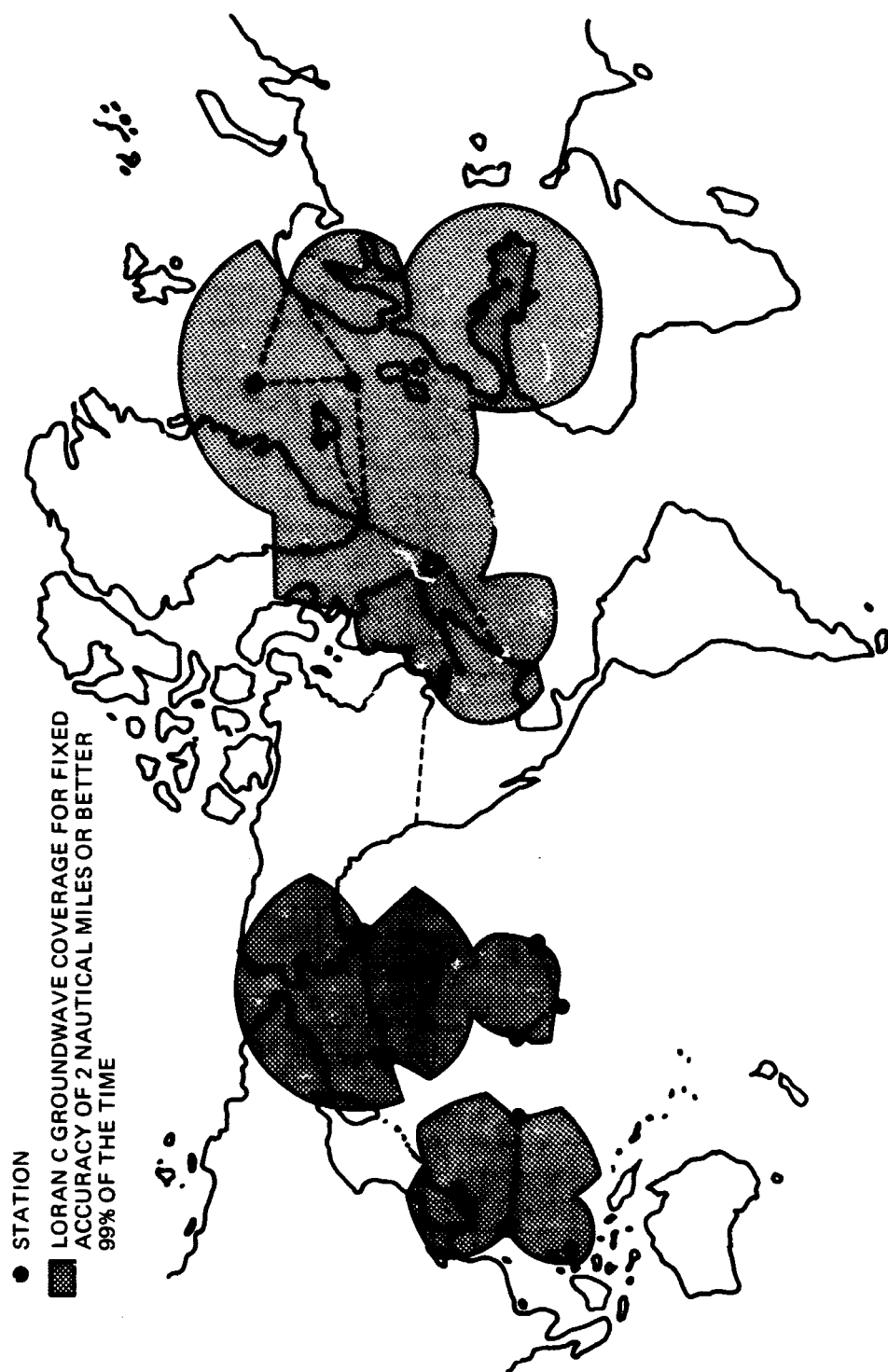


FIGURE A8.— LORAN C COVERAGE

calculated. Tracks spaced 120 nautical miles laterally are defined centered on the MTT (fig. A9). Typically these tracks are between longitude 50°W and either longitude 8°W, 10°W, or 15°W (depending upon latitude) in segments crossing each 10° meridian at a whole or 1/2° of latitude. Each segment is a great-circle element.

- (2) Gander personnel confer with Prestwick personnel to coordinate implementation of the organized system. Prestwick generally assigns two westbound altitudes (FL 31 and FL 35) to Gander for eastbound use. Thus, Gander has the four most desired flight levels (FL 31, 33, 35, and 37) available for eastbound use. The system is flexible, and during extreme peaks up to six tracks as shown may be defined. Altitude exchanges may be made for part of or all of the tracks, and often westbound altitudes will not be released until the eastbound peak has built up and the altitudes have been emptied of westbound traffic.
- (3) The organized tracks are made known to the airline planners for planning purposes as soon as possible. The airlines provide Gander with the desired flight plan (including track, altitude, and Mach number) prior to flight departure. These flight plans are used by Gander for preliminary planning on use of the organized system.
- (4) Flights approach the Gander center along the domestic airways. When within VHF range of Gander, the flights are assigned tracks, altitude, and Mach number. They then navigate to the track entry point at 50°W.
- (5) Westbound operations are handled in a similar fashion by Prestwick ACC. Since today's westbound and eastbound diurnal traffic peaks are separated by several hours, the two organized systems can normally be used without significant conflict.

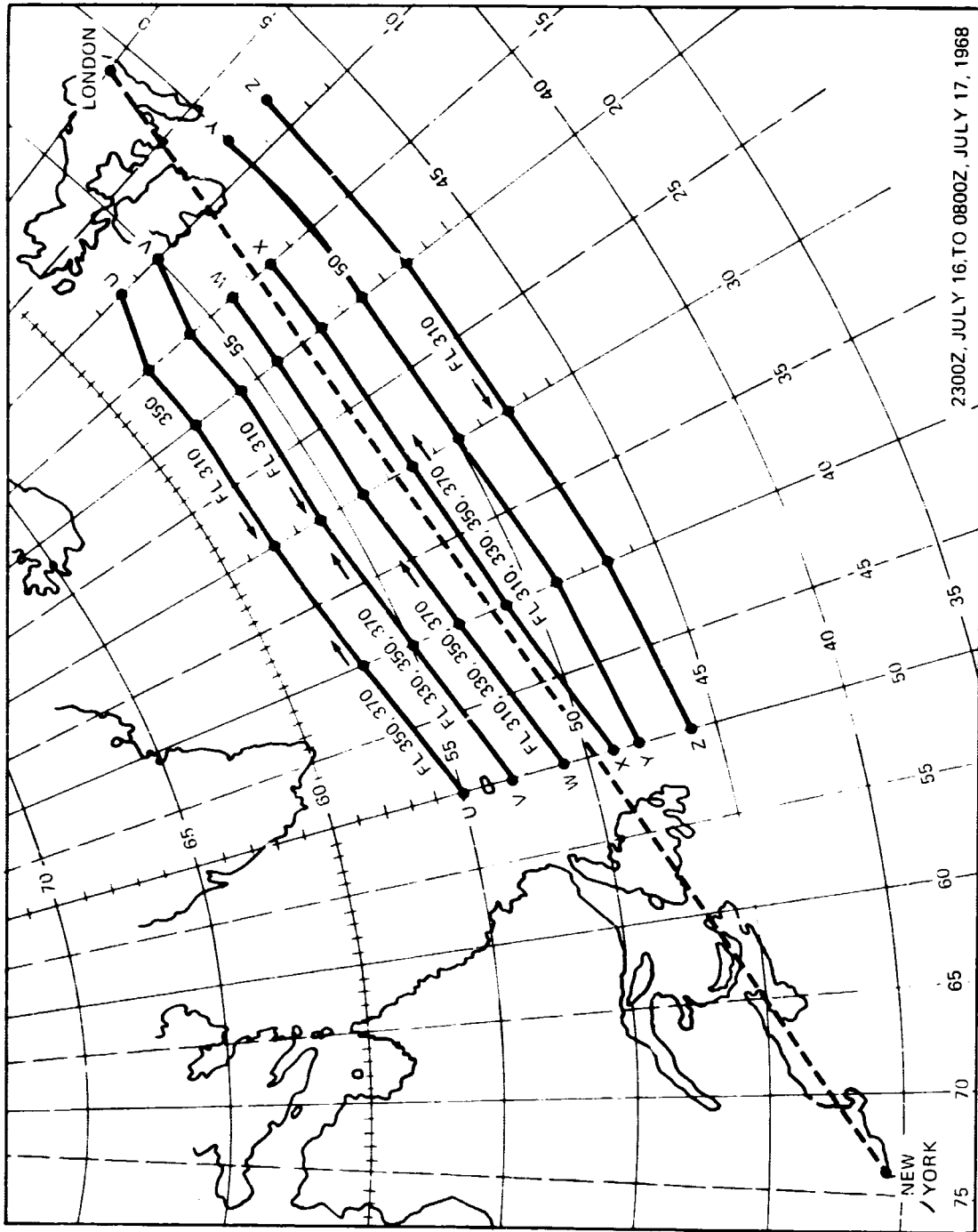


FIGURE A9. — ORGANIZED SYSTEM TRACKS AND FLIGHT LEVELS

APPENDIX B AIRPLANE TRAFFIC MODEL

B1.0 INTRODUCTION

This appendix describes methods used to predict air traffic movements over the North Atlantic during the 1975-1980 period. Section B2.0 discusses the forecasting models that were used to predict annual passenger crossings. Section B3.0 describes a model that predicts the distribution of flights in time based on estimated passenger crossings.

B2.0 FORECASTS OF ANNUAL PASSENGER CROSSINGS

For the past decade, air travel has grown faster than most other segments of the Free World economy. This growth has been due to many factors: lower fares, greater convenience, faster block time, etc.

The typical way of forecasting future passenger air travel is to assume that this trend continues and to extrapolate the past growth into the future. The following numbers for the 1975-1980 period were derived in this way (extrapolated from FAA data, refs. 1 and 8).

<u>Year</u>	<u>NAT annual passenger crossings</u>
1975	14 024 000
1976	16 045 000
1977	18 371 000
1978	21 100 000
1979	24 000 000
1980	27 300 000

Although past extrapolations of this type have produced low estimates, continued extrapolation eventually leads to airline revenues in excess of the Gross National Product (GNP). For this reason, the passenger projection above has been used as an upper limit; a more conservative approach is developed to determine a lower limit.

The approach adopted is to tie the growth of air traffic to historical trends in population, GNP, and fares.

Traffic is defined as embarkations and debarkations of passengers at U.S. and Canadian ports of entry that originate or terminate in selected European countries. The countries selected are:

Belgium	Netherlands
Denmark	Norway
France	Sweden
Germany	United Kingdom
Ireland	Portugal
Italy	

Given constant yield, the rate of traffic growth is assumed to be a function of the present level of traffic, the difference between the present level of traffic and the saturation level y^* , and the rate of growth of GNP per capita. Expressed mathematically,

$$\left(\frac{\partial y}{\partial x_1}\right) \left(\frac{dx_1}{dt}\right) = \frac{1}{b_1} \left[\ln y^* - \ln y \right]^2 y \left(\frac{dx_1}{dt}\right) \quad (B1)$$

where $y = \frac{\text{traffic}}{\text{population}}$ $x_1 = \frac{\text{GNP}}{\text{population}}$ $x_2 = \text{yield (average fare)}$

$b_1 = \text{constant of proportionality}$

Also, we assume that the elasticity of traffic with respect to fare is constant. That is, if fare changes by 2%, then traffic will change by $2b_2\%$. This assumption gives the differential equation:

$$\left(\frac{\partial y}{\partial x_2}\right) \left(\frac{x_2}{y}\right) = b_2 \quad (B2)$$

Integrating equations B1 and B2, we have

$$\ln y = \ln y^* - \frac{b_1}{x_1 - x_0} + b_2 \ln x_2 \quad (B3)$$

where x_0 is the standard of living (as given on p. 57)

Let

$$b_0 = \ln y^*$$

Then

$$y = \left(e^{b_0 - \frac{b_1}{x_1 - x_0}} \right) (x_0^{b_2}) \quad (B4)$$

We then have in the forecasting equation, eq. (B4), traffic as a function of population, GNP, and yield, with the constants b_0 , b_1 , b_2 , and x_0 to be determined. Equation (B4) can be linearized by the following transformations:

$$Y = \ln y \quad X_1 = \frac{1}{x_1 - x_0} \quad X_2 = \ln x_2 \quad (B5)$$

Which gives

$$Y = b_0 + b_1 X_1 + b_2 X_2$$

From historical data, we know x_1 , x_2 , and y . The problem is to estimate b_0 , b_1 , b_2 , and x_0 . Since the system is under-determined, we choose an initial x_0 and estimate b_0 , b_1 , and b_2 by a linear regression analysis. We calculate R , the coefficient of correlation of historical traffic and predicted traffic for the same period. An optimal search technique is then applied to choose x_0 such that R is maximized.

The coefficients can be interpreted in the following way:

- x_0 Standard of living below which one does not make transatlantic flights.
- b_0 Parameter which specifies the saturation level of traffic, $y^* = e^{b_0}$.
- b_1 Parameter which measures the effect of the income variable. It is not simply an elasticity, as can be seen from eq.(B1).
- b_2 Elasticity of traffic with respect to yield.

Population and GNP are forecast for each country by linear regression of historical data. A single yield series is developed for the average fare on transatlantic flights by linear regression of historical fares.

The forecasting eq. (B4) is plotted in fig. B1.

Table B1 contains the values of the coefficients in the forecasting equation and the coefficient of correlation for each country. Table B2 gives observed and forecast GNP, table B3 gives observed and forecast population, and table B4 gives the yield series.

Figure B2 shows the historical traffic data plotted on a logarithmic scale. The forecast developed here is called the NATEM forecast to distinguish it from two forecasts made by the FAA for the International Civil Aviation Organization (ICAO). NATEM refers to an economic model of North Atlantic ATC that is currently under development and also requires a traffic input. Figure B3 plots the NATEM forecast and two forecasts from ICAO. Table B5 tabulates observed and forecast traffic by country for the NATEM forecast. The observed traffic for NATEM is taken from U.S. Immigration Service records of passengers crossing the North Atlantic. The data consists of embarkations and debarkations at Boston, New York, and Chicago.

A slight discrepancy will be noted between NATEM historical data and ICAO historical data. The ICAO forecasts are based on passengers carried by International Air Transport Association (IATA) airlines. Hence, the ICAO data base is slightly larger than the base upon which the NATEM forecast is built. To compensate for this inadequacy, the NATEM

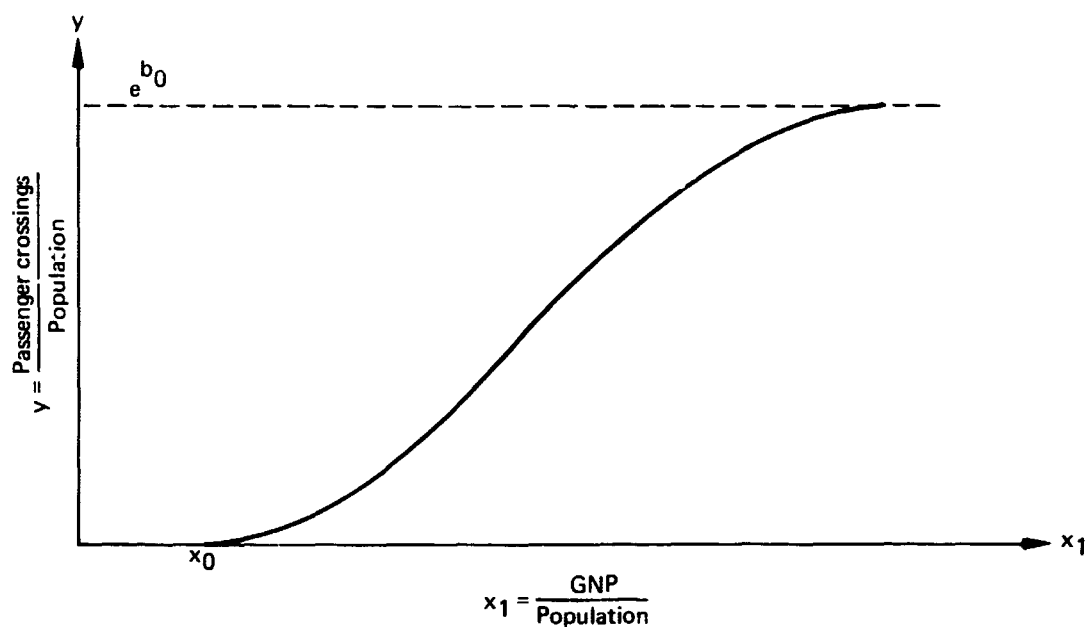


FIGURE B1. – FORECASTING HYPOTHESIS WITH CONSTANT YIELD

TABLE B1. – FORECASTING EQUATION COEFFICIENTS

Country	b_0	b_1	b_2	x_0	R
Belgium	5.30	-0.276	-1.318	0.679	0.962
Denmark	5.12	-0.322	-0.422	0.736	0.975
France	4.72	-0.807	-0.191	0.210	0.988
Germany	4.69	-0.515	-0.747	0.081	0.982
Ireland	5.74	-0.274	-0.446	0.361	0.975
Italy	4.53	-0.690	-0.152	0.084	0.984
Netherlands	5.11	-0.622	-0.434	0.192	0.968
Norway	4.44	-0.141	-0.933	0.426	0.836
Sweden	3.84	-0.338	-0.399	0.416	0.690
United Kingdom	5.51	-1.172	-0.191	0.495	0.994
Portugal	4.64	-0.281	-0.399	0.040	0.966

**TABLE B2. – OBSERVED AND FORECAST GNP
(BILLIONS OF 1958 DOLLARS)**

Year	Belgium	Denmark	France	Germany	Iceland	Italy
1950	8.96	4.18	31.90	28.80	1.58	18.49
1951	9.47	4.08	33.47	32.58	1.55	19.63
1952	9.70	4.20	35.81	36.34	1.62	19.87
1953	9.38	4.51	37.35	39.98	1.67	21.31
1954	9.66	4.66	39.54	42.91	1.69	22.22
1955	10.29	4.59	42.35	47.99	1.72	23.80
1956	10.62	4.62	45.93	52.32	1.66	24.85
1957	10.93	4.76	49.97	55.18	1.66	26.42
1958	10.90	4.98	49.94	57.88	1.65	27.44
1959	11.10	5.42	51.49	62.11	1.75	29.31
1960	11.72	5.79	54.95	72.74	1.85	31.32
1961	12.26	6.18	57.24	77.67	1.93	33.93
1962	12.94	6.48	61.11	82.06	1.99	36.44
1963	13.65	6.49	64.66	84.86	2.08	37.09
1964	14.58	7.13	68.85	90.75	2.25	40.01
1965	14.93	7.41	71.25	94.96	2.31	41.36
1966	15.59	7.62	74.70	97.42	2.33	43.58
1967	15.96	7.89	79.42	107.89	2.37	46.31
1968	16.38	8.18	84.11	118.69	2.42	49.04
1969	16.85	8.49	88.91	129.93	2.46	51.88
1970	17.35	8.83	93.88	141.72	2.52	54.85
1971	17.89	9.18	99.08	154.16	2.57	57.99
1972	18.47	9.56	104.54	167.37	2.63	61.30
1973	19.07	9.95	110.29	181.44	2.69	64.80
1974	19.70	10.36	116.35	196.49	2.75	68.51
1975	20.36	10.79	122.74	212.63	2.82	72.42
1976	21.05	11.24	129.48	229.95	2.88	76.55
1977	21.76	11.71	136.58	248.58	2.95	80.92
1978	22.50	12.20	144.08	268.64	3.03	85.54
1979	23.27	12.71	151.99	290.25	3.10	90.43
1980	24.07	13.24	160.33	313.55	3.18	95.59
1981	24.89	13.80	169.12	338.67	3.26	101.05

TABLE B2. – Concluded

Year	Netherlands	Norway	Sweden	United Kingdom	Portugal
1950	6.78	3.23	8.39	54.68	1.35
1951	7.11	3.50	8.79	54.92	1.47
1952	7.33	3.40	8.96	54.72	1.63
1953	7.81	3.45	9.06	56.67	1.58
1954	8.43	3.60	9.54	58.37	1.76
1955	9.24	3.79	10.02	60.65	1.89
1956	9.85	4.09	10.38	62.20	2.04
1957	10.03	4.26	10.71	63.73	2.06
1958	9.99	4.03	10.62	64.48	2.06
1959	9.50	4.21	11.19	67.12	2.16
1960	11.52	4.47	11.69	70.44	2.31
1961	11.85	4.72	12.50	73.10	2.44
1962	12.48	4.80	12.95	73.15	2.54
1963	12.99	5.00	13.70	76.25	2.69
1964	14.66	5.28	14.71	81.23	2.93
1965	15.41	5.57	15.22	83.48	3.14
1966	16.24	5.82	15.64	84.70	3.28
1967	16.77	5.90	16.17	86.92	3.41
1968	17.57	6.06	16.76	89.35	3.58
1969	18.49	6.27	17.38	91.93	3.76
1970	19.48	6.49	18.04	94.62	3.96
1971	20.54	6.72	18.73	97.43	4.17
1972	21.66	6.96	19.47	100.33	4.39
1973	22.84	7.21	20.23	103.33	4.62
1974	24.09	7.47	21.03	106.42	4.87
1975	25.40	7.74	21.87	109.60	5.13
1976	26.79	8.02	22.74	112.89	5.40
1977	28.25	8.31	23.64	116.27	5.69
1978	29.79	8.60	24.59	119.75	5.99
1979	31.42	8.91	25.57	123.34	6.31
1980	33.13	9.24	26.59	127.04	6.64
1981	34.94	9.57	27.66	130.85	6.99

**TABLE B3. – OBSERVED AND FORECAST POPULATION
(MILLIONS)**

Year	Belgium	Denmark	France	Germany	Iceland	Italy
1950	8.93	4.27	41.70	50.00	2.96	46.70
1951	8.97	4.30	42.00	50.50	2.96	47.09
1952	9.02	4.33	42.30	50.80	2.95	47.35
1953	9.08	4.37	42.60	51.40	2.95	47.60
1954	9.12	4.41	43.00	51.90	2.94	47.91
1955	9.17	4.44	43.40	52.30	2.92	48.20
1956	9.23	4.47	43.80	53.00	2.90	48.47
1957	9.29	4.49	44.30	53.60	2.88	48.74
1958	9.36	4.51	44.80	54.20	2.85	49.04
1959	9.41	4.55	45.20	55.00	2.85	49.36
1960	9.47	4.58	45.70	55.40	2.83	49.64
1961	9.50	4.61	46.20	56.20	2.82	49.90
1962	9.54	4.65	47.00	57.00	2.82	50.24
1963	9.61	4.68	47.80	57.60	2.84	50.64
1964	9.71	4.72	48.40	57.30	2.85	51.12
1965	9.79	4.76	49.00	58.10	2.87	51.57
1966	9.86	4.80	49.40	58.70	2.88	51.86
1967	9.91	4.83	49.91	59.46	2.86	52.16
1968	9.96	4.86	50.44	60.15	2.85	52.46
1969	10.01	4.89	50.97	60.81	2.83	52.78
1970	10.07	4.93	51.51	61.45	2.82	53.10
1971	10.13	4.96	52.06	62.11	2.81	53.42
1972	10.19	5.00	52.61	62.76	2.80	53.75
1973	10.25	5.03	53.17	63.42	2.79	54.08
1974	10.31	5.07	53.75	64.09	2.78	54.42
1975	10.37	5.10	54.33	64.70	2.77	54.76
1976	10.44	5.14	54.91	65.44	2.76	55.11
1977	10.50	5.18	55.51	66.12	2.75	55.45
1978	10.56	5.21	56.11	66.82	2.74	55.81
1979	10.63	5.25	56.72	67.52	2.73	56.16
1980	10.69	5.29	57.34	68.23	2.72	56.52
1981	10.76	5.32	57.97	68.95	2.71	56.87

TABLE B3. — Concluded

Year	Netherlands	Norway	Sweden	United Kingdom	Portugal
1950	10.11	3.26	7.00	50.60	8.40
1951	10.26	3.30	7.10	50.60	8.50
1952	10.38	3.33	7.10	50.70	8.50
1953	10.50	3.36	7.20	50.90	8.50
1954	10.61	3.39	7.20	51.00	8.60
1955	10.75	3.43	7.30	51.20	8.60
1956	10.89	3.46	7.30	51.40	8.60
1957	11.02	3.49	7.40	51.60	8.60
1958	11.19	3.52	7.40	51.80	8.70
1959	11.35	3.55	7.40	52.10	8.80
1960	11.48	3.58	7.48	52.50	8.83
1961	11.64	3.61	7.52	53.00	8.89
1962	11.80	3.64	7.56	53.50	8.97
1963	11.97	3.67	7.60	53.80	9.04
1964	12.13	3.69	7.66	54.20	9.11
1965	12.29	3.72	7.73	54.40	9.20
1966	12.45	3.75	7.81	55.00	9.22
1967	12.61	3.78	7.82	55.24	9.26
1968	12.77	3.82	7.87	55.48	9.31
1969	12.94	3.86	7.92	55.74	9.36
1970	13.10	3.89	7.97	56.00	9.40
1971	13.27	3.92	8.01	56.27	9.46
1972	13.45	3.96	8.06	56.54	9.51
1973	13.62	4.00	8.12	56.82	9.56
1974	13.80	4.03	8.17	57.10	9.62
1975	13.98	4.07	8.22	57.39	9.67
1976	14.17	4.10	8.27	57.68	9.73
1977	14.35	4.14	8.32	57.97	9.79
1978	14.54	4.18	8.37	58.27	9.84
1979	14.73	4.21	8.42	58.58	9.90
1980	14.92	4.25	8.48	58.88	9.96
1981	15.12	4.29	8.53	59.19	10.02

**TABLE B4. - OBSERVED AND FORECAST YIELD
(1958 \$/MILE)**

Year	Yield
1950	0.1788
1951	0.1292
1952	0.1227
1953	0.0840
1954	0.0839
1955	0.0840
1956	0.0861
1957	0.0797
1958	0.0754
1959	0.0760
1960	0.0742
1961	0.0697
1962	0.0648
1963	0.0635
1964	0.0567
1965	0.0543
1966	0.0514
1967	0.0479
1968	0.0449
1969	0.0421
1970	0.0396
1971	0.0373
1972	0.0351
1973	0.0331
1974	0.0312
1975	0.0294
1976	0.0277
1977	0.0261
1978	0.0246
1979	0.0232
1980	0.0219
1981	0.0206

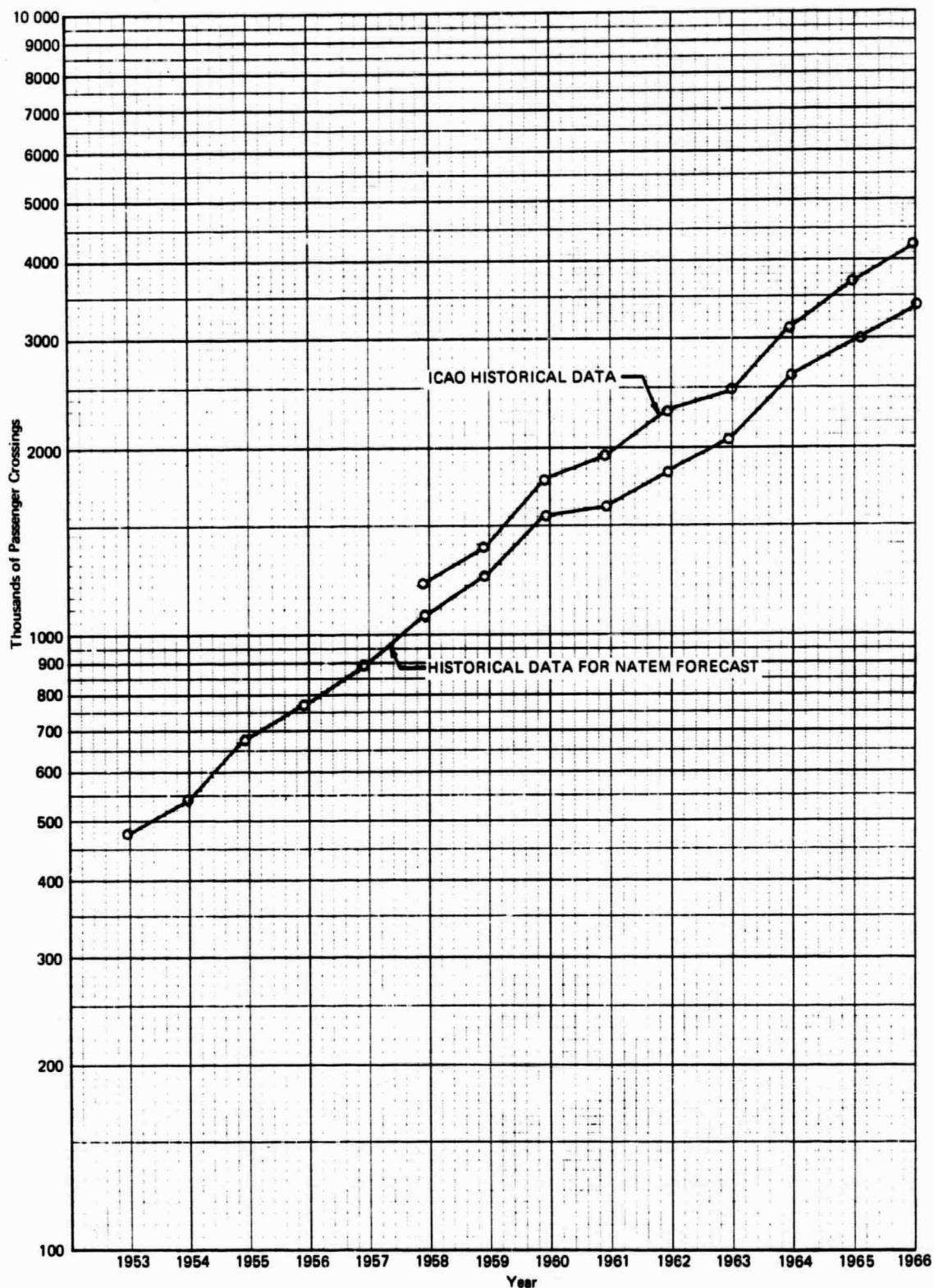


FIGURE B2. – HISTORICAL NORTH ATLANTIC ANNUAL PASSENGER CROSSINGS

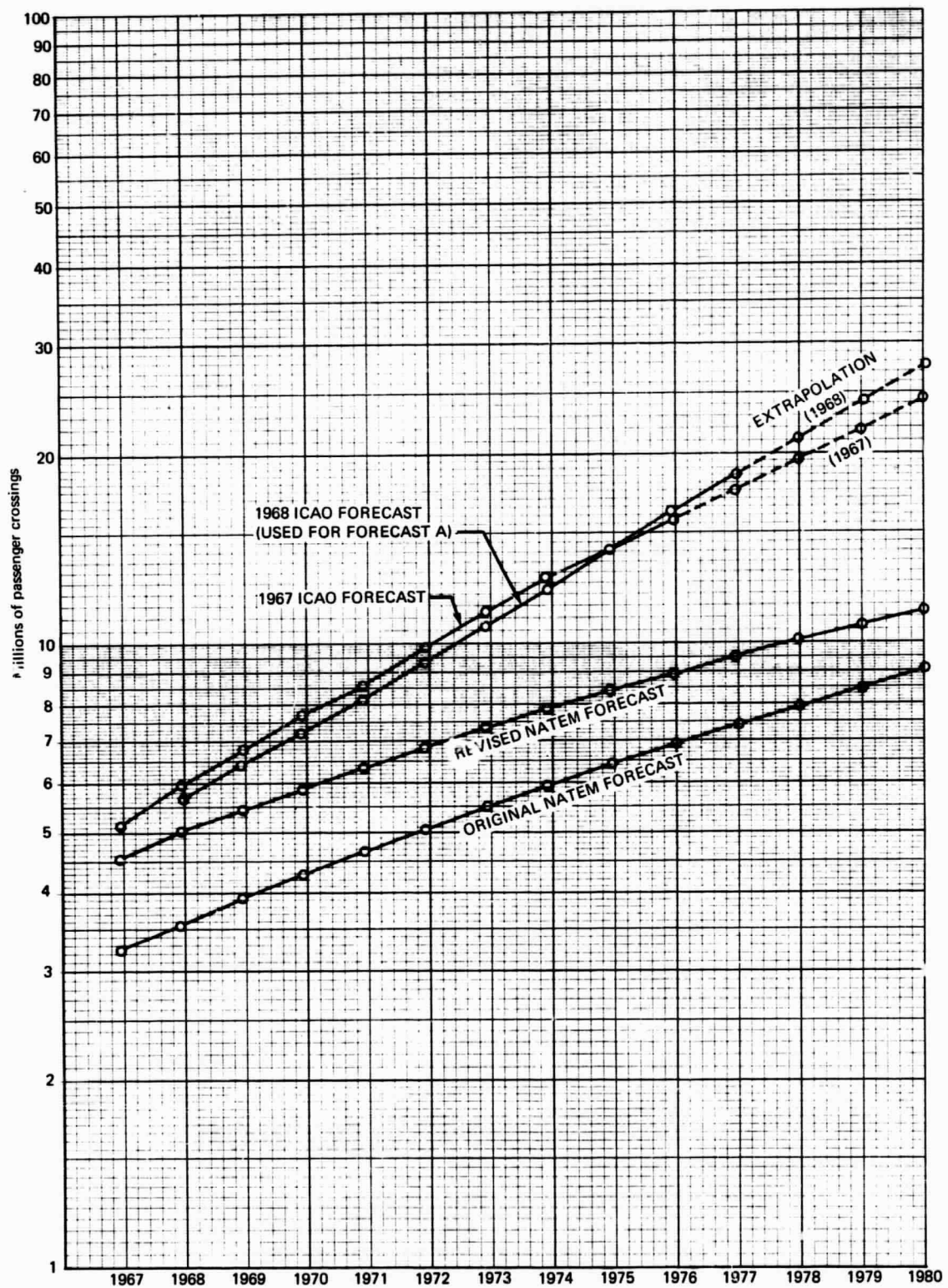


FIGURE B3. — NATEM AND ICAO PASSENGER FORECASTS

**TABLE B5. — NATEM OBSERVED AND FORECAST TRAFFIC
(THOUSANDS OF ANNUAL PASSENGER CROSSINGS)**

Year	Belgium	Denmark	France	Germany	Ireland	Italy
1950	7.3	6.9	44.9	31.2	14.9	19.2
1951	8.1	6.1	60.7	32.6	9.4	16.5
1952	12.2	10.6	88.2	63.2	16.5	24.3
1953	20.6	14.2	96.3	81.4	22.3	31.1
1954	15.9	15.0	100.0	106.3	24.8	38.4
1955	20.8	16.6	120.3	154.2	29.2	41.4
1956	22.7	20.4	144.2	157.2	35.4	51.2
1957	31.6	35.5	163.7	157.0	46.2	54.1
1958	57.1	50.2	189.0	194.5	56.3	70.8
1959	41.6	55.6	227.2	190.8	56.0	85.9
1960	62.2	82.9	283.2	213.6	66.7	116.7
1961	48.0	77.0	279.2	216.9	103.4	132.5
1962	62.8	79.3	324.5	250.3	101.9	174.6
1963	70.4	91.6	344.2	269.8	119.4	214.8
1964	86.9	111.3	411.4	368.7	157.2	273.2
1965	97.8	123.2	440.8	412.5	186.0	291.6
1966	101.0	124.0	504.4	463.2	212.3	347.1
1967	126.1	145.0	506.8	455.3	205.7	310.9
1968	141.6	156.7	556.5	512.4	222.6	345.4
1969	158.5	168.9	606.6	570.8	240.7	380.3
1970	177.2	181.5	657.8	631.0	259.3	416.2
1971	197.7	194.6	710.5	693.8	279.0	452.9
1972	220.4	208.2	764.9	759.5	299.6	490.5
1973	245.3	222.1	821.1	828.4	320.7	528.7
1974	272.8	236.5	879.1	901.1	342.8	567.4
1975	302.8	251.3	938.9	977.5	365.5	606.6
1976	336.0	266.6	1000.6	1058.4	389.1	645.9
1977	372.4	282.3	1064.1	1143.9	413.4	685.4
1978	412.2	298.4	1129.4	1233.8	438.2	725.0
1979	456.0	315.0	1196.5	1329.1	464.0	764.3
1980	504.1	332.1	1265.5	1429.7	490.2	803.5
1981	556.6	349.6	1336.2	1535.9	517.2	842.3

