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EVALUATION OF ATCRBS PERFORMANCE IN AN INTERFERENCE ENVIRONMENT

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Mitre Corporation

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16. Abstract

Uplink and downlink ATCRBS interference measurements in terminal areas were coordinated with assessments of the sources of these mutual interference conditions. The average values of these observations as well as many burst characteristics corroborated the results of an analytical model coupling the environmental features to their effects on the surveillance system. Simulation efforts based on statistical representation of the input conditions enabled an association of these interference levels with deterioration in performance of the ARTS III and TPX-42 processors. Results of these modeling efforts indicate that the performance of both processors is degraded for transponder reply probabilities below 0.85; both systems exhibit a relatively high level of immunity to reasonably expected fruit rates. Forecasts based on these results indicate that ARTS III performance degradation due to asynchronous interference may limit the terminal area traffic count to about 600 aircraft when approximately 40 interrogators are within view. An unexpected random pulse response in the test transponder degraded its performance more seriously thad did the observed interrogation rates in the area of New York City.

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TABLE OF CONTENTS

		Page
1.	INTRODUCTION	1-1
	1.1 Approach and Specific Work Activities	1-1
	1.2 Review of Report	1-3
2.	MUTUAL INTERFERENCE MEASUREMENTS	2-1
	2.1 Measured Parameters	2-1
	2.1.1 Uplink Measurements	2-2
	2.1.2 Downlink Measurements	2-3
	2.2 Test Program	2-3
3.	FLIGHT TEST RESULTS AND ANALYSIS	3-1
	3.1 Interference Sources	3-1
	3.1.1 Interrogator Population	3-2
	3.1.2 Traffic Distribution	3-3
	3.2 Interference and Performance Measurements	3-5
	3.2.1 Uplink Measurements	3-5
	3.2.2 Downlink Measurements	3-6
	3.3 Results and Analysis	3-7
	3.3.1 Typical Results	3-7
	3.3.2 Average Characteristics	3-10
	3.3.3 Short Term Characteristics	3-23
	3.3.4 Burst Interrogation Features	3-24
	3.3.5 Performance Degradation	3-34
	3.4 Transponder Reply Failure	3-40
4.	ARTS III PERFORMANCE DEGRADATION	4-1
	4.1 Examined Variables	4-1
	4.2 Tracker Performance	4-2
5.	TPX-42 PERFORMANCE DEGRADATION	5-1
	5.1 Summary of Results	5-1
	5.2 Figure of Merit	5-2

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TABLE OF CONTENTS (Continued)

	Page
5.2.1 Merit Concept	5-4
5.2.2 Application to Output Data	5-6
5.2.3 Tolerable Limits	5-13
6. IMPLICATIONS OF RESULTS	6-1
6.1 General Comments	6-1
6.2 Forecasting	6-3
APPENDIX A: INTERROGATION ANALYSIS	A-1
APPENDIX B: LIST OF SYMBOLS	B-1
APPENDIX C: REFERENCES	C-1
APPENDIX D: ARTS III DEGRADATION	D-1
APPENDIX E: TPX-42 DEGRADATION	E-1
APPENDIX F: DESCRIPTION OF EXPERIMENT	F-1

LIST OF ILLUSTRATIONS

		Page
FIGURE 3-1:	CUMULATIVE DISTRIBUTION OF AIR TRAFFIC VERSUS RANGE (FLIGHT OF 2-9-72)	3-4
FIGURE 3-2:	TIME HISTORY OF STATISTICAL RESULTS 2-9-72	3-8
FIGURE 3-3:	INTERROGATION RATE VS. NUMBER OF INTERROGATIONS IN VIEW	3-14
FIGURE 3-4:	EFFECTIVE RANGE VS. INTERROGATOR OUTPUT POWER	3-15
FIGURE 3-5:	EFFECTIVE RANGE VS. TRANSPONDER OUTPUT POWER	3-20
FIGURE 3-6:	FRUIT RATES VS. INTERROGATION RATE FOR SEVERAL TRAFFIC COUNTS	3-22
FIGURE 3-7:	PROBABILITY OF NOT BEING SEEN BY AT LEAST ONE BEAM OF N RANDOMLY RELATED BEAMS	3-26
FIGURE 3-8:	SEQUENCE LENGTH DISTRIBUTIONS FOR SEVERAL PROBABILITIES	3-28
FIGURE 3-9:	OBSERVED AND COMPUTED CLEAR DWELL DISTRIBUTION FOR FLIGHT OF 2/16	3-31
FIGURE 3-10:	PROBABILITY DISTRIBUTIONS OF L OVERLAPPING BEAMS, P(L), FOR SEVERAL PROBABILITIES OF L = 0, P(0)	3-33
FIGURE 3-11:	INTERROGATOR DETECTOR PERFORMANCE IN A FRUIT ENVIRONMENT	3-36
FIGURE 3-12:	COMPARISON OF MEASURED REPLY PROBABILITIES WITH THEORETICAL VALUES	3-39
FIGURE 3-13:	TRANSPONDER REPLY LOGIC	3-42
FIGURE 4-1:	ARTS III TRACK CORRELATION DEPENDENCE FOR FIXED WIDTH TARGETS AND INDICATED FRUIT RATES	4-4
FIGURE 4-2:	ARTS III TRACK CORRELATION DEPENDENCE FOR VARIABLE WIDTH TARGETS AND INDICATED FRUIT RATES	4-5
FIGURE 5-1:	MISSING MODE RESPONSE FOR 16 HITS, CL = 0	5-8

LIST OF ILLUSTRATIONS (Continued)

		Page
FIGURE 5-2:	MISSING MODE RESPONSE FOR 16 HITS, CL = 4	5-10
FIGURE 5-3:	MISSING MODE RESPONSE FOR 9 HITS, CL = 0	5-11
FIGURE 5-4:	MISSING MODE RESPONSE FOR 9 HITS, CL = 4	5-12
FIGURE 5-5:	PROBABILITY OF FAILURE IN n LOOKS VS. NUMBER OF LOOKS, n, FOR SEVERAL AVERAGE PROBABILITIES OF SUCCESS, O	5-14
FIGURE 6-1:	SYSTEM LOADING IMPACT ON ARTS III PERFORMANCE	6-6
FIGURE 6-2:	ARTS III PERFORMANCE VARIATION WITH SYSTEM LOADING	6-8

LIST OF TABLES

TABLE 3-1:	NEW YORK ENVIRONMENTAL AVERAGE MEASUREMENTS	3-11
TABLE 3-2:	ANALYSIS OF CLEAR DWELL INTERVALS FOR FLIGHT OF 2/16	3-29
TABLE 5-1:	SENSITIVITY OF PERFORMANCE PARAMETERS TO CHANGES IN ENVIRONMENT	5-3

1. INTRODUCTION

The purpose of this task was to determine the present status of the ATCRBS interference environment as caused by multiple interrogators and transponders, and how this interference impacts the performance of the system. It was hoped that these results would; (a) provide pertinent data and an indication of the existence of mutual interference between FAA and nearby DOD sites, and indicate whether cooperative efforts between these users are required; (b) provide a basis for predicting the future state of ATCRBS system performance; and (c) enhance the capabilities of simulation models being developed by ECAC and TSC, by providing a deeper insight into the existing status of the system.

The effort was focused on obtaining data in a coordinated ground-air experiment near a high-density terminal. Measurements were conducted in such a manner as to disclose the causes of interference as well as the result of the interference. The results of the measurements were then projected into the future to account for future increases in air traffic. The measurements and projections were also related to their effects upon ATC system operation, by the utilization of existing simulation models of the ARTS III and TPX-42 systems. Concentration was placed on achieving an early, reliable result, and on providing a minimum-cost program. Maximum use was made of existing equipment, such as the instrumented van at MITRE; maximum use was also made of existing models of the ARTS III and TPX-42 processors. Results are in a form useful for the development of computer models of the ATCRBS environment and for DABS planning purposes.

1.1 Approach and Specific Work Activities

Ground and airborne instrumentation systems were used to measure the effects of self-interference of the Radar Beacon System in a

high-density environment.[1,2] In parallel with the measurement and its subsequent analysis, an investigation using existing computer-simulation models of the ARTS III and TPX-42 systems was conducted to assess the impact of various levels of interference on measurable parameters of these systems.[3,4]

The experimental program was specifically designed so that such equipment-sensitive parameters as RF signal strength, the interrogator antenna pattern, and the aircraft antenna pattern, did not impact the results. The determination of such environmental-sensitive parameters as the number of replies by the instrumented aircraft to the instrumented interrogator, the level of asynchronous interference (fruit), and the number of interrogators and transponders in the environment were included in the program. In addition, the aircraft was equipped to indicate the reason for any missing replies - whether it be caused by dead-time resulting from a response to a normal interrogation, an SLS signal, or reply-rate limiting.

While the experimental program was conducted, the impact of interference on the semi-automatic TPX-42 system and the automatic ARTS III system was examined. This was accomplished by exercising existing simulation models to determine, as a function of various levels of reply probability and fruit, such factors as probability of detection, azimuth splits, azimuth accuracy, and code validation. For the ARTS III system, further factors of track coast and track disassociation were determined.

The results of the above investigations were used to relate the present status of ATCRBS to scan-independent factors of interference; by projecting for future traffic densities, a forecast was developed of future status.

1.2 Review of Report

The following section briefly reviews the way in which the interference measurements experiment was implemented. Parameters measured and the means for synchronizing the uplink and downlink data records are also outlined.

Section 3 summarizes the test results for the New York and Boston areas. These results are analyzed and compared with predicted values based on an earlier-developed model of interference circumstances.[5] Both the interference environment and its relationship to its causes, as well as equipment performance vulnerability to these effects are considered. The treatment in this section and in Appendix A includes certain short term characteristics as well as average features. Some comments regarding particular equipment design aspects are also related to these efforts.

Sections 4 and 5 give a synopsis of the extent of ARTS III and TPX-42 performance degradation produced by interference. These results are based on computer simulations utilizing statistical description of the input environmental conditions.

General comments and recommendations based on this total effort are then given in Section 6. This section also illustrates how these results may be employed in forecasting the average system characteristics as a function of interrogator population and air traffic count.

Summaries of three of the principal tasks in this program are included in this report as appendicies. Simulation of the ARTS III performance degradation in the interference environment is reviewed in Appendix D; a similar treatment of the

TPX-42 study is given in Appendix E. Implementation of the experimental effort and a summary of the flight test program are contained in Appendix F. Each of these overviews is extracted from the pertinent final report.

2. MUTUAL INTERFERENCE MEASUREMENTS

Synchronized measurements of the ATCRBS uplink and downlink interference condition were conducted in the vicinities of New York and Boston. Appendix C reviews this experimental arrangement as well as the monitoring methods employed to estimate the population of the producers of these interference conditions. The following is a brief summary of the measurements program.

2.1 Measured Parameters

The interrogator van was instrumented for tracking the test aircraft position on a scan-to-scan basis. During the scanning beam dwell interval, the interrogator uniquely addressed the test transponder with a Mode D interrogation sequence. The attempt of the tracking arrangement was to center this series of interrogations about the beam maximum as it illuminated the test aircraft. Synchronizing signals were transmitted to the aircraft at the beginning and end of this series of Mode D interrogations; these synchronizing signals simultaneously turned the airborne and ground data collection systems on and off. Between these beam dwell intervals, each of these systems separately monitored the interference conditions on the uplink and on the downlink.

Monitoring of the signal strength and the tracking loop condition was used on both the ground and airborne units to flag data if a solid link was not established. The purpose of these flags was to insure to the maximum extent possible that the uplink and downlink failures recorded in the experiment were isolated to failures solely attributable to the measured interference conditions.

2.1.1 Uplink Measurements

Uplink interference conditions influence whether or not a transponder will be busy when interrogated by a particular unit. Both the interrogation rate and the side lobe inhibit rate are of interest in this regard. In an attempt to relate these interference rates to the transponder reply probability, the experiment was configured so that the number of replies to unique interrogations (Mode D) were counted over the same interval in which interference rates were monitored. The transponder used in the test aircraft was operated as a normal ATCRBS unit augmented by inhibit lines which prevented a reply to a unique interrogation when the unit had been captured by a previous normal mode interrogation or side lobe inhibit signal.

The aim of the experiment was to collect these data over the beam dwell interval consisting of ten unique address interrogation periods centered about the beam maximum. The total length of this data collection interval was 38 ms; this represented the finest level of resolution of interference variations directly measured in the experiment. This sample of the uplink environment was only possible once per scan of the interrogator beam; an additional measure of the interrogation was, however, obtained from the calibrated reply rate limit voltage. Counts of the interrogation and suppression rates were also made over the approximately seven second scan period between beam dwells. Collecting data in this way over these integration intervals thus enabled some assessment of the burst characteristics of these rates. In summary, then, the following measurements were made on the uplink:

1. Mode 3A and Mode C combined interrogation replies over a 38 ms dwell period, from the calibrated reply rate limit voltage, and also over a seven second scan period.
2. SLS inhibits over the same intervals of 38 ms and seven seconds.
3. Number of Mode D replies made over the 38 ms dwell interval.

Contributions to this environment by the test interrogator were minimized by restricting its Mode D operation to the interval needed for the tracking gates; Mode 3A radiation was employed only at 10 minute intervals for several scan periods while traffic distributions were photographed.

2.1.2 Downlink Measurements

Downlink interference may garble or overlap the transponders reply thereby preventing detection or code validation. Asynchronous interference or fruit is produced by aircraft (within range of the interrogator receiver) when they are interrogated by other units.

Both the temporal and the spatial features of this fruit distribution are of interest. Normal operation of the van interrogator therefore measured fruit rates during the 38 ms dwell time, and over the seven second scan interval. Periodically, these measurements were interrupted and the azimuthal variation of the fruit distribution was monitored over consecutive 18 degree sectors during one antenna scan.

2.2 Test Program

A detailed description of the test implementation and the flight test program in the New York area is found in the above-mentioned

appendix. A similar description for measurements in the vicinity of Boston is given in Reference 2. The majority of the data were obtained during circular or radial flights with reference to the test van interrogator. Flight durations were nominally two hours at altitudes of 7.5Kft. or 9.0Kft.

Coordinated uplink and downlink measurements were obtained in the test flight series. The interrogator population producing uplink conditions was estimated from FAA files, and the aircraft distribution associated with the downlink interference was determined from scope photographs periodically made during the test duration. All of these features of the interference environment were considered in the analysis and interpretation of the test results.

3. FLIGHT TEST RESULTS AND ANALYSIS

Data reduction was accomplished by processing the synchronized ground and airborne tapes. Scan by scan records of uplink and downlink conditions were thus available both for examination of the variational characteristics of the data as well as for comparison against the related sources of interference, i.e., the interrogator and transponder populations. In addition to these scan by scan records of coordinated interference conditions, the processing program also provided a statistical analysis of measurements over specified intervals.

Average values of these analyses were compared with an earlier developed model output to determine to what extent the average performance of ATCRBS could be related to interference-producing sources. The distribution features measured in the data collected were compared with analytical model to determine whether or not burst characteristics in the data could be accounted for on the basis of statistically independent events.

Coordinated determinations of the interrogator and aircraft populations are described next; the uplink and downlink interference environments are then compared with predicted values. An examination of beacon equipment response to these interference conditions concludes this section.

3.1 Interference Sources

Uplink interrogation and suppression rates are determined by the population and characteristics of the interrogators within the field of view of the aircraft. Since virtually all units within line of sight will provide above minimum threshold level (MTL) signals on their main beams, it is not of first order importance what their specific locations are in terms of the expected average

interrogation rate when these units are SLS equipped. The side-lobe inhibit rate, however, should be more sensitive to the relative location of the aircraft and interrogators since the side lobe response range is on the order of tens of miles and units beyond this range therefore will not contribute to the SLS count.

Downlink fruit rates are determined by the reply rate of the aircraft within range of the interrogator and so are critically dependent upon the distribution of the traffic. This distribution is particularly important in terms of the minor lobe contribution to the total fruit rate.

The next two sections describe how these contributing sources were monitored in the test program. Implications of these factors are then treated.

3.1.1 Interrogator Population

A list of interrogators, their locations, and their general characteristics was provided by the FAA. A search routine centered at the test aircraft location was used to cull from this list those units within radio line of sight. This number varied in the New York area from 36 to 42 over the flight of 2/9/72 and was nominally 28 for the flight of 2/11/72. The number for the flight of 2/16/72 varied from 40 to 42.

The retrieval program enables an actual determination of this authorized interrogator population distribution. Since, as indicated in Reference 5, this precise distribution does not critically affect the analysis of average uplink characteristics (except for SLS inhibit rates), we will only note here that the

total number of interrogators indicated for a flight altitude of 7.5 thousand feet are in close agreement with other assessments. A more refined treatment of the impact of the interrogator distribution is possible, of course, since the required data is available. Limitations on the scope of the efforts prevented this approach at this time however.

3.1.2 Traffic Distribution

Airborne transponders out to a maximum displayed range of 160 miles from the interrogator were monitored by periodically photographing the scope while interrogating on Mode 3A. Such photographs were taken on an approximately ten minute basis at both the test van and at the nearby JFK tower. Counts thus obtained agreed to within several percent, indicating that siting or antenna lobe characteristics did not critically alter the measure.

The photographed displays were segmented into 10 mile range intervals and an aircraft count within each interval was recorded. Cumulative distributions of the percent of the total traffic within these range intervals were then averaged over the flight time and plotted verses the range. These plots, of which Figure 3-1 is typical, indicated that the normalized cumulative traffic distributions were proportional to the range, at least out to 40 or 50 miles, on all days monitored.* The total count out to 160 miles averaged over the flight of 2/9/72 was 160 transponder equipped aircraft. The average total number for the flight of

*This figure, as well as other program results, is extracted from the appropriate reference.

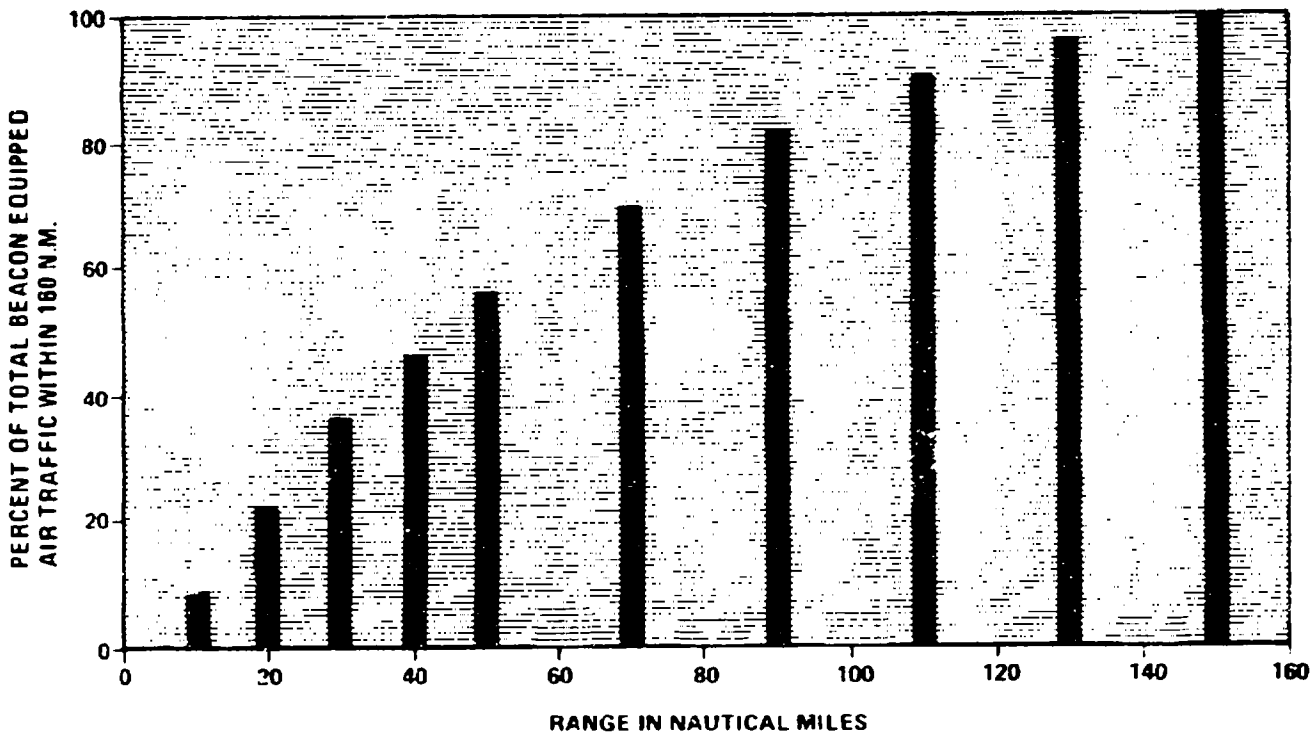


FIGURE 3-1
CUMULATIVE DISTRIBUTION OF AIR TRAFFIC VERSUS RANGE (FLIGHT OF 2-9-72)

2/11/72 was 150 aircraft, and for 2/16/72, the count was about 140. The peak variation on these totals over the data collection interval was on the order of ± 10%.