TABLE B5. – Concluded

Year	Netherlands	Norway	Sweden	United Kingdom	Portugal
1950	20.2	4.5	7.2	91.4	9.0
1951	24.1	4.2	7.1	98.3	8.4
1952	30.5	4.3	6.6	127.8	10.2
1953	37.6	6.6	8.8	145.1	10.2
1954	41.1	6.9	9.8	160.2	15.6
1955	49.0	9.7	10.5	200.3	19.2
1956	56.8	8.5	12.2	225.8	24.0
1957	70.5	9.6	12.3	272.4	29.7
1958	78.9	13.6	11.5	306.3	35.6
1959	100.2	13.5	8.8	404.1	32.5
1960	130.5	5.8	6.0	516.3	46.6
1961	131.9	11.6	6.6	520.8	49.2
1962	144.0	13.6	11.5	578.4	55.0
1963	137.5	11.2	16.7	653.5	64.7
1964	170.7	12.0	21.7	847.4	86.9
1965	193.7	13.9	21.5	963.1	115.6
1966	212.2	24.7	23.5	1058.4	148.0
1967	234.2	18.3	18.2	1087.2	105.5
1968	256.2	19.8	19.1	1201.0	113.2
1969	281.1	21.4	20.1	1324.8	121.6
1970	307.9	23.0	21.1	1457.8	130.3
1971	336.4	24.8	22.1	1599.3	139.1
1972	366.7	26.7	23.1	1749.3	147.9
1973	398.6	28.7	24.1	1907.3	156.7
1974	432.4	30.9	25.2	2073.5	165.3
1975	468.0	33.1	26.4	2247.5	173.8
1976	505.6	35.6	27.5	2430.0	182.0
1977	545.2	38.2	28.7	2620.6	190.0
1978	586.8	41.0	29.9	2819.3	197.7
1979	630.5	44.0	31.2	3026.3	205.1
1980	676.5	47.2	32.5	3241.7	212.2
1981	724.7	50.5	33.8	3465.2	219.0

forecast was revised upward by a standard linear regression formula to reflect the ICAO historical data. The revised NATEM forecast was used in this study and is plotted in fig. B3 and tabulated as follows:

<u>Year</u>	<u>NAT annual passenger crossings</u>
1975	8 454 000
1976	8 978 000
1977	9 515 000
1978	10 061 000
1979	10 621 000
1980	11 243 000

B3.0 FORECAST OF DAILY FLIGHT DISTRIBUTIONS

The forecast annual passenger crossings are input to a computer program called the Demand Model. The Demand Model uses the passenger forecast and assumptions about passenger preference for supersonic versus subsonic flight, preference for flights at certain times of the day, load factor, and the percentage of military and cargo flights to calculate the hour-by-hour number of flights entering the oceanic area on a busy summer day. Figure B4 illustrates the procedure used by the Demand Model. Table B6 gives the input quantities that were used in developing the two forecasts used in this study.

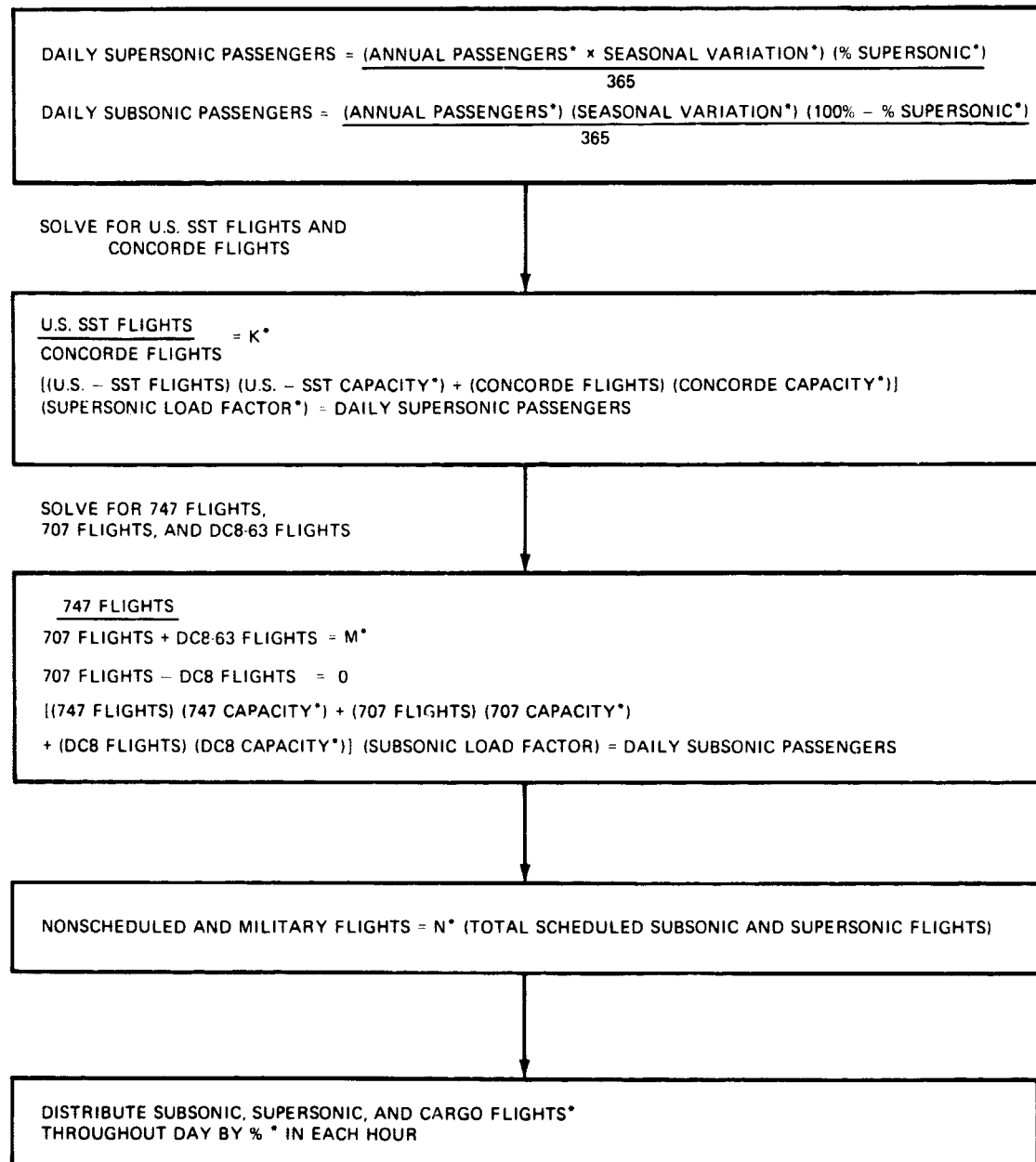
Two forecasts of hourly entries into the oceanic system have been developed. The input parameters are selected in forecast A to maximize the number of flights. In forecast B, a lower limit of North Atlantic flights has been determined. These two forecasts should bracket the actual situation and were used to determine a minimum and preferred capability for the ATC satellite system.

Forecast A uses the upper-limit passenger forecast described previously and an assumption of 75% preference for supersonic flight. Forecast B uses the revised NATEM forecast, a 50% preference for supersonic flights, and a higher proportion of 747's than forecast A.

The seasonal variation adjusts the average daily flight to compensate for seasonal peaking. The assumption is the same as in Dunmire (ref. 9); that is, 40% of the annual traffic is evenly distributed in the months of June, July, August, and September.

The parameter K, the ratio of U.S. SST flights to Concorde flights, was taken from a variety of sources. For forecast A, K was computed for 1980 from Dunmire (ref. 9). The basic assumption used by Dunmire was that the U.S. SST would have 70% of the 2800- to 4000-n.mi. market and the Concorde would have 10%. The values for 1975 through 1979 are interpolated at constant growth rate. The values of K for forecast B are taken from the ICAO 1967 forecast for 1975 and 1976. The values used for 1977 through 1980 are estimates made from published delivery schedules.

The ratio of 747 flights to other subsonic flights M was also taken from a variety of sources. The values for 1975 and 1976 for forecast B were approximated from the



* DENOTES INPUT QUANTITY

FIGURE B4. – DEMAND MODEL LOGIC

TABLE B6. - DEMAND MODEL INPUT PARAMETERS

Parameter	Forecast A					
	1975	1976	1977	1978	1979	1980
1. DRS (% supersonic)	75	75	75	75	75	75
2. SV (seasonal variation)	1.2	1.2	1.2	1.2	1.2	1.2
3. K (ratio of U.S.-SST flights to Concorde flights)	0	0.8	1.6	2.4	3.2	4.05
4. PLF (supersonic passenger load factor)	75%	60%	60%	60%	60%	60%
5. CC (Concorde passenger capacity)	134	134	134	134	134	134
6. ASC (U.S.-SST passenger capacity)	280	280	280	280	280	280
7. M (ratio of 747 flights to other subsonic flights)	1.25	2.22	2.22	2.22	2.22	2.22
8. PLF2 (subsonic passenger load factor)	0.56	0.56	0.56	0.56	0.56	0.56
9. JC (747 passenger capacity)	363	363	363	363	363	363
10. BC (707 passenger capacity)	141	141	141	141	141	141
11. N (ratio of nonscheduled and military flights to scheduled flights)	0.15	0.15	0.15	0.15	0.15	0.15
12. DC (DC8-63 passenger capacity)	250	250	250	250	250	250
13. FCF (daily number of all- cargo crossings)	70	79	90	104	118	134
14. A (annual passenger crossings)	14.0 x 10 ⁶	16.0 x 10 ⁶	18.4 x 10 ⁶	21.0 x 10 ⁶	24.0 x 10 ⁶	27.3 x 10 ⁶

TABLE B6. — Concluded

Parameter	Forecast B					
	1975	1976	1977	1978	1979	1980
1. DRS (% supersonic)	50	50	50	50	50	50
2. SV (seasonal variation)	1.2	1.2	1.2	1.2	1.2	1.2
3. K (ratio of U.S. - SST flights to Concorde flights)	0.16	0.26	0.295	1.0	2.0	2.0
4. PLF (supersonic passenger load factor)	75%	60%	60%	60%	60%	60%
5. CC (Concorde passenger capacity)	134	134	134	134	134	134
6. ASC (U.S.-SST passenger capacity)	280	280	280	280	280	280
7. M (ratio of 747 flights to other subsonic flights)	0.85	1.52	2.5	2.5	2.5	2.5
8. PLF2 (subsonic passenger load factor)	56%	56%	56%	56%	56%	56%
9. JC (747 passenger capacity)	363	363	363	363	363	363
10. BC (707 passenger capacity)	141	141	141	141	141	141
11. N (ratio of nonscheduled and military flights to scheduled flights)	0.15	0.15	0.15	0.15	0.15	0.15
12. DC (DC8-63 passenger capacity)	250	250	250	250	250	250
13. FCF (daily number of all- cargo crossings)	70	79	90	104	118	134
14. A (annual passenger crossings)	8.454 $\times 10^6$	8.978 $\times 10^6$	9.515 $\times 10^6$	10.061 $\times 10^6$	10.621 $\times 10^6$	11.243 $\times 10^6$

1968 ICAO forecast. The ratio is assumed to level off and remain constant at 2.5 for 1977 through 1980. The values of M for forecast A were approximated from delivery schedules.

Flights other than scheduled passenger flights or cargo flights are assumed to comprise 15% of all flights exclusive of cargo.

The number of cargo flights is estimated by the Boeing Market Research Organization. The forecast assumes a growth factor of 9.2 from 1965 to 1980. Forecasts A and B use the same projection of cargo flights. A constant growth rate of 12.9% is assumed for 1975 through 1980.

Passenger load factors for supersonic flights are assumed to be 75% during the early years of SST operations, declining to 60%. Subsonic passenger load factors were assumed to remain at the current level of 56%.

The final step in the Demand Model is to distribute the daily flights into an hour-by-hour schedule. Three categories of flight distributions are input to the model: (1) supersonic passenger flights, (2) all-cargo flights, and (3) all other subsonic flights. The supersonic flight distributions were taken from Dunmire (ref. 9). Mr. Dunmire considers supersonic scheduling at great length in his report. The distribution used here was determined to be the best of several alternative schedules in terms of daily utilization and the necessity to remain overnight on the opposite side of the Atlantic from the point of origination. Figures B5 and B6 illustrate the flight scheduling.

The schedules developed for use with the Demand Model give the time of entry into the oceanic control area (OCA). For the purposes of the model and of this study, the OCA is considered to be the area between 10°W and 50°W.

The all-cargo flight distribution was derived from all-cargo flights listed in the *Official Airline Guide* (Worldwide Timetable Edition) for December 1967. The frequency of flights during each hour of each day of the week was tabulated. The average percentage of departures for each hour was computed and projected to the time that the flights would cross 10°W for westbound flights and 50°W for eastbound flights.

The other subsonic flight distributions were taken from data collected by the Gander Air Traffic Control Center from August 4 to 10, 1967. The number of flights for each hour of each day was tabulated and each hour was averaged over the week. Figures B7 and B8 plot the hourly flight distributions. Tables B7 and B8 also list the hourly distribution.

Busy-day flights, peak hourly flow, peak instantaneous count, and the spatial distributions of the peak instantaneous counts are tabulated in tables B9 through B15. Peak instantaneous count is calculated for all flights crossing the North Atlantic in the area from 0°W to 70°W. This larger area was necessary to encompass subsonic tracks that fall in the New York Oceanic Control Area. To calculate the peak instantaneous count, it was assumed that subsonic aircraft spend 5-1/2 hours and supersonic aircraft spend 2-1/2 hours in the area from 0°W to 70°W.

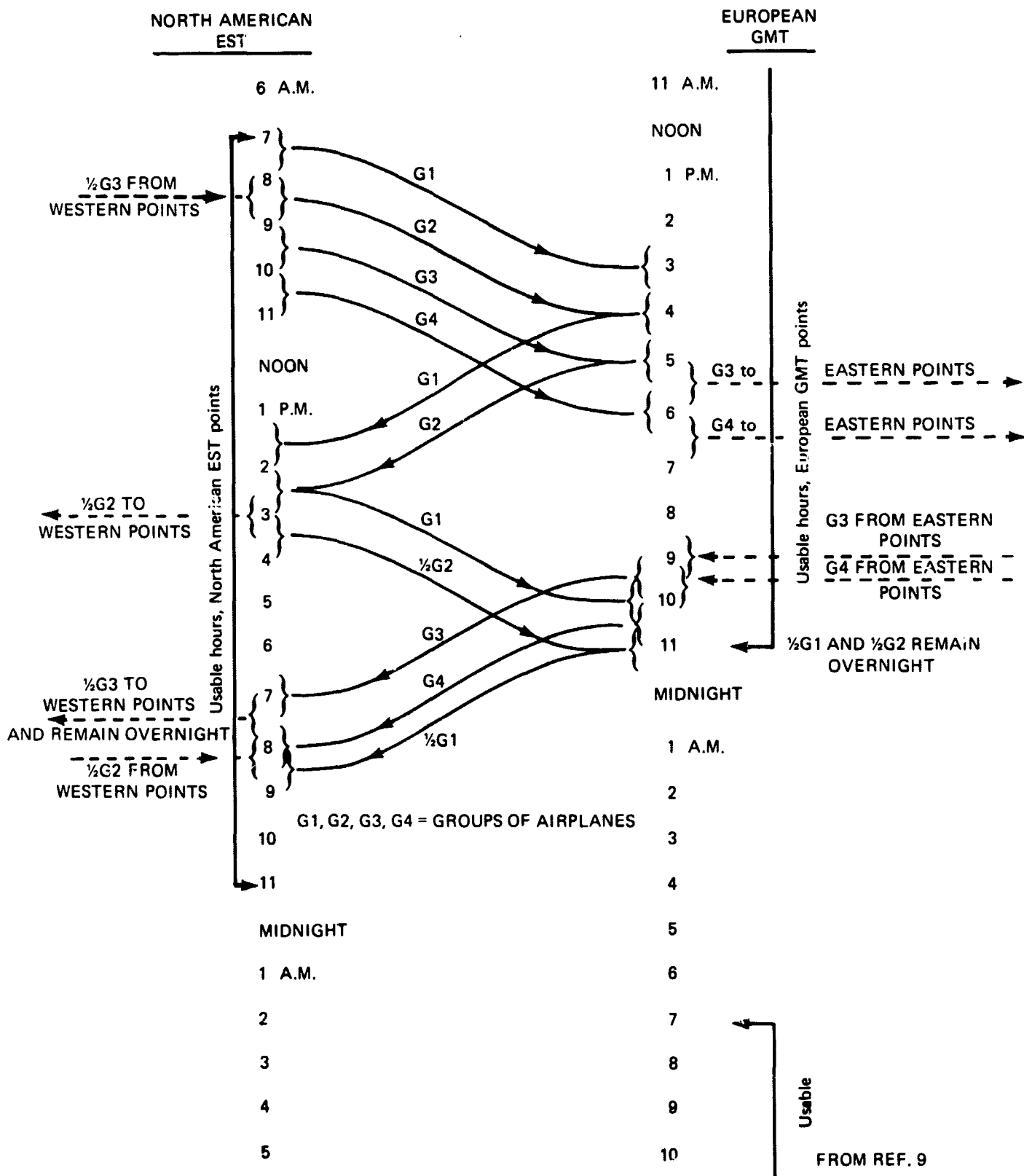
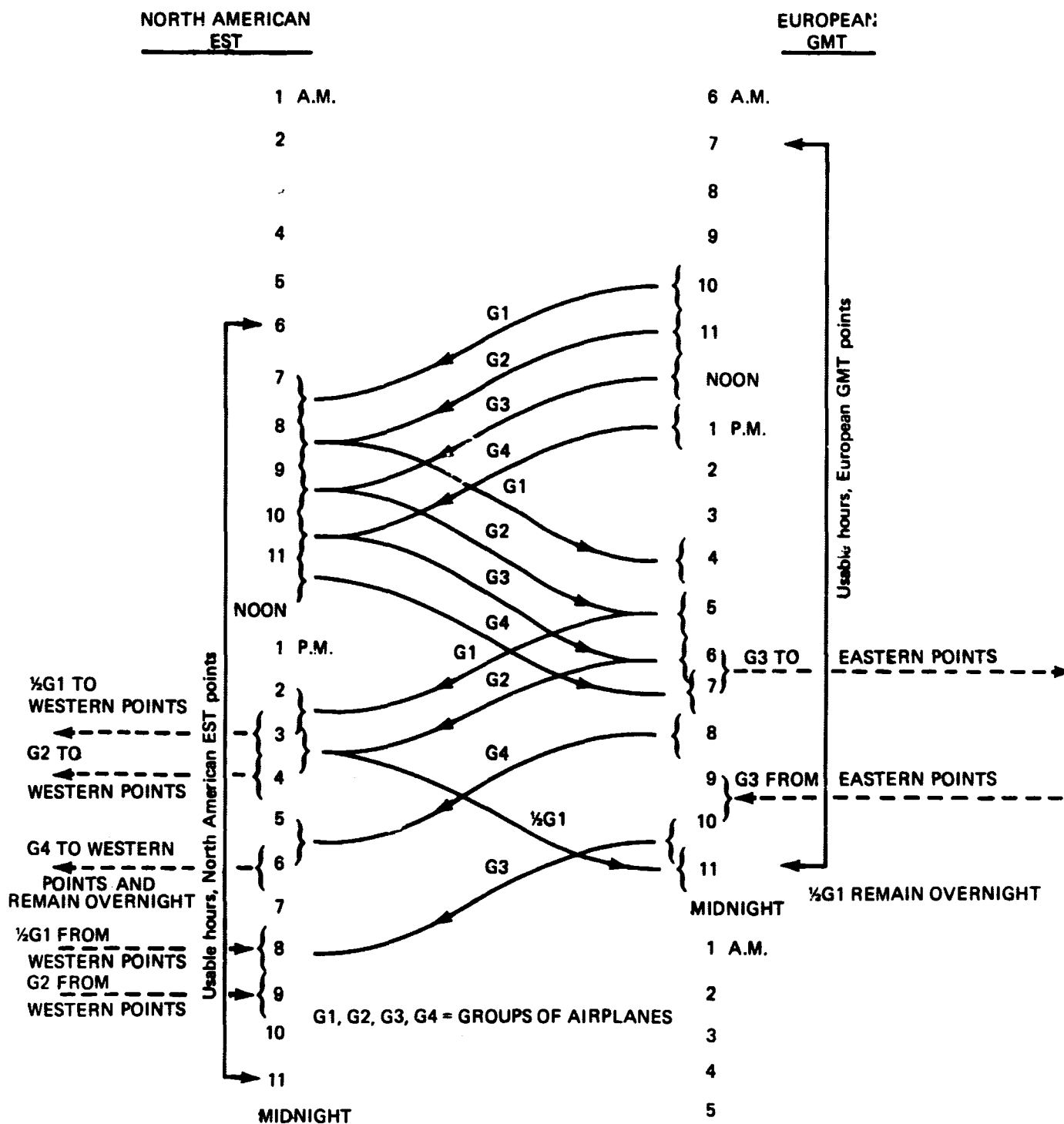


FIGURE B5. – SST SCHEDULING: NORTH AMERICA TO EUROPE



FROM REF. 9

FIGURE B6. – SST SCHEDULING: EUROPE TO NORTH AMERICA

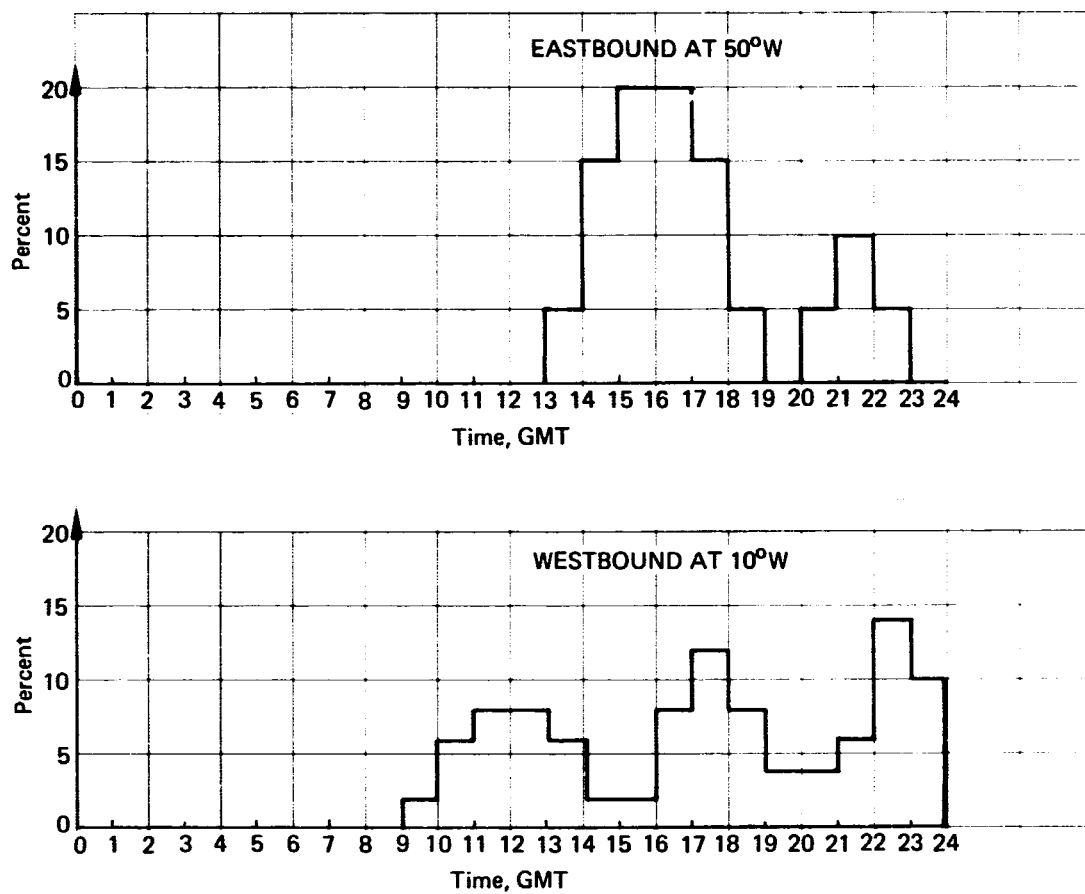


FIGURE B7. – SUPERSONIC FLIGHT DISTRIBUTIONS

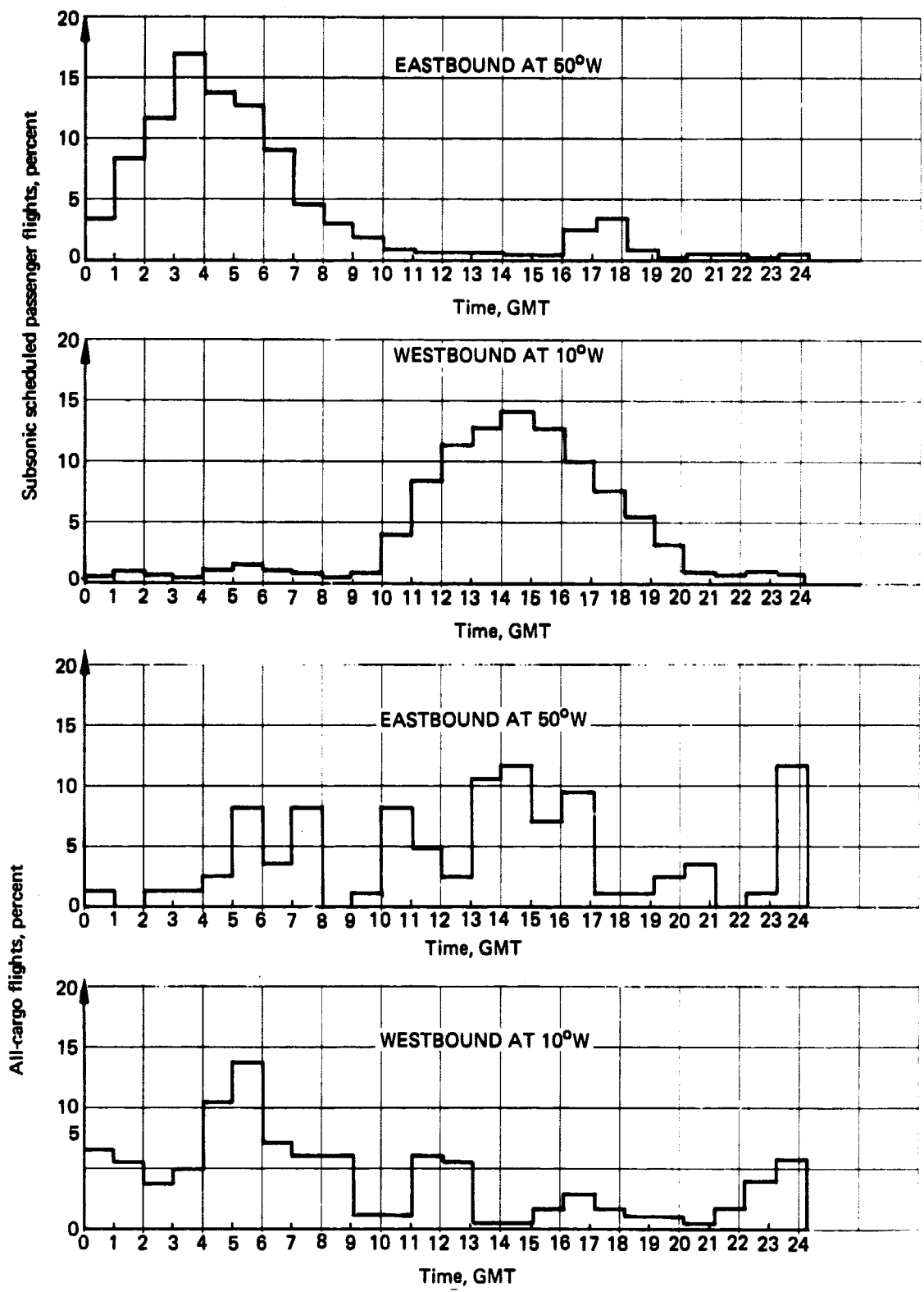


FIGURE B8. – SUBSONIC FLIGHT DISTRIBUTIONS

**TABLE B7. – HYPOTHETICAL SUPERSONIC TRAFFIC DISTRIBUTION
(PERCENT OF DAILY TRAFFIC IN EACH HOUR)**

Time, GMT	Eastbound at 50°W	Westbound at 10°W
0 to 1	----	----
1 to 2	----	----
2 to 3	----	----
3 to 4	----	----
4 to 5	----	----
5 to 6	----	----
6 to 7	----	----
7 to 8	----	----
8 to 9	----	----
9 to 10	----	2.0
10 to 11	----	6.0
11 to 12	----	8.0
12 to 13	----	8.0
13 to 14	5.0	6.0
14 to 15	15.0	2.0
15 to 16	20.0	2.0
16 to 17	20.0	8.0
17 to 18	15.0	12.0
18 to 19	5.0	8.0
19 to 20	----	4.0
20 to 21	5.0	4.0
21 to 22	10.0	6.0
22 to 23	5.0	14.0
23 to 24	----	10.0