3.2 Interference and Performance Measurements

Reply rates to Mode 3A/C interrogations monitored by the per dwell count, the per scan count, and the calibrated overload control voltage were converted to per second rates. The same conversion was applied to the SLS count for both the dwell interval and scan period records. Monitored fruit rates on the downlink were similarly treated. These sampled data enable a separate, but coordinated, representation of the uplink and the downlink interference conditions produced by the monitored traffic and interrogator populations. Synchronization of the airborne and ground data collection systems also provided a correlated measure of link performance for this interference condition.

3.2.1 Uplink Measurements

The uplink measure was obtained on a scan to scan basis by recording the number of Mode D interrogations made while the beam illuminated the test aircraft; synchronized initiation of a counter in the aircraft recorded the number of times to which the transponder replied to Mode D during this dwell period. The statistical average of this ratio is then a measure of the transponder average reply probability. An noted before, a record of Mode 3A and C replies, and SLS inhibits occurring during each of these dwell periods was also obtained. These data were used to infer (on a statistical basis) the cause of failure of the transponder to reply to any of these valid Mode D interrogations. These statistical inferences were supported by similar data monitored on the seven second scan interval basis.

3.2.2 Downlink Measurements

Downlink interference of transponder replies due to asynchronous fruit was similarly examined from the scan synchronized records. Incident fruit (bracket pairs per second) was recorded during the interval in which the ten possible replies were expected from the Mode D equipped test aircraft. The actual sequence of these ungarbled replies was recorded from the contents of a synchronized shift register clocked from the interrogator repetition rate. A one in a shift register bit position indicated that the transponder replied and that this reply was received without overlap from an interfering fruit reply. A zero was recorded at any bit position corresponding to either failure of the transponder to reply, or to garbling of this reply by incident fruit. A reply by reply distribution of the two-way round reliability features of the ATCRBS site was thus available.

The difference in the total number of replies received in the clear at the interrogator and the total number of Mode D replies recorded in the aircraft over the corresponding beam dwell interval provided a measure of the number of replies garbled or overlapped by fruit replies. Statistical averaging of these counts indicated the average probability of a garbled reply for the detector used in the experiment. This measure could then be compared with the fruit rate averaged over these same intervals to determine the extent of correlation between fruit rate and the probability of it garbling a desired reply.

Fruit monitored on the above basis is perhaps the closest approximation to what a similar operational site might experience except for the fact that no defruiter was used in the measurement. Additional information on the temporal and spatial distribution of these asynchronous replies was obtained by integrating the fruit

count over the remainder of the antenna scan after the target dwell interval, and also, by periodically changing the operational mode so that fruit was monitored in successive eighteen degree azimuthal sectors during some scans.

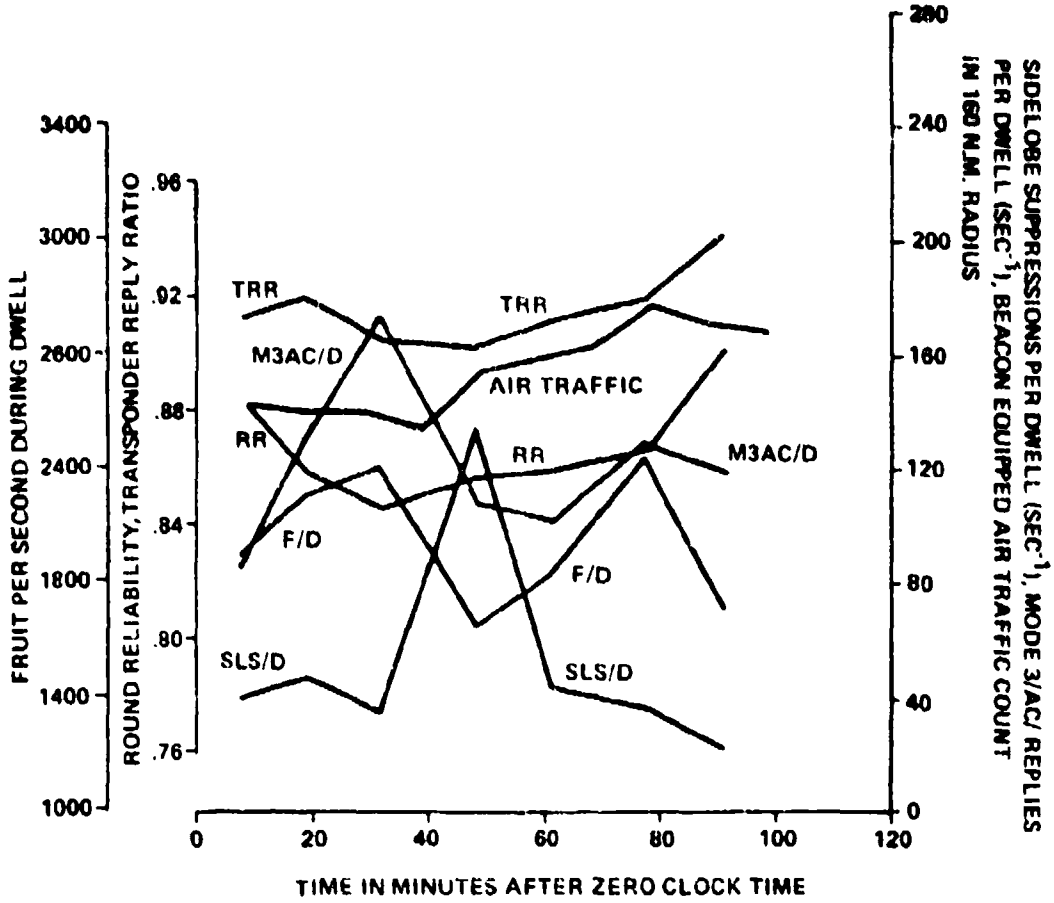
3.3 Results and Analysis

Presentations of some of the more detailed aspects of the results obtained are given in Reference 2 for the Boston tests, and in Reference 1 for the New York tests. Emphasis in this section is placed on the average values of the properties of interest since these averages are potentially the most useful index for describing and forecasting overall behavior of the ATCRBS operational network. Short term system effects are examined in this report only to the extent required to support the above efforts.

3.3.1 Typical Results

Aggregate behavior of the per dwell monitored interference conditions is shown in Figure 3-2 along with the transponder reply probability, the two-way round reliability, and the beacon equipped traffic count for the flight of 2/9/72 in the New York area. These data are smoothed over adjacent ten minute sections of the ground/flight records.

From these variations it would appear that the transponder reply probability and the round reliability are reasonably well correlated when consideration is made for the 3A/C reply rate variation and the indicated fruit rates. Similarly, the fruit rate seems to vary approximately as expected for the indicated changes in 3A/C reply rate and traffic count. It is doubtful that an extremely high level of correlation would occur for some of these parameters even though they may be deterministically related, since their



TRR. TRANSPONDER REPLY RATIO
RR: ROUND RELIABILITY
F/D: FRUIT PER SECOND DURING DWELL
M 3AC/D: MODE 3A/C REPLIES PER DWELL
SLS/D: SIDELOBE SUPPRESSION PER DWELL

FIGURE 3-2
TIME HISTORY OF STATISTICAL RESULTS 2-9-72

magnitudes are relatively low; the indicated change in SLS rate, for example, does not noticeably alter the round reliability, since even this peak level of SLS occurrences is negligible in its influence on link performance.

Values shown in Figure 3-2 reflect temporal variations in the interference conditions as well as changes in the geometry of the relationships between the aircraft, the interrogator, and the air traffic distributions. The geometry changes occur as the test aircraft position and the traffic distribution change over the interval of time examined. Although a detailed treatment of such variations may be useful in the assessment of particular circumstances, the required level of complexity appears to be incompatible with the usual level of knowledge available in most planning and forecasting efforts. The approach adopted in this work is therefore one that bases predictions and interpretation on statistical averages with the short term variations indicating the general deviations from these averages which would be expected. This argument may be most convincingly framed by reflecting on the process normally associated with the establishment of creditability to any simulation model analysis - when possible, this is achieved by performing critical experiments and comparing measured results with those predicted by the model. After the analytical model has been thus validated, it may then be used to predict or extrapolate to other conditions. The essential point to be made here is that the level of refinement in the experiment and the model are generally compatible. Average values lend themselves to such treatments with the results then perturbed by short term variations. This concept is used in the following assessment of the measured data.

Figure 3-2 is typical of most of the results obtained during the approximately 10 hours of data collection in the test program. One flight, however, that of 2/11/72, seemed to be subjected to an unusually high level of Mode D interference presumably originating in the vicinity of Fort Monmouth. This data is not used in the following examination of average characteristics although it is used to illustrate how one of the measurements, reply probability, is especially sensitive to these uncontrolled aspects of the experiment.

3.3.2 Average Characteristics

The interference phenomena represented in Figure 3-2 were also averaged over adjacent time intervals of 39,22, and 20 minutes. These data are shown in Table 3-1 with similar results from the flight of 16 February in the New York area; smoothing intervals for the latter flight were approximately one hour for each segment. Similar averages were also made for flights in the Boston area. The tabulated data summarize the average uplink and downlink interference conditions as determined from the various monitoring techniques employed.

Uplink average interrogation rates are listed on a per second basis and are the sums of Mode 3A and C interrogations. Values indicated by the calibrated automatic overload control voltage are labeled AOC, those computed from the total count over an antenna scan period of seven seconds are labeled per scan, and those computed from the count over the dwell period of 38 ms are labeled per dwell. The average SLS inhibit rates are also given on a per second basis as computed from counts over the scan

TABLE 3-1
NEW YORK ENVIRONMENTAL AVERAGE MEASUREMENTS

FLT. DATE	VAN RCD	DATE INTERVAL	3A + C INTERROGATION RATE			SLS RATE		FRUIT RATE	
			AOC	PER SCAN	PER DWELL	PER SCAN	PER DWELL	PER SCAN	PER DWELL
			ν_i (EFF)	ν_i (S)	ν_i (d)	ν_S (S)	ν_S (d)	ν_f (S)	F_f (d)
2/9	1-22	39 MIN.	117	128	132	34	41	1861	2082
2/9	23-37	22	95	92	93	56	48	1476	1827
2/9	39-52	20	115	102	120	15	22	1575	1779
2/16	1-38	64	106	106	109	38	48	1433	1378
2/16	39-68	57	122	120	109	57	54	1475	1542

period (per scan), and as computed from the count over the dwell interval (per dwell). Downlink average asynchronous fruit rates are also tabulated from the per scan and dwell counts and are given terms of replies (bracket pairs) per second.

Interrogation Rates

An earlier analysis of an SLS equipped interrogator environment as well as the results of Appendix A yield an estimate of $\bar{\nu}_I$, the average uplink interrogation rate, given by*

$$\bar{\nu}_I \simeq n \quad \frac{\phi}{360} \tag{3-1}$$

where,

n = number of interrogators within view

$\bar{\nu}$ = average repetition rate of this interrogator population

ϕ = effective beamwidth in degrees of the scanning beams

Using a typical value of ϕ = 4 degrees, and obtaining $\bar{\nu}$ = 270Hz from the available data base, then

$$\bar{\nu}_I \simeq 3n \tag{3-2}$$

*The subsequent relationships are based on models described in Ref. 5.

which is graphed in Figure 3-3. This figure also shows the average measured reply rates for the New York area and the Boston area plotted against the estimated number of interrogators within view in each case. The reply rate and interrogation rate are nearly equivalent since the average reply rate, $\overline{\nu}_R$, is just

$$\overline{\nu}_R = P_R \overline{\nu}_I \tag{3-3}$$

where P_R is the transponder reply probability. The reply rate, therefore, would be expected to be only slightly lower than the interrogation rate for reasonably high values of P_R. The level of agreement shown in the figure between these measured data and the predicted results is exceptional.

The predicted results graphed in Figure 3-3 assume all interrogators within the minor lobe response range to the aircraft are SLS equipped; reference to Figure 3-4 shows this range to be less than 10 miles for a typical average minor lobe level of -33dB and a transmitter power output less than 1Kw. A National Standards indicated transponder MTL of -71dBm and 0dB aircraft antenna gain are assumed in this plot. On this basis it is clear that the average interrogation rate over a region should not be too sensitive to the presence of several non SLS interrogators since their range of influence is fairly well localized; in these localized regions, however, higher interrogation rates would be

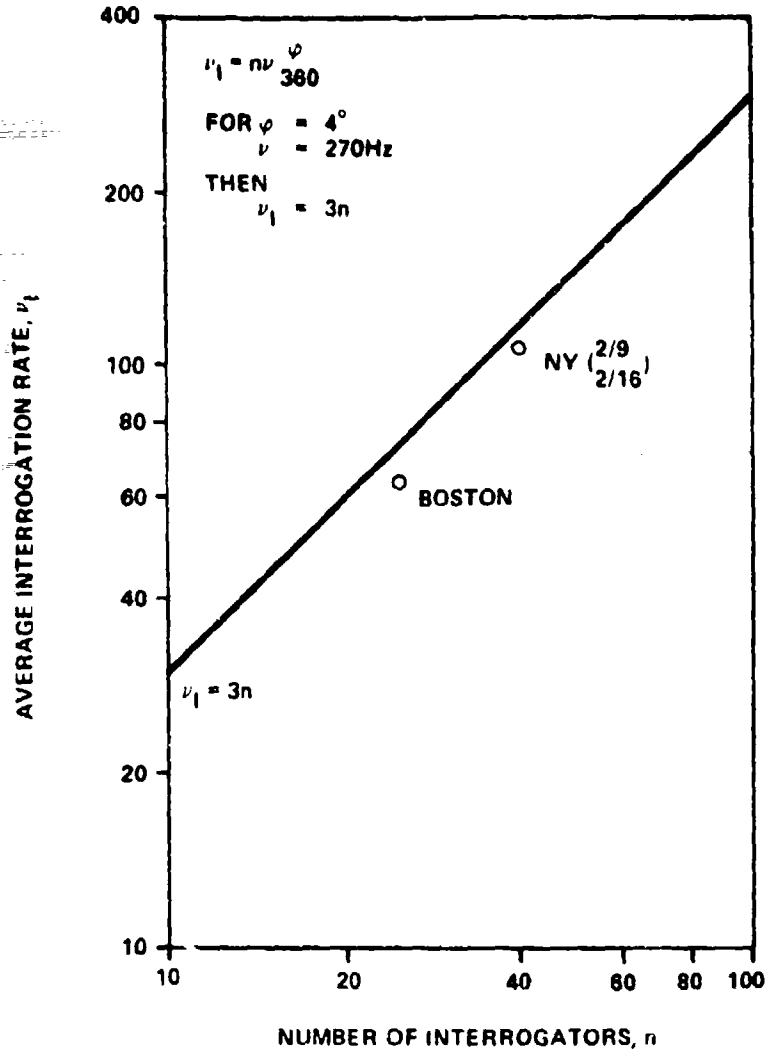


FIGURE 3-3
INTERROGATION RATE VS. NUMBER OF INTERROGATORS IN VIEW

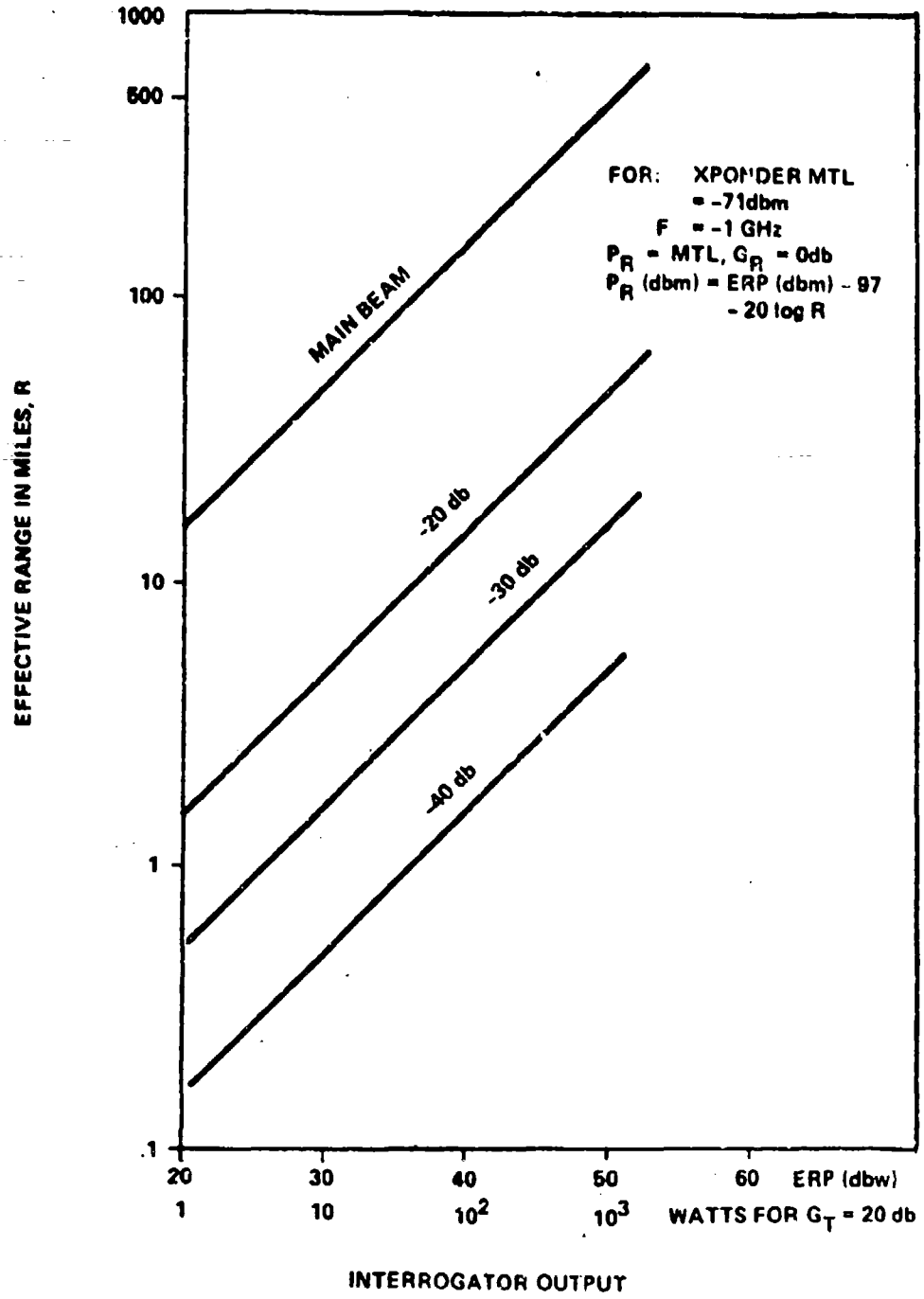


FIGURE 3-4
EFFECTIVE RANGE VS. INTERROGATOR OUTPUT POWER

expected just as they would be if the majority of the interrogator population were non SLS equipped.

SLS Rates

A somewhat greater variance is noted in the SLS rates shown in Table 3-1 than for the interrogation rates discussed above. This would be expected on the basis of the more localized behavior of the minor lobe response of a typical interrogator. Despite this greater sensitivity of this effect to the relative geometry of the aircraft and interrogator population, it is nevertheless of some interest to estimate average SLS rates on the basis of a flight through a random distribution of SLS equipped interrogators.

Suppose these randomly distributed interrogators have typical power outputs on the order of 500W and average minor lobe levels of -33dB below the main beam. From Figure 3-4, the effective range, r, of the SLS inhibit signal is then nearly 10 miles. At 8 thousand feet, the line of sight range, R, to the most remote interrogator is 125 miles, so that the average SLS rate, $\overline{\nu}_S$, might be expected to be roughly given by

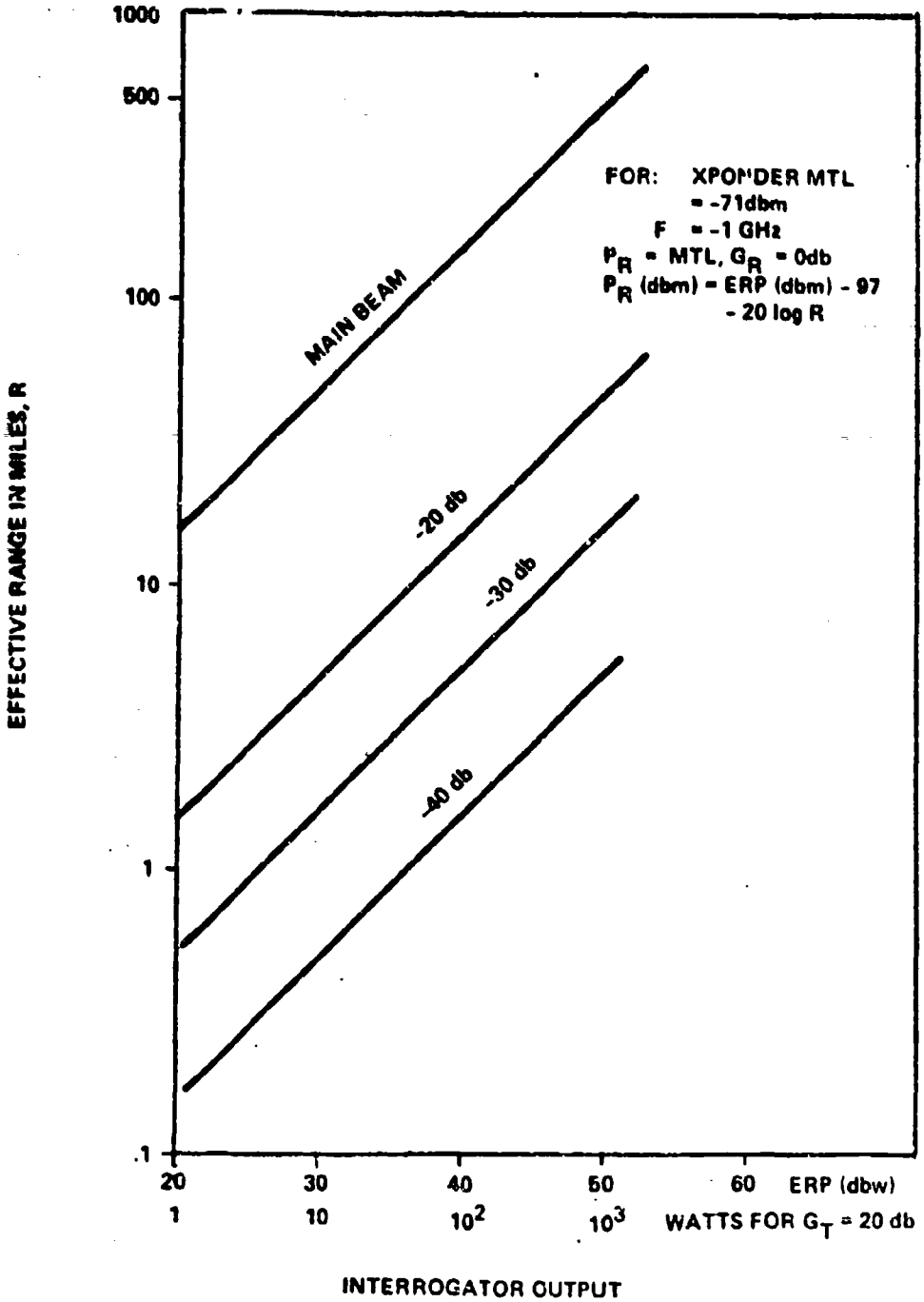
$$\overline{\nu}_S \simeq n\ \overline{\nu}\ \gamma\left(\frac{r}{R}\right)^2 \qquad (3\text{-}4)$$

where

n = number of interrogators within a range R

$\overline{\nu}$ = average interrogation rate of these units

γ = minor lobe volume efficiency factor determined by the radiation pattern lobe structure



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EFFECTIVE RANGE VS. INTERROGATOR OUTPUT POWER

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n = number of interrogators within a range R

$\overline{\nu}$ = average interrogation rate of these units

γ = minor lobe volume efficiency factor determined by the radiation pattern lobe structure

For $\overline{\nu}$ = 270Hz, and γ = 0.5, then

$$\overline{\nu}_S \simeq n \tag{3.5}$$

With n = 40 in the New York area, this result is in fair agreement with the values shown in Table 3-1. Using Equation (3.2) in Equation (3.5), we find

$$\overline{\nu}_S \simeq \frac{1}{3} \overline{\nu}_I \tag{3.6}$$

which is of some interest in terms of overall network characteristics. For example, if the output power of the interrogators increased by 10dB, then from Figure 3-4, r 30 miles. Using this in Equation (3.4), we find the new rate, $\overline{\nu}'_S$,

$$\overline{\nu}_S' \simeq 9 \overline{\nu}_S \tag{3.7}$$

from which

$$\overline{\nu}_S \simeq 3 \overline{\nu}_I \tag{3.8}$$

Hence, on an average basis, we find that a 10dB change in output power can change the relative level of the SLS rate from about one third the interrogation rate to about three times the interrogation rate.

Although these results should be regarded as only rough estimates, they may be indicative of the effects attributable to network discipline. Air Force data over New York prior to the initiation of the power reduction policy in 1968 indicated an SLS rate of about three times the interrogation rate; measurements shown in

Table 3-1 indicate that this rate is now only about one third the interrogation rate.[10]

It should be clear from the above that these averages apply only over typical flight paths through a region and would not reflect the circumstances associated with the portion of a flight path in the vicinity of one or more interrogator. In this latter case, the SLS rate may be expected to increase to levels on the order of hundreds. This condition was approximated in the Boston area flights where data was intentionally collected for flights near an interrogator; the average SLS rate over the whole flight in that case was about equal to the average interrogation rate of 65Hz.

Fruit Rates

Asynchronous interference on the downlink, or fruit, is indicated in the last two columns of Table 3-1 for the New York weekday afternoon conditions monitored. Similar measurements with the interrogator van located at Bedford, near Boston, resulted in an average fruit rate of about 300 replies per second.

Consideration of the average fruit rates shown in Table 3-1 show close agreement between values computed from the total fruit count over an antenna scan period, and those values extrapolated from the count only during the 38 ms interval in which returns were monitored while the beam illuminated the test aircraft. The net average of the fruit monitored over the flight of 2/9/72 is about 1,750 replies per second; the average value for the flight of 2/16/72 is approximately 1/460 replies per second. These measurements were made without the defruiter, and without sensitivity time control; they therefore typify the input interference conditions that would be seen by any ATC processor similarly located and with antenna pattern characteristics similar to the test unit.

Rather elementary considerations suggest that the fruit rate, on the average, should be the total interference incident through the antenna mainbeam plus the contribution attributable to the antenna minor lobe response. On this basis, we may write for the average fruit rate, $\overline{\nu}_f$,

$$\overline{\nu}_f = [\alpha\gamma + (1 - \alpha)\frac{\phi}{360}]\, M\, \overline{\nu}_R \tag{3.9}$$

where,

M = total transponder equipped traffic count within view of the interrogator

α = fraction of this traffic within the minor lobe range

$\overline{\nu}_R$ = average reply rate (approximately equal to $\overline{\nu}_I$ for most conditions of interest)

γ = minor lobe volume efficiency factor

ϕ = effective beamwidth in degrees

It has already been noted that the value of M for the flight of 2/9/72 was about 160; for the flight of 2/16/72, $M \simeq 140$; and for the Boston data, $M \simeq 40$. The fraction of these totals within the minor lobe range depends upon the cumulative traffic distribution with radius from the interrogator, and upon the effective range of the minor lobes of the antenna.

Figure 3-5 shows the effective range of the interrogator receiver as a function of the transponder transmit power and for different antenna gain levels relative to the main beam level. The interrogator receiver minimum signal level is assumed to be -82Bm as

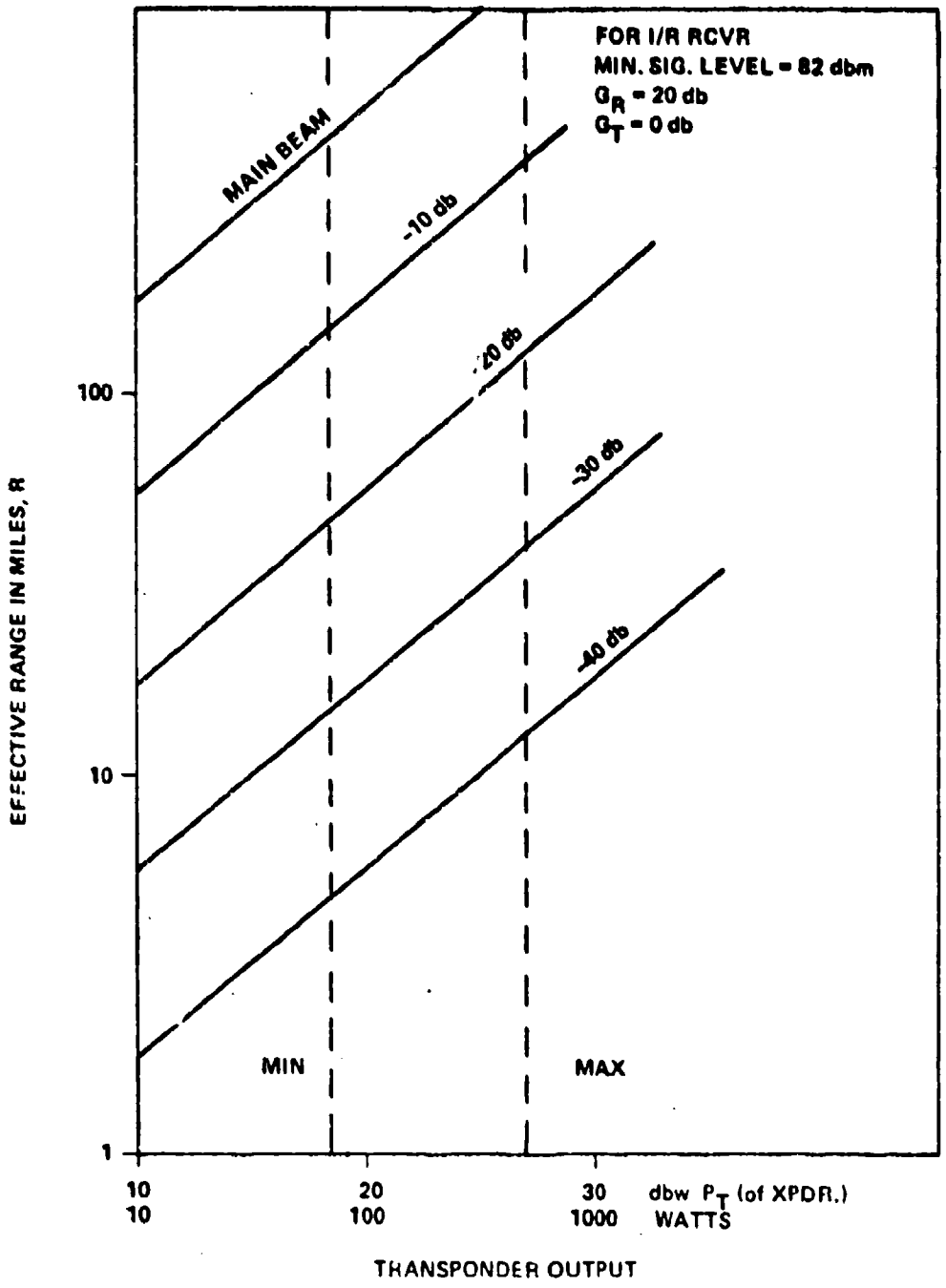

FIGURE 3-5
EFFECTIVE RANGE VS. TRANSPONDER OUTPUT POWER

specified in the ATCRBS National Standards, the aircraft antenna gain is taken as 0dB, and a 20dB interrogator main beam gain is used. The vertical dashed lines denote the National Standards specifications on minimum and maximum permitted levels of transponder output power. For a -33dB minor lobe level, and a mean level of transponder power, the effective range of the minor lobe region is then about 20 miles. Aircraft beyond this range will contribute fruit only when illuminated by the scanning main beam of the interrogator. With this minor lobe range value of 20 miles, and reference to the typical traffic cumulative distribution of Figure 3-1, we find that $\alpha \simeq 0.2$.

Again using $\gamma = 0.5$, and $\phi = 4°$, Equation (3.9) then reduces to

$$\overline{\nu}_f \approx 0.1\ M\ \overline{\nu}_I \tag{3.10}$$

where $\overline{\nu}_R$ is approximated by $\overline{\nu}_I$. This relationship is graphed in Figure 3-6 for values of M = 40 and M = 150. Results from the Boston and New York tests are also shown on this plot for comparative purposes. In Boston, $\overline{\nu}_f \approx 300$ replies/sec with a corresponding $\overline{\nu}_I = 65$Hz and a traffic count of M = 40. Fruit rates in New York averaged about 1,750 replies/sec on 2/9/72 with $M \simeq 160$, and about 1,460 replies/sec on 2/16/72 with $M \approx 140$; $\overline{\nu}_I \approx 110$Hz for both these days. The agreement between those measured values and those predicted by Equation (3.10) is excellent.

Several features of the fruit environment and its relationship to the sources of this interference are evident from this treatment. First, the major portion of the incident fruit under the measured conditions appears to arrive via the minor lobes of the antenna rather than through the scanning main beam. Traffic within the

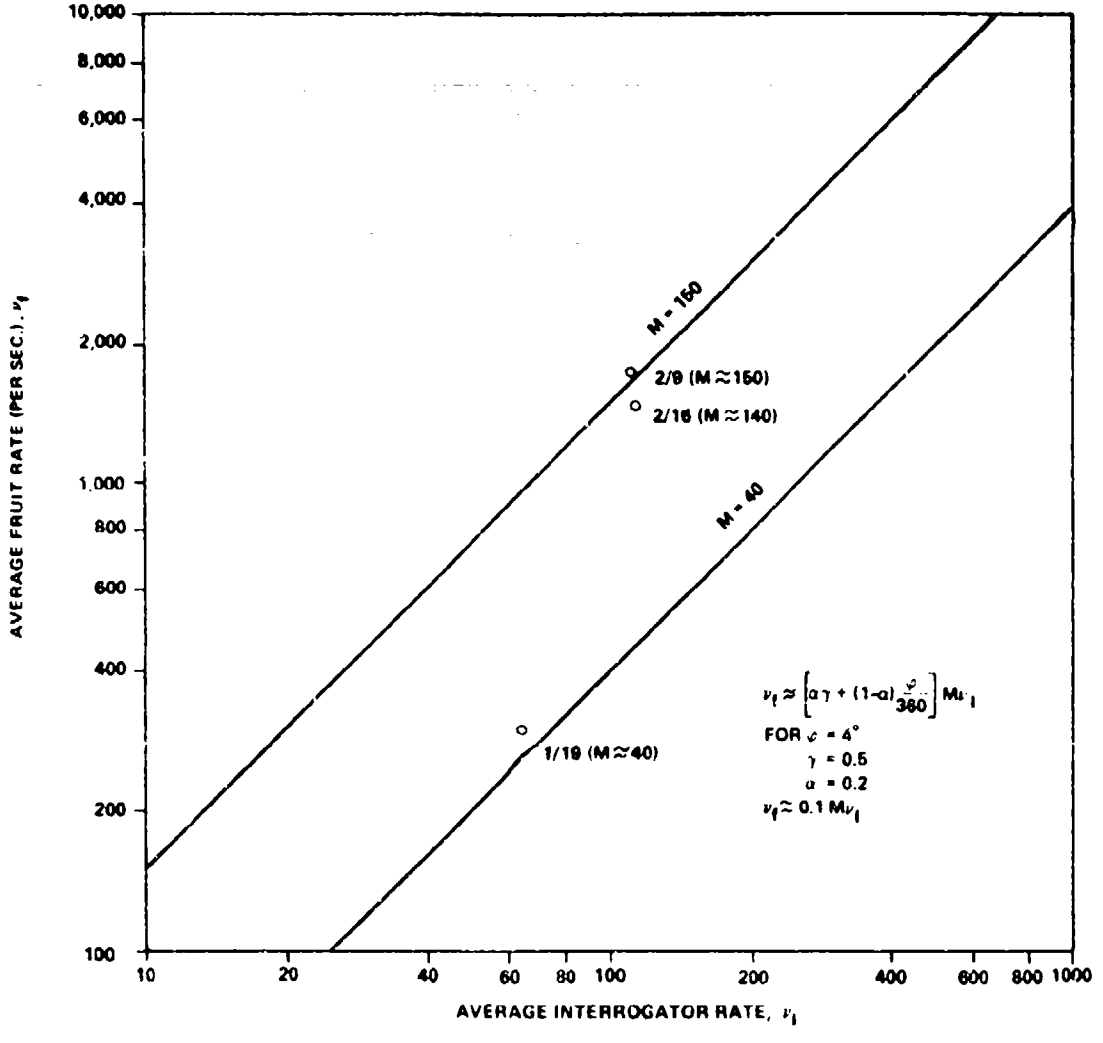

FIGURE 3-6
FRUIT RATES VS. INTERROGATION RATE FOR SEVERAL TRAFFIC COUNTS

minor lobe range will contribute more to the fruit count than it will in the main beam region due to the higher effective receiver duty ratio in the minor lobe region. For the radial traffic distribution that was measured, over 10 times as much fruit is associated with the minor lobes as is with the main beam. If this is verified by further tests, then defruiting by minor lobe blanking rather than by synchronous defruiting should provide some system advantage. The second point to be made is that the same total traffic would produce a far lower fruit level if uniformly distributed, or located in such a way that only a small fraction of the count was within the minor lobe region.

3.3.3 Short Term Characteristics

Although the previously considered average characteristics are useful in system planning, the scan to scan interference properties are of equal or perhaps greater importance in the actual design and evaluation of ATC related equipment. Uplink synchronization limitations precluded a direct reading of the interrogation by interrogation interference conditions at the transponder, but such a record was available on a two-way link basis at the interrogator receiver shift register output. Analysis of these records indicate that failures in the two-way link (either due to a transponder busy condition or to garbling of the reply on the downlink) were random, or Poisson. No suggestion of interrogator network synchronous or near synchronous induced behavior was apparent from these measurements.

Chi-squared tests also showed the fruit per scan, the fruit per dwell, and, to a lesser degree, the Mode 3A/C per scan rates exhibited a high degree of correlation with the Gaussian distribution hypothesis. Such results would be intuitively expected when

an ensemble of statistically independent events are acting in concert as they do in the ATCRBS environment. The following sections describe some additional inferences that may be drawn from the flight data.