**TABLE B2. – SUBSONIC TRAFFIC DISTRIBUTION
(PERCENT OF DAILY TRAFFIC IN EACH HOUR)**

Time, GMT	Eastbound passenger at 50°W	Westbound passenger at 10°W	Eastbound cargo at 50°W	Westbound cargo at 10°W
0 to 1	3.5	0.5	1.2	6.7
1 to 2	8.4	0.8	0.0	5.6
2 to 3	11.8	0.6	1.2	3.8
3 to 4	16.9	0.4	1.2	5.0
4 to 5	13.6	1.0	2.3	10.5
5 to 6	12.7	1.4	8.0	13.7
6 to 7	9.0	1.0	3.4	7.2
7 to 8	4.6	0.8	8.0	6.1
8 to 9	3.3	0.4	0.0	6.1
9 to 10	2.0	0.8	1.2	1.1
10 to 11	1.8	4.0	8.0	1.1
11 to 12	0.7	8.3	4.6	6.1
12 to 13	0.7	11.2	2.3	5.6
13 to 14	0.7	12.7	10.3	0.6
14 to 15	0.6	14.0	11.4	0.6
15 to 16	0.5	12.6	6.9	1.7
16 to 17	2.4	9.9	9.2	2.8
17 to 18	3.4	7.6	1.2	1.7
18 to 19	0.9	5.4	1.2	1.1
19 to 20	0.3	3.2	2.3	1.1
20 to 21	0.6	1.0	3.4	0.6
21 to 22	0.6	0.7	0.0	1.7
22 to 23	0.3	0.9	1.2	3.9
23 to 24	0.7	0.8	11.5	5.6

TABLE B9. - BUSY-DAY FLIGHTS BY AIRCRAFT TYPE

Type of flight	Year											
	1975		1976		1977		1978		1979		1980	
	Forecast											
	A	B	A	B	A	B	A	B	A	B	A	B
U.S.— SST	0	18	147	34	193	40	257	78	306	100	358	106
Concorde	344	112	184	130	120	132	107	78	96	50	89	53
747	40	37	52	48	60	58	68	61	78	65	89	68
DC8-63	16	22	12	16	13	12	15	12	18	13	20	14
707	16	22	12	16	13	12	15	12	18	13	20	14
All cargo	70	70	79	79	88	90	104	104	118	118	134	134
General aviation and military	58	29	60	30	65	36	76	28	77	35	92	34
TOTAL	544	310	546	353	552	380	642	373	711	394	802	423

**TABLE B10. - AIRPLANE TRAFFIC PARAMETERS
(FORECAST A): PEAK BUSY-HOUR FLOW**

Year	Subsonic		Supersonic	
	Eastbound	Westbound	Eastbound	Westbound
1975	11	10	34	21
1976	12	11	33	20
1977	14	12	34	20
1978	15	13	36	22
1979	17	15	40	24
1980	19	17	45	27

Note: Noncoincident peaks

**TABLE B11. – AIRPLANE TRAFFIC PARAMETERS
(FORECAST A): PEAK INSTANTANEOUS COUNT**

Year	Subsonic	Supersonic	Total
1975	56	108	164
1976	64	113	177
1977	68	106	174
1978	80	125	205
1979	89	137	226
1980	104	154	258

Assumptions:

1. North Atlantic principal area: 40°N to 60°N
2. High-assumption passenger forecast
3. 75% supersonic preference

**TABLE B12. – AIRPLANE TRAFFIC PARAMETERS
(FORECAST B): PEAK BUSY-HOUR FLOW**

Year	Subsonic		Supersonic	
	Eastbound	Westbound	Eastbound	Westbound
1975	10	9	13	8
1976	10	9	16	10
1977	10	9	17	10
1978	11	10	16	9
1979	12	11	15	9
1980	12	11	16	9

Note: Noncoincident peaks

**TABLE B13. – AIRPLANE TRAFFIC PARAMETERS
(FORECAST B): PEAK INSTANTANEOUS COUNT**

Year	Subsonic	Supersonic	Total
1975	53	44	97
1976	57	56	113
1977	58	59	117
1978	65	54	119
1979	70	52	122
1980	73	55	128

Assumptions:

1. Optimistic 747 forecast
2. 50% supersonic preference
3. Low-assumption passenger forecast
4. North Atlantic principal area: 40°N to 60°N

**TABLE B14. – NORTH ATLANTIC TRAFFIC SPATIAL DISTRIBUTION
(FORECAST A)**

Region	Longitude	Number of airplanes	
		Subsonic	Supersonic
Polar (60°N to 90°N)	----	10	4
Principal area (40°N to 60°N)	0°W to 10°W	12	19
	10°W to 20°W	20	16
	20°W to 30°W	16	15
	30°W to 40°W	16	16
	40°W to 50°W	16	16
	50°W to 60°W	14	37
	60°W to 70°W	10	35
Other (0° to 40°N)	----	26	9
TOTAL		140	167

Assumptions:

1. For 1980; transoceanic traffic; peak busy summer day; instantaneous count; 75% supersonic preference.
2. High-assumption passenger forecast

**TABLE B15. – NORTH ATLANTIC TRAFFIC SPATIAL DISTRIBUTION
(FORECAST B)**

Region	Longitude	Number of airplanes	
		Subsonic	Supersonic
Polar (60°N to 90°N)	----	10	4
Principal area (40°N to 60°N)	0°W to 10°W	17	13
	10°W to 20°W	12	6
	20°W to 30°W	14	5
	30°W to 40°W	13	5
	40°W to 50°W	10	6
	50°W to 60°W	13	7
	60°W to 70°W	9	7
Other (0° to 40°N)	----	26	9
TOTAL		124	62

Assumptions:

For 1980; transoceanic traffic; peak busy summer day; instantaneous count; 50% supersonic preference

APPENDIX C COMMUNICATIONS TRAFFIC MODEL

C1.0 INTRODUCTION

The communications capacity requirements were determined in three steps:

- (1) Message identification
- (2) Message analysis
- (3) Delay analysis

Message identification was accomplished using studies (refs. 3 and 10) of both the typical U.S. communications environment and the North Atlantic message traffic in today's ATC system. The U.S. traffic was used to postulate the future North Atlantic environment with the improvements in capability that a communications satellite would bring.

The message analysis was performed using the referenced studies and some simple mathematical operations on the typical content of the identified messages.

Finally, a delay analysis was performed using a computer simulation of the message queueing situation.

The message delay statistics were used as the criterion for selecting the required channel capacity. The results are summarized in table 6 of the text. A detailed description of the process is given in the following paragraphs.

C2.0 MESSAGE IDENTIFICATION

Reference 3 contains the details of an exhaustive survey of the U.S. air traffic control communications environment. The messages identified in table C1 were extracted from this report. These messages represent the major bulk of the ATC communications load presently being experienced in the U.S. domestic airspace.

To project these typical ATC messages into a North Atlantic environment, a modification based on the North Atlantic operational procedures is required. Reference 10 was used as the basic source of data for this task. A summary of the North Atlantic background material is given in app. A.

The result of this procedure is to eliminate the communications incident messages as a major category and to modify the grouping of the other messages slightly. Also, a first-priority group of messages was added to the categories. This group contains messages that should be transmitted with minimum delay.

TABLE C1. – U.S. DOMESTIC ATC COMMUNICATIONS

Message	Probability of occurrence	Duration, seconds	Distribution percentage
Air traffic control instructions			
Aircraft vectoring message	0.035	6.6	5.5
Altitude control	0.094	7.4	10.6
Clearance control	0.076	13.52	10.4
Communication support messages			
Report in message	0.127	3.07	7.6
Beacon control	0.045	5.87	7.9
Vector and speed reports	0.046	7.59	8.0
Air traffic control support			
Position report	0.125	6.9	5.0
Altitude report	0.255	4.19	26.5
Vector and speed reports	0.012	6.78	1.4
Advisory messages			
Aircraft traffic advisory	0.026	8.81	1.7
Weather	0.081	9.44	3.4
Airport status	0.004	4.87	----
Communication incidents	0.074	8.0	10.1
Miscellaneous messages	Negligible	----	1.9

Using this procedure, the following list of message types was used as a base:

First-Priority	
Messages	Emergency
	Conflict resolution
	Other
Air Traffic Control	
Messages	Position reports
	Clearance control
	Vectoring messages
Advisory	
Messages	Aircraft traffic advisories
	Airport status
	Weather
Unclassified	
Messages	Miscellaneous
	Non-ATC Messages

This list is ordered by importance to the ATC system. The messages fall naturally into four priority groups as indicated.

In this listing, no attempt has been made to produce a narrowly defined message structure. For example, an emergency message in this list might involve anything from a faulty engine or meter reading to an ill passenger, solar flare warnings, or even an inflight collision causing an airplane crash. The conflict resolution message is meant to include all those messages that ATC handles that change the airplane flightpath to avoid a possible collision risk.

The ATC messages are less critical. They are messages upon which ATC operates to determine possible conflicts. The position report is the most important of these. This includes both the required complete position report and the shorter altitude, speed, or vector reports.

The clearance control message is required for aircraft passing from one control area to another. Vectoring messages are included to handle a situation in which an aircraft requests a deviation from a planned flightpath that requires precise control of aircraft position.

The advisory-type messages are less critical again to the ATC. They are messages that do not require quick response. Information about nearby (nonconflicting) airplanes, airport delays, and weather are included.

Finally, a category is included for miscellaneous ATC messages not categorized above and non-ATC messages that might be considered for transmission, such as airline management data.

C3.0 MESSAGE ANALYSIS

The next step was to choose the lengths and frequency of transmission of the identified messages. Briefly, the lengths were chosen by examining typical content of the messages and determining the time required for the controller/pilot to speak this content. Additional time was added to account for voice access to the communications link and for pauses and acknowledgments.

C3.1 Talking Rate

The talking rate is defined as the speech rate in words per second. Table C2 was extracted from ref. 3. Table C3 indicates that controllers speak at a 5% greater word rate than pilots. This may be because controllers become more expert at subject matter. A speech rate of 2.5 words per second was selected.

C3.2 Message Length

The longest and most frequent message transmitted over the North Atlantic is the required position report (every 10° of longitude). A typical message (from the International Civil Aviation Organization specifications) might read as follows.

Pilot: PAN AMERICAN BOEING SEVEN ZERO SEVEN PAPA ALFA
WUN ZERO SIX OVER.

Controller: CLIPPER ROGER PAPA ALFA WUN ZERO SIX THIS IS GANDER
CENTER OVER.

Pilot: GANDER CENTER ROGER CLIPPER PAPA ALFA ONE ZERO SIX
HEADING TWO AIT ZERO POSITION FOWEr NINer FOWEr FIVE
NORTH FIVE ZERO WEST AT WUN TREE WUN SEVEN FLIGHT
LEVEL WUN NINer ZERO NEXT POSITION FIVE ZERO ZERO
ZERO NORTH FOWEr ZERO WEST AT TREE FIVE ESTIMATED
TIME OF ARRIVAL ONE FOWEr ZERO ZERO GREENWICH
ENDURANCE NINer HOURS TREE ZERO MINUS ONE AIT TOO FIVE
FIVE TREE FIVE SPOT TURBULENCE MODERATE BROKEN
CUMULONIMBUS TOP FLIGHT LEVEL TREE ZERO OVER.

Controller: CLIPPER ONE ZERO SIX CONTINUE ON PRESENT COURSE
OVER.

This message has 113 words. Assuming an average speech rate for controllers and pilot as 2.5 words per second, the message duration is then 45 seconds. Similar procedures were used to specify lengths of the other messages. The following values were used:

TABLE C2. – TALKING RATE FOR PILOTS AND CONTROLLERS

Low or transitional altitudes		High altitudes	
Controller words/second	Pilot	Controller words/second	Pilot
2.45 (1.18)	2.36 (1.04)	2.70 (0.57)	2.73 (0.59)

() Indicates pauses per 100 words; strong negative correlation between talking rate and pausing rate.

TABLE C3. – TALKING AND PAUSING RATES FOR A/G/A COMMUNICATIONS

Type talkers	Range of talking rates, wps	Average talking rate, wps	Average pauses per 100 words
Fast-talking communicators	2.81 to 3.15	2.97	0.30
Average communicators	2.32 to 2.76	2.51	0.88
Slow communicators	1.92 to 2.33	2.21	1.72
All communicators	1.92 to 3.16	2.54	0.92

NOTE: The average A/G/A communicator talks at the rate of about 2.5 words per second, and the overall range extends from about 1.9 to 3.2 words per second.

	<u>Time (sec)</u>
Emergency	30
Conflict resolution	30
Other first priority	30
Position report.	45
Clearance control	15
Vectoring messages	10
Aircraft traffic	10
Airport status	5
Weather advisory	10
Non-ATC	20
Miscellaneous	20

C3.3 Information Bit Rate

Two methods were used to determine the number of digital bits that could transmit the required information content of the messages. First, it is assumed that the position report and the other two ATC messages in a digital system would be formatted and coded. Seven bits per alphanumeric character were used to allow for redundancy and coding. Table C4 shows information required in the position report:

TABLE C4. – POSITION REPORT INFORMATION

Message	Alphanumeric Characters	Bits
Identification	3	21
Time	4	28
Heading	3	21
Latitude	4	28
Longitude	4	28
Altitude	3	21
Next position	8	56
ETA	4	28
Total	33	231

For the position report, 230 bits were used as a possible code. The other two messages contain 60 bits each.

For the noncoded messages, it is assumed that a straight alphanumeric transmission is required. However, a 50% reduction of the voice redundancy was assumed. For example, a typical aircraft traffic advisory from ATC would take 7 seconds (excluding access, etc.) This would be 17 words at 2.5 words per second. At four alphanumeric characters per word this message would be 68 characters—assuming 34 to eliminate redundancy, with 7 bits per character, a figure of 250 bits was selected.

C3.4 Message Frequency

The number of each type of message expected during a busy hour must now be determined. This is a function of the number of airplanes and the ATC procedure used. The number of airplanes in the communications gap was selected as 131 (68 subsonic and 63 supersonic) from the traffic analysis described previously. Using present procedures, a subsonic airplane makes 1 position report per hour, while a Concorde and Boeing SST would make 2 and 3 position reports per hour respectively. The position reports made by these airplanes during the busy hour would be $(68 \times 1) + (50 \times 3) + (13 \times 2)$ or 244. Also taking into account position reports made by the airplanes crossing at 10°W and 50°W , the total number of position reports during busy hour is 300. During the busy hour, 63 supersonics and 30 subsonics would be expected to cross from one control to another. This would generate 100 clearance control messages.

The results of this analysis are summarized in table C5. The increases in communications traffic postulated for the communications satellite case are based on an assumption that the satellite system will tend to produce loads similar to those identified in ref. 3.

C4.0 DELAY ANALYSIS

There are two approaches that could be used to arrive at the required number of channels for a satellite terminal. One approach is to remove the uncertainties from the system and define it within certain constraints. Equations could be formulated to represent this system and solved to yield the optimal solution. The second approach is to simulate the message-arrival process at the terminal where the variables are generated by using certain statistical rules; the optimal system is obtained by defining required system criteria.

The second approach rather than the first one was adopted for this study for the following reasons:

- (1) The simulation technique is a more realistic approach, because it affords an opportunity to simulate the actual system very closely.
- (2) The mathematic techniques are not yet fully developed to simulate mathematical equations that could closely represent the actual system.
- (3) It is easier to see how accurate and reliable the solution is when using the simulation technique.

C4.1 Program Description

The following assumptions were used in developing the computer program required for this task.

The system under consideration employs a satellite with a limited number of communications channels. Messages arrive at the satellite Poisson-distributed over a period of 1 hour. Only the peak traffic hour is investigated. It is assumed that message traffic routed to any ground station behaves identically to traffic routed to other ground stations; therefore, only one communications link is considered. Furthermore, it is assumed that:

TABLE C5. – COMMUNICATIONS REQUIREMENTS

Priority	Message category	Message type	Average duration c ² contact, seconds	Information bits (a)	Number of messages (peak hour loading)	
					Present procedures (b)	Comm/Surv Satellite System (c)
1	First priority	Emergency	30	900	10	10
		Conflict resolution	30	600	35	70
		Other	30	750	---	60
2	ATC messages	Position report	45	225	300	---
		Clearance control	15	60	100	100
		Vectoring messages	10	60	---	100
3	Advisory messages	Aircraft traffic	10	250	---	30
		Airport status	5	100	---	5
		Weather advisory	10	200	50	100
4	Unclassified	Non-ATC	20	600	50	200
		Miscellaneous	20	500	60	70

^aATC messages formatted; other messages transmitted with elimination of voice redundancy

^b1980 traffic with 10⁰ position reports (present-day North Atlantic message load)

^c1980 traffic with 20 position reports per hour and typical U.S. message load

- (1) Messages that arrive at the satellite are Poisson distributed.
- (2) No delay is caused by the operation of the ground station.
- (3) Messages are assigned channels with no delay in operation.
- (4) The airplanes are continuously informed of their transmission possibilities.
- (5) One message occupies one channel at one time.
- (6) Channels are assigned on priority basis only.
- (7) A message is allowed to complete its transmission even though another message of higher priority now requests use of the channel in the transmission period of time.
- (8) Messages of same priority are assigned channels on a "first come first served" basis.
- (9) The only delay occurring in the system is that from messages having to wait because channels are occupied.

C4.2 Program Details

It is assumed that message arrival times at the terminal have a Poisson distribution. Subroutine **PØISS** employs a random generator to create a random number that, in turn, determines the number of messages arriving in a certain time interval. Each time interval in the program is defined as a time unit that can be of any length. For instance, for a case of taking a sample every 10 seconds for 1 hour, each time unit is equivalent to 10 seconds and there are 360 time units in the entire period. Subroutine **PRIØ** assigns priority and message length to each message. Available channels are assigned to the message with high priority. Among those of the same priority, the rule of "first come first served" is observed. But the high-priority message does not interrupt the transmission of a low-priority message. It must wait until a channel is available. Program **DELAY** analyzes the message delay with respect to different numbers of channels as specified by the initial number of channels **NCHANL**, channel increment **NDCHNL**, and the number of cases **NCASE** that are read into the program. Program **DELAY** may also repeat the analysis with different sets of random numbers as specified by the user through the number of sets of random numbers **NRANDM** and the input arguments (**IU's**, **IX's**) of the random-number generator that are input data to the program. The program can handle messages of up to four different priorities. The number of messages of any one priority shall not exceed 3000. There may not be a channel available when a message arrives; thus, a queueing table categorized in different priorities is needed as a temporary parking place for the arriving messages. Each priority category of the queueing table has a capacity of 500. Since a random-number generator is employed in simulating the message distribution, accuracy depends upon the total number of messages and their distribution. The confidence factor in the answer obtained is a function of the number of runs made to obtain the data.

C4.2.1 Subroutines. — This program contains three special-purpose subroutines and one general-purpose subroutine, which were obtained from the Boeing Computing Department Library:

- (1) Subroutine SHIFT – This subroutine advances every element of a single-subscripted array by one place, except the first element in the original array. The first element will be destroyed. This subroutine can operate on two arrays simultaneously.
- (2) Subroutine PØISS – Based on a Poisson distribution, this subroutine generates the number of messages arriving at a certain time. The number will be between zero and 10.
- (3) Subroutine PRIØ – Based on a given distribution, this subroutine picks a number among 1, 2, 3, and 4. This number represents the priority of a message.
- (4) Subroutine RAND – This is a random-number generator that generates a random number from 0.0 to 1.0.

C4.2.2 Program logic.— The logic diagrams are included in fig. C1.

C4.2.3 Output.—The computer prints out the number of messages of each priority that have been processed within the given time period. The input number of total messages is also listed as a reference. The message delays are tabulated in four columns of different priorities. The average message delay of each priority is presented at the bottom of the table. The messages that have not been processed during the given time period (if there are any) are also listed as special cautions at the end of the output.

C5.0 RESULTS

The computer program described in the last section was used to obtain the message-delay statistics for various numbers of channels and operational concepts. The frequency of messages by message category for these concepts was selected from the results detailed in table C5.

C5.1 Operational Concepts

The improved communications that a satellite will provide the ATC system can be used in varying ways. Each concept requires different message-loading characteristics and thus different capacities. To evaluate the effects of this variation, the concepts described in the following paragraphs were used.

C5.1.1 Present procedures.— The North Atlantic ATC system requires position reports every 10⁰ of longitude, as detailed previously (table C5). This requires 300 position reports and 100 clearance-control messages for the high 1980 traffic estimate. The total message load by priority is as follows:

First priority		45
ATC messages		400
Advisory messages		50
Unclassified		110

Integer: D1, D2, D3, D4, DELAY1, DELAY2, DELAY3, DELAY4
TIN1, TIN2, TIN3, TIN4, CHANEL

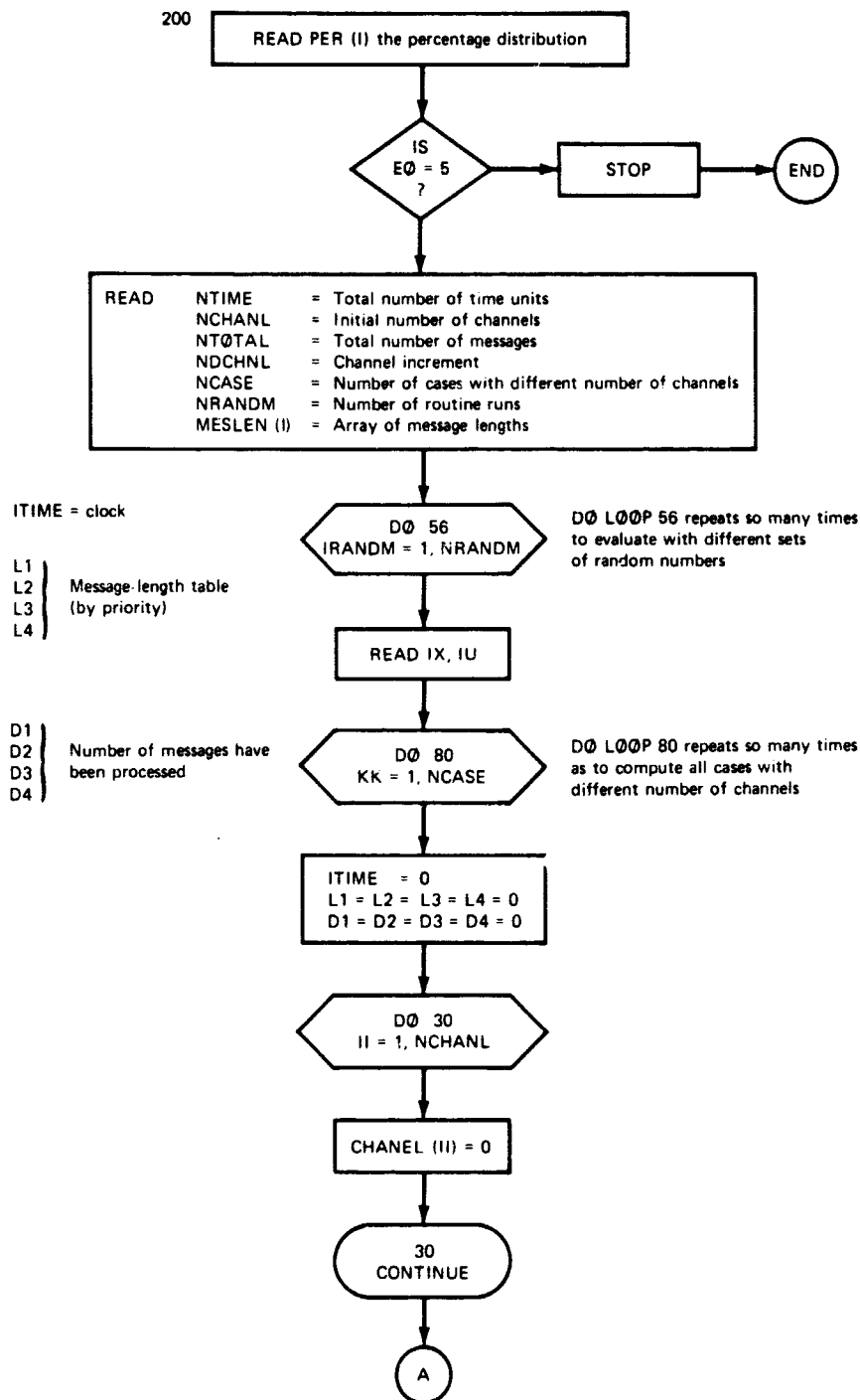


Figure C1.— COMMUNICATIONS PROGRAM LOGIC DIAGRAM

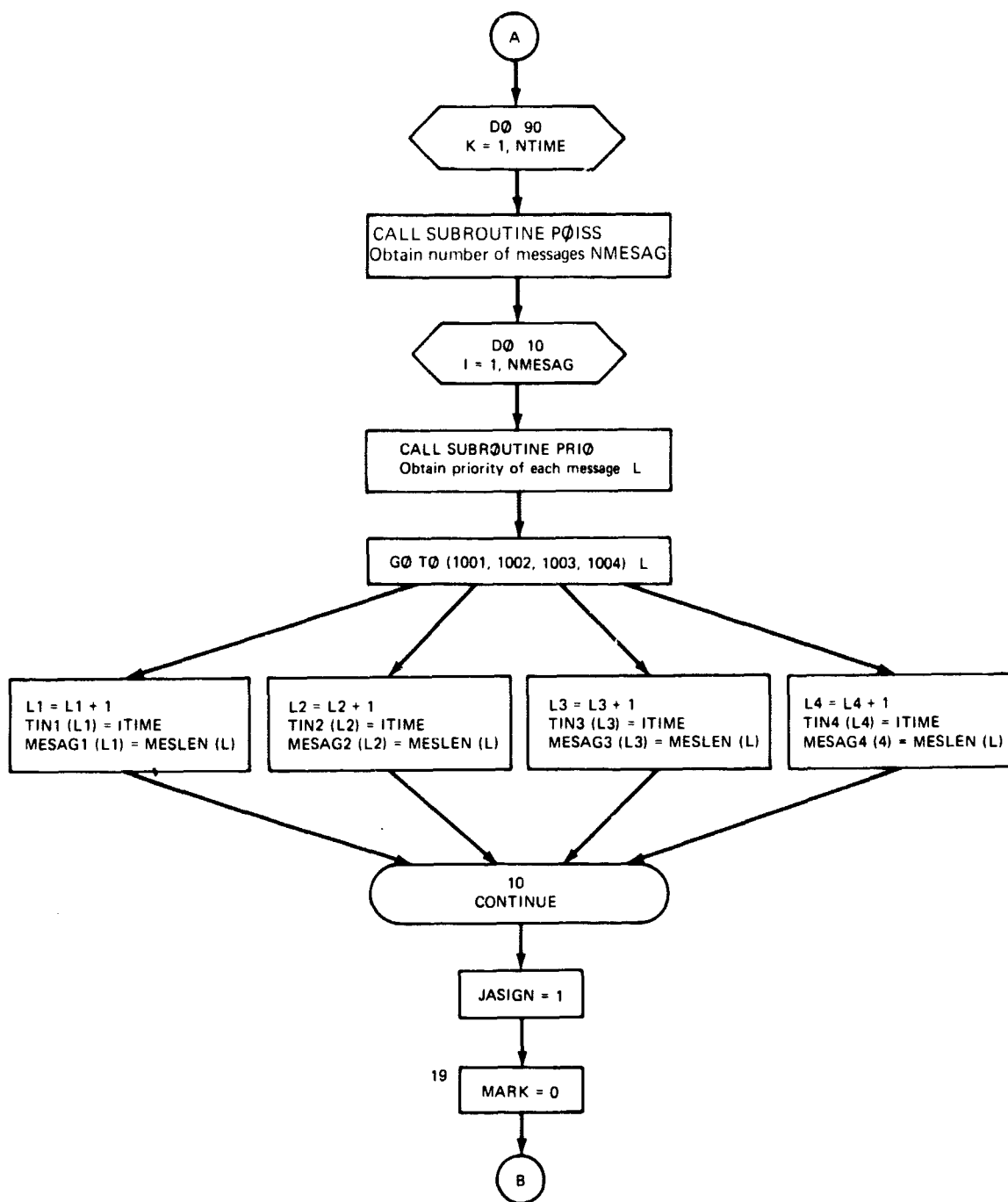


Figure C1.— Continued

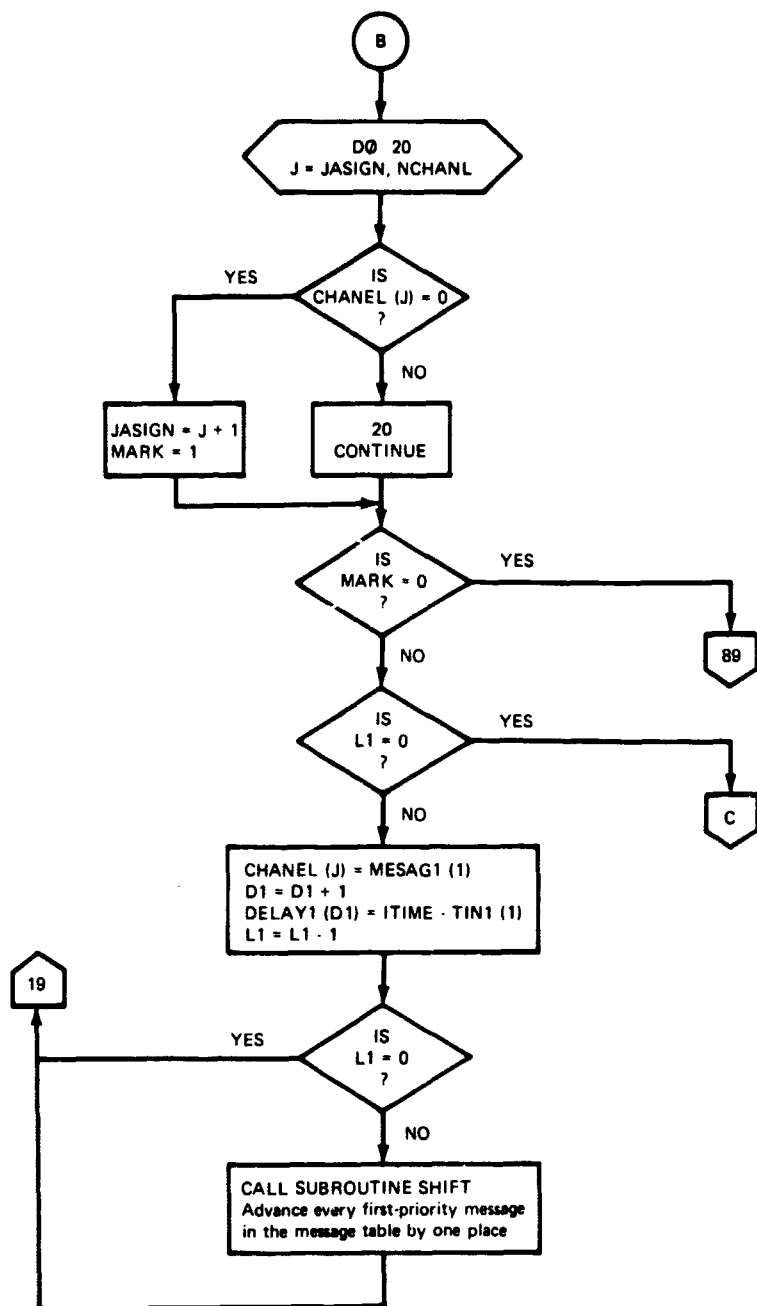


Figure C1.— Continued

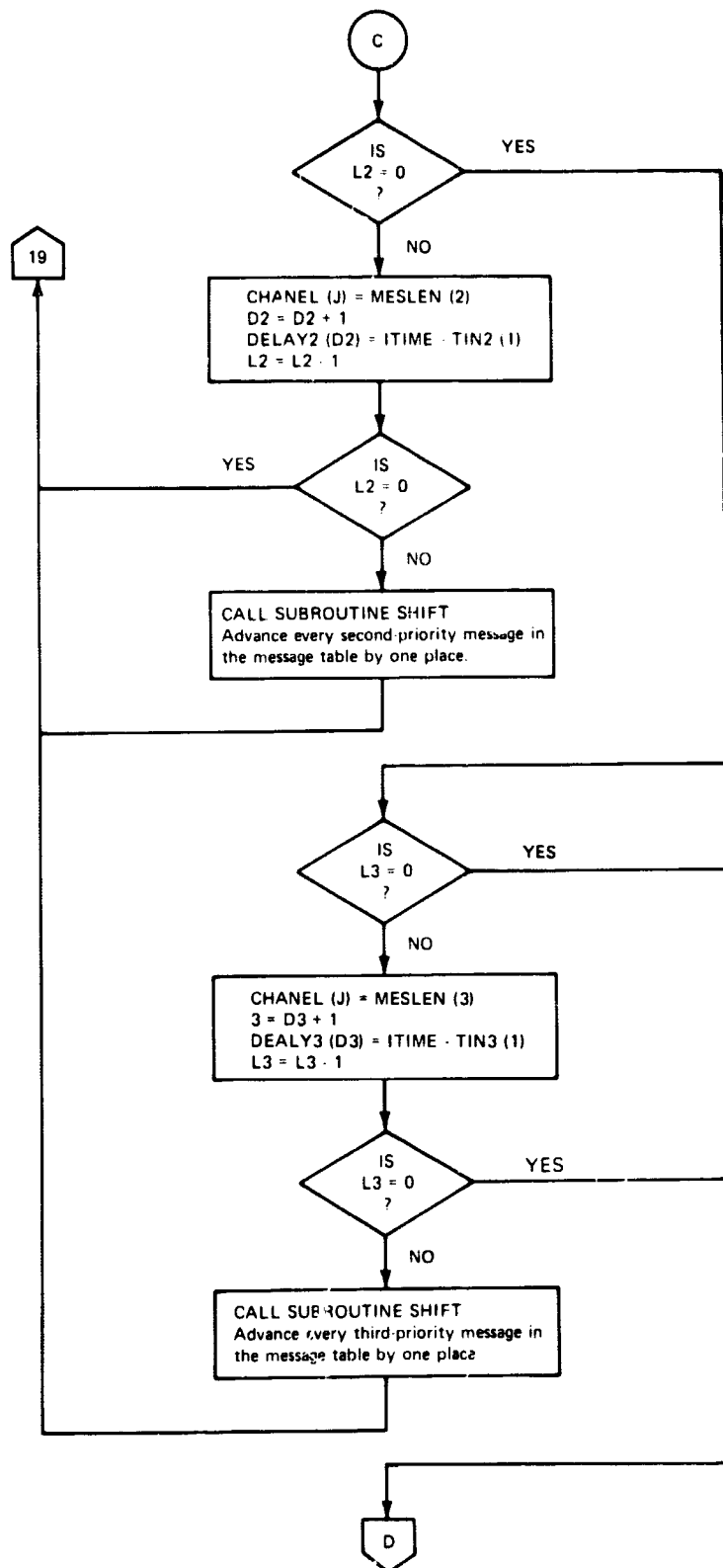


Figure C1.— Continued

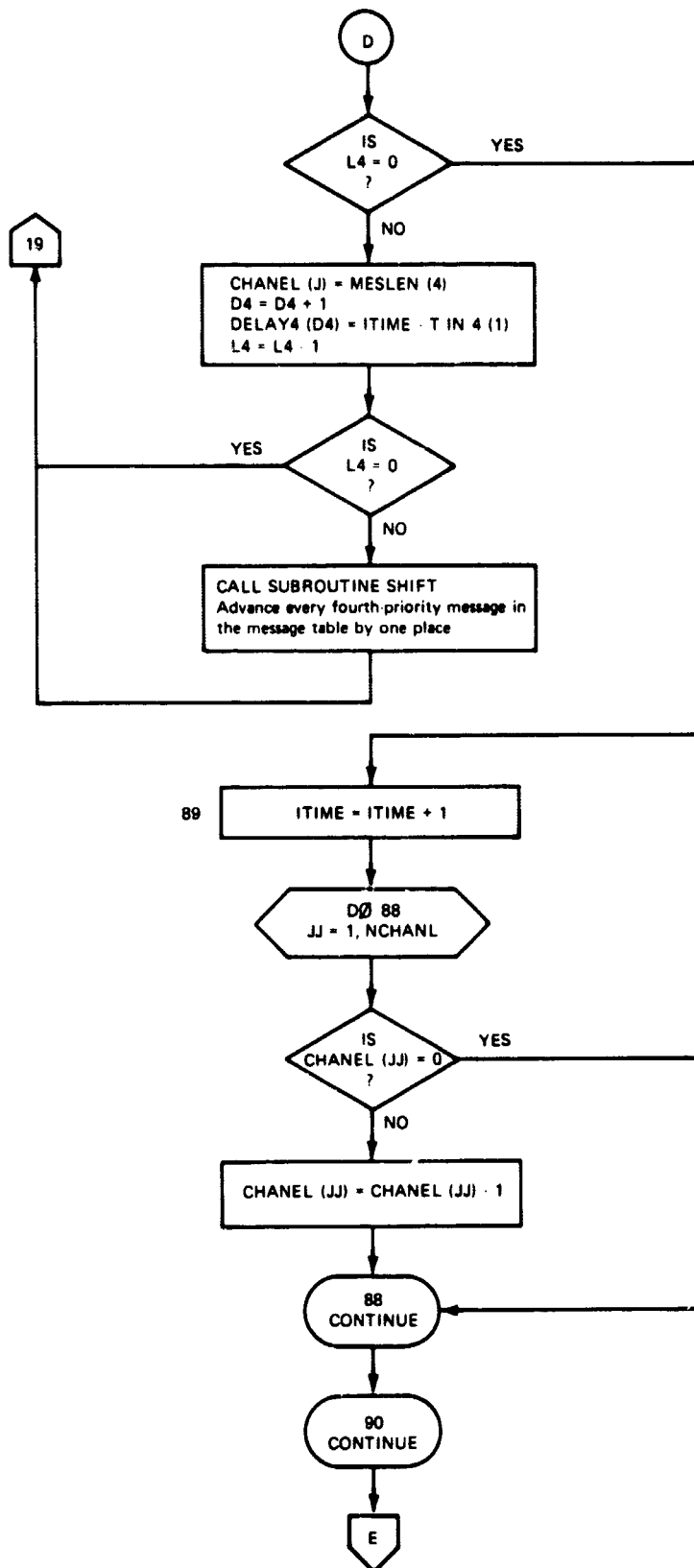


Figure C1.— Continued

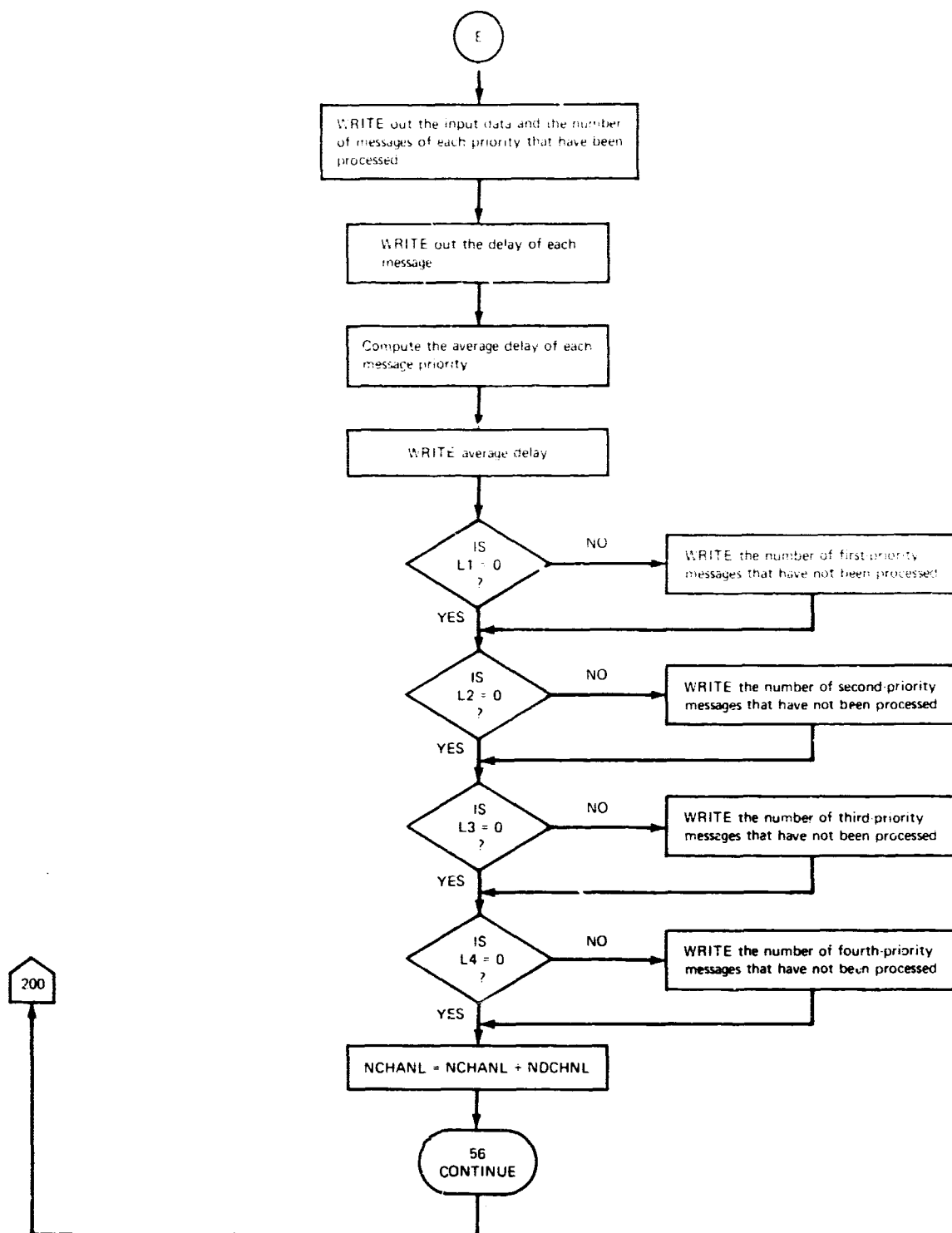


Figure C1.— Concluded

A minimum airplane traffic load was also postulated. This led to an estimate of 55 subsonic and 21 supersonic airplanes. The subsonics would generate about 50 position reports and the supersonics, 40. Also, about 30 clearance control messages would be expected. The following is an estimated minimum message load with the other categories also reduced by the reduction in traffic:

First priority	40
ATC messages	120
Advisory messages	40
Unclassified	80

This load is believed to represent an absolute minimum requirement.

C5.1.2 Increased position reports.— In this concept, position reports were increased to every 5° of longitude. The number of position reports with this concept increased from 300 to 500. The other numbers were kept the same as the first concept.

C5.1.3 Automatic digital position reports.— In this concept, it is assumed that a digital position reporting capability is available and that position reports are made every 3 minutes. This requires about 2500 position reports to be transmitted in the peak hour at 225 bits per report for a total of 562×10^3 bits. The other (voice) messages were kept at the same number.

C5.1.4 All-digital system—U.S. message load.— In this concept, all messages are in digital form, and an increased number of messages are assumed (reference last column of table C5). The total message load by priority is given in table C6.

TABLE C6. — U.S. MESSAGE LOAD — ALL-DIGITAL SYSTEM

Message	Number	Bits
First priority	140	96×10^3
ATC messages	2700	574×10^3
Advisory messages	135	32×10^3
Unclassified	270	124×10^3

C5.1.5 Surveillance function—present procedures.— This concept has the same voice message load as the first two concepts with high airplane traffic, except that addition of a surveillance capability is assumed to eliminate the need for position reports.

C5.1.6 Surveillance function—U.S. message load.— The final concept examined is a U.S.-type ATC message load with no position reports (surveillance). This concept uses the voice message loading specified in the last column of table C5:

First priority	140
ATC messages	200
Advisory messages	135
Unclassified	270

Table C7 summarizes these message distributions.

TABLE C7. – MESSAGE FREQUENCIES

Operational concept		Run number	Peak hour number of voice messages by category				Peak hour digital bits by category			
			1	2	3	4	1	2	3	4
All voice (present procedures) ^a	Minimum capability	1a	40	120	40	80	---	---	---	---
	Preferred capability	1b	45	400	50	110	---	---	---	---
All voice (increased position reporting) ^b		2	45	600	50	110	---	---	---	---
Automatic digital position reporting ^c		3	45	100	50	110	---	562 x 10 ³	---	---
All-digital system – U.S. ATC message load		4	---	---	---	---	96 x 10 ³	574 x 10 ³	32 x 10 ³	124 x 10 ³
Surveillance function added (present procedures) ^d		5	45	100	50	110	---	---	---	---
Surveillance function added (U.S. ATC message load) ^d		6	140	200	135	270	---	---	---	---

^aBased on position reports every 10° of longitude; low traffic estimate for minimum capability; high traffic estimate for preferred capability

^bPosition reports every 5° of longitude

^cDigital position report transmitted every 3 minutes

^dSurveillance function assumed to eliminate need for position reports

C5.2 Delay Results

The total messages in table C7 were run through the computer simulation described previously with various numbers of channels. The selection of the required number of channels was made based on the following outputs of the simulation.

Average delay All messages
Average delay First-priority messages
Maximum delay First-priority messages

The maximum-delay value is the average worst-case delay for 100 computer runs. It was found that 100 runs provided consistent results for these parameters and that additional runs made no significant changes in the results.

The procedure used to select the required number of channels can be seen from table C8. This details the delay criteria above for both the selected channel numbers and for one channel less than the selected number. The resulting number of channels in table C8 satisfy three conditions:

- (1) The average delay for all messages was kept below 20 seconds.
- (2) The average delay of first-priority messages was kept below 1 second.
- (3) The worst-case delay for first-priority messages was kept at approximately 10 seconds or less.

Table C9 illustrates this process. In the table, an X indicates that the delay figure meets the criterion and a zero indicates a failure to meet the criterion. It can be seen that only the selected channel requirements meet all three. For example, in concept 6 with four channels, only the third criterion failed; whereas in concept 1b with six channels, none of the criteria was fulfilled. Adding additional channels over the number selected did not produce a significant gain in operating effectiveness.

Figure C2 is presented as a typical example of the distributions of the average delay obtained in the simulation. This shows the cumulative probability curves for the five-channel and 4-channel runs of concept 6 (the surveillance function added with U.S. message load). The curves are drawn for the first-priority messages. The average delay for all first-priority messages was 0.19 second for five channels and 0.75 second for four channels. The distribution was obtained from 100 computer runs. The added benefit obtained from five channels is apparent from considering the two curves. For example, the reduction in spread (or standard deviation) of the five-channel curve would permit a five-channel system to operate with more predictable operating characteristics than a four-channel system. Consider that while the average delay for the two systems differs by $0.75 - 0.19 = 0.56$ second, the 99% average delay difference is approximately $1.69 - 0.69 = 1.00$ second. This condition is generally true for all the selected channel numbers over the next lower numbers. However, a similar condition does not exist for the next higher number of channels.

Using the procedure described above, the required number of channels was selected for all concepts defined. Table C10 presents a summary of the requirements with the associated delays obtained in the simulation.

TABLE C8. -- DELAY RESULTS

Run number (a)	Number of channels	Average delay (all messages), seconds	Average delay (first priority), seconds	Maximum delay (first priority), seconds (b)
1a	3	14.80	2.15	18.6
	^d 4	2.58	0.58	10.6
1b	6	42.23	1.20	12.4
	^d 7	8.05	0.52	9.3
2	8	54.86	0.86	11.3
	^d 9	11.39	0.30	7.5
^c 3	2	22.86	---	---
	^d 3	2.89	---	---
^c 4	3	12.07	1.73	13.4
	^d 4	2.29	0.42	6.9
5	2	8.41	1.36	16.2
	^d 3	1.24	0.20	6.0
6	4	15.12	0.75	14.4
	^d 5	2.83	0.19	9.6

^aFrom table C4

^bFor digital messages

^cAverage worst delay for 100 runs

^dSelected number of channels

TABLE C9. -- CHANNEL SELECTION

Run number	Channels	Criteria ^b		
		1	2	3
1a	3	X	O	O
	^a 4	X	X	X
1b	6	O	O	O
	^a 7	X	X	X
2	8	O	X	O
	^a 9	X	X	X
3	2	O	---	---
	^a 3	X	---	---
4	3	X	O	O
	^a 4	X	X	X
5	2	X	O	O
	^a 3	X	X	X
6	4	X	X	O
	^a 5	X	X	X

^aSelected number of channels

^b X = Criterion met
O = Criterion failed

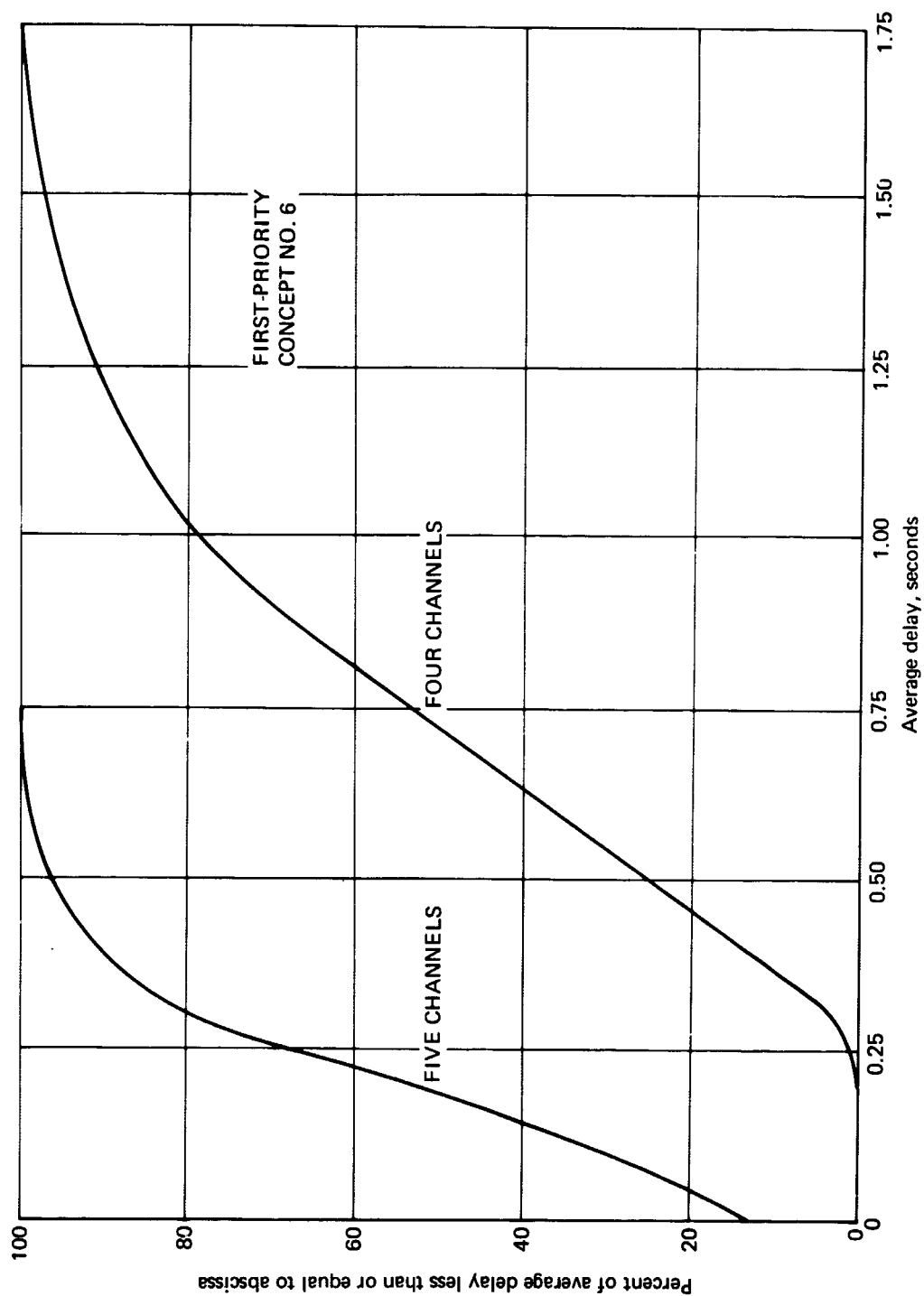


Figure C2.— DELAY DISTRIBUTION

TABLE C10. -- SUMMARY OF CHANNEL REQUIREMENTS

	Channel requirements				Average delay by message category, seconds				Maximum delay, seconds (b)
	Voice		Digital (a)						
	Number of channels	Channel utilization, percent	Number of channels	Channel utilization, percent	1	2	3	4	
Operational concepts									
All voice (minimum capability)	4	56	----	----	0.6	1.4	3.0	5.1	10.6
All voice (preferred capability)	7	77	----	----	0.5	3.5	14.5	24.9	9.3
All voice (increased position reports)	9	86.6	----	----	0.3	4.6	27.0	46.2	7.5
Automatic digital position reports	3	46	3	52.7	----	^c 2.9	----	----	----
					^d 0.2	^d 0.6	^d 1.1	^d 2.3	^d 6.0
All-digital system (U.S. message load)	1	Emergency only	4	75	^c 0.4	^c 1.6	^c 3.6	^c 5.2	^c 6.9
Surveillance function added (present procedures)	3	46	----	----	0.2	0.6	1.1	2.3	6.0
Surveillance function added (U.S. ATC message load)	5	77.7	----	----	0.2	0.7	1.8	6.3	9.6

^a100 bit/sec data rate^bMaximum delay is the average delay for the worst delayed message of each run (100 or more runs)^cFor digital messages^dFor voice messages

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APPENDIX D NAVIGATION/SURVEILLANCE MODELS

D1.0 INTRODUCTION

This appendix discusses the mathematical details of two Boeing-developed models that were used to determine the position-fixing requirements specified in Sec. 4.0. A collision-risk model based on work at the Royal Aircraft Establishment (RAE) (refs. 4, 11, and 12) is used to quantify the basic safety criteria. This model is fed path-keeping parameters from an air traffic control surveillance model based on superimposing a surveillance capability on the airplane's self-contained navigation capability.

D2.0 COLLISION-RISK MODEL

The collision-risk model is oriented toward a long-range air traffic control system such as exists over the enroute portion of the North Atlantic air route. In this type of system, the collision risk (number of expected collisions) between two aircraft becomes significant only when they enter into what is called "proximity." Proximity is defined as a condition in which the aircraft are nominally separated in only one dimension (lateral, longitudinal, or vertical separation).

In this analysis, the equations are derived only for the lateral-risk case, which is the collision risk due to the failure of lateral separation between two aircraft that are nominally at the same altitude and that are both contained within the same along-track separation segment. Figure D1 shows this condition, which is called "lateral proximity."

This is a reasonable limitation since the navigation and surveillance parameters being specified are most critical in maintaining this separation situation safely.

D2.1 Mathematical Derivation

The lateral collision risk C_y can be expressed as a function of the following parameters:

- (1) The total time during which the aircraft are laterally proximate—This time is determined from the amount of traffic, the area of the traffic routes, the ATC procedures, the transit time, and the total time period. The time must be calculated for same-direction traffic T_{ys} and opposite-direction traffic T_{yo} .
- (2) The probability of vertical overlap of proximate aircraft P_{zo} and the frequency with which vertical overlap occurs N_{zo} —These parameters are evaluated for aircraft at nominally the same altitude. They depend on the aircraft vertical thickness, the vertical separation standard, and the altitude variations of the aircraft.
- (3) The along-track separation standard S_x —This parameter does not enter directly into the final result in the collision-risk computation. In the form in which the model has been developed, the proximity values defined previously are determined as a function of S_x . This permits S_x to be canceled out from the final equation.

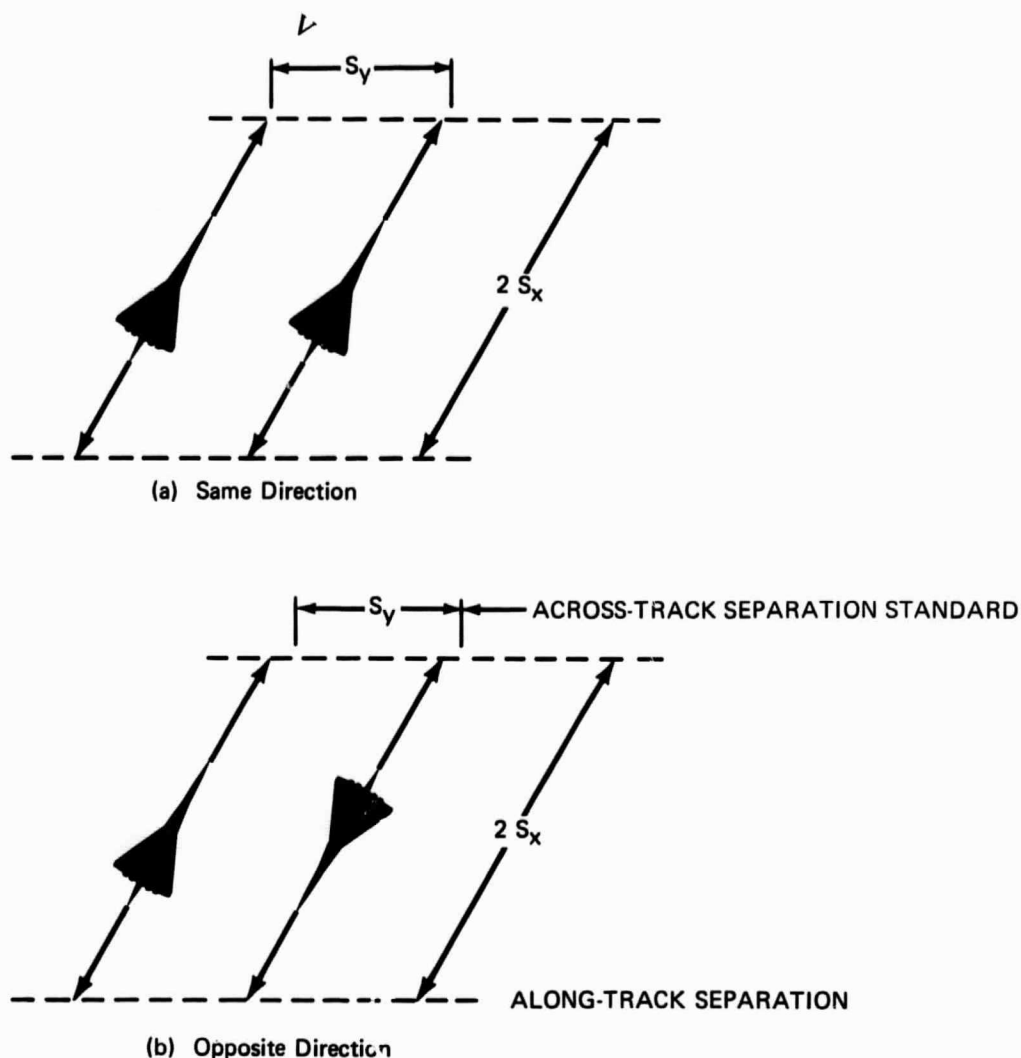


FIGURE D1.— LATERAL PROXIMITY

- (4) The aircraft parameters. The following terms are contained in the model
- Average velocity $\bar{V}$
 - Mean cruising speed difference for same-direction proximate pairs $\Delta\bar{V}$
 - Aircraft dimensions, λ_x , λ_y
 - Relative across-track velocity $|\dot{y}|$

The velocity parameters are really random variables whose distribution functions must be determined from actual operational observations. In the present evaluation, an expected value is used based on planned SST design parameters and on observed subsonic values.

- (5) The probability of across-track overlap of laterally proximate aircraft P_y . This parameter is the critical one as far as specification of navigation accuracy is concerned, because collisions are possible only when error magnitudes of at least half the separation standard occur. Errors this large fall in the tail area of typical navigation system position error distributions. Therefore, the proportion of errors falling in the tail area determines the relative effectiveness of navigation systems in reducing collision risk. Figure D2 shows the error distribution for Gaussian and exponential assumptions about the shape of the main body of errors. Also plotted are observed values of Project Accordion (ref. 13) data. All these distributions have a standard deviation of 12 n.mi. The variation of tail area proportions is apparent from this graph. The exponential assumption is used in the analysis presented here.

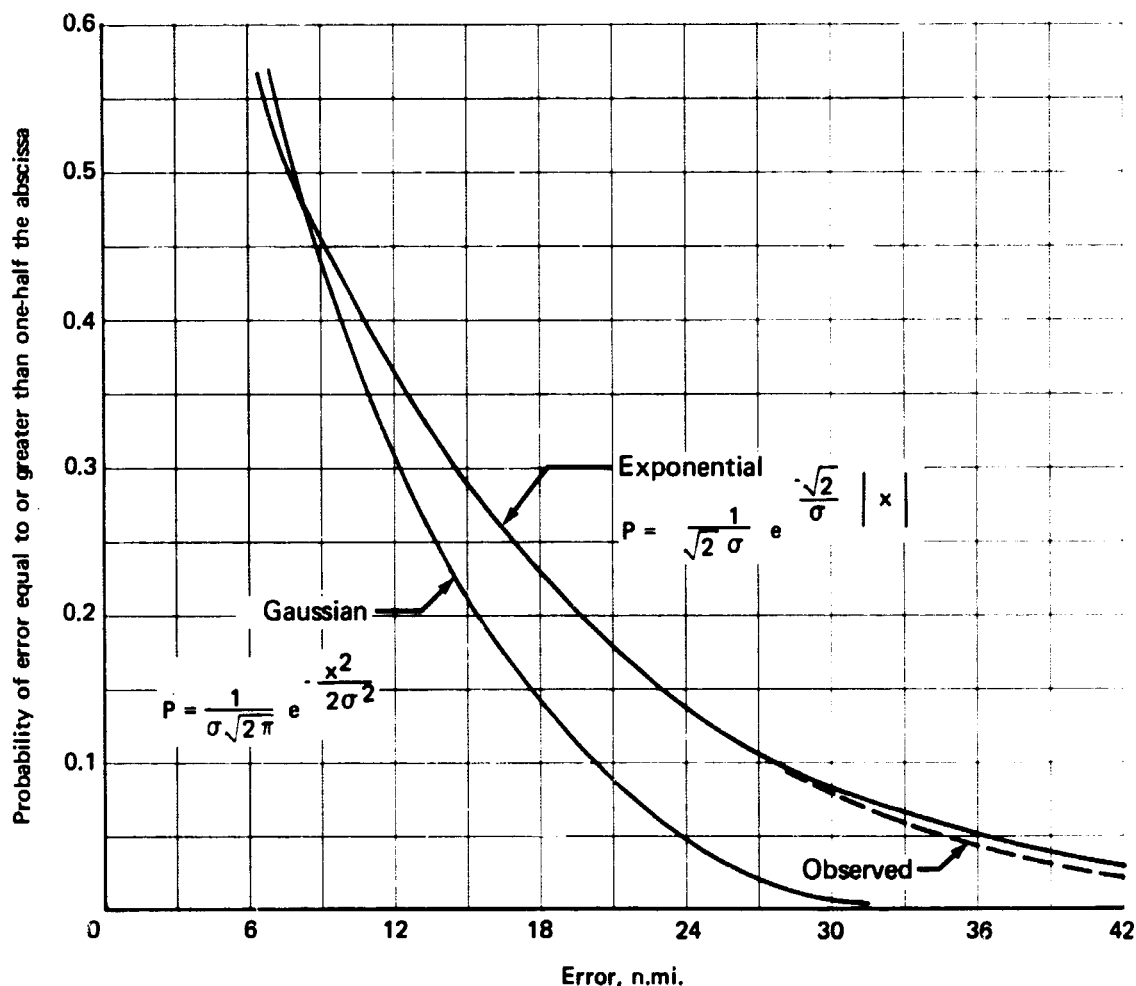


FIGURE D2.— TAIL AREA OF ERROR DISTRIBUTIONS

The collision risk (C_y = number of collisions) as a function of this probability and using the preceding notation becomes:

$$\frac{C_y}{P_y} = \frac{T_{ys}}{S_x} \left[\frac{\Delta \bar{V}}{2} P_{zo} + \lambda_x N_{zo} + \frac{\lambda_x P_{zo} |\dot{y}|}{2\lambda_y} \right] + \frac{T_{yo}}{S_x} \left[\bar{V} P_{zo} + \lambda_x N_{zo} + \frac{\lambda_x P_{zo} |\dot{y}|}{2\lambda_y} \right]$$

The detailed derivation of this equation follows.