3.3.4 Burst Interrogation Features

The transponder busy condition was sampled over 38 ms intervals at a scan rate of approximately 7 seconds. The probability that none of n possible interrogators was illuminating the transponder at the time of this look can be estimated rather easily if all scanning beams are randomly related. Since each interrogator is an independent unit, this assumption of randomness should be valid over at least an interval sufficient for our purposes.

Probability of a Clear Look

If τ_o is the average dwell interval for the ensemble of interrogators, and T_s is our scan period, or sample interval, then the average probability of illumination for a single unit is

$$q = a \frac{\tau_o}{T_s} \tag{3.11}$$

where a is the average number of times the particular interrogator of interest looked at the aircraft during the sample time, T_s. Now this average number of looks is just

$$a = \frac{T_s}{T_o} \tag{3.12}$$

where T_o is the scan period of the typical unit*. Thus, for a single unit, we may write the probability of not being in the clear as

*This assumes that data is collected over an interval long enough for this average to be valid.

$$q = \frac{\tau_o}{T_o} \tag{3.13}$$

which is the ratio of its dwell time to its scan period. This may also be expressed in terms of ϕ, the effective beamwidth in degrees, as

$$q = \frac{\phi}{360} \tag{3.14}$$

The factor q, is therefore seen to be similar in concept to the illumination duty cycle of each of the n possible contributors. The probability, g, that the transponder will be in the clear at some sample time due to the behavior of a single interfering unit is given by

$$g = 1 - q \tag{3.15}$$

Moreover, for n statistically independent units, the probability of not being seen by any of the units is

$$p(n) = g^n \tag{3.16}$$

or, upon substitution,

$$p(n) = \left[1 - \frac{\phi}{360}\right]^n \tag{3.17}$$

This probability of not being seen by any of n interrogators is shown in Figure 3-7 as a function of n for effective beamwidths of $\phi = 4°$ and $\phi = 6°$. Notice that for n = 40, the indicated aggregate probability of not being illuminated by any of the 40 interrogators at the sample time is 0.5 or greater, depending upon the effective value of ϕ.

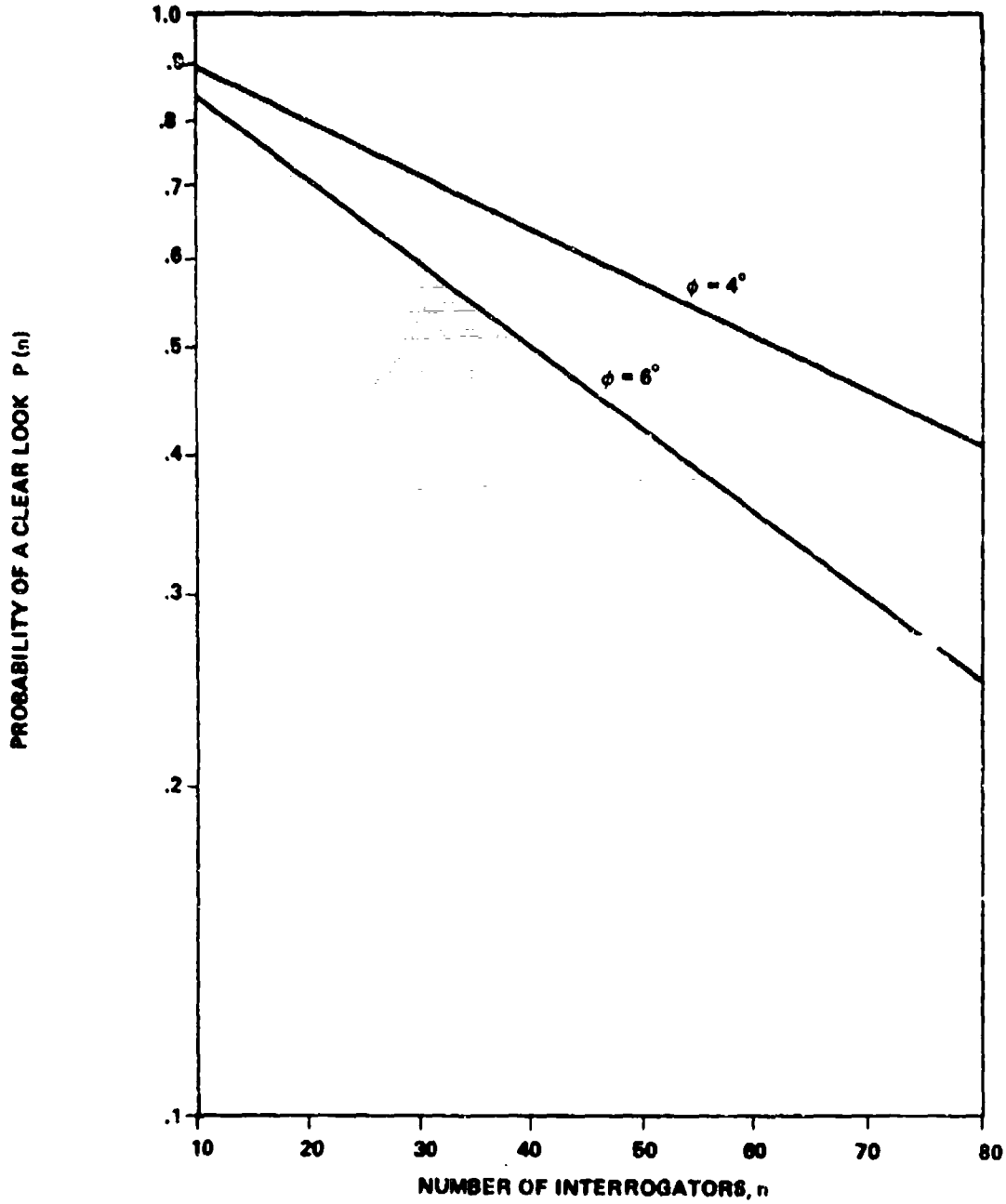

FIGURE 3-7
PROBABILITY OF NOT BEING SEEN BY AT LEAST ONE BEAM
OF N RANDOMLY RELATED BEAMS

Distribution of Clear Looks

The probability of having m successive scans with clear looks at the transponder may also be estimated for independent statistical events if the average probability of a clear look, p, is known. This is just the conditional probability of m events, given the occurrence of an event, or $p(m|1)$. For random occurrences,

$$p(m|1) = p^{m-1}q \tag{3.18}$$

where q is the failure of the event to occur and so $q = 1 - p$. Thus, Equation (3.18) becomes

$$p(m|1) = \frac{1 - p}{p} \; p^{m} \tag{3.19}$$

Figure 3-8 illustrates the behavior of the expected distribution of clear look sequence lengths for values of p equal to 0.3, 0.5, and 0.8. These values of p may be related to the number of interrogators considered, n, through the previous relationship of Figure 3-7.

This model of the behavior of a population of n independently scanning interrogators was applied to the data from the flight of 2/16/72. The airborne record was examined for the times when the transponder did not reply to any other interrogator during the 38 msec in which the Mode D interrogation series occurred on each scan. The total number of samples over this flight was 360, and the transponder was in the clear 178 of these times. The measured value of the probability of being in the clear was thus $\hat{p} = 0.495$. The frequency distribution of the zero reply sequences was also tabulated and is given in Table 3-2. For example, a single zero reply (or clear look) occurred 41 times

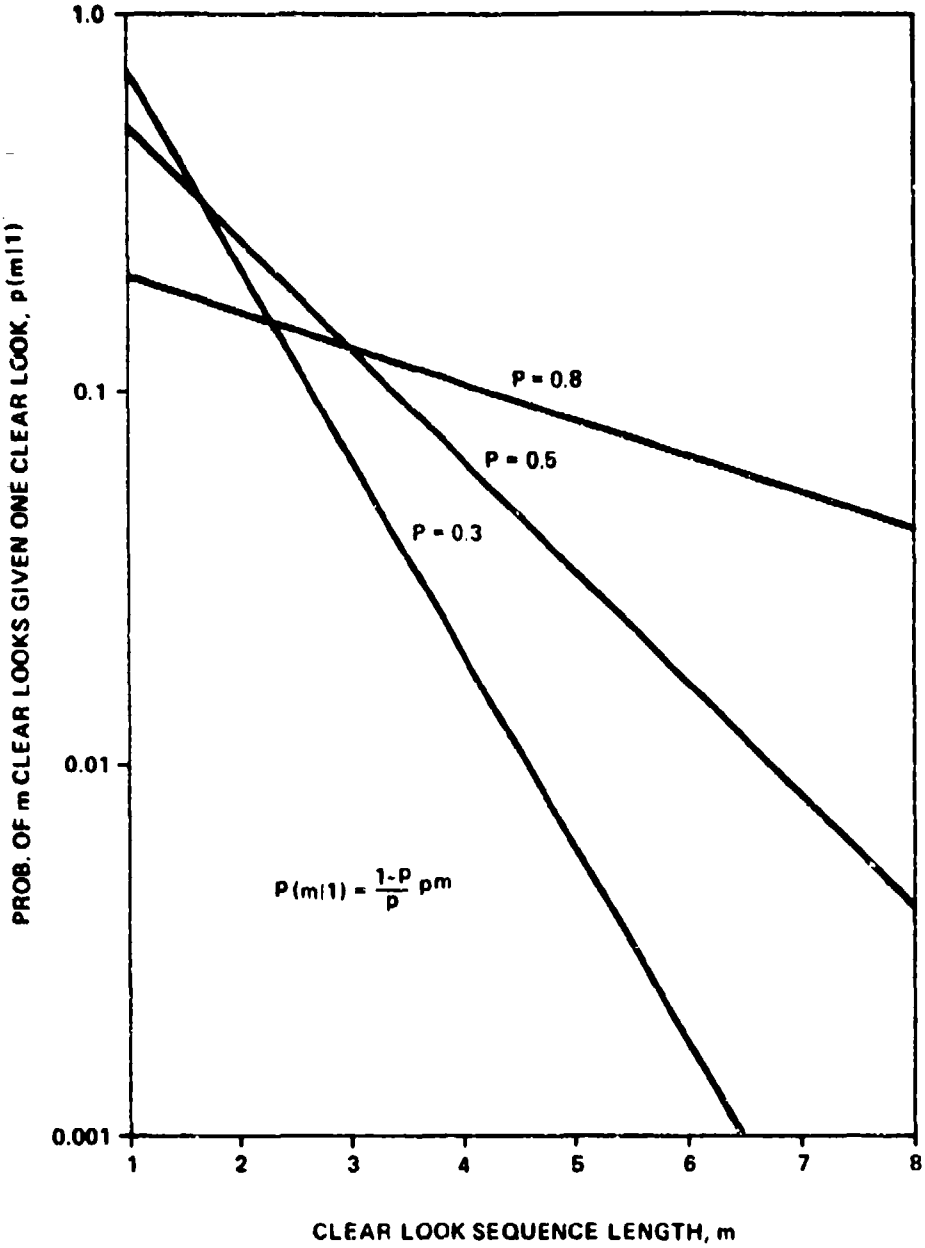

FIGURE 3-8
SEQUENCE LENGTH DISTRIBUTIONS FOR SEVERAL PROBABILITIES

TABLE 3-2
ANALYSIS OF CLEAR DWELL INTERVALS FOR FLIGHT OF 2/16

ZERO SEQ. LENGTH, m	NUM. OF m SEQ., 0_m	NUM. OF ZEROS	OBSERVED $\hat{p}(m\|1) = \frac{0_m}{n}$	THEORY $\hat{p}(m\|1) = \hat{p}^{m-1}(1-\hat{p})$	EXPECTED $e_m = p(m\|1)n$	$\frac{(0_m - e_m)^2}{e_m}$
1	41	41	0.5061	0.5056	40.95	0.00
2	17	34	0.2098	0.2500	20.25	0.52
3	9	27	0.1111	0.1236	10.01	0.10
4	4	16	0.0493	0.0611	4.95	0.18
5	4	20	0.0493	0.0302	2.45	0.98
6	3	18	0.0370	0.0149	1.21	2.65
7	2	14	0.0246	0.0074	0.60	3.27
8	1	8	0.0123	0.0037	0.30	1.63
	n = 81	m = 178	1.000	.9985	80.8	9.33

TOTAL SAMPLE, N = 360

$\hat{p} = \frac{M}{N} = \frac{178}{360} = 0.495$ = PROB. OF A ZERO

over the flight, while two clear looks in succession occurred 17 times.

The remainder of this table presents the results of a Chi-square test of the measured data against the assumed distribution given in Equation (3.19).* The resulting error term of 9.33 is regarded as a highly significant level of agreement. Thus the random model assumption is justified by the measurements. The actual data are plotted in Figure 3-9 for comparison with the predicted distribution for independent events with an average probability of 0.5. The successive differences in the points beyond m = 4 are determined by a single event difference in their occurrence and so should not be considered with too much significance for the available sample size.

Distribution of Overlapped Looks

The probability of no other scanning beam illuminating the transponder at the time it is illuminated by the interrogator of interest has been examined above along with the distribution of these expected clear looks at the transponder. If other sources of transponder reply failure are ignored, then the reply probability is unity over the entire dwell interval of these clear looks and the only cause of two-way link failure would be due to downlink garbling of the reply by fruit.

When, however, the transponder is illuminated by other interrogators, it is of interest to know how many other interrogators are simultaneously looking at the transponder at the time of the desired look. If the interrogation rates of the different

*This analysis is due to Dr. J. S. Matney, MITRE Corporation

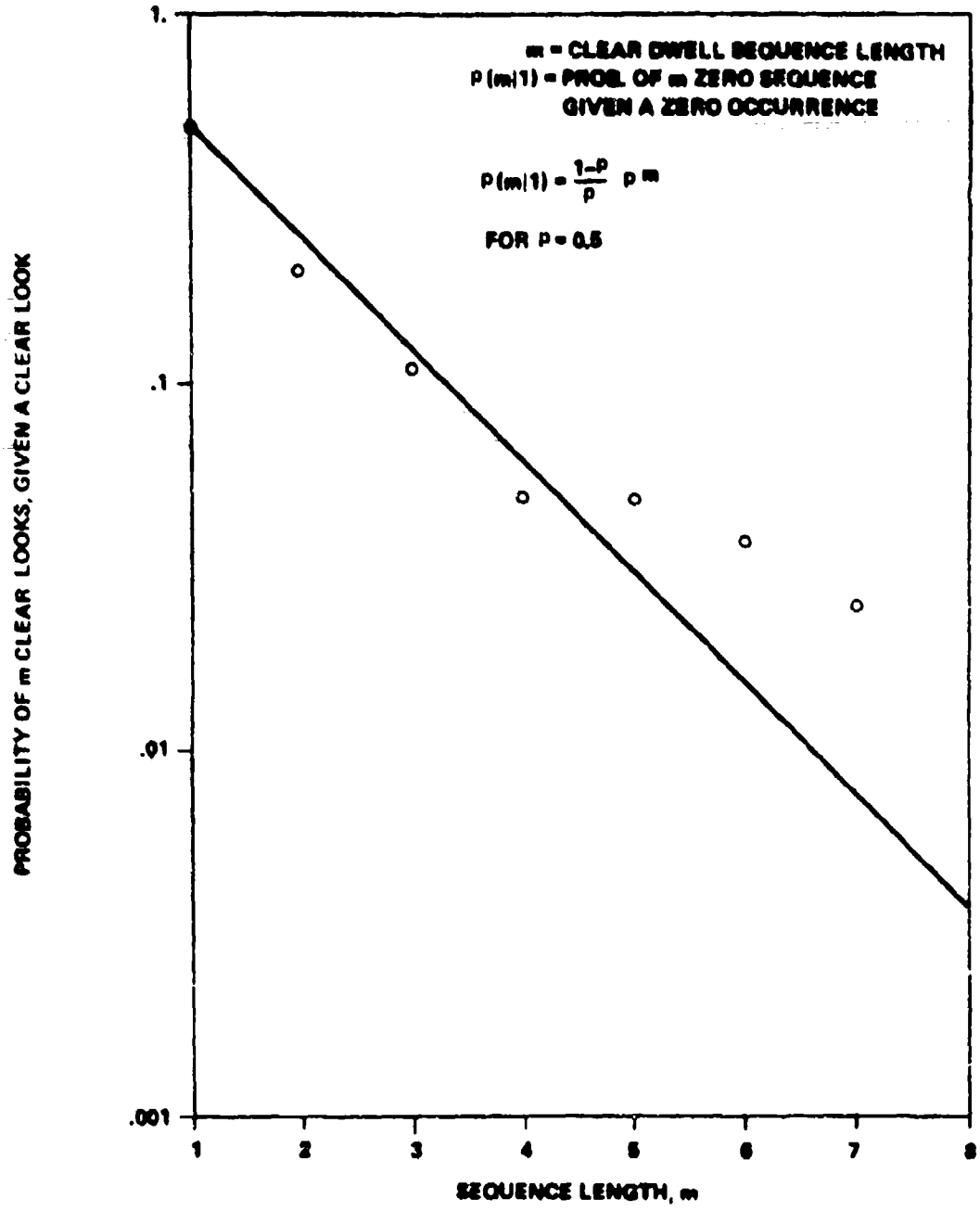

FIGURE 3-9
OBSERVED AND COMPUTED CLEAR DWELL DISTRIBUTION
FOR FLIGHT OF 2/16

interrogators are asynchronous, as well as their scan rates, then the probability of the transponder being busy at the time of a desired reply is related to the number of these overlapping beams. Time did not permit an analysis of the Mode 3A/C reply data to the extent necessary to substantiate this model, but the following treatment may be infered by a simple extention of the looks-in-the-clear data examined above. The treatment is predicated on the fact that the clear look distributions correspond with the distribution expected for a random model. For Poisson or randomly distributed illuminations, we may write the probability of L beams simultaneously illuminating the transponder, P(L), as

$$P(L) = \frac{\lambda^L e^{-\lambda}}{L!} \tag{3.20}$$

where λ is the average number of beams simultaneously illuminating the target at the time of the desired look. The analysis of the flight record just presented showed the probability of no beam illuminating the target during the desired beam dwell interval ($L = 0$) was 0.5 as illustrated in Table 3-2. In this case, for $L = 0$, $P(0) = 0.5$ and Equation (3.20) yields $\lambda = 0.69$ overlapping beams. This value of λ in the Poisson relationship enables the computation of the probabilities of occurrence of one, two, three, etc. overlapping beams.