D2.2 Mathematical Basis

The derivation presented here provides sufficient background to the model used to enable judgments to be made of the validity of the results. A mathematically rigorous exposition has not been attempted. Rather than reproduce the total step-by-step evolution of the equations as contained in the referenced RAE papers, a summary of the logic involved is presented. Full details of the mathematics are contained in refs. 4 and 12. The symbols used are those defined previously in Sec. 2.1.

The general assumptions are:

1. Blind flying; that is, evasive action based on visibility is not taken.
2. Position determination errors in three dimensions are independent.
3. Collisions occur only between aircraft flying with separation intended in only one dimension. This assumption defines the term "dangerously small" to be a proximity condition as described in fig. D1.

In general (see ref. 4), the collision rate due to collisions from a particular direction can be stated as the product of three terms: the frequency with which the separation in that direction becomes dangerously small multiplied by the proportion of time spent with separation dangerously small in each of the other directions. Mathematically:

$$(CR)_y = N_y P_z P_x$$

Where: x, y, z = the along-track, across-track, and the vertical axes, respectively

$(CR)_y$ = collision rate due to intrusions from both sides

N_y = frequency of lateral overlap of two aircraft nominally provided lateral separation

P_z = probability of vertical overlap of two aircraft at nominally the same altitude

P_x = probability of longitudinal overlap of two aircraft within nominally the same along-track separation segment

In a similar manner, collision rates from intrusions in front and back and on top and bottom can be written as $(CR)_x = N_x P_y P_z$ or $(CR)_z = N_z P_y P_x$ with appropriate subscript changes.

The total collision rate becomes

$$CR = N_x P_y P_z + N_z P_x P_y + N_y P_z P_x \quad (D1)$$

The problem now becomes one of defining the frequencies and probabilities in a way that will develop an explicit expression containing all the parameters of interest.

We will consider the case of collisions due to breakdown of planned lateral separation since this condition is mostly the result of navigation errors. In this case, the y subscript terms of eq. (D1) are defined for aircraft flying with nominally lateral separation. The x and z subscript terms are defined for aircraft with nominally the same longitude and altitude.

For this case, the following relationships hold (these relationships assume that the aircraft are uniformly distributed in the along-track direction):

$$P_x = \lambda_x / S_x$$

$$N_x = |\dot{x}| / 2S_x$$

Where: λ_x = aircraft length

S_x = along-track separation standard

$|\dot{x}|$ = average rate of change of the along-track separation

The average rate of change of x assumes two values: $|\dot{x}| = 2\bar{V}$ for opposite-direction traffic and $|\dot{x}| = \Delta\bar{V}$ for same-direction traffic, where: $\bar{V}$ is the average velocity and $\Delta\bar{V}$ is the average relative velocity.

Substituting these values into eq. (D1) results in two equations:

$$CR_{(same)} = \frac{\Delta\bar{V}}{2S_x} P_z P_y + \frac{\lambda_x}{S_x} N_z P_y + \frac{\lambda_x}{S_x} N_y P_z$$

$$CR_{(opp)} = \frac{\bar{V}}{S_x} P_z P_y + \frac{\lambda_x}{S_x} N_z P_y + \frac{\lambda_x}{S_x} N_y P_z$$

The frequency of lateral overlap of laterally proximate aircraft N_y can be expressed in terms of its probability of occurrence, the rate of lateral change, and the aircraft wingspan.

$$N_y = \frac{|\dot{y}|}{2\lambda_y} P_y \quad (\text{ref. 4})$$

Where: $|\dot{y}|$ = rate of lateral change

λ_y = wingspan

Substituting and rearranging terms

$$CR_{(same)} = \frac{1}{S_x} \left[\frac{\Delta \bar{V}}{2} P_z + \lambda_x N_z + \frac{\lambda_x}{2\lambda_y} P_z |\dot{y}| \right] P_y$$

$$CR_{(opp)} = \frac{1}{S_x} \left[\bar{V} P_z + \lambda_x N_z + \frac{\lambda_x}{2\lambda_y} P_z |\dot{y}| \right] P_y$$

The collision risk due to lateral separation failure C_y is the total collision rate multiplied by the time spent in proximity

$$C_y = (T_{ys}) CR_{(same)} + (T_{yo}) CR_{(opp)}$$

where T_{ys} and T_{yo} are the same-direction times and opposite-direction times, respectively.

Finally we arrive at the expression on page 110.

$$\frac{C_y}{P_y} = \frac{T_{ys}}{S_x} \left[\frac{\Delta \bar{V}}{2} P_{zo} + \lambda_x N_{zo} + \frac{\lambda_x P_{zo} |\dot{y}|}{2\lambda_y} \right] + \frac{T_{yo}}{S_x} \left[\bar{V} P_{zo} + \lambda_x N_{zo} + \frac{\lambda_x P_{zo} |\dot{y}|}{2\lambda_y} \right] \quad (D2)$$

where the subscript zo indicates that these parameters are evaluated at nominally zero altitude separation.

D3.0 AIR TRAFFIC CONTROL SURVEILLANCE MODEL

This section describes the development and application of a mathematical model with which to study the operational performance of overocean aircraft position-monitoring systems. In developing the model, it was necessary to make some basic assumptions about the system and its operation. The first assumption is simply that the surveillance system will be used by ATC to regulate the flow of air traffic.

The second assumption concerns the nature of the control action exercised by ATC. It is assumed that the control of aircraft will be accomplished as follows: An alarm threshold r_o is defined about each aircraft's intended track. An alarm occurs when an aircraft exceeds its alarm threshold (i.e., when it wanders a distance greater than $\pm r_o$ from intended track) as determined by surveillance. The occurrence of an alarm requires ATC to direct the pilot to alter his course appropriately. In the absence of an alarm, no control action is taken.

The third assumption is one of independence. We assume that the surveillance position information is independent of the individual aircraft navigation systems. We make no additional assumptions as to the type of surveillance system except to characterize it by its accuracy σ_μ and update interval t_0 . The term σ_μ represents the standard deviation of the surveillance system error distribution, and t_0 represents the time interval (per aircraft) between successive surveillance fixes.

The parameters that are used to measure operational performance of the surveillance system are

- (1) Alarm rate A_f^*
- (2) "Unfavorable" alarm rate $\bar{A}_f^*$ (An "unfavorable" alarm is defined as an alarm that would move an aircraft farther away from its intended track.)
- (3) Probability of overlap P_r

These parameters are measures of ATC workload and overall safety levels. Parameters A_f^* and $\bar{A}_f^*$ are directly related to the probability of alarm P_A and the probability of "unfavorable" alarm $\bar{P}_A$. Thus, the performance parameters may be expressed as functions of P_r , P_A , and $\bar{P}_A$. Our primary concern is to develop appropriate mathematical expressions for these three quantities.

D3.1 Preliminary Considerations

Let us postulate a system in which all aircraft must be separated in at least one of the three dimensions (i.e., longitudinal, lateral, or vertical). We shall denote the magnitude of the nominal separation in each of these dimensions as S_x , S_y , and S_z respectively. Suppose that we stop time and examine the probability that any two aircraft will overlap in the r th dimension where r may take on any of the values x , y , or z . We shall denote the nominal separation in the r th dimension as S_r .

The situation is depicted in fig. D3. The probability density function of the aircraft track-keeping errors about the aircraft's intended track will be denoted $f(r)$ for aircraft No. 1 and $g(r)$ for aircraft No. 2. The point $r = 0$ will be taken as the center of symmetry for mathematical simplicity. The probability that aircraft No. 1 is centered between r and $r + dr$ is

$$f\left(r + \frac{S_r}{2}\right) dr$$

The probability of aircraft No. 2 overlapping aircraft No. 1 is

$$\int_{r-L}^{r+L} g\left(r - \frac{S_r}{2}\right) dr$$

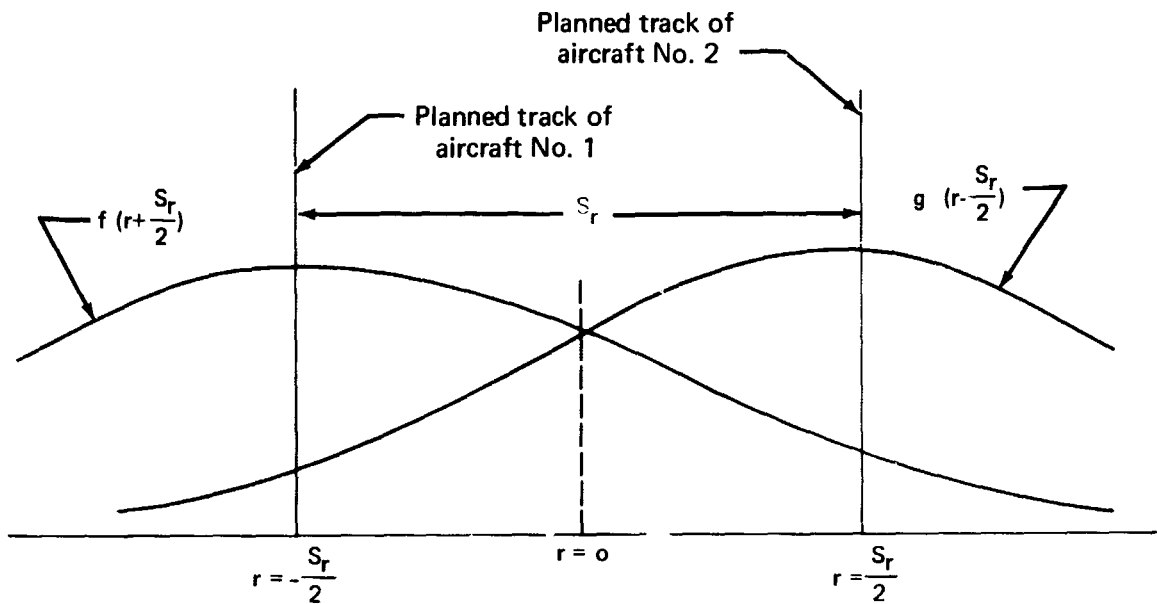


FIGURE D3.— PROBABILITY DISTRIBUTIONS OF AIRCRAFT POSITION ERRORS

$$\text{Where: } L = \frac{\lambda_1 + \lambda_2}{2}$$

λ_1 = physical size of aircraft No. 1 in the r th dimension

λ_2 = physical size of aircraft No. 2 in the r th dimension

The probability of an overlap occurring when aircraft No. 1 is between r and $r+dr$ is

$$f\left(r + \frac{S_r}{2}\right) dr \int_{r-L}^{r+L} g\left(\mu - \frac{S_r}{2}\right) d\mu$$

The total probability of overlap is

$$P_r = \int_{-\infty}^{\infty} f\left(r + \frac{S_r}{2}\right) \int_{r-L}^{r+L} g\left(\mu - \frac{S_r}{2}\right) d\mu dr \quad (D3)$$

A useful approximation to eq. (D3) may be made if we assume that second-order variations in $g(r)$ are small over the interval $r-L$ to $r+L$. With this assumption we have:

$$\int_{r-L}^{r+L} g\left(\mu - \frac{S_r}{2}\right) d\mu \approx 2L g\left(r - \frac{S_r}{2}\right)$$

Thus, eq. (D3) becomes

$$P_r \approx 2L \int_{-\infty}^{\infty} f\left(r + \frac{S_r}{2}\right) g\left(r - \frac{S_r}{2}\right) dr \quad (D4)$$

If the two aircraft are the same size (i.e., $\lambda_1 = \lambda_2 = \lambda_r$) and their track-keeping error distributions are the same [i.e., $f(r) = g(r)$], then eq. (D4) becomes:

$$P_r \approx 2\lambda_r \int_{-\infty}^{\infty} f\left(r + \frac{S_r}{2}\right) f\left(r - \frac{S_r}{2}\right) dr \quad (D5)$$

Equations (D3), (D4), and (D5) represent the probability of overlap between two aircraft in any of the three dimensions where S_x , S_y , and S_z are the nominal separations between the aircraft at a given instant in time. The terms $f(r)$ and $g(r)$ represent the probability density functions of the aircraft track-keeping errors. In extending this analysis to the problem of calculating overall collision rate for a system of aircraft, the time derivatives of S_x , S_y , and S_z must also be considered. For example, the probabilities indicated in eqs. (D3), (D4), and (D5) are valid for a single instant in time only. Since S_x , S_y , and S_z are functions of time in an actual system, the probability of overlap between any two aircraft must be considered over the entire time interval for which the two aircraft are close enough to contribute a significant collision risk. The collision risk for each pair of aircraft must then be summed over the entire region to provide the overall collision rate. Such a summation must take into consideration the type and number of aircraft in the system as well as the routes over which those aircraft will fly. The problem of calculating overall collision rate has been considered in Sec. D2.0 and will not be considered further here. The parameter that will be used in the following analysis as a measure of collision risk is the probability of overlap in the r th dimension (i.e. P_r).

D3.2 A Surveillance System

Suppose now that ATC uses a surveillance system to monitor the positions of all air traffic. An aircraft is allowed to navigate without interference using its own independent navigation system unless its position as determined by surveillance falls outside a distance $\pm r_0$ from its intended track. The occurrence of this situation will be denoted as an alarm (r_0 will be called the alarm threshold). If an alarm occurs, the aircraft will be directed to return to its intended track according to the position fix indicated by the surveillance system.

Consider fig. D4. Let us denote the probability density function for the aircraft track-keeping errors just before a surveillance fix as $f(r)$ and the probability density function for the surveillance system errors as $h(\mu)$. The random variable r represents the aircraft position relative to its intended track, and μ represents the aircraft position indicated by the surveillance system relative to the actual aircraft position. We will take the point $r = 0$ to be the aircraft's intended track.

The probability of an alarm at r , denoted as $P_a(r)$, is equal to the probability that μ will occur in the interval $r^2 \geq r_0^2$; thus

$$P_a(r) = \int_{-\infty}^{-(r+r_0)} h(\mu) d\mu + \int_{(r-r_0)}^{\infty} h(\mu) d\mu \quad (D6)$$

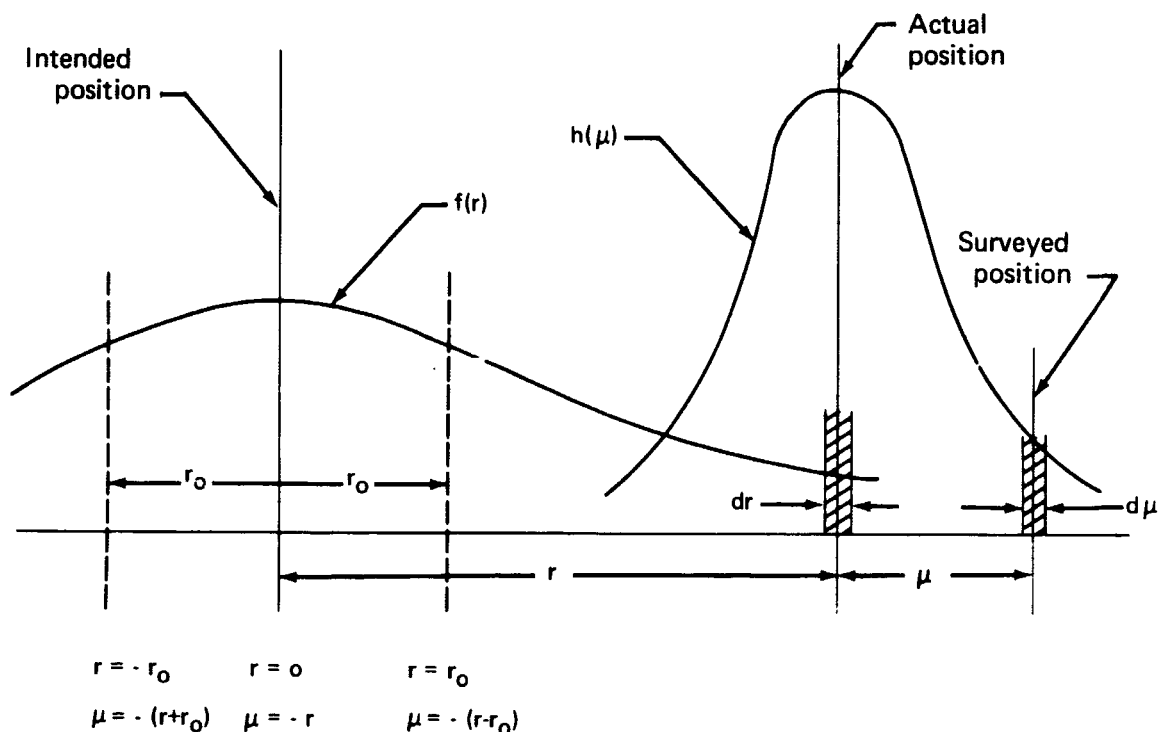


FIGURE D4.— ERROR DISTRIBUTIONS OF NAVIGATION AND SURVEILLANCE SYSTEMS

Conversely, the probability that an alarm will not occur at r , $P_a'(r)$, is

$$P_a'(r) = \int_{-(r+r_0)}^{-(r-r_0)} h(\mu) d\mu \quad (D7)$$

Notice that

$$P_a'(r) = 1 - P_a(r) \quad (D8)$$

The probability that an alarm will occur between r and $r+dr$ is equal to the probability of r between r and $r+dr$ times the probability of an alarm at r , or

$$P_a(r) f(r) dr$$

The overall probability of an alarm P_A is then

$$P_A = \int_{-\infty}^{\infty} P_a(r) f(r) dr \quad (D9)$$

where $P_a(r)$ is defined by eq. (D6).

Another parameter of considerable interest is the probability of an alarm that will cause the aircraft to move to a less favorable position (i.e., farther away from its intended track). We shall call this parameter $\bar{P}_A$ (probability of an unfavorable alarm). To find an expression for $\bar{P}_A$ we must first consider the various circumstances under which such a condition might arise.

D3.2.1 Case 1. — Consider the case in which the aircraft lies between $r = -\infty$ and $r = -r_0/2$. An alarm would move the aircraft to a less favorable position if the surveyed position falls in the interval $\mu = -\infty$ to $\mu = 2r$ or in the interval $\mu = -(r-r_0)$ to $\mu = \infty$. Thus,

$$\bar{P}_a(r) = \int_{-\infty}^{2r} h(\mu) d\mu + \int_{-(r-r_0)}^{\infty} h(\mu) d\mu \quad \text{where } -\infty \leq r \leq -\frac{r_0}{2} \quad (D10)$$

D3.2.2 Case 2. — In the interval $r = -\frac{r_0}{2}$ to $r = \frac{r_0}{2}$, an unfavorable alarm would occur for a surveyed position between $\mu = -\infty$ and $\mu = -(r+r_0)$ or between $\mu = -(r-r_0)$ and $\mu = \infty$. Thus

$$\bar{P}_a(r) = \int_{-\infty}^{-(r+r_0)} h(\mu) d\mu + \int_{-(r-r_0)}^{\infty} h(\mu) d\mu \quad \text{where } -\frac{r_0}{2} \leq r \leq \frac{r_0}{2} \quad (D11)$$

D3.2.3 Case 3. — In the interval $r = \frac{r_0}{2}$ to $r = \infty$, an unfavorable alarm would occur for a surveyed position between $\mu = -\infty$ and $\mu = -(r+r_0)$ or between $\mu = 2r$ and $\mu = \infty$. Thus,

$$\bar{P}_a(r) = \int_{-\infty}^{-(r+r_0)} h(\mu) d\mu + \int_{2r}^{\infty} h(\mu) d\mu \quad \text{where } \frac{r_0}{2} \leq r \leq \infty \quad (D12)$$

The probability of an unfavorable alarm occurring between r and $r+dr$ is

$$f(r) \bar{P}_a(r) dr$$

The overall probability of an unfavorable alarm is

$$\bar{P}_A = \int_{-\infty}^{\infty} f(r) \bar{P}_a(r) dr \quad (D13)$$

where $\bar{P}_a(r)$ is defined in piecewise fashion by eqs. (D10), (D11), and (D12).

Consider now a single instant in time after the surveillance fix. As before, assume that prior to the fix all aircraft were distributed according to $f(r)$ and that all aircraft which received an alarm have moved to their assigned positions. The system operates so that all aircraft receiving alarms are redistributed about their intended tracks according to the probability density function $h(r)$. All aircraft not receiving an alarm will be distributed about their intended tracks according to the probability density function

$$\frac{P_a'(r)}{1 - P_A} f(r) \quad (D14)$$

The probability density function of the aircraft position errors after the surveillance fix will be equal to the probability density function for the aircraft that received an alarm $h(r)$ times the fraction of aircraft receiving an alarm P_A plus the probability density function for the aircraft not receiving an alarm [eq. (D14)] times the fraction of aircraft not receiving an alarm $1 - P_A$. Thus the probability density function $F(r)$ after the surveillance fix is

$$F(r) = P_A h(r) + P_a'(r) f(r) \quad (D15)$$

It may be easily verified that this expression is an admissible probability density function in that

$$\int_{-\infty}^{\infty} F(r) dr = 1 \quad (D16)$$

Thus we have established a very useful result. Equation (D15) is an expression for the probability density function of the aircraft track-keeping errors after a surveillance fix as a function of the error distribution before the fix. Equations (D9) and (D13) respectively define the probability of an alarm and the probability of an "unfavorable" alarm.

D3.3 Steady-State Surveillance Equations

Although the equations developed in the previous section are very interesting, we would like to develop expressions for $F(r)$, P_A , and $\bar{P}_A$ when the system has reached a steady-state condition (i.e., after the surveillance system has been in operation for quite some time). The final solution will take into account the aircraft drift between successive surveillance fixes. This will best be accomplished by first examining the system for the situation in which we assume the aircraft do not drift between surveillance fixes.

Let us consider the surveillance system as an "operator" on the aircraft distribution function. Each time a surveillance fix is taken, some of the aircraft are removed from the tails of the distribution and redistributed about their intended tracks according to $h(r)$. This section will develop an expression for the probability density function of the aircraft track-keeping errors under steady-state conditions in the absence of aircraft drift.

Immediately before the first surveillance fix we shall assume that the aircraft are distributed according to $f(r)$, where $f(r)$ now represents the probability density function of the aircraft track-keeping errors in the absence of surveillance. The following parameters are defined: P_{A1} is the probability of alarm for the n th surveillance fix and $F_n(r)$ is the probability density function of the aircraft track-keeping errors after the n th surveillance fix.

For the first surveillance fix we have, . . . eq. (D9),

$$P_{A1} = \int_{-\infty}^{\infty} P_a(r) f(r) dr \quad (D17)$$

Let us abbreviate P_{A1} as P_A . From eq. (D15) we may write

$$F_1(r) = P_A h(r) + P_a'(r) f(r) \quad (D18)$$

For the second surveillance fix we notice that $P_a(r)$ and $P_a'(r)$ [eqs. (D6) and (D7)] remain unchanged regardless of the n and, therefore, eq. (D9) becomes

$$P_{A2} = \int_{-\infty}^{\infty} P_a(r) F_1(r) dr \quad (D19)$$

or

$$P_{A2} = P_A \int_{-\infty}^{\infty} P_a(r) h(r) dr + \int_{-\infty}^{\infty} P_a(r) P_a'(r) f(r) dr \quad (D20)$$

Substituting eq. (D8) into this expression yields

$$P_{A2} = P_A \int_{-\infty}^{\infty} P_a(r) h(r) dr + \int_{-\infty}^{\infty} P_a(r) f(r) dr - \int_{-\infty}^{\infty} P_a^2(r) f(r) dr \quad (D21)$$

Digressing briefly, let us examine the function $P_a(r)$ shown, qualitatively, in fig. D5. Ideally we would like this function to be a step function having a value of zero within a distance $\pm r_0$ of intended track and a value of one outside these limits. $P_a(r)$ approaches this ideal function as the variance of $h(\mu)$ becomes small. More precisely we may state that the shape of $P_a(r)$ approaches a step function as the ratio r_0/σ_μ becomes large, where σ_μ is the standard deviation of $h(\mu)$. Thus it would appear that a highly accurate surveillance system is desirable. If this is the case and $P_a(r)$ may indeed be approximated by a unit step function, then $P_a^2(r)$ approaches this same function and eq. (D21) becomes

$$P_{A2} \approx P_A \int_{-\infty}^{\infty} P_a(r) h(r) dr \quad (D22)$$

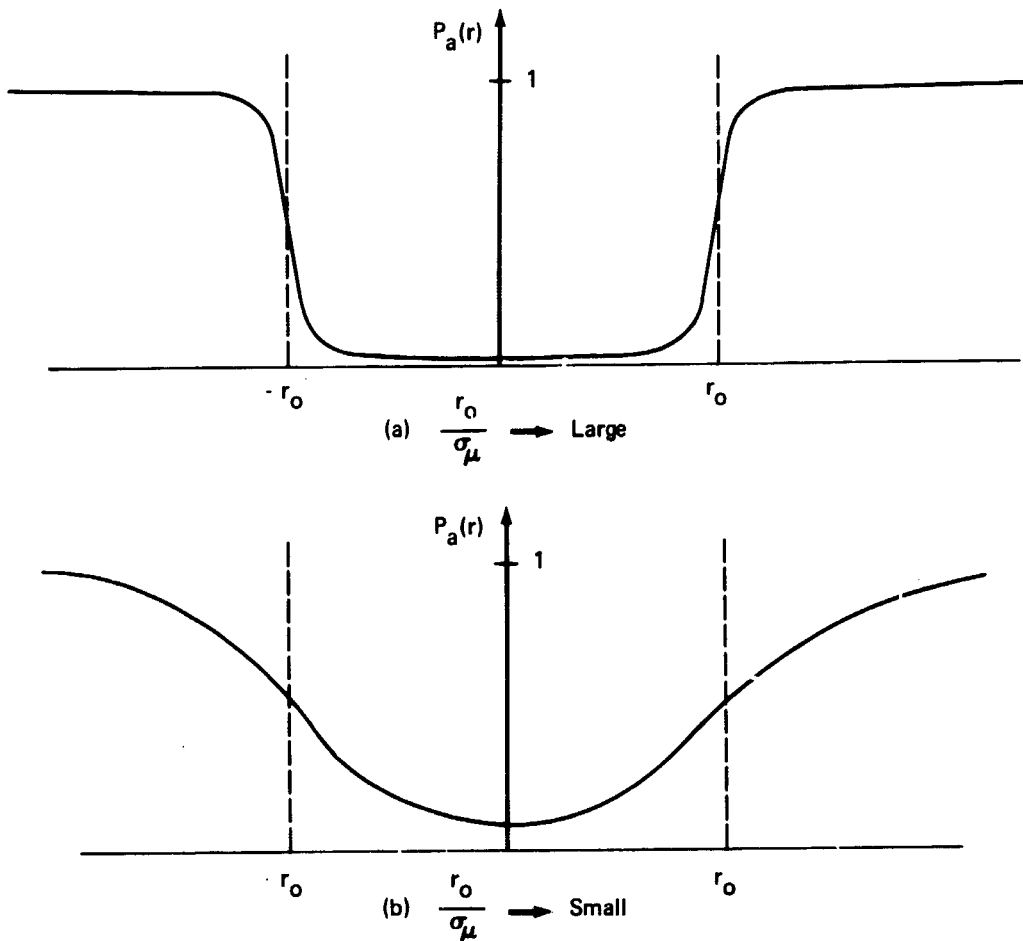


FIGURE D5.— $P_a(r)$ VERSUS r_0/σ_μ

For a reasonably designed surveillance system it is obvious that

$$\int_{-\infty}^{\infty} P_a(r) h(r) dr \leq \int_{-\infty}^{\infty} P_a(r) f(r) dr \equiv P_A \quad (D23)$$

and thus eq. (D22) becomes

$$P_{A2} \leq P_A^2 \quad (D24)$$

As a pessimistic estimate for P_{A2} we shall assume

$$P_{A2} = P_A^2 \quad (D25)$$

Now, according to eq. (D15), we may write

$$F_2(r) = P_{A2} h(r) + P_a'(r) F_1(r) \quad (D26)$$

However, noting our approximation for P_{A2} [eq. (D25)] and substituting eq. (D18) for $F_1(r)$, we obtain

$$F_2(r) \approx P_A^2 h(r) + P_A P_a'(r) h(r) + P_a'(r)^2 f(r) \quad (D27)$$

If we repeat this line of reasoning using the same approximations, it may be ultimately shown that

$$\begin{aligned} F_n(r) \approx & P_A^n h(r) + P_A^{n-1} P_a'(r) h(r) + P_A^{n-2} P_a'(r)^2 h(r) \\ & + \dots + P_A^i P_a'(r)^{n-i} h(r) + \dots + P_A P_a'(r)^{n-1} h(r) \\ & + P_a'(r)^n f(r) \end{aligned} \quad (D28)$$

The relative shapes of the various functions appearing in eq. (D28) are sketched in fig. D6. The effect of the surveillance system upon the aircraft track-keeping errors is to remove aircraft from the tails of $f(r)$ and redistribute them about their intended tracks according to $h(r)$. The terms $F_n(r)$ and $f(r)$ are shown comparatively in fig. D6(d).

Returning to eq. (D28), we notice that $F_n(r)$ approaches zero for $r^2 \geq r_0^2$ as n becomes large. In addition, if $P_A \ll 1$ and if $P_a'(r)$ approaches a unit step function, then $F_n(r)$ approaches zero for $r^2 \geq r_0^2$ even for small values of n , and $F_n(r)$ is approximated by $f(r)$ for $r^2 \leq r_0^2$.

With these assumptions we may write:

$$\begin{aligned} F_n(r) &\approx C f(r) & r^2 &\leq r_0^2 \\ F_n(r) &\approx 0 & r^2 &> r_0^2 \end{aligned} \quad (D29)$$

where C is defined such that

$$C \int_{-r_0}^{r_0} f(r) dr \equiv 1 \quad (D30)$$

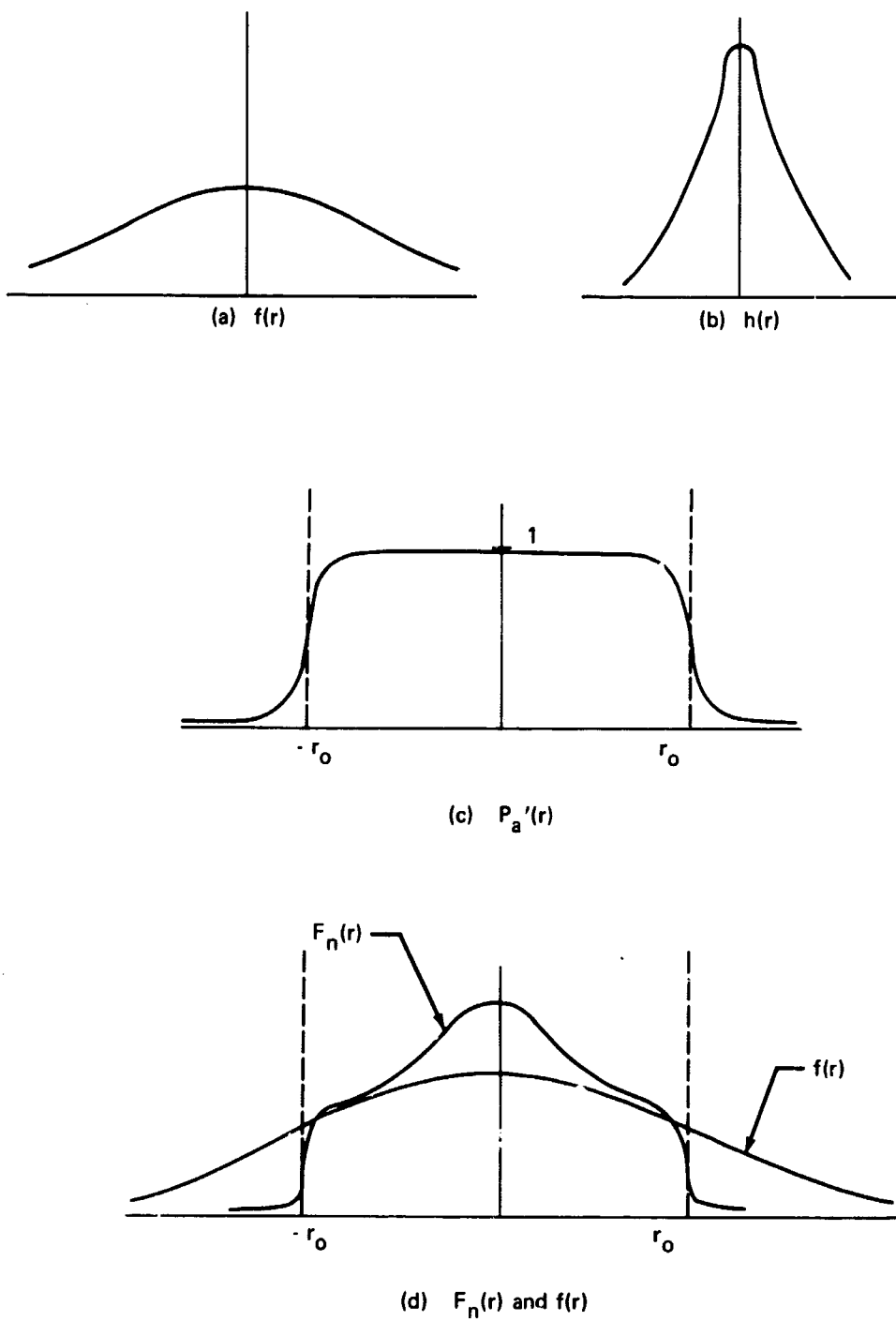


FIGURE D6.— COMPARATIVE SHAPES OF VARIOUS FUNCTIONS

D3.4 Aircraft Drift

We are now in a position to consider the case in which the aircraft are allowed to drift between successive surveillance fixes. If we can assume that the relationships in eq. (D29) are true in the absence of drift for small n (say $n = 1$ or 2), then it seems reasonable to assume that immediately after a surveillance fix, the relationships in eq. (D29) are still approximately true even though the aircraft are allowed to drift about between surveillance fixes. Let the time interval between successive surveillance fixes be denoted by t_0 . Since the aircraft are assumed to drift between surveillance fixes, the distribution of the aircraft track-keeping errors will be a function of time and the aircraft will, in general, be at their most unfavorable positions at the end of time interval t_0 . The next surveillance fix will then return the system to the state described by eq. (D29). To provide a pessimistic estimate for P_r , we will calculate P_r , P_A , and $\bar{P}_A$ at the end of time interval t_0 . To accomplish this, we must first find the steady-state probability density function of the aircraft track-keeping errors $F(r)$ at the end of this same time interval t_0 .

Let the probability density function for the aircraft drift errors at the end of time t_0 be denoted by $G(r)$. The standard deviation of $G(r)$ will be $\sigma_r t_0$, where σ_r is the standard deviation of the aircraft drift rate. The probability density function for the aircraft position errors excluding aircraft drift will be $F_n(r)$ defined by eq. (D29). The combined probability density function at the end of time t_0 will simply be the convolution of these two distributions, or

$$F(r) = \int_{-\infty}^{\infty} F_n(s) G(r-s) ds \quad (D31)$$

or equivalently

$$F(r) = \int_{-\infty}^{\infty} G(s) F_n(r-s) ds \quad (D32)$$

Expressions for P_r , P_A , and $\bar{P}_A$ may now be written directly from eqs. (D5), (D9), and (D13) as

$$P_r = 2 \lambda_r \int_{-\infty}^{\infty} F(r - \frac{S_r}{2}) F(r + \frac{S_r}{2}) dr \quad (D33)$$

$$P_A = \int_{-\infty}^{\infty} F(r) P_a(r) dr \approx 2 \int_{r_0}^{\infty} F(r) dr \quad (D34)$$

$$\bar{P}_A = \int_{-\infty}^{\infty} F(r) \bar{P}_a(r) dr \quad (D35)$$

Where $F(r)$ is defined by eqs. (D31) or (D32) and $P_a(r)$ and $\bar{P}_a(r)$ are defined by eqs. (D6), (D10), (D11), and (D12).

Remember that the conditions under which the above equations are valid are

$$P_A \ll 1 \quad (D36)$$

and

$$\frac{r_0}{\sigma_\mu} \rightarrow \text{large}$$

*The latter expression is derived as eq. (D50).

In words, we may state these conditions as

- (1) The probability of alarm for any given surveillance fix must be small. For definiteness let us state:

$$P_A \leq 10^{-2} \quad (D37)$$

- (2) The errors associated with the surveillance system must be small compared to the alarm threshold. For definiteness let us state:

$$\frac{r_0}{\sigma_\mu} \geq 10 \quad (D38)$$

Given $f(r)$, $h(\mu)$, and $G(r)$ and the assumptions of eqs. (D37) and (D38), we are now in a position to calculate $F(r)$, P_A , $\bar{P}_A$, and P_T using eqs. (D31) through (D35).

D3.5 Applications

D3.5.1 The assumed probability density functions.— Before proceeding further we must make some assumption about the probability density function of the aircraft track-keeping errors and the surveillance errors. Historically, the Gaussian distribution has been used to describe these errors. The data from many measurements taken over the past few years indicate that, although the Gaussian distribution agrees quite closely with experimental data within two to three standard deviations of the mean, the tails of the distribution contain 20 to 100 times as many aircraft as would be predicted by the Gaussian curve. Since the probability of overlap in a dimension where the nominal separation is being enforced is very sensitive to the tails of the distribution function, the Gaussian assumption tends to yield highly optimistic estimates of collision risk.

Two basic causes for the relatively large number of aircraft appearing in the tails of the experimentally derived distribution functions are: (1) equipment failures and (2) human errors. Such sources of error have been termed "blunders." Human error appears to be an unusually prolific source of blunders with the navigation equipment used extensively over the North Atlantic today.

The tails of the experimentally derived distribution functions strongly suggest the exponential probability density function. Also, consider that future navigation systems (nav/sat, inertial, etc.) will probably eliminate many of the human and equipment blunders occurring today, because the new systems will have higher levels of automation and higher reliability with solid-state microminiaturized equipment. In view of the above statements it is believed that an accuracy specification for a future surveillance system should be determined using the assumption that the tails of the error distribution for such a system will not be worse than exponential.

Thus, a reasonable assumption for $f(r)$ and $h(\mu)$ would be a probability density function that is Gaussian shaped within two or three standard deviations of the mean and

exponential beyond this limit. Such a distribution would be mathematically unwieldy, however, and so we shall approximate this distribution by the first Laplacian distribution: that is,

$$f(r) = \frac{1}{\sqrt{2} \sigma_r} e^{-\sqrt{2} |\mu_r - r| / \sigma_r} \quad (D39)$$

This function assumes that both the body and the tails are exponentially distributed. The distribution provides an excellent compromise because:

- (1) It is a mathematically tractable function
- (2) Its cumulative distribution approximates the Gaussian distribution between 1.5 and 2 standard deviations of the mean (see table D1)
- (3) The tails of the distribution are exponentially distributed

TABLE D1.— GAUSSIAN AND EXPONENTIAL CUMULATIVE DISTRIBUTION FUNCTIONS

r/σ_r	Gaussian	Exponential
0.5	0.691	0.753
1.0	0.841	0.877
1.5	0.933	0.940
2.0	0.977	0.970
2.5	0.994	0.984
3.0	0.999	0.993

For reasons stated in the preceeding paragraphs we shall choose the probability density function for the aircraft navigation errors to be

$$f(r) = \frac{1}{\sqrt{2} \sigma_r} e^{-\frac{\sqrt{2}}{\sigma_r} |r|} \quad (D40)$$

and likewise the probability density function for the surveillance system errors will be

$$h(\mu) = \frac{1}{\sqrt{2} \sigma_r t_o} e^{-\frac{\sqrt{2}}{\sigma_r t_o} |\mu|} \quad (D41)$$

In addition to these two distributions we must make an assumption on the distribution of the aircraft drift errors, that is, $G(r)$. We will not attempt to justify a

particular distribution for $G(r)$, but in the absence of better information will arbitrarily choose

$$G(r) = \frac{1}{\sqrt{2} \sigma_r t_0} e^{-\frac{\sqrt{2}}{\sigma_r t_0} |r|} \quad (D42)$$

since this function is relatively easy to integrate.

The application of the model in the following section is valid for any dimension insofar as eqs. (D40), (D41), and (D42) are valid. Since the observations that allowed us to assume an exponential distribution function were based upon measurements of track-keeping errors in the lateral dimension, our discussion of the results will be limited to separation in the lateral dimension.

D3.5.2 Application of the model.— The remaining task is to evaluate eqs. (D31) through (D35) for the assumed probability density functions of eqs. (D40), (D41), and (D42). The following discussion evaluates these equations one at a time and examines each to see if there are any simplifying assumptions that may be made.

The steady-state probability density function: The probability density function for the aircraft track-keeping errors at the end of time interval t_0 is given by eq. (D31) as

$$F(r) = \int_{-\infty}^{\infty} F_n(s) G(r-s) ds \quad (D43)$$

where, from eqs. (D29), (D40), and (D42):

$$F_n(s) = \frac{C}{\sqrt{2} \sigma_r} e^{-\frac{\sqrt{2}}{\sigma_r} |s|} \quad s^2 \leq r_0^2$$

$$F_n(s) = 0 \quad s^2 > r_0^2 \quad (D44)$$

$$G(r-s) = \frac{1}{\sqrt{2} \sigma_r t_0} e^{-\frac{\sqrt{2}}{\sigma_r t_0} |r-s|} \quad (D45)$$

The convolution of eqs. (D44) and (D45), as indicated by eq. (D43), is evaluated with the following result:

$$F(r) = \frac{CKK'}{4} \left[\begin{array}{cccc} -K'r & -Kr & -(K+K') r_0 & -K'r \\ K_a e & + K_b e & - K_c e & - K_c e \end{array} \right] \quad 0 \leq r \leq r_0$$

$$F(r) = \frac{CKK'}{4} \left[\begin{array}{cccc} -K'r & -(K+K') r_0 & -K'r & -(K-K') r_0 \\ K_a e & - K_c e & - K_d e & - K'r \end{array} \right] \quad r \geq r_0 \quad (D46)$$

Where:

$$\begin{aligned}
 K &= \frac{\sqrt{2}}{\sigma_r} \\
 K' &= \frac{\sqrt{2}}{\sigma_i t_o} \\
 C &= \frac{1}{1 - e^{-Kr_o}} \\
 K_a &= \frac{1}{K+K} + \frac{1}{K-K'} \\
 K_b &= \frac{1}{K+K'} - \frac{1}{K-K'} \\
 K_c &= \frac{1}{K+K'} \\
 K_d &= \frac{1}{K-K'} \tag{D47}
 \end{aligned}$$

Probability of Alarm:

Combining eqs. (D6) and (D34), the probability of alarm becomes:

$$P_A = \int_{-\infty}^{\infty} F(r) \left[\int_{-\infty}^{-(r+r_o)} h(\mu) d\mu + \int_{-(r-r_o)}^{\infty} h(\mu) d\mu \right] dr \tag{D48}$$

where $h(\mu)$ is defined by eq. (D41) and $F(r)$ is defined by eqs. (D46) and (D47). Equation (D48) is evaluated to yield

$$\begin{aligned}
 P_A &= \frac{CKK'}{4} \left[\left(\frac{K_d - K_c}{K' + K''} - \frac{K_b}{K'K''} - \frac{2K_d}{K'} \right) e^{-Kr_o} + \right. \\
 &\quad \left(\frac{2K_a}{K'} - \frac{K_a}{K' + K''} - \frac{K_a}{K' - K''} \right) e^{-K'r_o} + \\
 &\quad \left(\frac{K_a}{K' + K''} + \frac{K_b}{K + K''} + \frac{K_a}{K' - K''} - \frac{K_b}{K - K''} \right) e^{-K''r_o} + \\
 &\quad \left(\frac{K_c}{K'' - K} - \frac{K_b}{K + K''} - \frac{K_d}{K' + K''} \right) e^{-(K+2K'')r_o} + \\
 &\quad \left. \left(\frac{K_c}{K' + K''} + \frac{K_c}{K' - K''} - \frac{2K_c}{K'} \right) e^{-(K+2K')r_o} \right] \tag{D49}
 \end{aligned}$$

where $K'' = \frac{\sqrt{2}}{\sigma_\mu}$.

This expression yields larger than expected values of P_A for small values of the parameter $\sigma_r t_o$. This is because the approximation for $F_n(r)$, eq. (D29), does not accurately describe the shape of the actual distribution in the immediate vicinity of the alarm threshold. The resulting error in P_A is not serious, however, except for small values of $\sigma_r t_o$. In order to estimate P_A for small $\sigma_r t_o$ we may assume that P_A is approximately equal to the fraction of aircraft that drift beyond the limits of the steady-state probability density function $F_n(r)$ during the update interval t_o . For the $F_n(r)$ given by eq. (D29) this would simply be

$$P_A \approx 2 \int_{r_o}^{\infty} F(r) dr \quad (D50)$$

Equation (D50) is evaluated with the following result:

$$P_A \approx \frac{CK}{2} \left[K_a e^{-K' r_o} - K_c e^{-(K+2K') r_o} - K_d e^{-K r_o} \right] \quad (D51)$$

For small values of $\sigma_r t_o$, eq. (D51) provides an excellent approximation for P_A . For large values of $\sigma_r t_o$ eqs. (D49) and (D51) yield quite similar results.

Probability of an unfavorable alarm: The probability of an unfavorable alarm is defined by eq. (D35) as

$$\bar{P}_A = \int_{-\infty}^{\infty} \bar{P}_a(r) F(r) dr \quad (D52)$$

where $F(r)$ is given by eqs. (D46) and (D47) and $\bar{P}_a(r)$ is given by eqs. (D10), (D11), and (D12). Equation (D52) is evaluated with the following result:

$$\begin{aligned}
\bar{P}_A = & \frac{CKK'}{4} \left[\left(\frac{K_a + K_b}{K' + K''} + \frac{K_a + K_b}{K' - K''} \right) e^{-K'' r_0} + \right. \\
& \left(-\frac{K_b}{K + K''} + \frac{K_c}{K'' - K'} - \frac{K_b}{K + 2K''} - \frac{K_d}{K' + K''} - \frac{K_d}{K' + 2K''} \right) e^{-(K + 2K'') r_0} + \\
& \left(-\frac{K_c}{K' + K''} - \frac{K_c}{K'' - K'} \right) e^{-(K + \frac{K'}{2} + \frac{K''}{2}) r_0} + \\
& \frac{K_a}{K' + K''} \left(e^{-(K' + \frac{3K''}{2}) r_0} - e^{-(\frac{K'}{2} + \frac{3K''}{2}) r_0} \right) + \\
& \frac{K_b}{K + K''} \left(e^{-(K + \frac{3K''}{2}) r_0} - e^{-(\frac{K}{2} + \frac{3K''}{2}) r_0} \right) + \\
& \frac{K_c}{K'' - K'} \left(e^{-(K + K'') r_0} - e^{-(K + \frac{3K'}{2} + \frac{K''}{2}) r_0} \right) + \\
& \frac{1}{K' + 2K''} \left(K_a e^{-(\frac{K'}{2} + K'') r_0} + K_b e^{-(\frac{K}{2} + K'') r_0} - K_c e^{-(K - \frac{3K'}{2} - K'') r_0} \right) + \\
& \left. \frac{1}{K' - K''} \left(-K_a e^{-(\frac{K'}{2} + \frac{K''}{2}) r_0} - K_b e^{-(\frac{K}{2} + \frac{K''}{2}) r_0} \right) \right] \quad (D53)
\end{aligned}$$

where $K'' = \sqrt{\frac{2}{\sigma_\mu}}$

Probability of overlap: The probability of overlap is given by eq. (D33)

$$P_r = 2 \lambda_r \int_{-\infty}^{\infty} F\left(r - \frac{S_r}{2}\right) F\left(r + \frac{S_r}{2}\right) dr \quad (D54)$$

If we substitute eq. (D46) for $F(r)$ into eq. (D54), the resulting expression becomes unmanageable; thus, a simplifying approximation for $F(r)$ is in order. Suppose we let $F_n(r)$ [eq. (D44)] be approximated by a uniform distribution between $\pm r_0$. This would provide a much simpler form for $F(r)$ and would yield a more conservative estimate for P_r . Thus, in the interest of simplicity, eqs. (D44) and (D45) become

$$\begin{aligned}
F_n(s) &\approx \frac{1}{2r_0} & s^2 &\leq r_0^2 \\
F_n(s) &= 0 & s^2 &> r_0^2
\end{aligned} \tag{D55}$$

$$G(r-s) = \frac{K'}{2} e^{-K'|r-s|} \tag{D56}$$

F(r) now becomes, from eq. (D43),

$$F(r) = \int_{-r_0}^{r_0} \frac{K'}{4r_0} e^{-K'|r-s|} ds \tag{D57}$$

Equation (D57) is evaluated with the following result:

$$\begin{aligned}
F(r) &= \frac{1}{4r_0} \left(2 - e^{-K'(r_0+r)} - e^{-K'(r_0-r)} \right) & 0 \leq r \leq r_0 \\
F(r) &= \frac{1}{4r_0} e^{-K'r} \left(e^{K'r_0} - e^{-K'r_0} \right) & r > r_0
\end{aligned} \tag{D58}$$

If $K'r_0 > 2$, eq. (D58) becomes

$$\begin{aligned}
F(r) &= \frac{1}{4r_0} \left(2 - e^{-K'(r_0+r)} - e^{-K'(r_0-r)} \right) & 0 \leq r \leq r_0 \\
F(r) &\approx \frac{1}{4r_0} e^{-K'(r-r_0)} & r > r_0
\end{aligned} \tag{D59}$$

Using this expression for F(r), eq. (D54) is evaluated with the following result:

$$\begin{aligned}
P_r &= \frac{\lambda_r}{4r_0^2} \left[\left(\frac{S_r}{2} - r_0 - \frac{3}{2K'} \right) e^{-K'(S_r-2r_0)} \right. \\
&\quad \left. + \frac{1}{2K'} e^{-K'(S_r+2r_0)} - \left(2r_0 + \frac{3}{2K'} \right) e^{-K'S_r} \right] \tag{D60}
\end{aligned}$$

where it is implicitly assumed that $r_0 \leq \frac{S_r}{2}$.

D3.5.3 Results. – For reference, all the parameters that will be used in presenting the results of this analysis are defined as follows:

- A_r = alarm rate
- $\bar{A}_r$ = “unfavorable” alarm rate
- λ_r = aircraft wingspan
- N = number of aircraft using the system
- P_A = probability of alarm
- $\bar{P}_A$ = probability of “unfavorable” alarm
- $\bar{P}_A/P_A$ = number of unfavorable alarms per alarm
- P_r = probability of overlap
- r_O = alarm threshold
- S_r = separation standard
- σ_r = standard deviation of aircraft navigation errors in the absence of surveillance
- σ_r = standard deviation of the aircraft drift rate
- σ_μ = standard deviation of the surveillance errors
- t_O = update interval (time between successive surveillance fixes per aircraft)

In presenting the results we have replaced the parameters P_A and $\bar{P}_A$ with two more meaningful terms: (1) the alarm rate, A_r , and (2) the ratio of unfavorable alarms to total alarms. The latter parameter is simply equal to $\bar{P}_A/P_A$. The alarm rate is defined as follows:

$$A_r = \frac{NP_A}{t_O} = \frac{\text{alarms}}{\text{unit time}} \quad (D61)$$

Likewise, the unfavorable alarm rate is

$$\bar{A}_r = \frac{N\bar{P}_A}{t_O} = \frac{\bar{P}_A}{P_A} A_r \quad (D62)$$

The equations for P_A , $\bar{P}_A$, and P_r developed in Sec. D3.5.2 along with the expression for A_r (presented above) were evaluated parametrically on a digital computer. The results are presented in graphical form in figs. D7 through D27. These curves may be used in a variety of ways to perform tradeoffs between the various parameters. The applicable curves are reproduced in Sec. 4.3.2 of this volume and were used in the specification of the ATC surveillance system requirements.

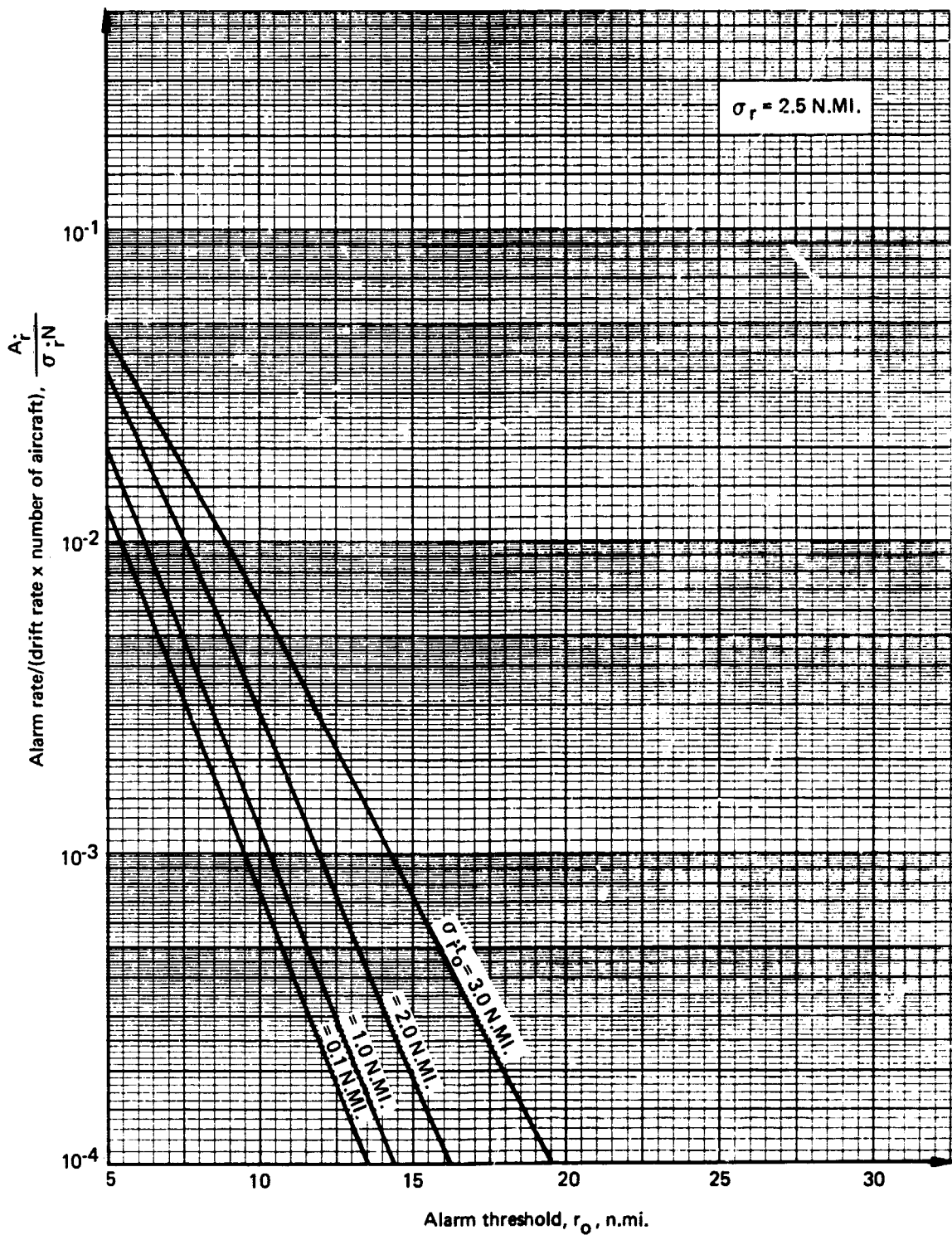


Figure D7.— SURVEILLANCE SYSTEM TRADEOFFS—ALARM THRESHOLD ($\sigma_r = 2.5$)

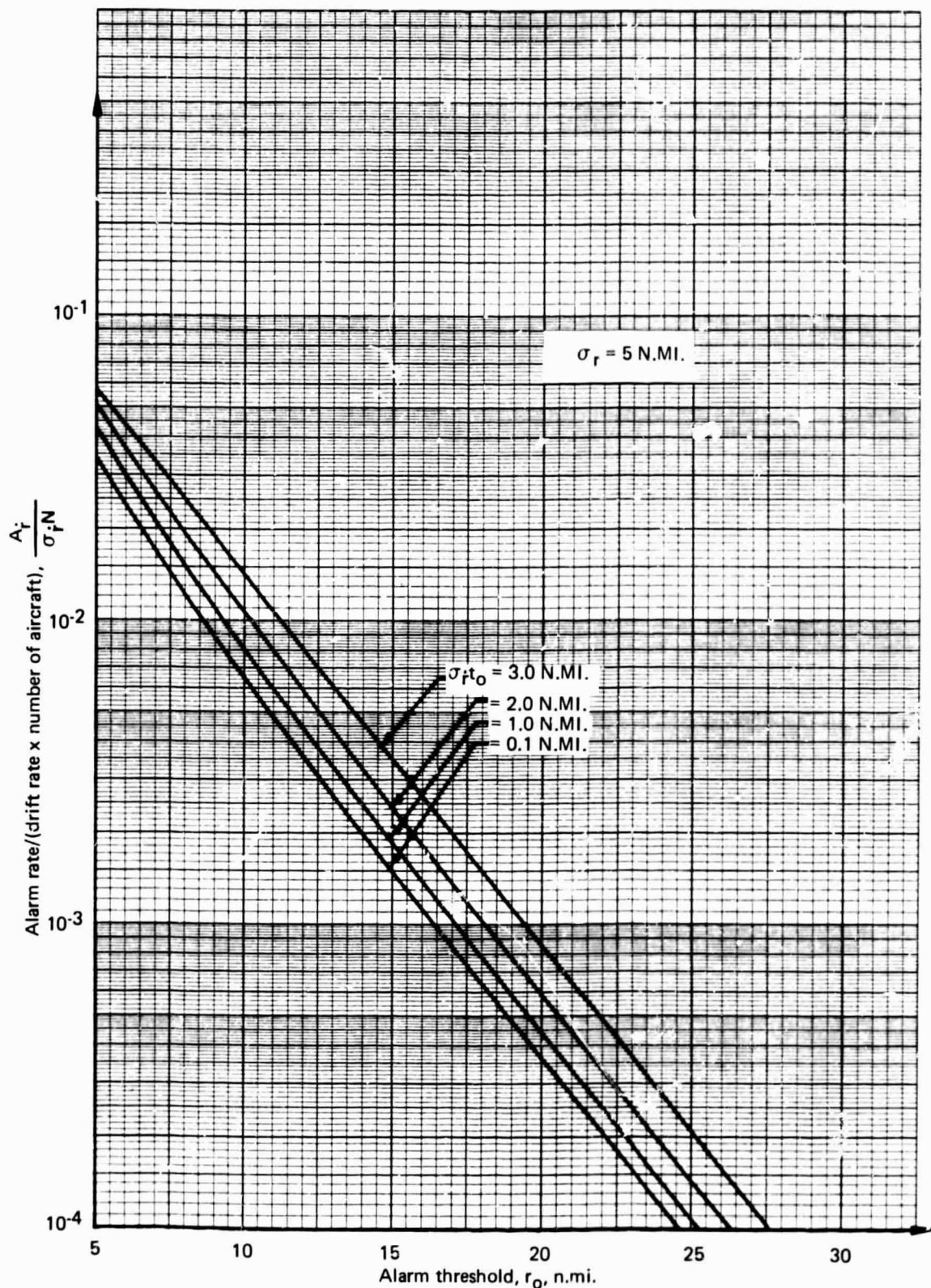


Figure D8.— SURVEILLANCE SYSTEM TRADEOFFS—ALARM THRESHOLD ($\sigma_r = 5$)

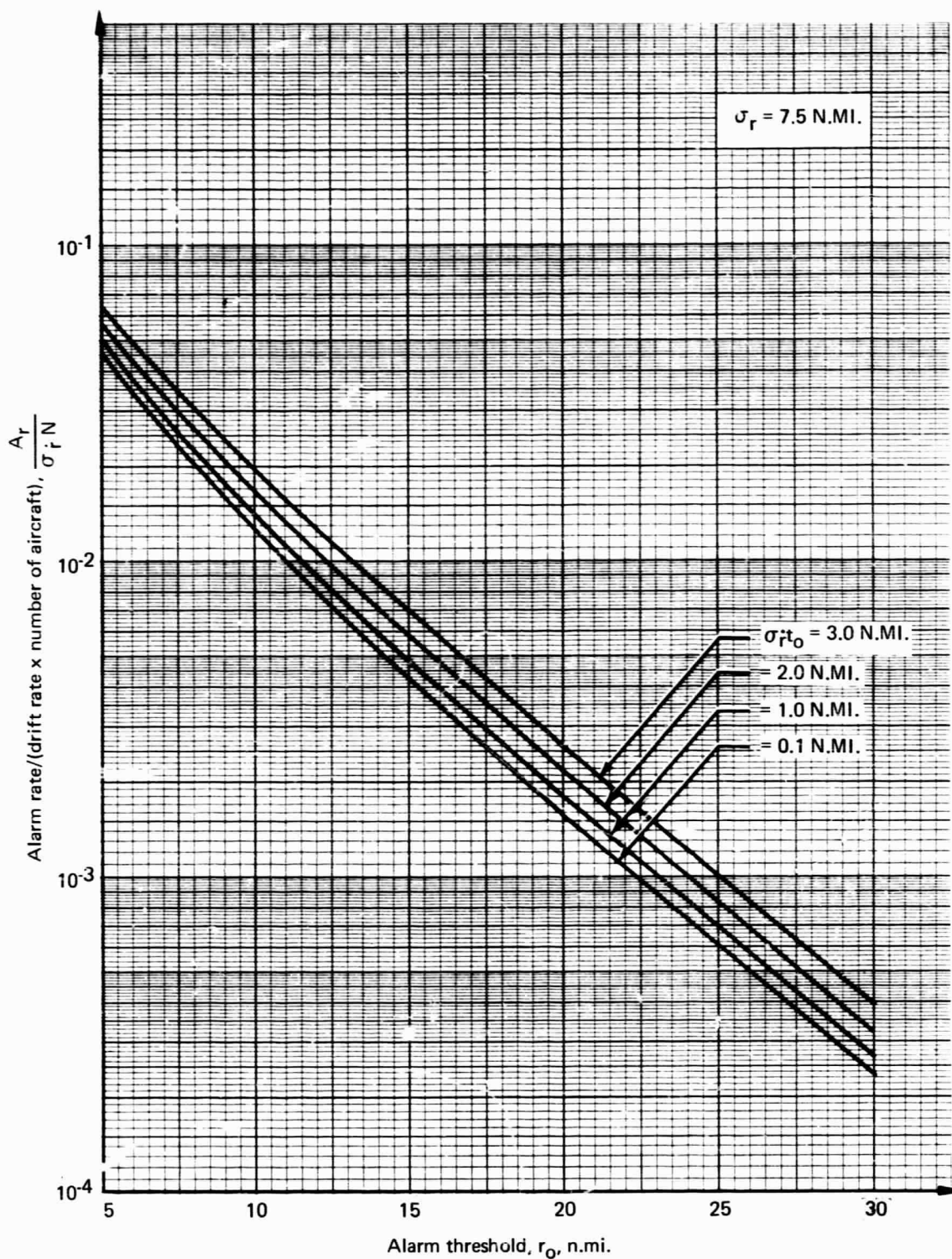


Figure D9. – SURVEILLANCE SYSTEM TRADEOFFS–ALARM THRESHOLD ($\sigma_r = 7.5$)