Similar probability distributions are computed for the average probability of a clear look given by $P(0) = 0.85$, and $P(0) = 0.25$ and the results are illustrated in Figure 3-10 along with the case of $P(0) = 0.50$. These plots show that as the probability of a clear look is reduced, the probability of more than one beam overlapping is increased. These burst circumstances may be related

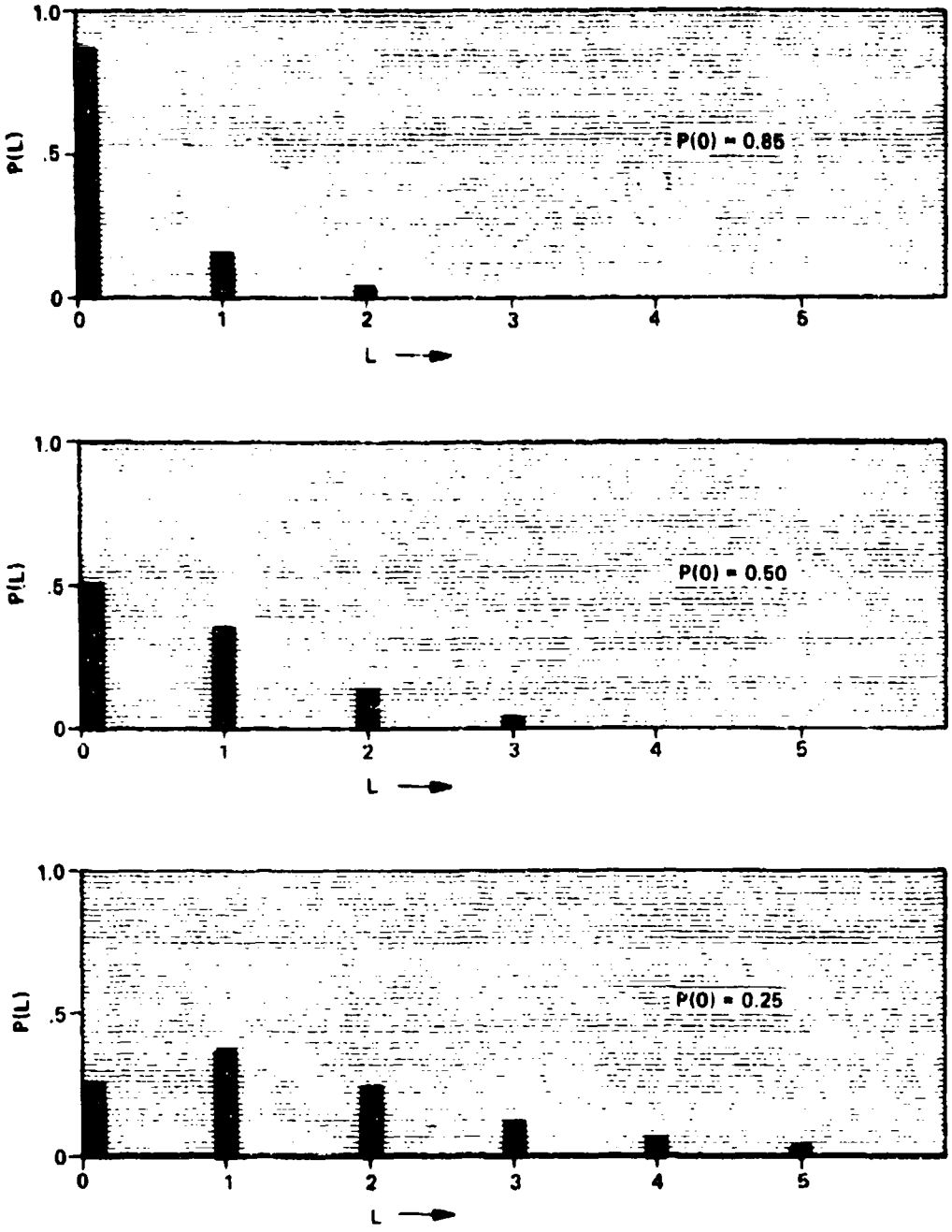

FIGURE 3-10
PROBABILITY DISTRIBUTIONS OF L OVERLAPPING BEAMS, P(L), FOR SEVERAL PROBABILITIES OF L = 0, P(0)

to the number of independently related scanning interrogators through the curves of Figure 3-7.

These various distribution features are employed in Appendix A to develop the transponder reply probability in terms of the interrogator population characteristics. The average value thus obtained is in agreement with the results of the simple formulation of the model used in reference 5. The treatment given in the appendix, however, enables an estimate of the variance on this average value assuming the validity of the Poisson model.

3.3.5 Performance Degradation

In addition to coordinated monitoring of interference conditions, the experiment also attempted to relate these conditions to degradations in equipment performance. The probability of the transponder being busy is a measure of this degradation on the uplink; the probability of a desired reply being garbled by a fruit reply is an index of degradation on the downlink.

Probability of Garbled Reply

Differences in the number of Mode D replies made by the test aircraft over each scan, compared with the number of Mode D replies received in the clear at the van interrogator on each scan were used to compute the average probability of reply garbling in the measured fruit environment. Now the probability of a reply arriving in the clear, p_c, is just

$$p_c = 1 - p_g \tag{3.21}$$

where p_g is the probability of garble. For random arrivals of the interfering fruit at a rate of $\bar{\nu}_f$ replies/sec, the probability of no arrival within an interval, τ, is given by

$$P_c = e^{-\bar{\nu}_f \tau} \tag{3.22}$$

where τ is some interval length over which the interference could overlap a desired reply.

Bracket pair spacing of replies is 20.3μs; adding 0.45μs for the pulse width results in a value of $\tau \approx 21\mu s$ for non-overlapped replies. While τ_R is the bracket pair interval, it does not necessarily relate directly the value of τ indicated in Equation (3.22). The value of τ for ungarbled replies used here depends upon the receiver detector characteristics; some detectors have greater de-interleaving capabilities than others. It is well known, for example, that simple bracket-pair detectors can produce erroneous detection reports if adjacent replies are separated by exactly a bracket pair spacing, since this would lead the detector to declaration of a ghost reply due to the adjacent reply spacing. Thus, although some latitude exists for a proper choice of τ, it should be greater than 21 μs and probably less than 42 μs for the relatively simple detector used in our experiments.

Two values of τ, 25 μs and 35 μs, are used in the plots of Equation 3.22 shown in Figure 3-11. The data points are measured values in Boston and New York; both the per dwell and the per scan measurements of the probabilities of clear replies are shown. The value of τ = 35 μs seems to provide the better fit to the data with this Poisson model.

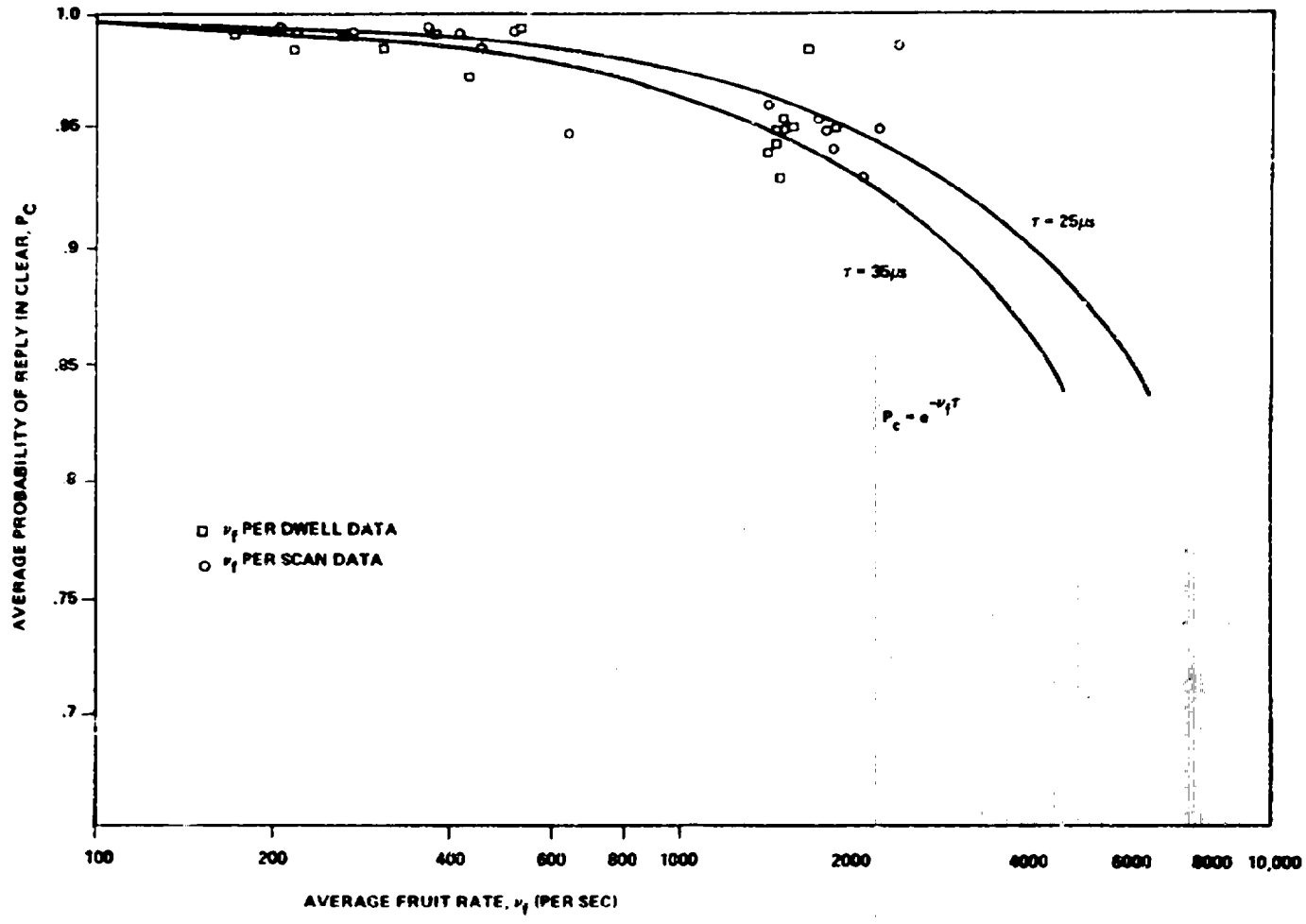

FIGURE 3-11
INTERROGATOR DETECTOR PERFORMANCE IN A FRUIT ENVIRONMENT

It should be clear that the real value of Figure 3-11 is the fact that probability of a reply being ungarbled in a fruit environment can be described by a Poisson process. Indicated values of P_c for the associated ν_f levels are valid only for the detector characteristics employed in the experiment; and a more sophisticated detector (such as those used in ARTS or NAS) would have better de-interleaving capabilities in sorting out replies under potentially garbling conditions. If the degarbling features of these detectors are known, however, they may be analyzed on the basis of this Poisson description of fruit arrivals.

Transponder Reply Probability

The average reply probability for the test aircraft was computed from the ratios of the number of Mode D replies made over each scan, compared to the 10 Mode D interrogations made on each scan. Correlation of these measurements with the related Mode 3A and C interrogation rates and SLS rates was then examined. Close agreement between these factors would indicate that failure of the transponder to reply to a desired Mode D interrogation could be statistically attributed to the transponder being busy with a 3A/C reply or SLS inhibit at the time of interrogation. The experiment was configured so that this cause of transponder failure was isolated as much as possible from other causes of reply failure.

On the basis of the random interrogation model presented in Section 3.3.4, we would expect the reply probability of the transponder to be given by

$$P_R = e^{-\bar{\nu}_I \tau_I} \tag{3.23}$$

when only the interrogation rate, $\bar{\nu}_I$, is considered. The time constant, τ_I, is the lockout time of the unit occupied in receiving and replying to an interrogation and then being inhibited from applying for a specified interval. An upper bound on τ_I might be approximately 80 μs.

Assuming the SLS rate, $\bar{\nu}_S$, is also randomly distributed and independent of $\bar{\nu}_I$, we may then express P_R as

$$P_R = e^{-(\bar{\nu}_I \tau_I + \bar{\nu}_S \tau_S)} \tag{3.24}$$

where τ_S is the inhibit interval for an SLS occurrence. Since τ_S is approximately one half τ_I, we may re-write Equation (3.24) as

$$P_R = e^{-\bar{\nu}_T \tau_I} \tag{3.25}$$

where

$$\bar{\nu}_T = \bar{\nu}_I + \frac{\bar{\nu}_S}{2}$$

to compensate for the difference in τ_S and τ_I.

Measured values of P_R in the Boston and New York areas are plotted in Figure 3-12 as a function of the weighted sum of the interrogation and suppression rates, $\bar{\nu}_T$. Equation (3.25) is also shown on this figure as the predicted value of P_R for the associated $\bar{\nu}_T$ based on a value of τ_I = 80 μs.

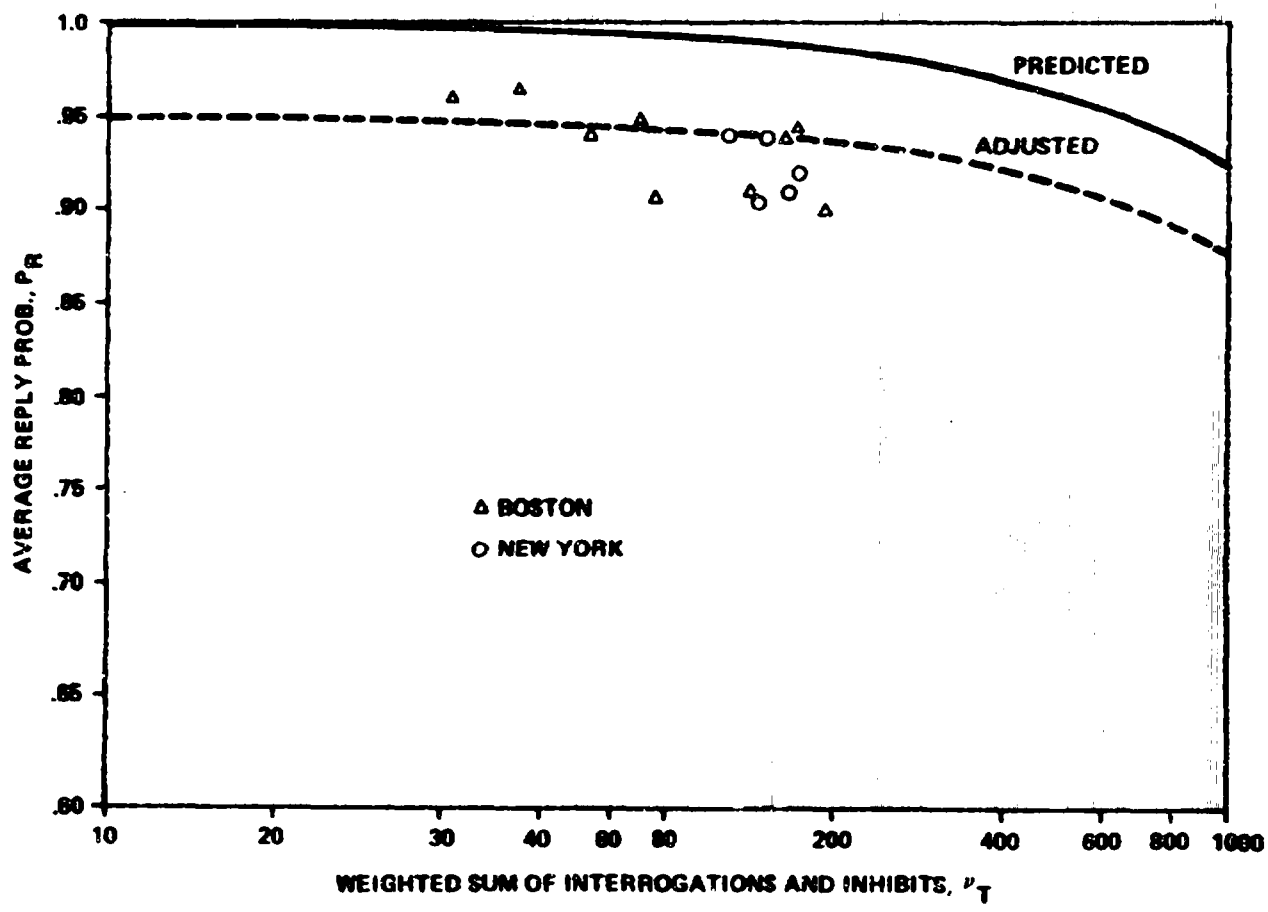

FIGURE 3-12
COMPARISON OF MEASURED REPLY PROBABILITIES WITH THEORETICAL VALUES

Measured values of the transponder reply probability were some five to six percent below the values expected on the basis of uplink interference due to measured 3A/C and SLS rates. This result of the test program reflected the only failure of the simple statistical model to closely describe average as well as many short term facets of ATCRBS performance under interference conditions.

Before leaving the results displayed in Figure 3-12, we might just note that if some constant multiplier, η, is used with the failure model represented by the Poisson distribution of uplink interrogations and suppressions, the first order result would be to lower the predicted curve for the range of $\bar{\nu}_T$ shown. Choosing $\eta = 0.95$ results in the dashed curve of the figure labled "adjusted". No conclusive preference of one curve over the other appears warranted on the basis of presently available data, but the following does develop some mechanism that may account for the use of the η factor.

3.4 Transponder Reply Failure

The reply or the absence of a reply by a transponder to a given interrogation is determined by three factors:

1. Signal condition - Bracket pair spacing, pulse width, and frequency must be within specified tolerances and the detected signal level must be above the minimum threshold level (MTL) of the transponder receiver.
2. Suppression condition - Replies are inhibited if the amplitude of the P_2 pulse relative to that of the P_1 pulse is above a certain level. This side lobe suppression (SLS) feature is intended to restrict transponder replies to only the main beam of the interrogator even though the P_1, P_3 pulse levels may be above the MTL in the minor lobe region of the interrogator.

3. Busy condition - A valid interrogation will not elicit a reply if the transponder is occupied at the time in responding to another valid interrogation or suppression from another interrogator within its field of view.

These effects are independent and each may be represented by a probability of success. The net reply probability is therefore the product of these three probabilities.

The intent of the measurement program was to limit data collection to only those circumstances when the transponder busy condition was the determining factor. Signal level monitors were therefore used to inhibit data gathering in the event of low detected signal strength. This provision minimized the possibility of falsely attributing a failure to reply to a busy condition when, in fact, the reply failure was due to a low signal to noise condition.

It was assumed in configuring the experiment that the suppression condition was either in an ON or an INHIBIT state over the beam dwell interval. If this discrete state assumption is valid, then no error is introduced in the results due to SLS since the reply probability due to this condition would be either unity or zero over the dwell interval. Thus, dwell data samples could be lost due to this inhibit effect, but if recorded, no error in the data would be produced by this phenomenon. The next section examines this assumption from the point of view of detection theory. Subsequent sections examine other possible causes for failure of the transponder to reply.

Suppression Characteristics

Figure 3-13 functionally indicates the transponder reply logic; two threshold tests are indicated before a reply is enabled. The

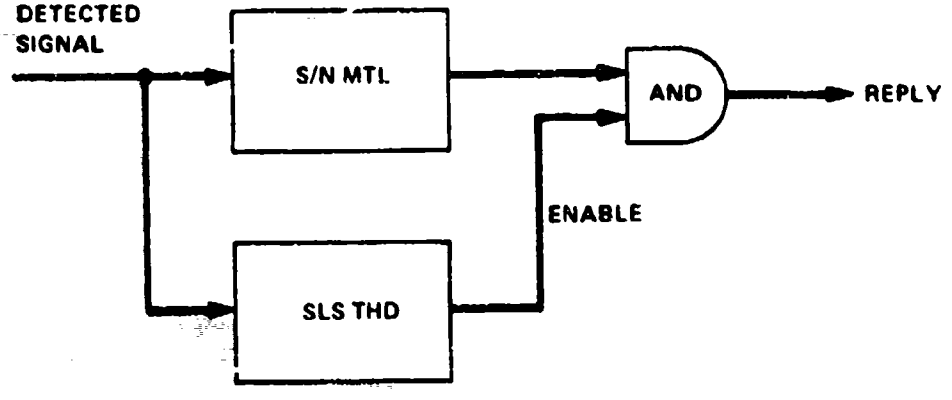

FIGURE 3-13
TRANSPONDER REPLY LOGIC

action of the signal to noise minimum threshold level has already been mentioned; the performance of this detector has been thoroughly analyzed in terms of the probability of detection for an acceptable false alarm rate. These treatments have considered both fluctuating and non-fluctuating targets in the presence of gaussian noise[6]. For a given false alarm rate in each case the probability of detection is a function of the input signal-to-noise ratio.

As stated above, the basic approach to the design of the data collection system assumed that the enable state on the output of the SLS threshold detector was a discrete and well behaved condition. That is, a particular ratio of the P_1 pulse to the P_2(SLS) pulse either inhibited a reply or it did not. This assumption would seem reasonable if no noise were present in the determination of this received pulse ratio.

In practice, of course, some noise is expected in the generation and detection of these two pulses and so a statistical treatment of the SLS inhibit condition seems in order. Under this concept, the reply AND gate in the figure is enabled only on the basis of the product of the probabilities of obtaining outputs from the two independent threshold circuits (assuming it is not busy).