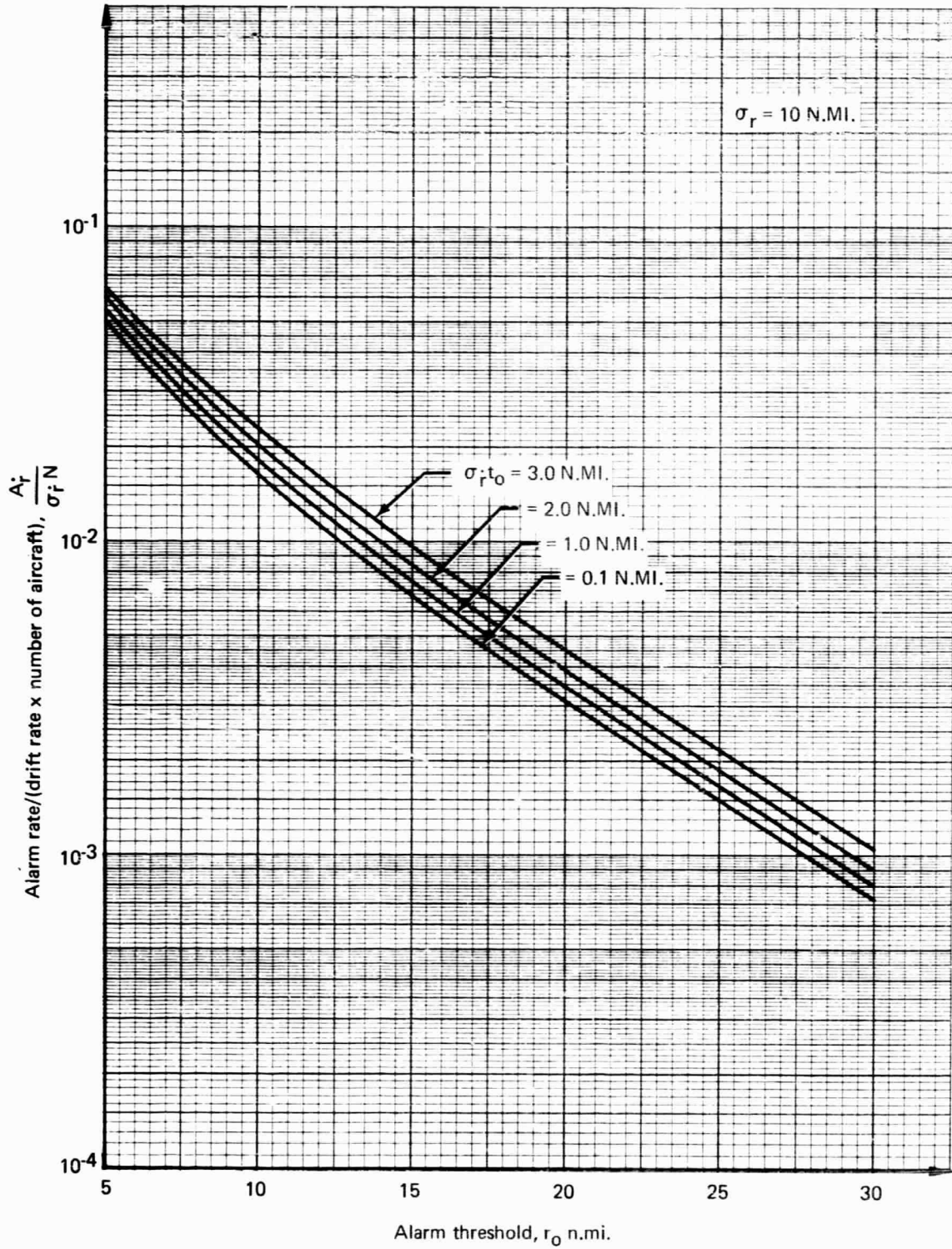


Figure D10.— SURVEILLANCE SYSTEM TRADEOFFS—ALARM THRESHOLD ($\sigma_r = 10$)

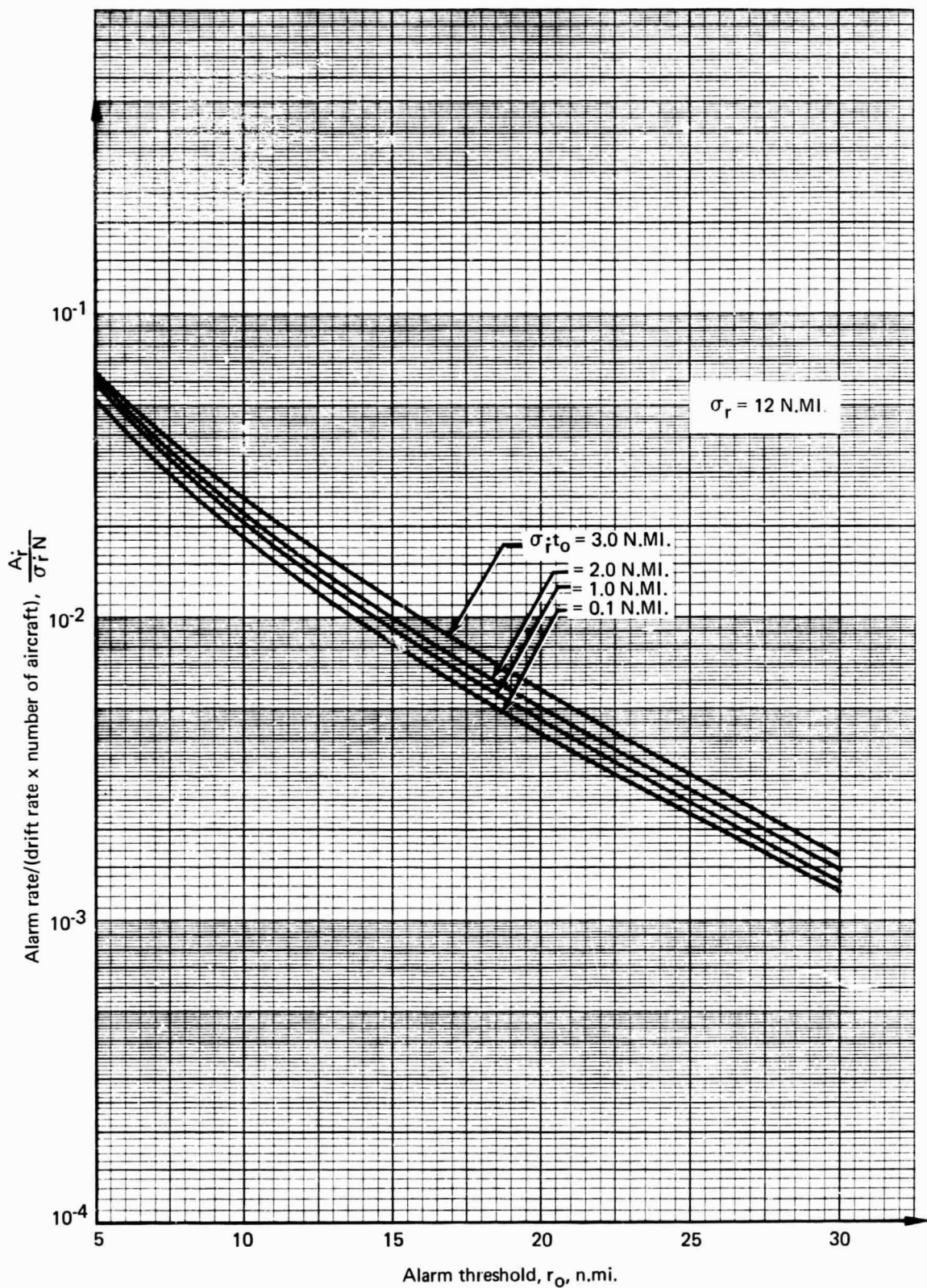


Figure D11.— SURVEILLANCE SYSTEM TRADEOFFS—ALARM THRESHOLD ($\sigma_r = 12$)

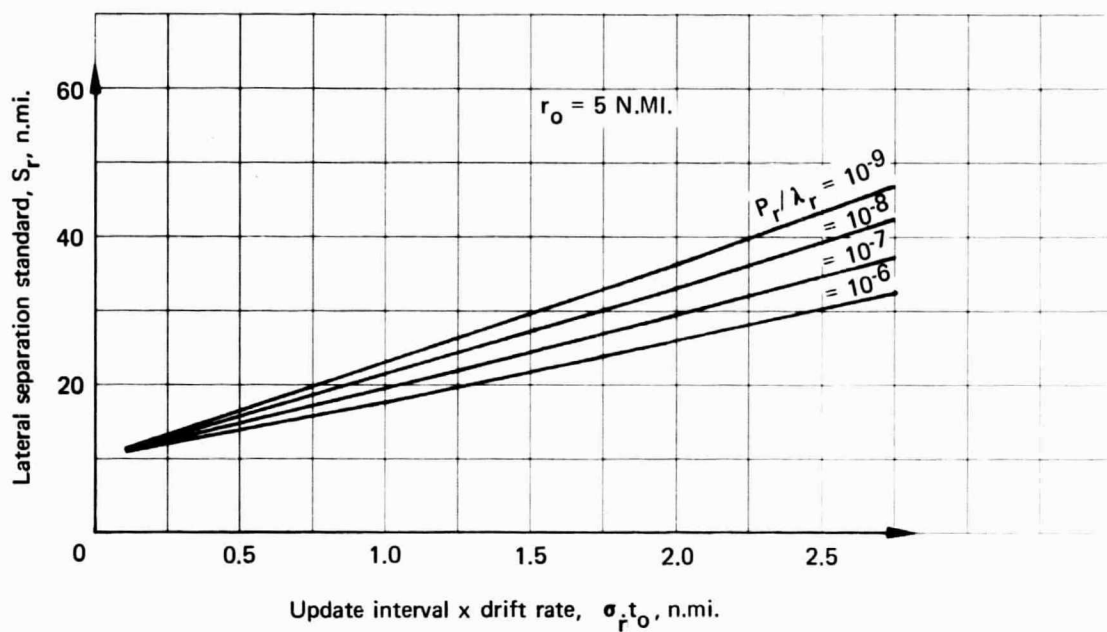


Figure D12.— SURVEILLANCE SYSTEM TRADEOFFS—UPDATE INTERVALS $\times$ DRIFT RATE ($r_o = 5$)

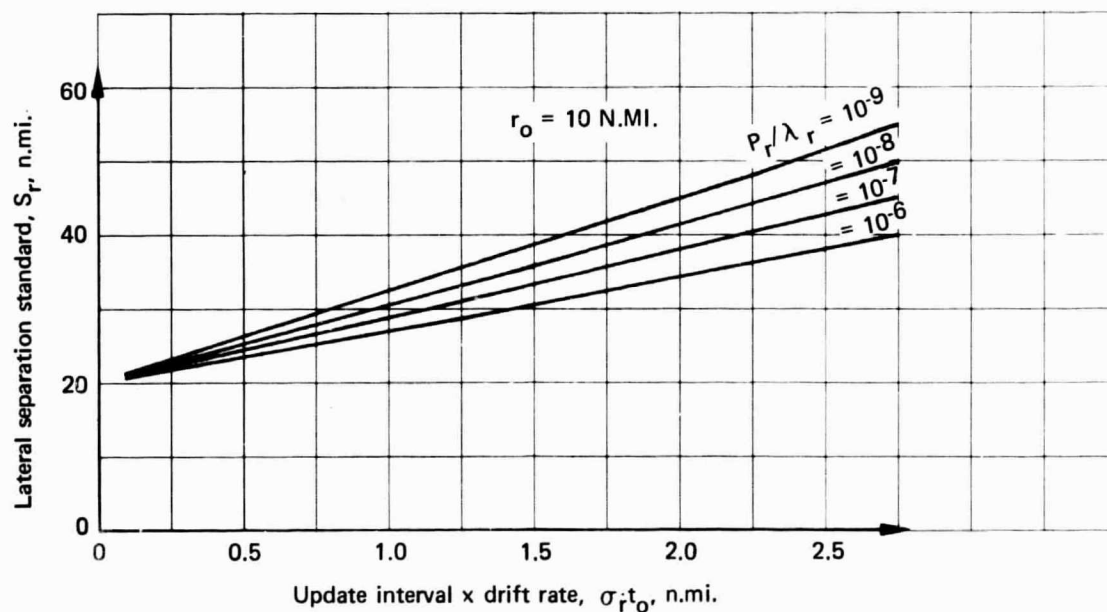


Figure D13.— SURVEILLANCE SYSTEM TRADEOFFS—UPDATE INTERVALS $\times$ DRIFT RATE ($r_o = 10$)

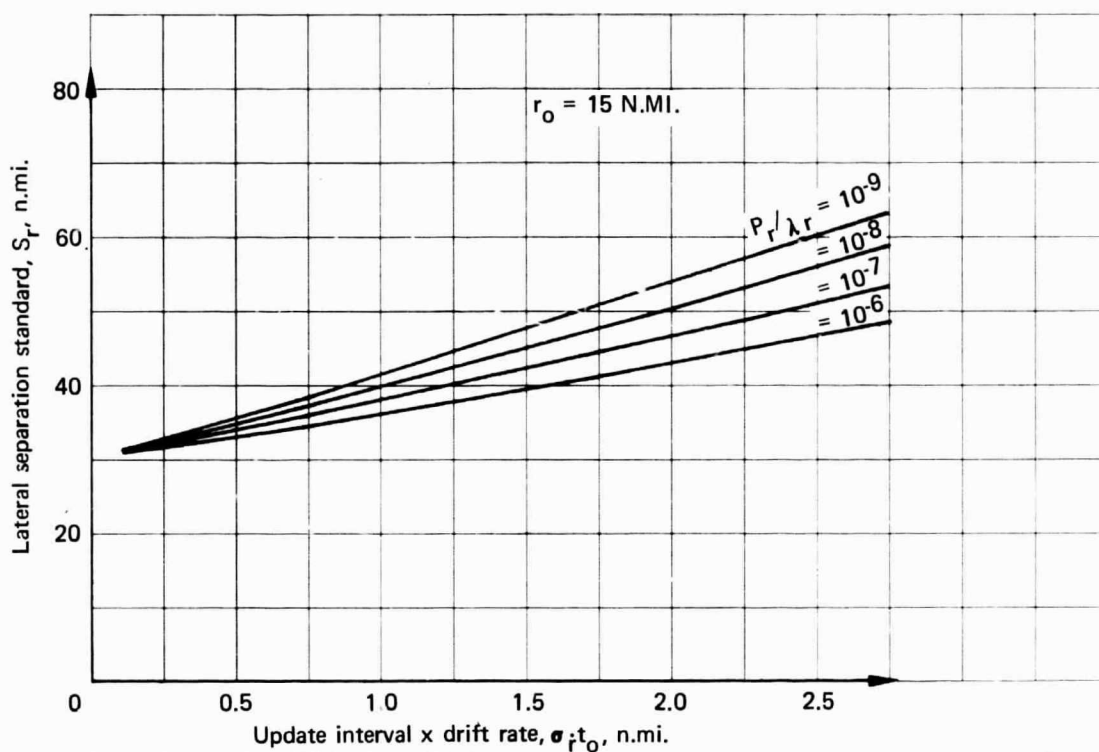


Figure D14.— SURVEILLANCE SYSTEM TRADEOFFS—UPDATE INTERVALS $\times$ DRIFT RATE ($r_0 = 15$)

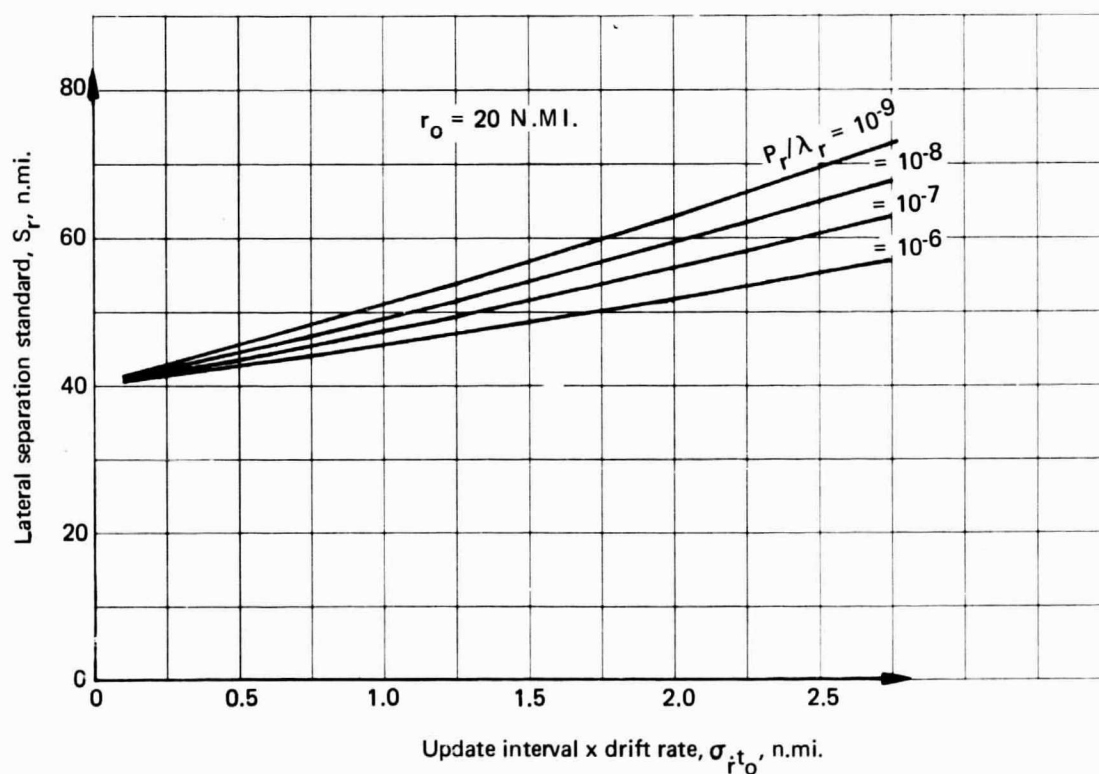


Figure D15.— SURVEILLANCE SYSTEM TRADEOFFS—UPDATE INTERVALS $\times$ DRIFT RATE ($r_0 = 20$)

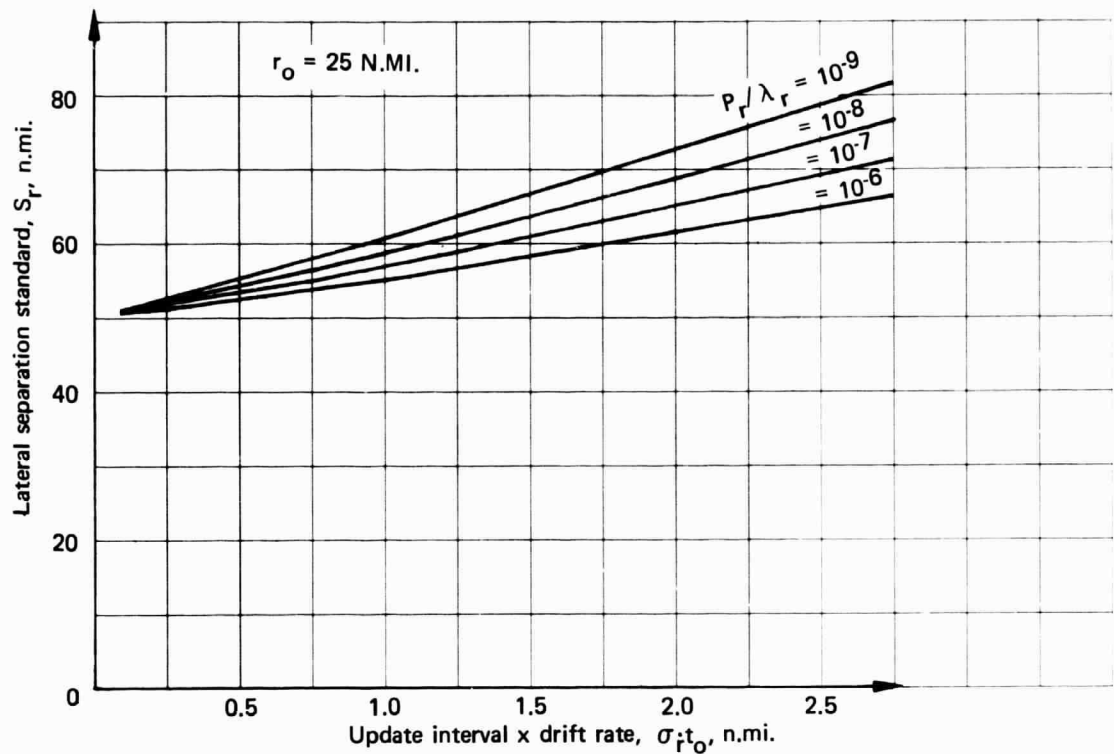


Figure D16.— SURVEILLANCE SYSTEM TRADEOFFS—UPDATE INTERVALS $\times$ DRIFT RATE ($r_o = 25$)

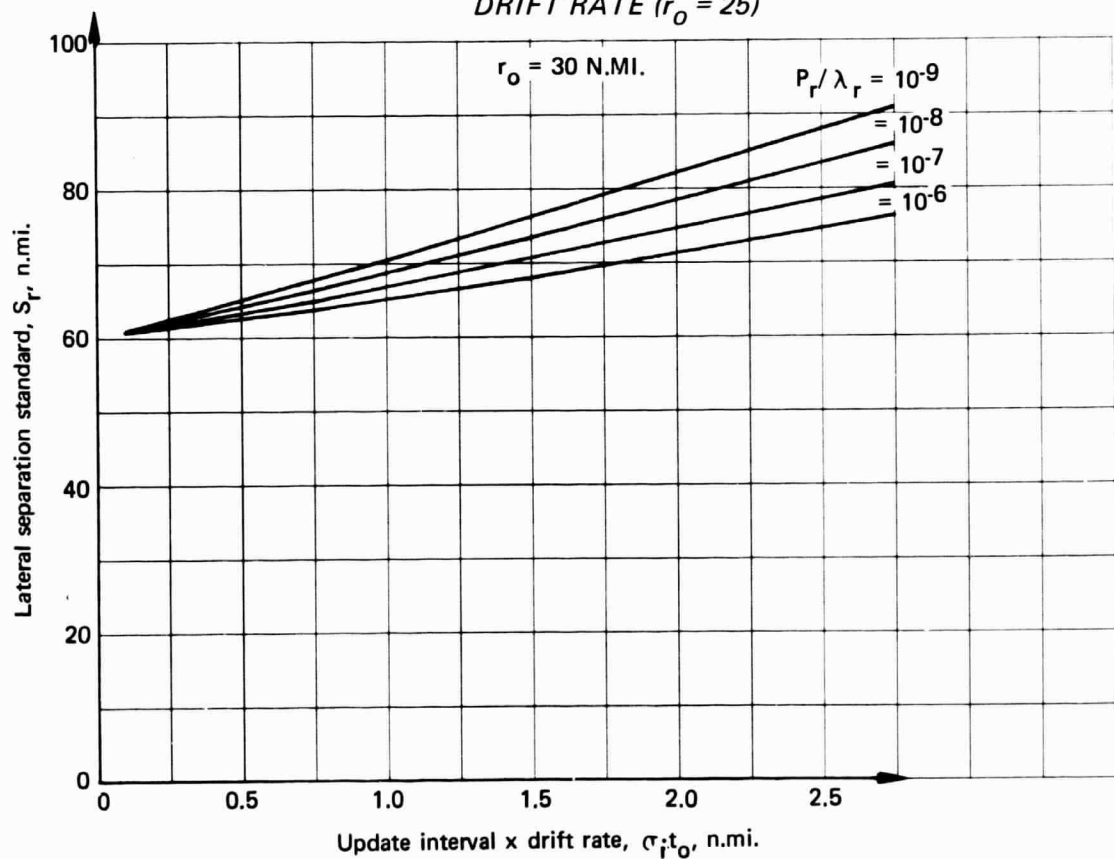


Figure D17.— SURVEILLANCE SYSTEM TRADEOFFS—UPDATE INTERVALS $\times$ DRIFT RATE ($r_o = 30$)

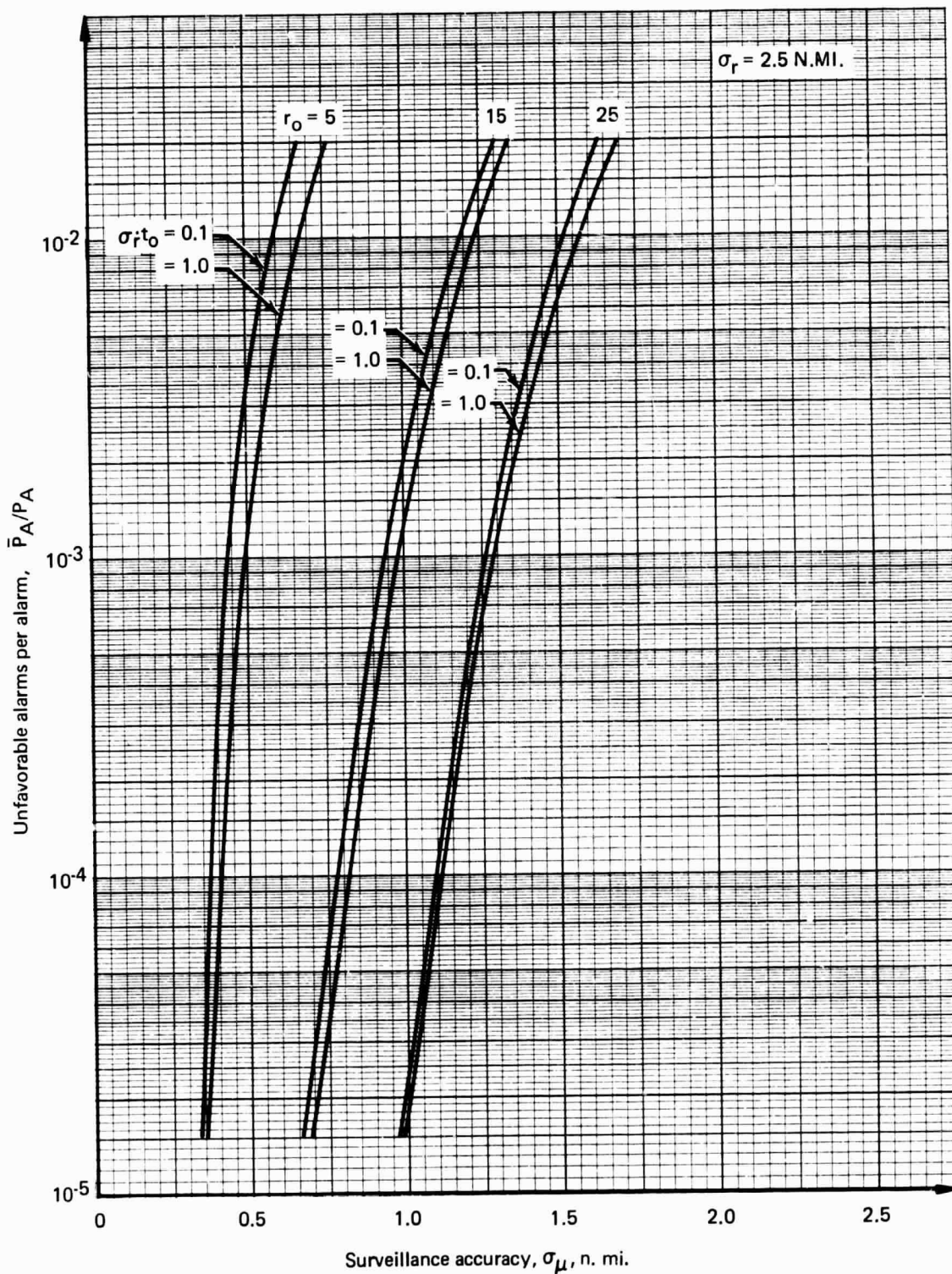


Figure D18.—SURVEILLANCE SYSTEM TRADEOFFS—SURVEILLANCE ACCURACY

($\sigma_r = 2.5$; $r_0 = 5, 15, \text{ and } 25$)

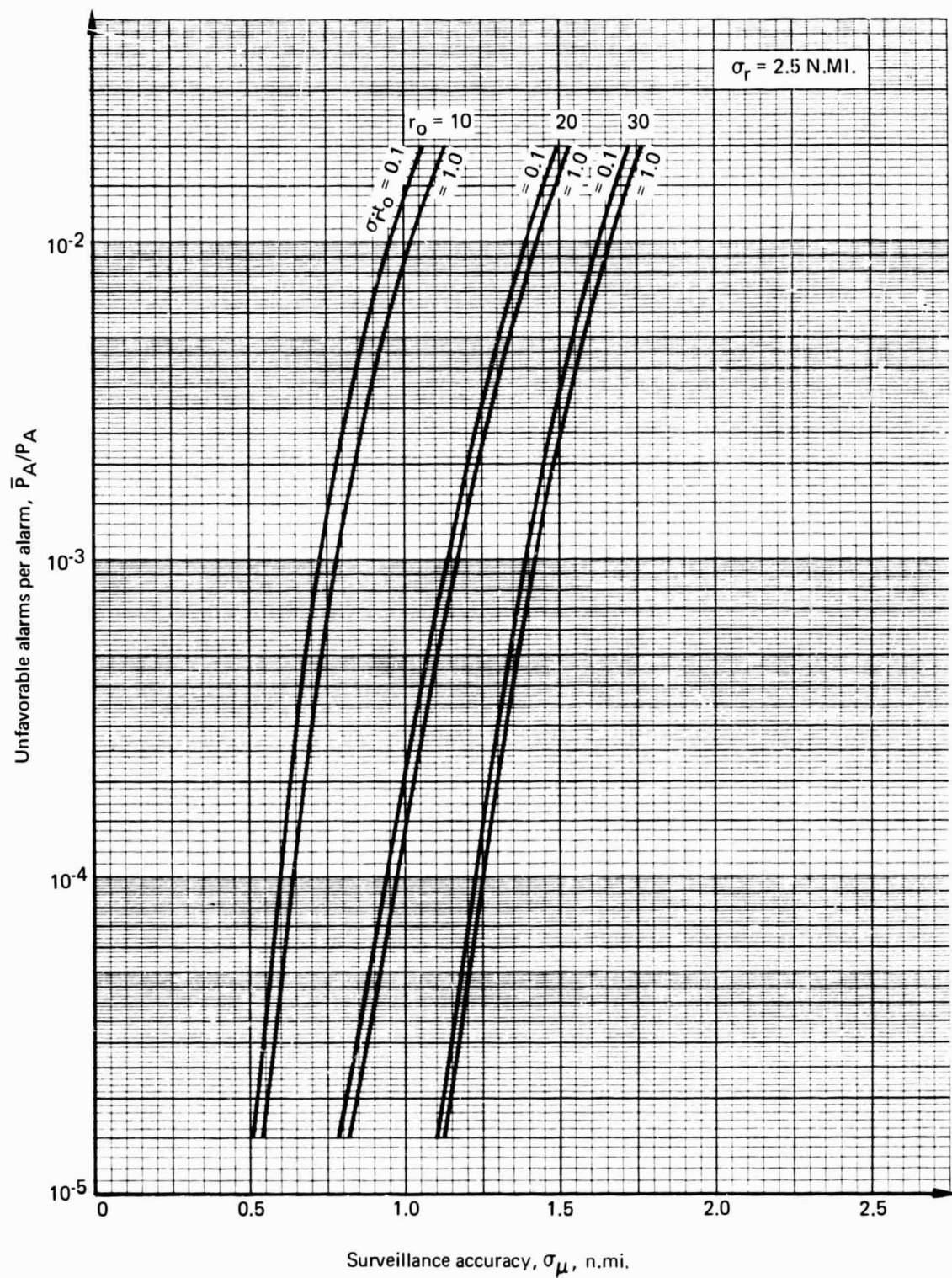


Figure D19.— SURVEILLANCE SYSTEM TRADEOFFS—SURVEILLANCE ACCURACY
 ($\sigma_r=2.5$; $r_0=10, 20$, and 30)