A more detailed description of this possible mechanism has been developed, but for this discussion it will only be noted that this probabilistic model could account for a significant degradation in the reply probability for SLS relative pattern levels of -9dB or less. These conditions are inevitable with the commonly used interrogator antenna configurations employing a separate SLS antenna. If this omni antenna is mounted above the scanning

antenna, these problems occur at certain ranges; if the omni is mounted to the side of the scanning antenna, these problems occur at certain azimuth sectors.

Tracking Behavior

Synchronization of the airborne and ground data was accomplished by an early-late tracking gate centered about the data collection interval. Initiation of this process was determined by a tracking cursor position which also generated a VHF tone to enable the gate counts. This process could result in a measurement bias if the anticipated beam center (on the basis of the tracking determination) was displaced from the actual beam center when data was collected. To guard against this possibility a criterion of two out of ten hits in these early-late gates was employed. It was expected that data would thus be collected over the beam center if these conditions were met on either side of the data collection interval since the SLS action would inhibit spurious replies beyond the beam edges.

Consideration of an enable probability variation such as that just mentioned for SLS could alter this response characteristic however. If this model of one aspect of the transponder reply probability is representative, then it is clear that the net reply probability measured over the appropriate portion of the beam must include the integrated value of the enable probability variation over that segment of the beam.

The enable probability variation due to the SLS pattern could also lead to data collection over an asymmetric portion of the beam since the low values of the probability of enabling a reply could still be adequate for the two out of ten test and result

in the data collection interval beginning at an extreme edge of the beam for instance rather than at a more symmetrical point.

Emphasis should be placed on the fact that the scope of the test program precluded any conclusive experimental examination of either the preceeding hypotheses or the one that follows. They are all offered as possibilities to account for reply failure mechanisms that could be as significant as the expected busy condition for valid interrogations and SLS inhibits.

SLS Recovery Time

A lower reply probability than expected on the basis of the recorded number of interrogations and suppressions could result if other events affected transponder operation and were not recorded due to limitations in the data collection system. Monitored events in the apparatus were limited to the recording of Mode D replies, Mode 3A plus Mode C replies, and the number of side lobe suppressions. The occurrence of Mode 2 interrogations or particular combinations of interference resulting from, say, TACAN or DME equipment could keep the transponder busy but not be recorded. If a mechanism of this sort is a feasible explanation for the measured reply probability, however, then it must be equally valid in the Boston area as well as in the New York area, since similar results were noted in both series of flights.

The ATCRBS interrogator network itself is also a source of high single pulse emission rates due to the P_2 pulse radiation from the suppression, or omni, antenna. Since the relative gain of this antenna is nominally + 2dB, the effective range of these pulses may be nearly 50 miles. Contributions from twenty such sources may not then be unusual, and, since each operates at

typically 280Hz, the net intensity of single pulses may be approximately 5.6×10^3 pulses/sec.

Transponder detector/decoder circuits vary in design, but a common method of determining the ratio, P_1/P_2, appears to use a desensitization of the unit for approximately 4μs following the receipt of a single pulse. If the P_2 pulse relative amplitude is then sufficiently great to overcome the desensitization, the unit is then suppressed on the basis that P_2 is greater in amplitude than the associated P_1 pulse. If P_2 is smaller in amplitude than P_1, then the detector recovers its sensitivity and looks for the P_3 pulse at the appropriate interval determined by its mode of response. This design approach treats any incident pulse as a P_1 pulse until a decision is made regarding the P_2 or P_3 test conditions.

With the above detector model, reception of a single pulse may be expected to reduce the probability of receiving a valid interrogation for at least 4μs after receipt of the pulse. Using $\tau = 4\mu s$, and a single pulse arrival rate of 5.6×10^3Hz, the Poisson model of the probability of the unit responding to a valid interrogation (when inhibited due to only single pulse considerations) is just

$$\begin{aligned} p &\simeq e^{-\nu\tau} \\ &\simeq 1 - \nu\tau \\ &\simeq 0.98 \end{aligned}$$

Although no extensive experimental confirmation of this model was possible during this program, it is nevertheless significant that a possible mechanism of this sort could, in some instances, be as important in influencing the net transponder reply

probability as is the expected condition for an average uplink Mode 3A/C interrogation rate of several hundred interrogations per second.

Decoder Recovery Time

All the above transponder inhibit mechanisms have been examined from the standpoint of their potential effect on the reply probability. It was discovered during the preparation of this report, however, that the NARCO ATC-A employs a Mode C decoder logic with a recovery time of almost 100μs.[7] This same multivibrator type design was also used for the Mode D decoder used in the experiment. The unit was subsequently modified to use tapped delay lines for these functions (the Mode A decoder was already supplied with a tapped delay line) and an additional flight in the New York area was conducted.

A duplication of the February 9 flight path was used for these measurements with the modified transponder. The results were in general agreement with the earlier tests except for the expected increase in the reply probability (and of course the round reliability). The measured reply probability in this flight was nearly 98 per cent, or almost the value expected on the basis of the random arrival model. This increase in the reply probability is attributable to the elimination of the unduely long recovery time noted in the original multivibrator logic design. This delay time is not believed to be intrinsic to the logic design and should be readily correctable in such units, if this action should prove necessary.

These more recent measurements appear to be accurate and so we may conclude that the assumed model provides a good estimate of all aspects of the system's average condition. This finding does

not appreciably alter the previous interpretation of the measurements except for the expected five or six percent increase in the measured values of the reply probability and the two way round reliability. On this basis, the reply probability data displayed in Figure 3-12 would be increased from the indicated average of about 93 percent to a nominal value of 98 percent if they had been measured with the modified transponder detector logic. A similar improvement would be noted in the round reliability measurement.

4. ARTS III PERFORMANCE DEGRADATION

Performance of the ARTS III processor in a high interference environment was examined by a Monte Carlo simulation employing a typical approach path for the tracked aircraft, and statistical representations of the interference conditions. Although the principal aim of this effort was the determination of performance breakdown conditions due to the degraded environment, the study also included some assessment of the effect of system operating parameters on this condition. Since the tracker output is also sensitive to target fading, the evaluation was undertaken for both fixed width targets (no fading) and for variable width targets (signal fluctuations).

4.1 Examined Variables

The interference conditions were represented by two independent variables, the reply probability, and the asynchronous fruit rate. Data were typically collected by holding the fruit rate at some specified value and varying the transponder reply probability. As mentioned above, these runs were repeated for both fixed width and variable width targets as well as for several processor parameters settings.

Response characteristics of ARTS III were monitored at the tracker output and at the detector output interface with the tracker. The detector was characterized by the following parameters:

1. Probability of Detection
2. Failure to Discern Mode C
3. Probability of Code Validation
4. Probability of Erroneous Code Reports
5. Fraction of Targets Classified Weak

6. Probability of Target Splits
7. Distribution of Azimuth Errors

Of these parameters, the most critical to tracker performance appear to be the probability of detection and the probability of erroneous code reports.

The tracker output is represented by the following:

1. Track Correlation Ratio (previously termed the tracking blip/scan).
2. Probability of Track Loss.
3. Number of Aircraft Tracked.

The first of these parameters is the most signif[illegible] index of the tracker operational state.

An estimate of general system capability was beyond the scope of this program, however, some observations on processing time utilization as well as controller work load factors were included. A detailed description of the evaluation process is given in Reference 3, and a summary of the major aspects of the effort is included here as Appendix D.

4.2 Tracker Performance

The ARTS tracker acquires or accepts assigned target information from the detector. The smoothed data from the tracker is compared with the detector output on a per scan basis; the track status is determined from this comparison. Targets not satisfying a specified set of criteria are initially assigned an active coast status. If these targets are not reacquired by the tracker within a certain number of scans, they are then

relegated to a tabular coast status and track must be reinitiated by the controller. (Manual insertion is also required for all non-discrete code targets.)

A track correlation ratio may then be defined by[3]

$$T_c = \frac{1}{n} \sum_{i=1}^{n} \left(1 - \frac{T_i + A_i}{S_i}\right)$$

where

n = number of targets tracked

T_i = number of scans in tabular coast for track i

A_i = number of scans in active coast for track i

S_i = number of scans in system for track i

The track correlation ratio is therefore the ratio of the number of scans a track correlated to the number of scans it is tracked.

Track correlation dependence on the degraded beacon environment is summarized in Figures 4-1 for fixed width targets and in 4-2 for variable width targets. All tracks considered had discrete mode 3/A codes and altitude reporting on Mode C. The fixed width targets were 4 degrees wide (16 hits) and the variable width targets ranged in run length from 0 to 26 hits with an average of 16 hits. The tracker was operated in the cases shown with the set of parameters used in the Chicago ARTS III System in July 1971. Performance improvements associated with a more recent choice of parameters are summarized in Appendix D.

The data in Figures 4-1 and 4-2 are the same as given in Appendix A except that they are replotted on a semilog scale in order to

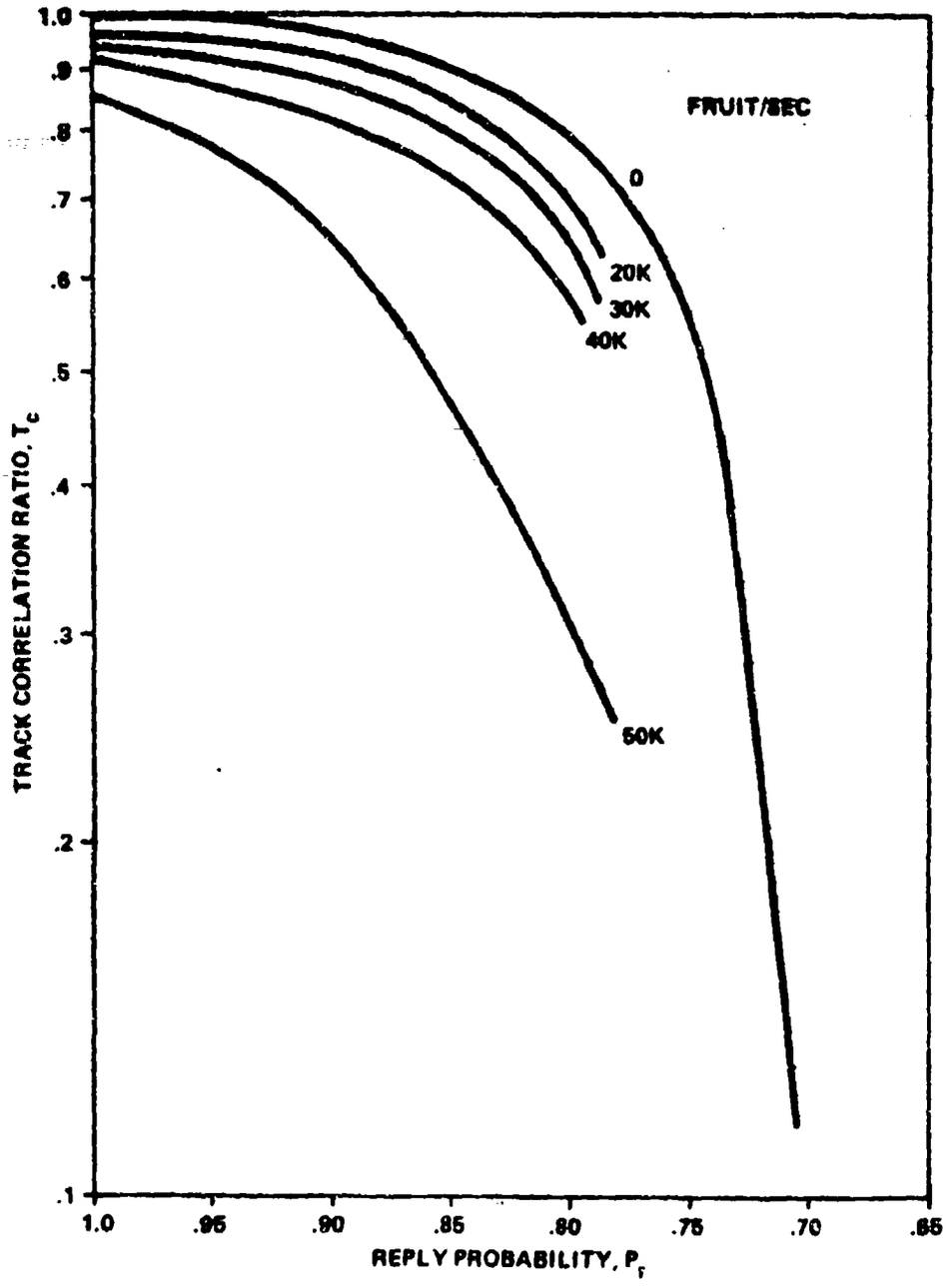

FIGURE 4-1
ARTS III TRACK CORRELATION DEPENDENCE FOR FIXED WIDTH TARGETS AND INDICATED FRUIT RATES

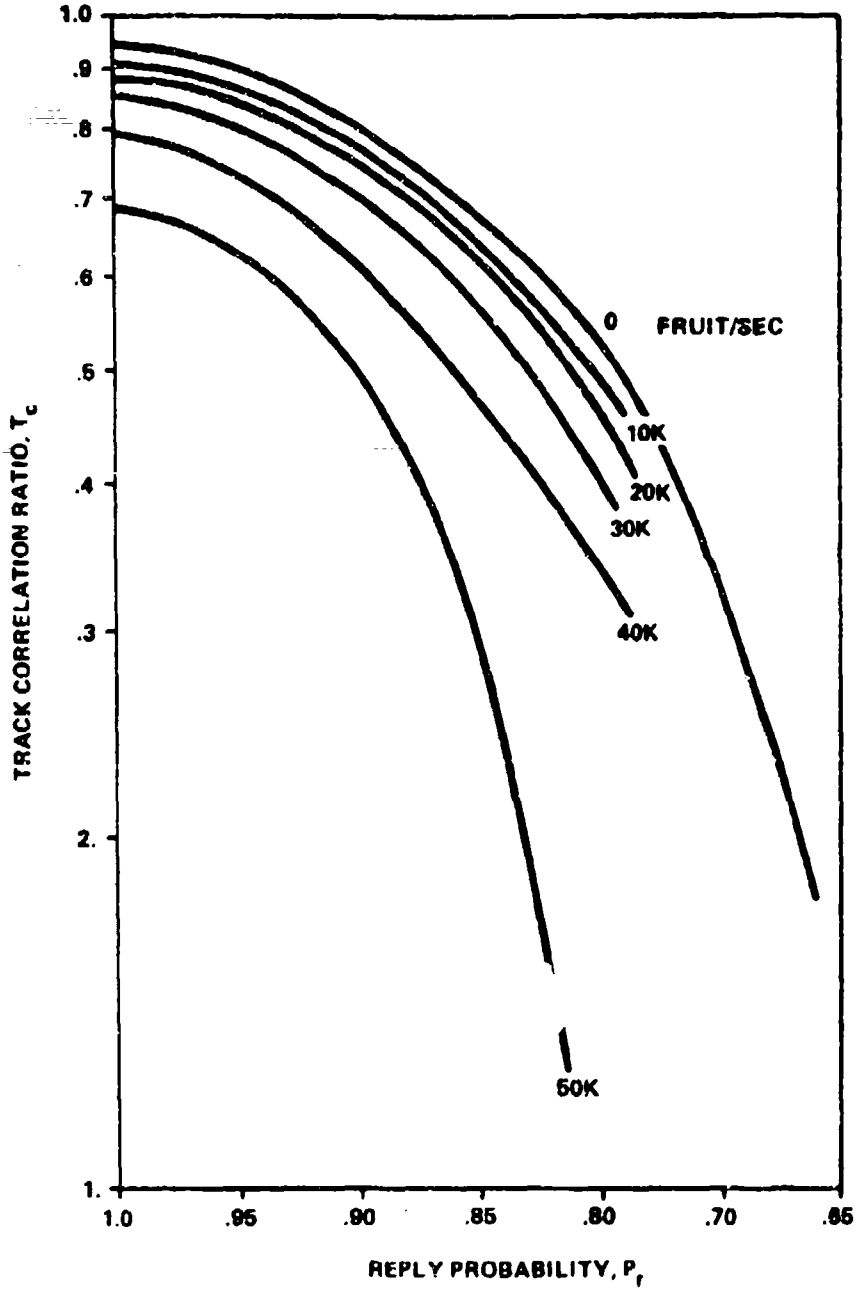

FIGURE 4-2
ARTS III TRACK CORRELATION DEPENDENCE FOR VARIABLE WIDTH TARGETS AND INDICATED FRUIT RATES

better illustrate relative effects and rates of degradation regardless of the magnitudes of the values. A constant rate of change in track correlation for a fixed incremental change in the reply probability would plot as a straight line on this scale for example.

Fixed Width Targets

Track correlation dependence on decreasing transponder reply probability is illustrated in Figure 4-1 for fixed targets in fruit environments ranging from 0 to 50 thousand replies per second.* It can be seen here that T_c remains above 90 percent for low or modest (up to several thousand replies/second) values of fruit until the reply probability falls below 85 percent. Below this point, however, the rate of performance deterioration is very rapid as indicated by the slope of the curve for 0 fruit. In general, increasing fruit rates degrade performance for a fixed reply probability, but the sensitivity to this effect is not as pronounced as it is to a decrease in reply probability.

Although a lower bound on a track correlation ratio tolerable to the controller cannot be fixed without an extensive human factors study, it would nevertheless appear that reply probabilities above 85% and fruit rates below 30K replies/second would be necessary for effective control activities. With this thought coupled with the indicated rates of decay, it seems evident that concern with the system condition should occur when P_r falls below 90%, and the fruit rates approach 20K replies/second.

*These fruit rates correspond to the input conditions to the defruiter.

Variable Width Targets

The fixed width targets just considered are representative of the ideal case that might be enjoyed through improvements in the interrogator elevation plane coverage and dual antenna installations on the airborne fleet. These assumptions were made in the above case in order to isolate the effects of the interference environment on an otherwise perfect system.

Such a circumstance does not prevail in today's environment and, indeed, the data used for target width variations in the simulations were obtained from monitoring target widths at Chicago. The performance indicated by Figure 4-2 is therefore more nearly representative of expected conditions without improved antenna coverage.

Comparison of Figure 4-2 with 4-1 shows, first of all, that T_c is degraded by the fluctuating target widths that occur during aircraft maneuvers. Secondly, it may be noted that the rate of deterioration in T_c (with a degraded interference environment) is more rapid in this case than it is with the assumed ideal coverage. In general, system tolerance to interference is sharply reduced in this more practical representation of circumstances.

According to Figure 4-2, a value of track correlation above 90% can be expected only for modest fruit rates and reply probabilities above 0.95. An average value of T_c of at least 80% results, for example, only for P_r greater than 0.90 and a fruit rate less than about 10K replies/second. It would seem that these latter values might serve as appropriate alarm levels for the interference environment under these rather practical coverage conditions.

5. TPX-42 PERFORMANCE DEGRADATION

The TPX-42 detects and displays the two dimensional position of beacon equipped targets on a scan by scan basis. Identification codes and altitude information are also displayed for Mode 3/A and Mode C reporting equipment. Although tracking is not employed in the basic TPX-42 considered in this study, the displayed information for each target so equipped includes the presence and position of the target as well as the detected code.

A Monte Carlo simulation was again used with statistical representations of the transponder reply probability and the incident fruit rate. In addition to these two independent variables, the target run length (or number of hits), the sliding window detector parameter settings, and the influence of failure to reply to an interlaced mode was examined. As outlined in Appendix E, and more completely reviewed in Reference 4, the detector parameter settings and the target run length were based on the best available estimate of the Air Force choice of these variables.

5.1 Summary of Results

The reply probability was equally incremented between values of 1.0 to 0.65 for fixed fruit rate levels for each set of Monte Carlo runs. Fruit levels from 300 to 30,000 replies per second were used. Since confidence level settings of either CL = 0, or CL = 4 are under consideration by the Air Force, both settings were examined in a degraded environment with a detector window length of eight. A mode interlace of 1, 2, 3 was used which might represent a military unit operating on Modes 3/A, C, and 2. Data were collected for all modes responding, and for one mode absent as would be the case for a civil transponder failing to reply to Mode 2.

Typical target widths of 16 hits were considered as well as were weak targets as represented by only 9 hits. Some data were also collected for run lengths of 30 hits to illustrate how an extremely wide target relative to the detector window length might behave.

The following output characteristics were used to typify system performance:

* Probability of detection
* Probability of code validation given detection
* Jitter in the azimuthal angle measurement
* Probability of target split

General response of these characteristics to the input variables is summarized in Table 5-1. Inspection of the rows of this sensitivity matrix shows that the transponder reply probability is much more critical than is the fruit rate. The action of fruit is to decrease the probability of code validation, while the reply probability has a relatively strong influence on all output features. Of the operating parameters examined, the target width and confidence level were of much greater relative importance than was the missing mode impact. The columns of this matrix suggest that all the output characteristics are degraded by worsening fruit and reply probabilities, but code validation is perhaps most sensitive to this environment.

5.2 Figure of Merit

TPX-42 performance under the circumstance of all interlaced modes responding is summarized in Appendix E. Code validation is found to be most sensitive to a degraded environment for this circumstance. A tolerable level of system degradation in this case should therefore be closely related to the

TABLE 5-1
SENSITIVITY OF PERFORMANCE PARAMETERS TO CHANGES IN ENVIRONMENT

ENVIRONMENT	INCREASING DETECTION PROBABILITY	INCREASING AZIMUTH ACCURACY	INCREASING CODE VALI-DATION PROBABILITY	INCREASING PERCENTAGE OF TARGET SPLITS
SEE FIGURES*	2-2 THRU 2-6	2-7 THRU 2-10	2-13 THRU 2-17	2-18 THRU 2-20
INCREASING FRUIT	0	0	-2	0
INCREASING TRANSPONDER REPLY RATIO	+3	+2	+3	-2
INCREASING CONFIDENCE LEVEL	-2	+2	+1	-3
INCREASING HITS	+3	-3	+3	+3
INCREASING MODE REPLY RATIO	+2	+1	0	0

SENSITIVITY RATINGS:

PLUS (+) POSITIVE CORRELATION
MINUS (-) NEGATIVE CORRELATION

SENSITIVITY LEVELS:

0 UNAFFECTED OR MILDLY AFFECTED
1 MODERATELY AFFECTED
2 STRONGLY AFFECTED
3 VERY STRONGLY AFFECTED

*FIGURES REFER TO HAZELTINE FINAL REPORT NO. 10773

importance of identification and altitude read out in the ATC function since the other facets of the detection process are not significantly deteriorated. As shown in Table 5-1, this condition is chiefly dependent upon the reply probability of the transponder.

It should be noted, however, that a missing reply condition in the mode interlace also reduced the probability of detection as well as reduced azimuth accuracy. The concept of a figure of merit is introduced in the following in order to quantify an aggregate condition resulting from the degradation of several aspects of the system.

5.2.1 Merit Concept

Information displayed to the controller by the TPX-42 consists of:

1. Presence or absence of a target, or probability of detection, P_D.
2. Aircraft identification and altitude, or the conditional probability of code validation given detection, $P(V|D)$.
3. Target position uncertainty, or azimuth jitter, σ_ϕ. Range jitter as well as the probability of target split are also important but their magnitudes are small in comparison to the angle measurement.

An overall index of system performance, Q, might then be formed by the weighted product of these different factors. Thus, if g is the selected weighting function for each parameter, then

$$Q = \left[g_D \quad (P_D)\right]\left[g_V \quad (P(V|D))\right]\left[g_\phi \quad (\sigma_\phi)\right] \qquad (5.1)$$

This quantity is a measure of how the composite information presentation compares to some standard which is determined by the weighting functions. A reasonable choice for g_D and g_V is unity weighting, i.e., equal importance is assigned to the presence of the target and to the display of the proper altitude and code. In this instance,

$$Q \approx \left[P_D \; P(V|D)\right]\left[g_\phi(\sigma_\phi)\right] \tag{5.2}$$

and degradation of any of these quantities reduces the resulting value of Q. Although this may at first appear somewhat arbitrary, it does have the advantage of indicating the likelihood of having all the required information available.

Treatment of the angle uncertainty may utilize two limiting cases.[8] First, it is desirable that the target jitter be small enough so that it is not a nuisance to the controller, and second, some penalty should be paid if this jitter should become so great that it prevents minimum separation of traffic at the maximum range of the unit. These determinations are to some extent subjective since controller tolerance may vary and since the penalty for greater than minimum aircraft separation should reflect the system demand.

For our purposes, however, suppose that a 3 σ_ϕ jitter of no greater than 1/4 inch is unnoticed by the controller. (That is, the standard deviation is slightly less than 0.1 inches). If the display and the interrogator are collocated, then we may form the ratio

$$\frac{R\left(3\sigma_\phi\right)}{1/4 \text{ inch}} \leq \frac{R}{11 \text{ inches}} \tag{5.3}$$

where R is the target range and a 22 inch CRT is assumed. This results in $\sigma_\phi \leq .44$ degrees or 1.8 pulse repetition periods for the conditions simulated. The corresponding weighting function would then have unity value for values of σ_ϕ less than 1.8 prp since jitter of this magnitude would not disturb the controller.

Target noise greater than this would degrade system operation to some extent, however, and a sufficiently large magnitude would require greater than normal aircraft separation for an acceptable level of safety. Consider a 3σ target position jitter of three miles, which might provide a safe minimum separation of six miles. If this standard is maintained at a maximum range of 100 miles, then the associated azimuth angle jitter is $\sigma_\phi = 0.6$ degrees of about 2.3 prp.

Exponentially degrading system utility from the point where jitter becomes noticeable (1.8 prp) to a value of 50% effectiveness when the jitter increases to 2.3 prps results in a linear plot on a semi-log scale. This form of presentation has the additional advantage of enabling piecewise linear approximate fits to the simulation output data.

5.2.2 Application to Output Data

TPX-42 performance with all interlaced modes responding is in Appendix B and it can be noted that code validation is, in this case, the chief cause of system degradation. A comparison of the system states of health is not as directly evident, however, when the transponder fails to reply to one of the interlaced modes since the various aspects of displayed data degrade at different rates for different conditions.

The notion of the figure of merit developed above does afford a means of normalizing these conditions for such a comparison. Figure 5-1 shows the concept applied to the simulation output when 16 hits occur over the beam dwell interval and a value of CL=0 is employed. Other detector settings are the same as previously listed. A fruit rate of one thousand replies per second is assumed and the results are presented as a function of the transponder reply probability.* The basic data obtained from the simulation are the probability of detection, P_D; the probability of code validation given detection, $P(V|D)$; and the azimuth angle measurement jitter, σ_ϕ. This last term is indicated by the weighting function, g_ϕ with the break at P_r = 0.8 occurring when σ_ϕ = 1.8 prp and the relative value of 0.5 at P_r = 0.7 occurring when σ_ϕ = 2.3 prp as discussed above.

The curve designated by $P_D P(V|D)$ represents the probability that the target is detected and the code is validated. If target position noise is of no concern, then this curve is a fair measure of performance. The additional requirement on the angle measurement results in the overall index, Q, shown as the product of $P_D P(V|D)$ and g_ϕ. Initial deterioration in performance is due to code validation which falls below the 90% level when P_r = 0.87. A slight decrease in P_D also occurs at this point, but the general condition of the display (except for poorer code validation) does not change appreciably until azimuth jitter becomes noticeable. On the basis of the standards used here, the displayed quality of information is

* Performance is much more sharply dependent upon P_R than on even reasonably high fruit rates as indicated by Table 5-1 and discussed more fully in the appendix.

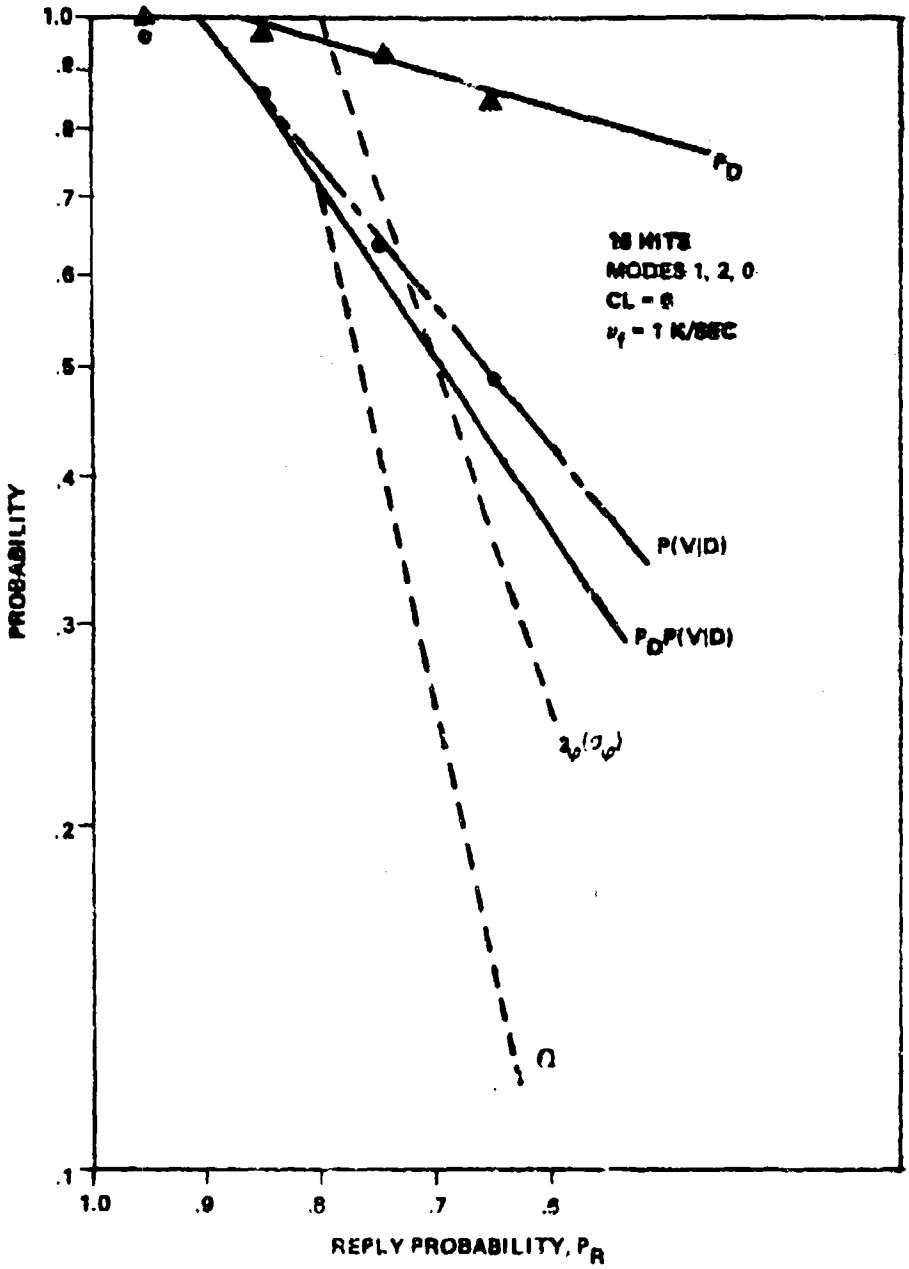

FIGURE 5-1
MISSING MODE RESPONSE FOR 16 HITS, CL = 0

about 40% poorer at a value of $P_r = 0.75$ than it is for a value of P_r of 0.9 or better.

A comparison with this circumstance is indicated in Figure 5-2, which represents the same case except the detector confidence level parameter is selected as CL=4 rather than the value CL=0 previously used. Here we again note a deterioration beginning at $P_r = 0.9$, but this time due to a decreased probability of detection. The onset of azimuth jitter limitations do not begin until the reply probability has fallen to 0.75. General quality of the display for this point is 55% of the desired quality, however, as indicated by the value for Q.

Thus, although little overall difference in performance is noticed between choices of CL=0 and CL=4 when $P_r \geq 0.8$, it would seem that a choice of CL=4 might be preferred in an environment typified by a transponder reply probability lower than 0.8.

Processor performance with weak targets is indicated in the next two figures. Conditions in Figure 5-3 are the same as those represented in Figure 5-1 except the target width is only 9 hits rather than 16. Although azimuth jitter is never a problem over the range of P_r indicated, the overall system figure of merit suffers from a low $P(V|D)$. Loss in the probability of detection causes a sharper drop in performance with values of P_r below 0.9 as shown by their joint effect, Q.

A change of confidence level setting to a value of CL=4 results in the variations shown in Figure 5-4. Here the probability of detection is the performance determining factor. Although