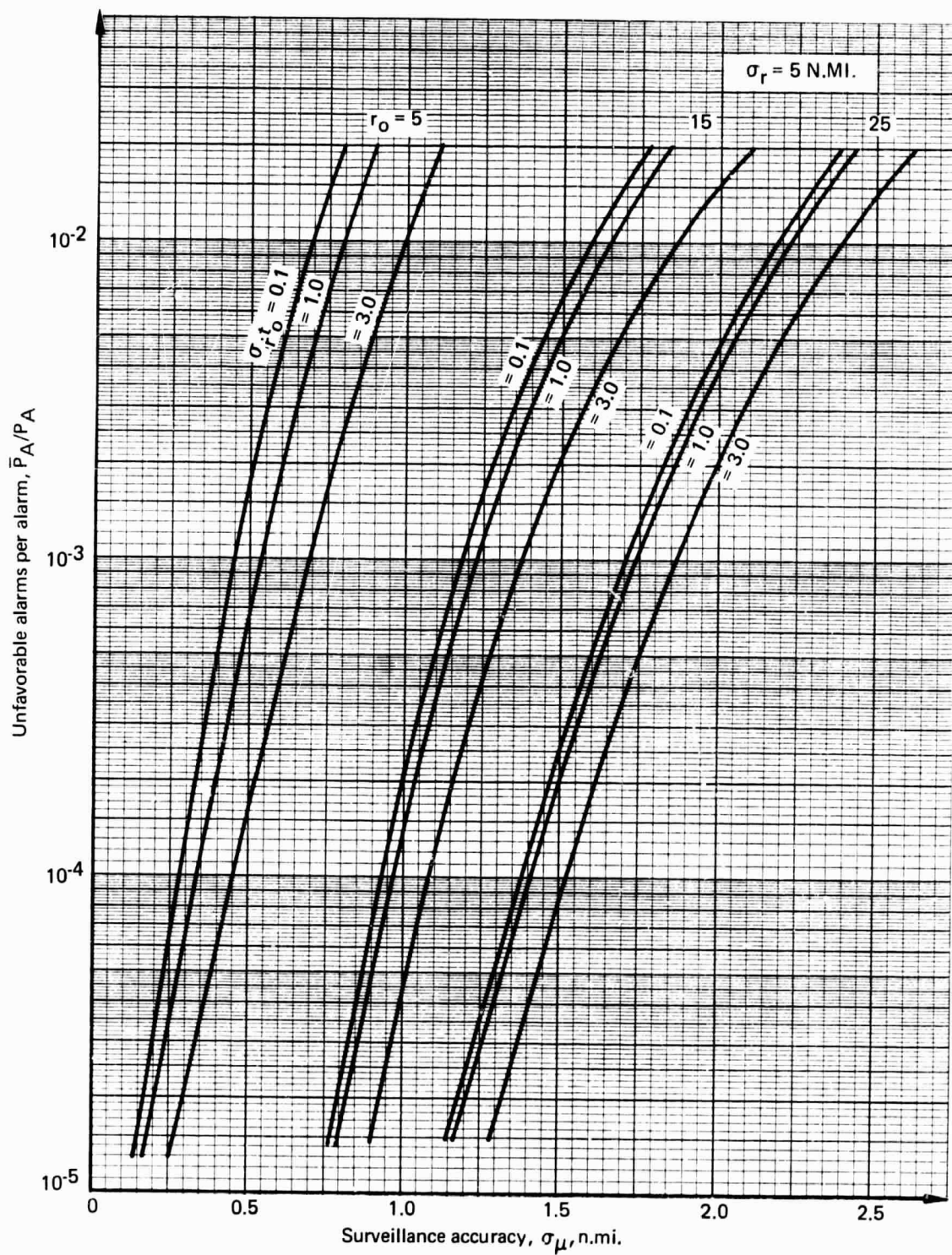


Figure D20.— SURVEILLANCE SYSTEM TRADEOFFS—SURVEILLANCE ACCURACY
 $(\sigma_r=5; r_0=5, 15, \text{ and } 25)$

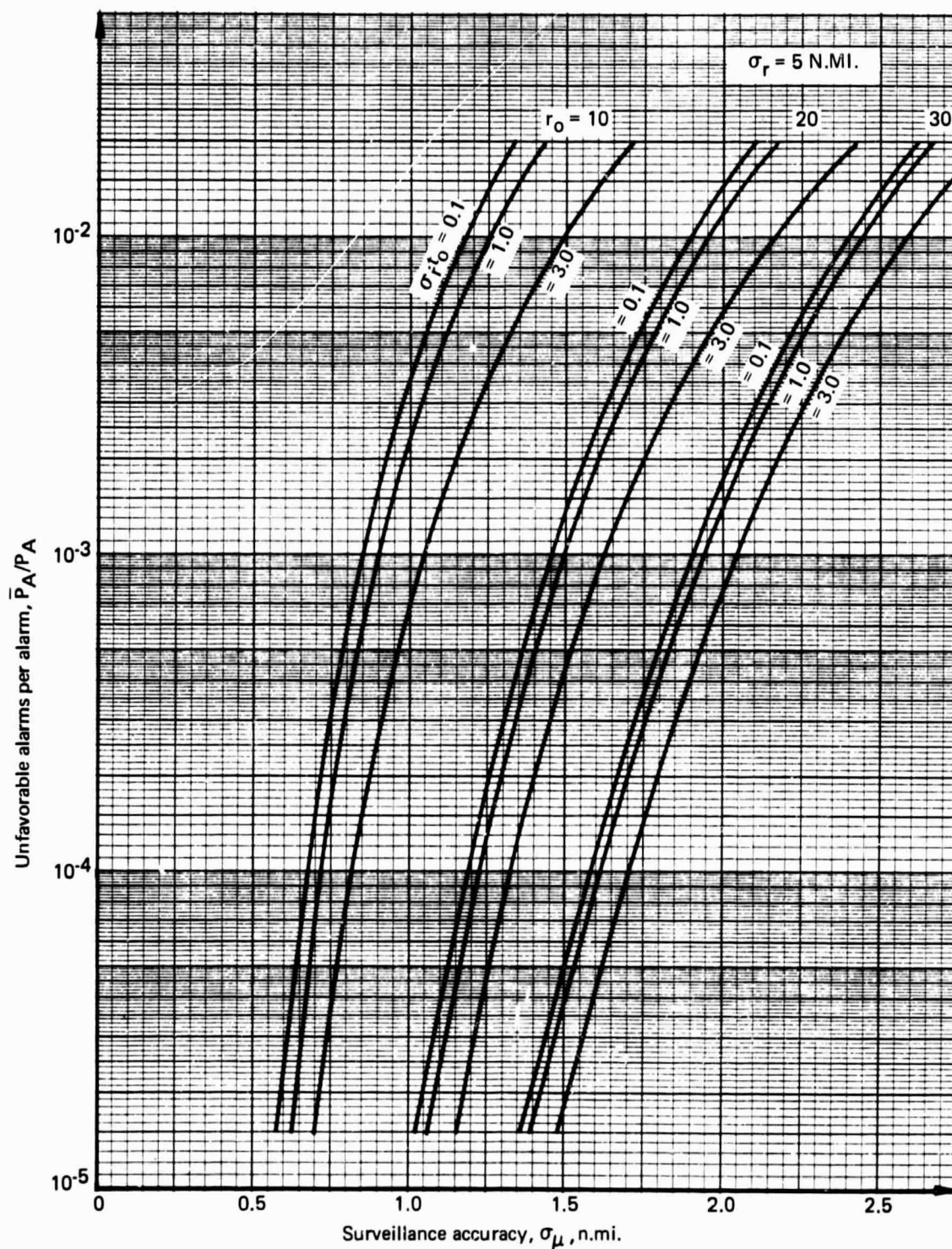


Figure D21.— SURVEILLANCE SYSTEM TRADEOFFS—SURVEILLANCE ACCURACY
 ($\sigma_r=5$; $r_0=10, 20$, and 30)

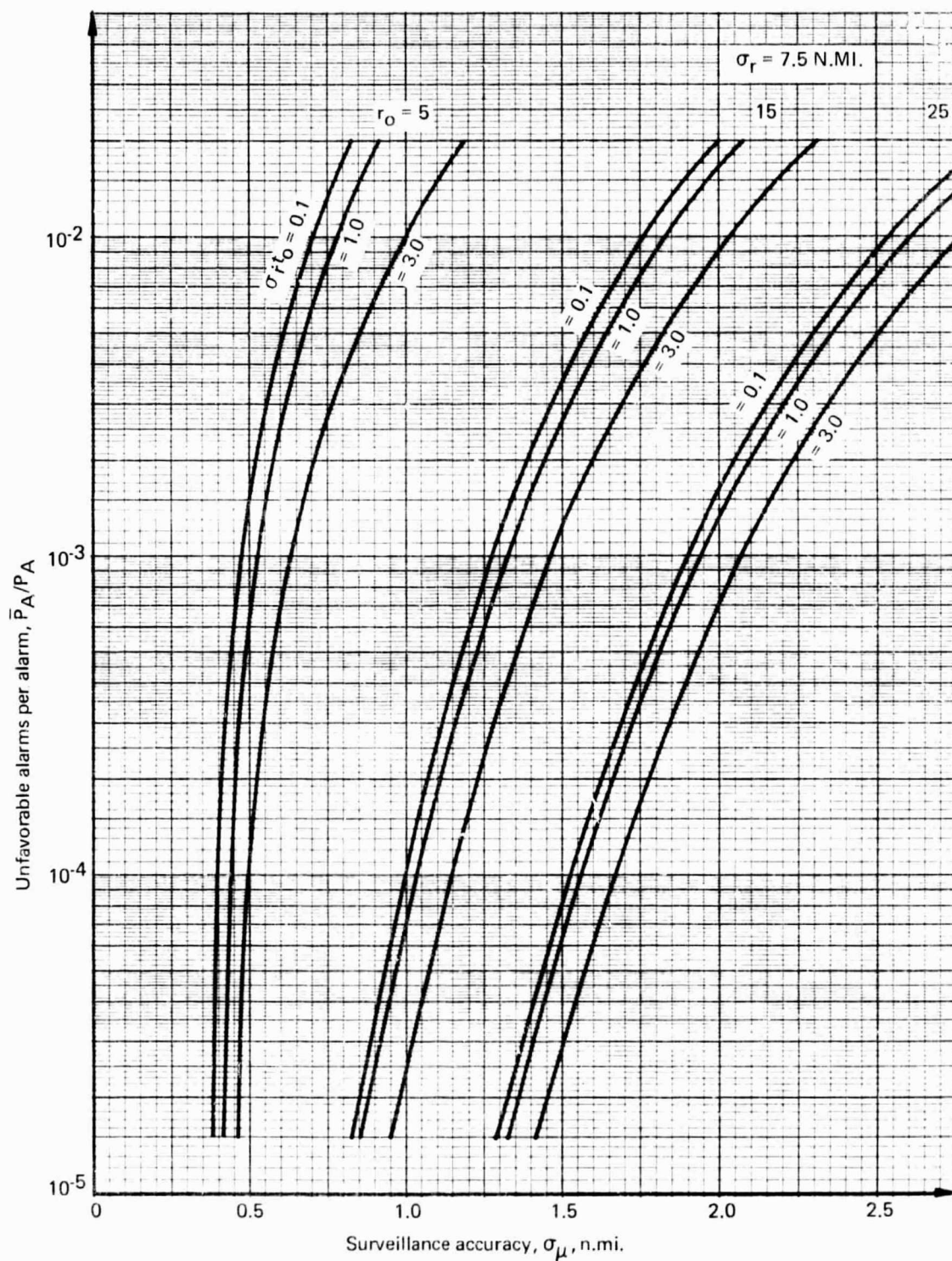


Figure D22.— SURVEILLANCE SYSTEM TRADEOFFS—SURVEILLANCE ACCURACY
 ($\sigma_r = 7.5$; $r_0 = 5, 15$, and 25)

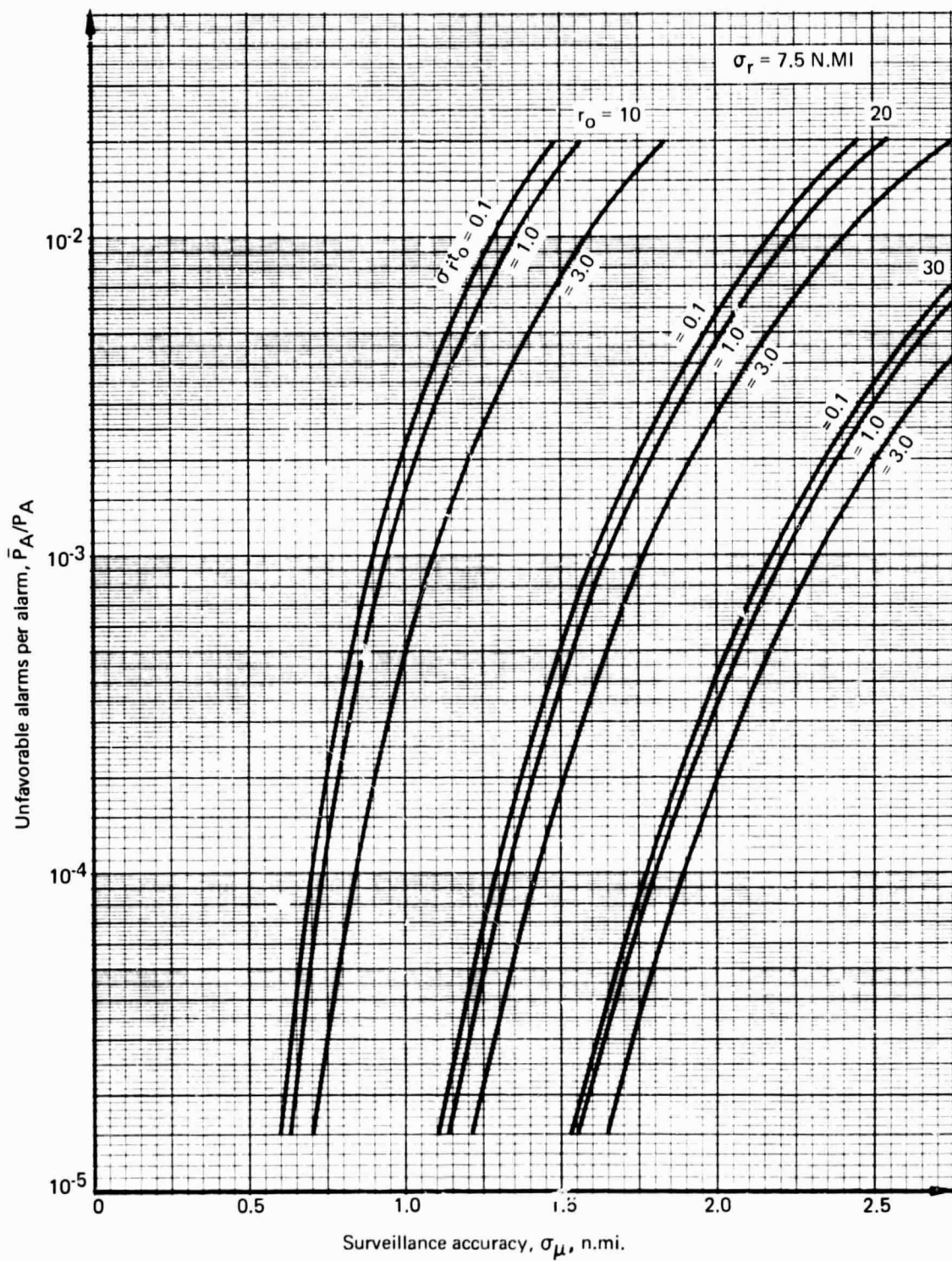


Figure D23.— SURVEILLANCE SYSTEM TRADEOFFS—SURVEILLANCE ACCURACY
 $(\sigma_r = 7.5; r_0 = 10, 20, \text{ and } 30)$

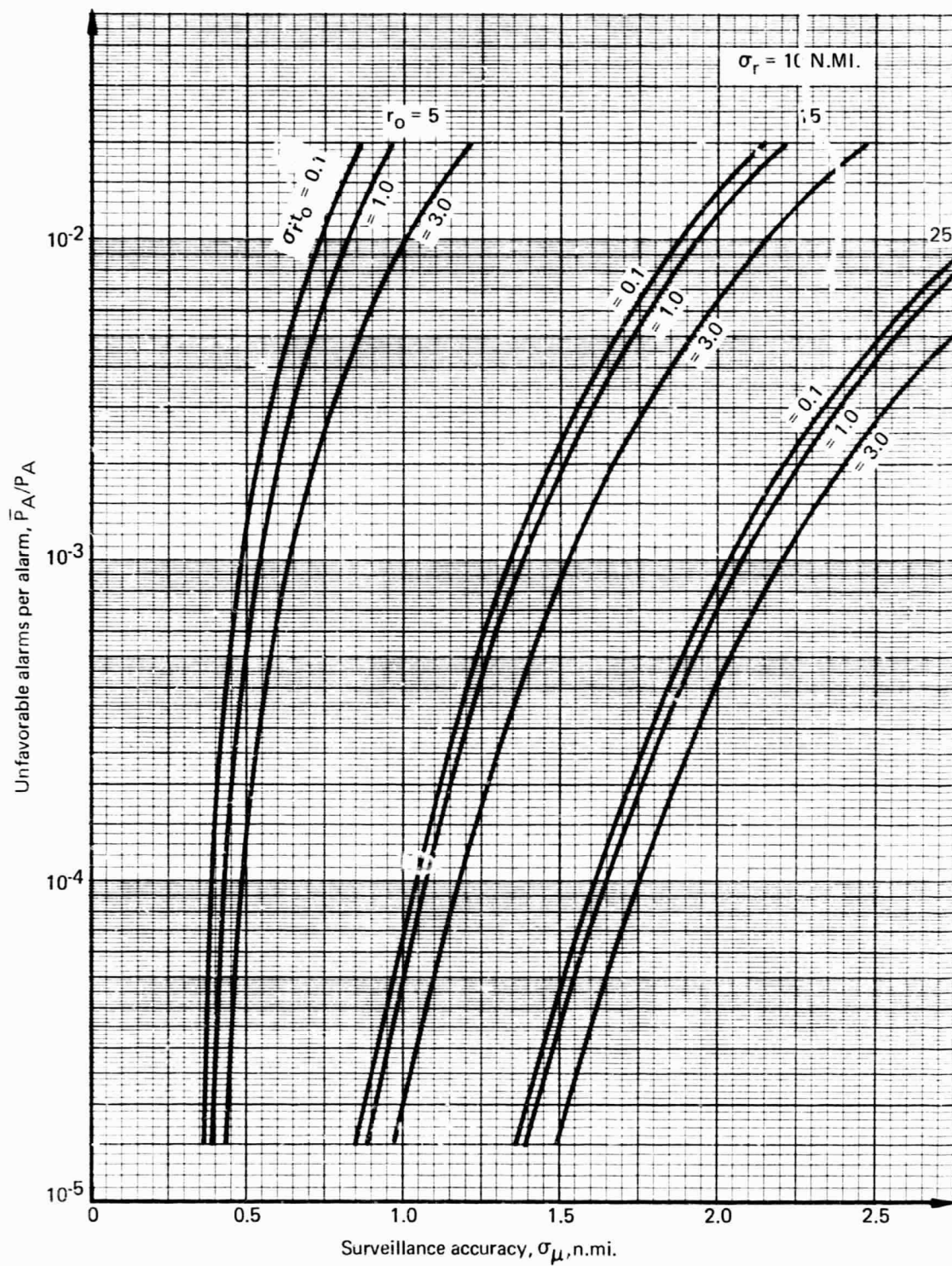


Figure D24.— SURVEILLANCE SYSTEM TRADEOFFS—SURVEILLANCE ACCURACY
($\sigma_r=10$; $r_0=5, 15$, and 25)

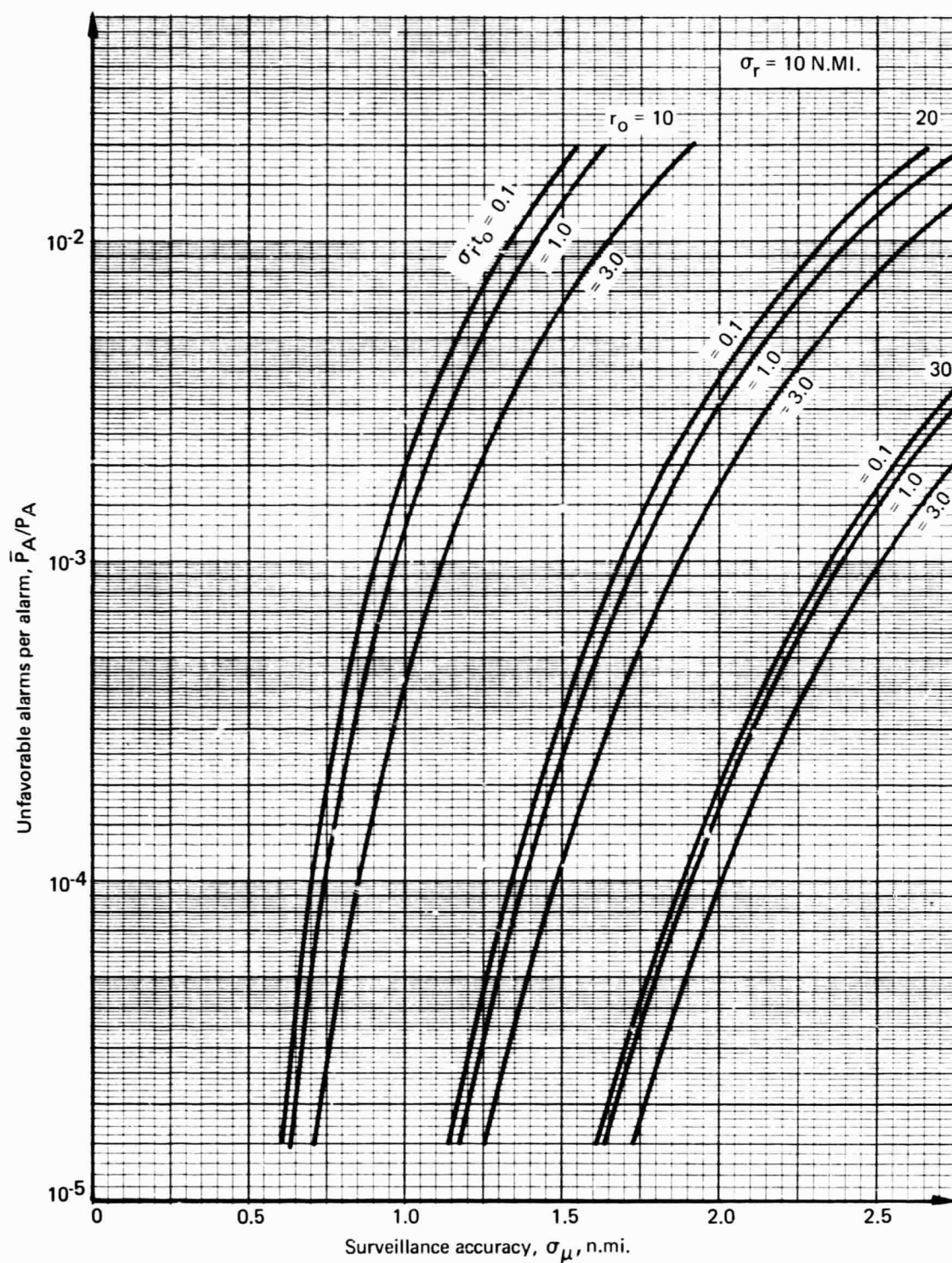


Figure D25.— SURVEILLANCE SYSTEM TRADEOFFS—SURVEILLANCE ACCURACY
 $(\sigma_r=10; r_o=10, 20, \text{ and } 30)$

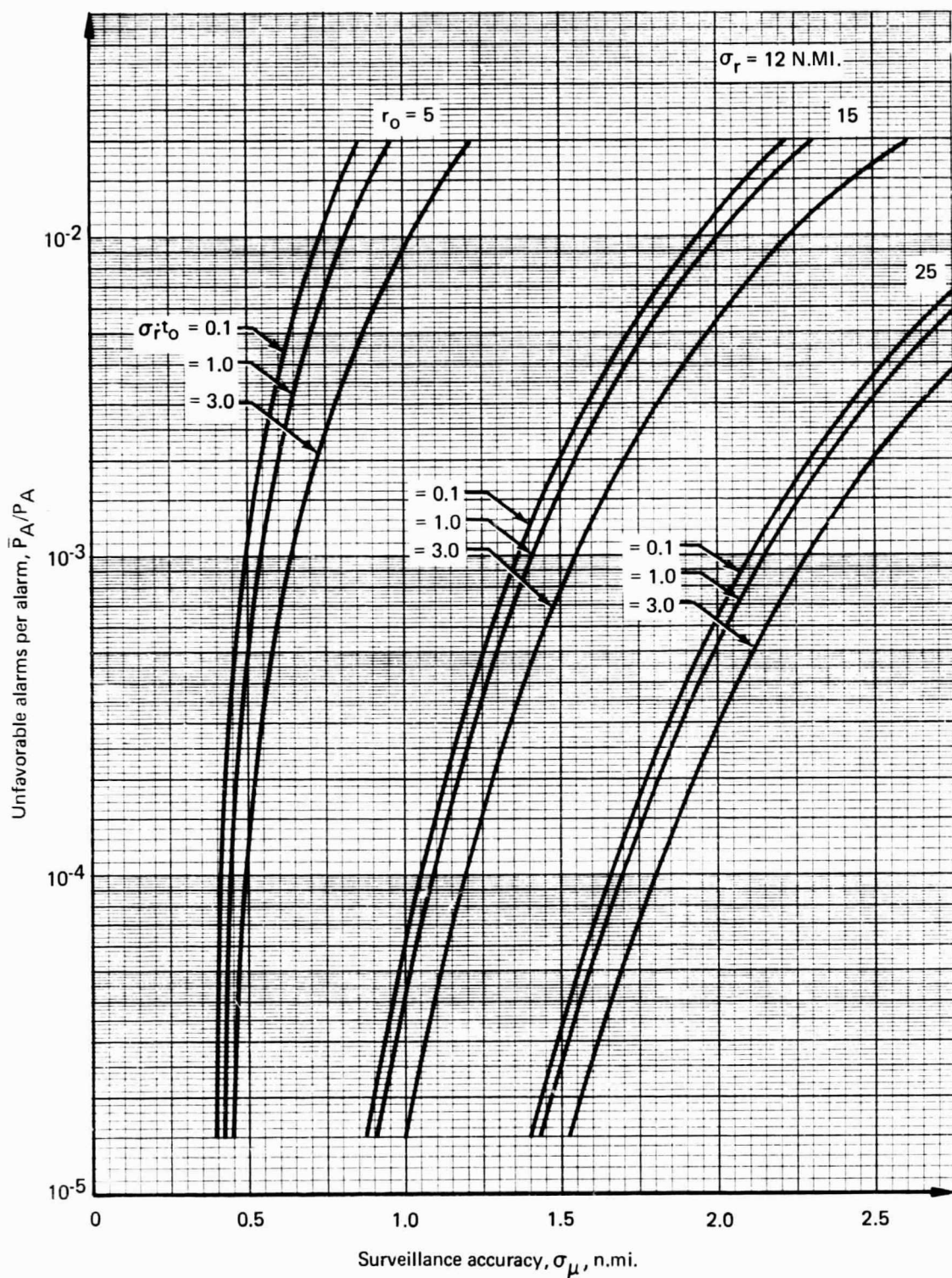


Figure D26.— SURVEILLANCE SYSTEM TRADEOFFS—SURVEILLANCE ACCURACY
 ($\sigma_r=12$; $r_0=5, 15$, and 25)

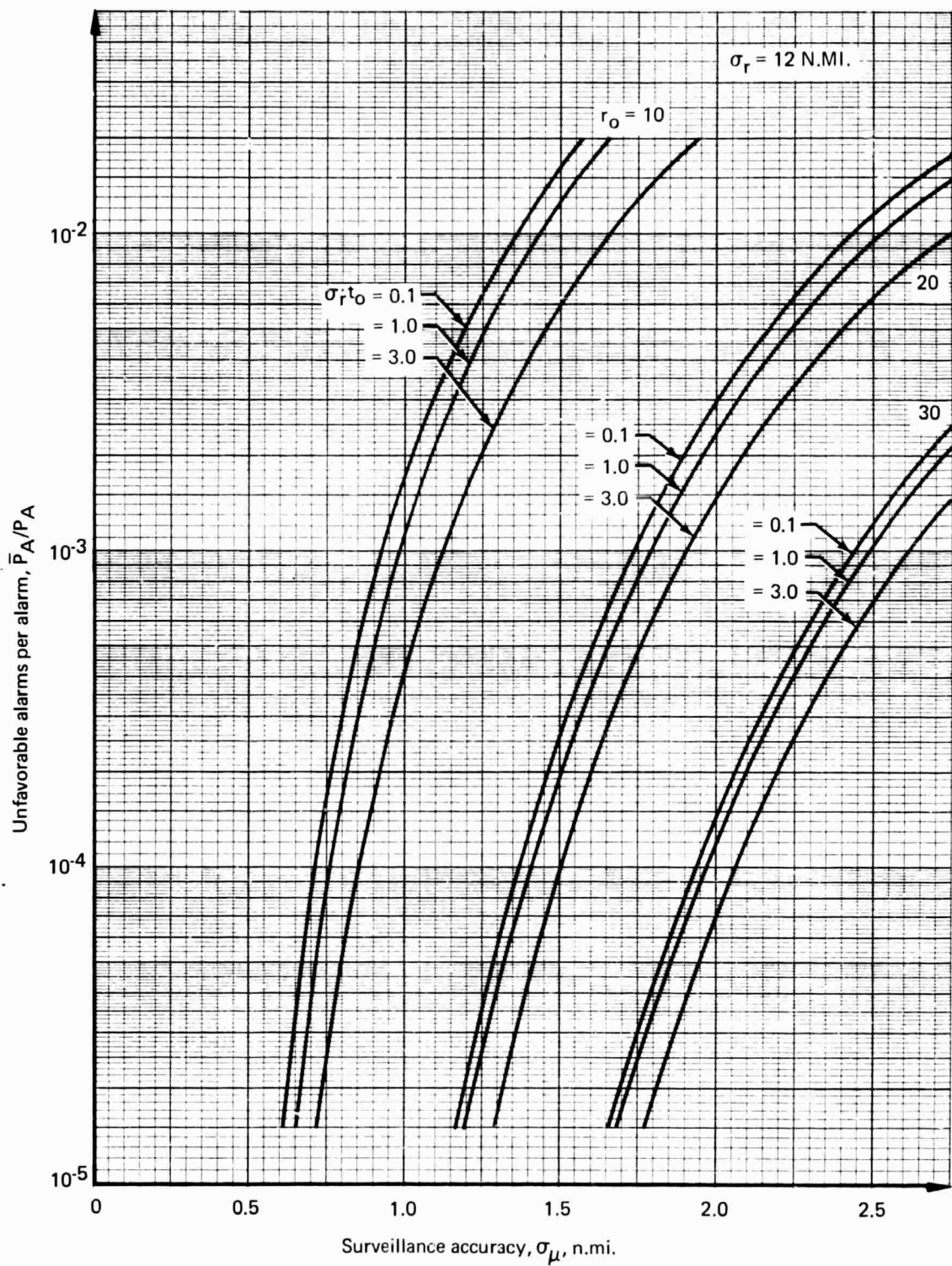


Figure D27.— SURVEILLANCE SYSTEM TRADEOFFS—SURVEILLANCE ACCURACY
($\sigma_r = 12$; $r_0 = 10, 20$, and 30)

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