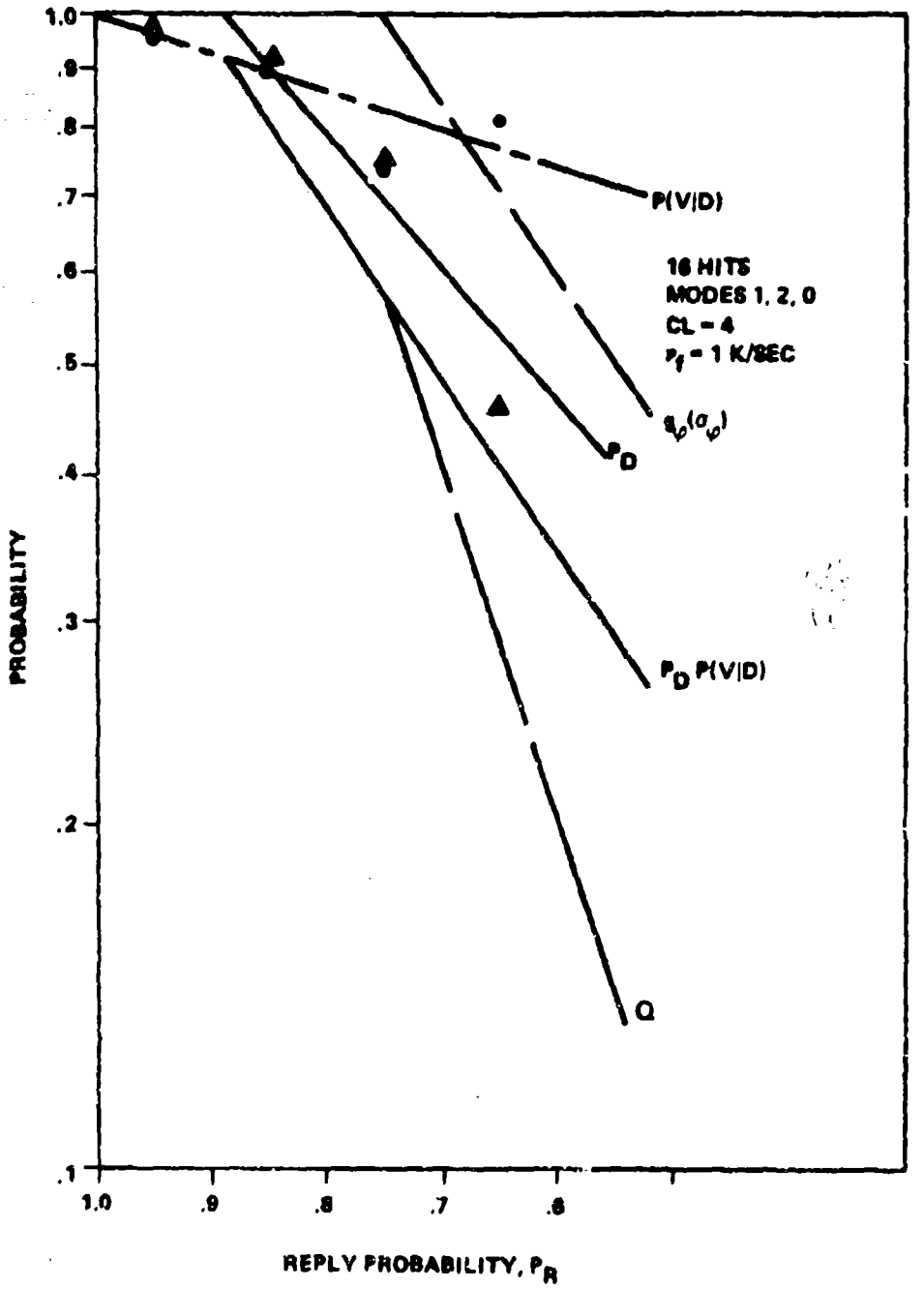

FIGURE 5-2
MISSING 3 MODE RESPONSE FOR 16 HITS, CL = 4

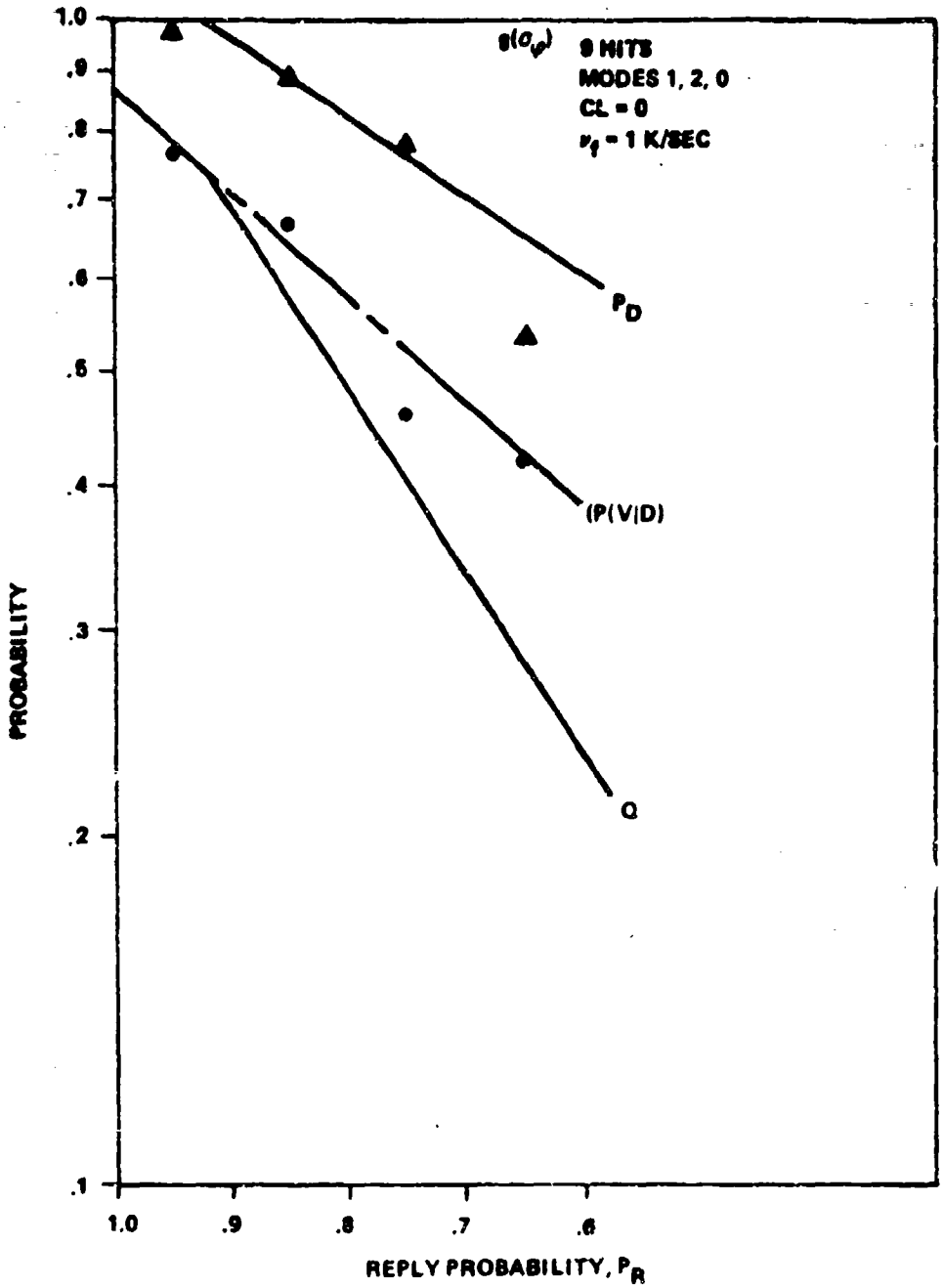

FIGURE 5-3
MISSING MODE RESPONSE FOR 9 HITS, CL = 0

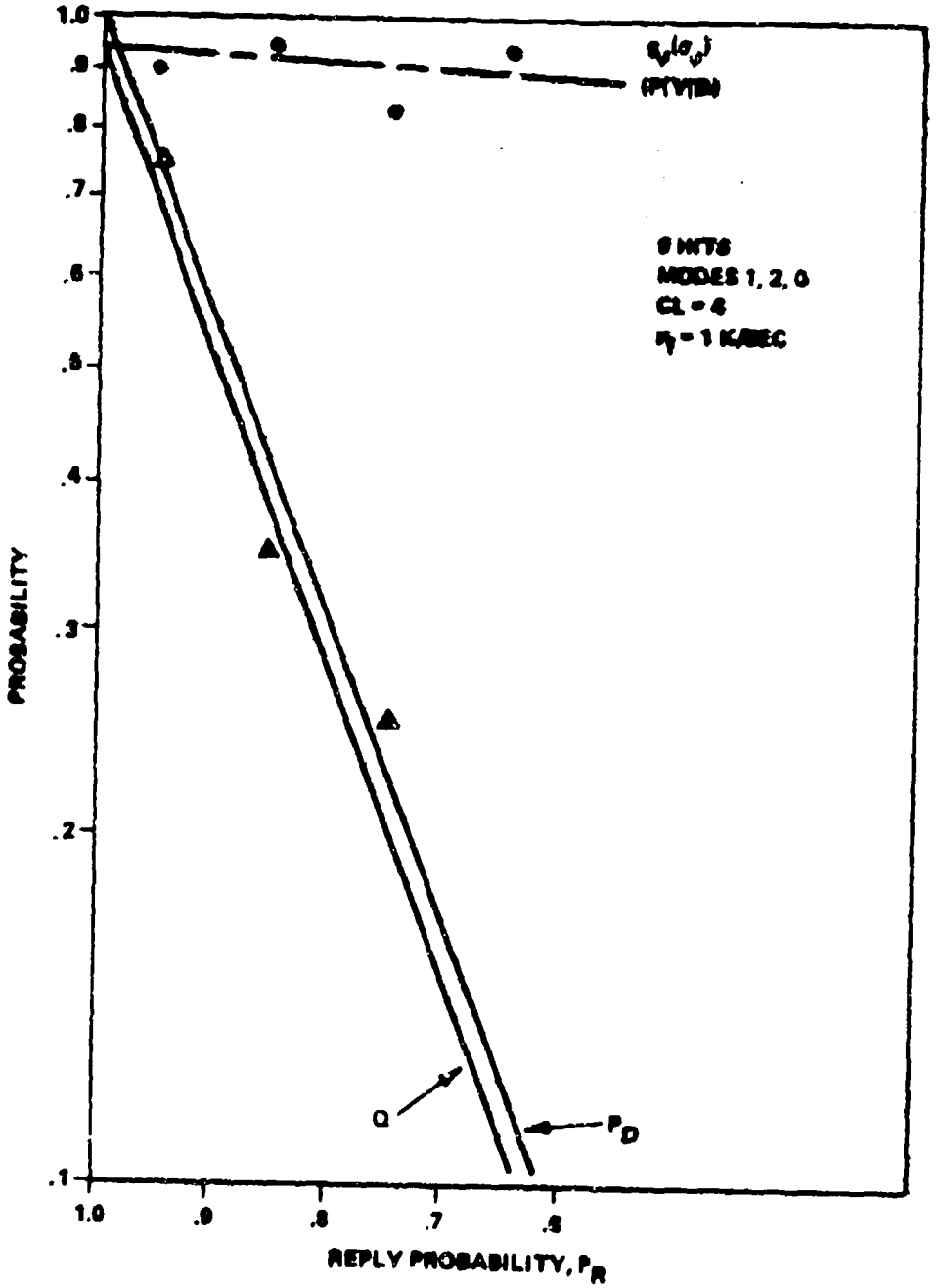

FIGURE 5-4
MISSING MODE RESPONSE FOR 9 HITS, CL = 4

both azimuth jitter and code validation remain acceptable, the overall characteristics represented by Q are worse than with a choice of CL=0.

5.2.3 Tolerable Limits

Establishment of acceptable limits on the degradation of the TPX-42 displayed information was beyond the scope of the present effort. This determination would involve human factors consideration of controller stress levels under a variety of circumstances as well as an analysis of work load effects attributable to the poorer information quality.

Indicated values of the figure of merit, Q, may be assigned a statistical significance, however, even though this is somewhat short of the desired goal of determining a lower bound on tolerable performance. If Q denotes the average probability of successfully obtaining a desired condition on a particular scan, the probability of the failure to achieve this condition in n successive scans, f(n), is given for statistically independent events by

$$f(n) = (1-Q)^n \tag{5.4}$$

This probability of failure for n successive looks is shown in Figure 5-5 for values of Q ranging from 0.9 to 0.5. Use of these curves is illustrated by supposing Q = 0.9; the probability of failing to obtain a success in two successive scans, f(2) is then 0.01. A reduction of the figure of merit to 0.8 would degrade this probability of two successive failures to 0.04. Treatment of the probability of successfully displaying a specified percentage of the targets on each scan might also use this approach.

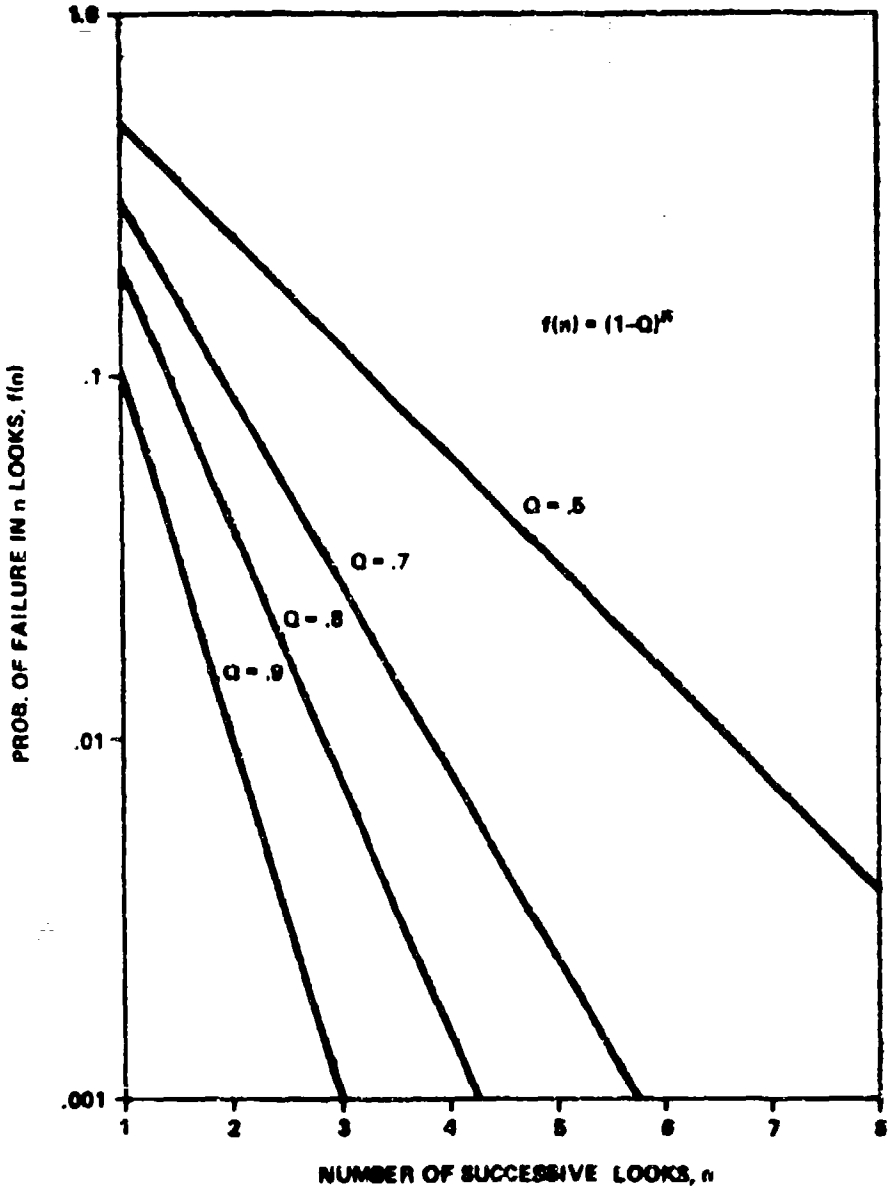

FIGURE 5-5
PROBABILITY OF FAILURE IN n LOOKS VS NUMBER OF LOOKS, n, FOR SEVERAL AVERAGE PROBABILITIES OF SUCCESS, Q

6. IMPLICATIONS OF RESULTS

Utility of any analytical or simulation effort is determined by the level of credibility imparted to its output. Field measurements and corroborative experiments usually determine this credibility when possible. The present evaluation effort has reflected this attitude. Additionally, it has attempted, when possible, to formulate the representative inputs and output characteristics in terms that have already achieved a level of accepted usage. Although the effect of mutual interference on ATCRBS has been isolated as far as possible from other system malaiies in this effort, an attempt has been made, nevertheless, to examine how these interference related effects behave in concert with other ATCRBS problem such as target fading.

On the basis of this evaluation, several judgments regarding ATCRBS performance may be made on a more quantitative basis than was previously possible. Certain of these points are described in the following section: an integration of the analytical model, experimental measurements, and the simulation outputs is next employed to yield a guideline type forecast of ATCRBS capabilities.

6.1 General Comments

Analytical results, supported by the experimental data, have indicated the interference conditions are more critically dependent upon the effective interrogation population than they are upon the traffic count. This seems intuitively apparent since the interrogators act to degrade the reply probability on the uplink as well as increase the fruit rate on the downlink for a fixed traffic distribution. Moreover, the fraction of the traffic within the interrogator minor lobe response range contributes much more significantly to the net fruit rate than does traffic

viewed only by the scanning main beam. In such a case the use of side-lobe blanking instead of synchronous defruiting should be considered.

A complete assessment of the behavior of transponders was not possible during this task, but the available data suggest that other factors may be as significant in influencing performance as is the busy condition caused by current uplink interrogation and SLS rates. Response to stray single pulses (e.g., P_2 pulses radiated on the suppression antenna) and possibly the relative properties of the SLS radiation characteristics at typical sites are examples of these other potential sources of performance degradation.

Several inferences may also be made concerning interrogator implementation and discipline. Restraining the proliferation of interrogators has enhanced system performance and should be continued with diligence. SLS implementation has been effective in reducing the uplink interrogation rate on Modes 3A/C, and the power reduction program seems to have reduced the average SLS inhibit rate. It should be evident also in this regard that any unnecessary use of Improved SLS should be avoided. In addition to this, further attention to the P_2 pulse radiation characteristics may be warranted.

No evaluation of the effects of signal fading on the ATC system due to nulls in antenna coverage was intended in this program. However, since the ARTS tracker is influenced by such effects, it was considered necessary to examine how this target width variation influenced the anti-interference capabilities of the system. Similarly, data were also collected on the weak target

response of the TPX-42 since this could impact the best overall choice of operational settings of the detector parameters. Hence, while these results should be regarded as only tentative, it is perhaps worthwhile to offer a few guidelines on the relative effects of signal fading and interference induced degradations.

Figure 4-1 for fixed width targets in ARTS III shows that the track correlation ratio, T_C, remains above 0.9 for low fruit rates and reply probabilities above 0.85; signal fading imposes a more stringent limitation on P_R for $T_C \geq 0.9$ as indicated in Figure 4-2. Here we see that reply probabilities greater than .95 are needed for equivalent tracker performance. Comparison of Figures 5-1 and 5-3 for the TPX-42 with CL = 0 and one mode missing in the reply train show similar behavior for strong targets (16 hits) and weak targets (9 hits). In this case for a common fruit rate of 1K replies/sec, it is noted that Q value above 0.7 obtains for 16 hits when P_R is above 0.8 while a value of $P_R \geq 0.9$ is required for the same lower bound on Q with 9 hits on the target.

As a general recommendation, an improvement in the elevation plane coverage of the interrogator antenna should improve both the signal fading problem in the system as well as provide a means of reducing the impact of interference on the ATC systems. While both aircraft and interrogator antenna improvements are needed, a major link improvement would result from a reduction in interrogator coverage null depths since this would enable the system to better tolerate aircraft antenna shielding occurring at these null location angles.

6.2 Forecasting

Measurements obtained in the test program support the initially assumed analytical model in all respects except for the slightly

lower reply probability associated with the measured uplink environment. Later measurements, however, indicate that much of this discrepancy can be accounted for and so for our present purpose we will suppose that the suggested model is adequate for representing system behavior from the point of view of interrogation and SLS rates. Under this circumstance and for typical system parameters, we may write

$$P_r \simeq e^{-10^{-4}\bar{\nu}_I} \tag{6.1}$$

where $\bar{\nu}_S$ is assumed to be about one third the value of ν_I. Substitution of

$$\bar{\nu}_I \simeq \bar{\nu}\, n \frac{\phi}{360} \tag{6.2}$$

into this relationship yields

$$P_R \simeq e^{-10^{-4}(\bar{\nu}\, n \frac{\phi}{360})} \tag{6.3}$$

which expresses the reply probability in terms of the interrogator population characteristics.

The downlink fruit rate was found to be closely approximated by the relationship

$$\bar{\nu}_f \simeq 0.1\, M\, \bar{\nu}_I \tag{6.4}$$

which becomes

$$\bar{\nu}_f \simeq 10^{-3}\, \bar{\nu}\, M\, n \tag{6.5}$$

using Equation (6.2) and $\phi = 4°$. Moreover, if $\bar{\nu} = 270$Hz, then

$$\bar{\nu}_f \simeq 0.3\ M\ n \tag{6.6}$$

where, as usual, M is the traffic count and n is the interrogator count. These same assumptions in Equation (6.3) result in

$$p_R \simeq e^{-4.2 \times 10^{-4} n} \tag{6.7}$$

Equations (6.6) and (6.7) provide coupling relationships between the sources of the interference condition and the average levels of this interference under typical conditions. Figure 4-2 depicts how these average values of p_R and $\bar{\nu}_f$ affect the ARTS III output, the track correlation ratio. From this curve we may read the various combination of P_R and $\bar{\nu}_f$ which combine to produce a constant level of T_C. A family of these curves of constant values of T_C may thus be constructed and, by use of Equations (6.6) and (6.7), these constant contour relationships may be plotted in terms of the population of interrogators, n, and the traffic count within view, M.

Figure 6-1 is the result of such an exercise. Limits on the average traffic count for a specified interrogator population and minimum permitted value on the average track correlation ratio are shown in this plot. A value of $T_C \geq 0.85$ with an interrogator count of $n = 40$, for instance, would permit a maximum average value of $M \approx 2{,}000$ aircraft. The slope of these curves is also of interest since it indicates that system performance is more critically dependent upon the number of interrogators than it is upon the traffic count. These limits are only those imposed by

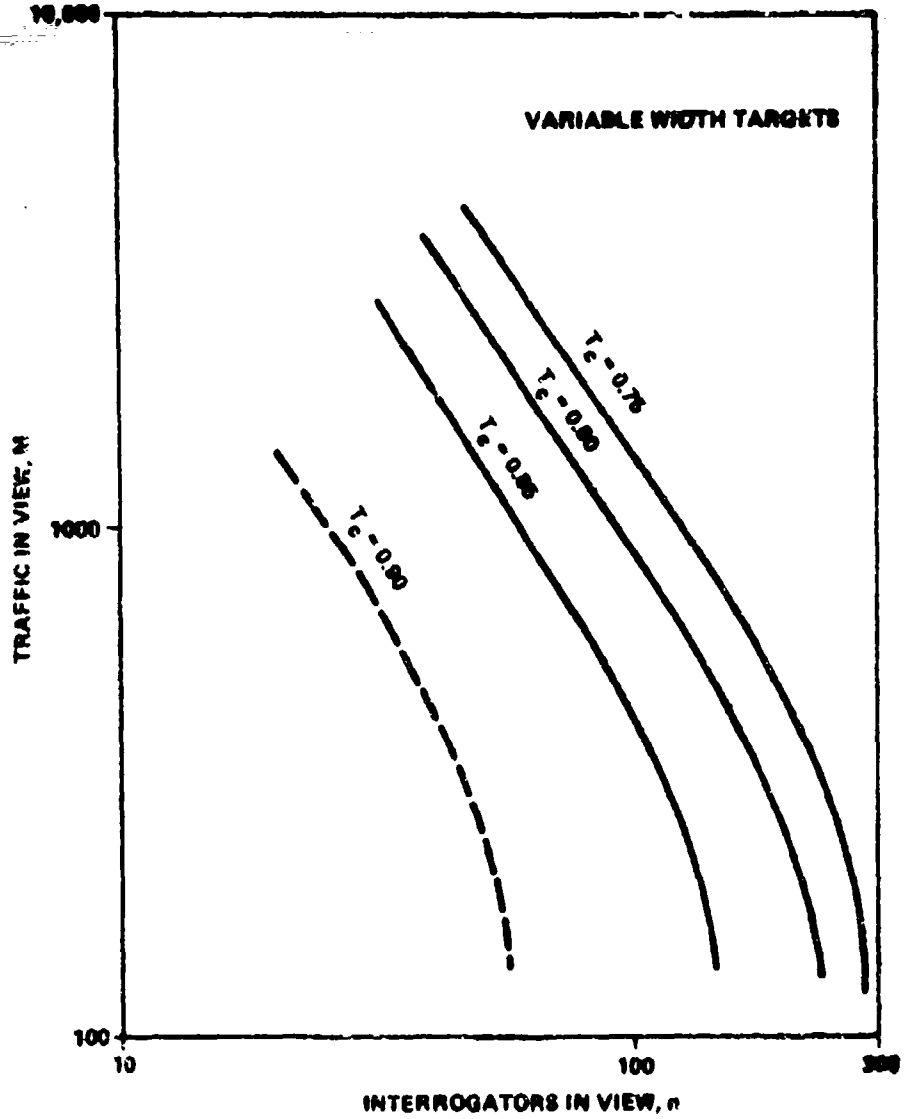

FIGURE 6-1
SYSTEM LOADING IMPACT ON ARTS III PERFORMANCE

the asynchronous interference effects considered here and do not include other possible limitations such as synchronous garble.

Values of T_C corresponding to a variation in n for fixed values of M may be read from Figure 6-1 in order to determine how system behavior is influenced when the traffic count, M, is the parameter examined. Two cases, M = 300 and M = 1,000, are indicated in Figure 6-2. We may note here that T_C = 0.9 for a typical busy condition today of M = 300 with n = 40; if this same level of T_C is to be retained for M = 1,000, then n must be reduced to about twenty-five. As a matter of interest, it might also be observed that changes in T_C associated with changes in M for fixed values of n are performance changes induced by different fruit levels. On the other hand, changes in n for fixed values of M correspond to variations in both the reply probability as well as the fruit level. This accounts for the increased slope of the curves and for the greater separation in them as n increases.

Performance characteristics shown in Figure 6-2 may also be related to available traffic forecasts in order to approximately assess future system limitations. Such traffic forecasts are available for the New York, Los Angeles, and Chicago terminal areas.[9] If a nominal radius of 50 to 60 miles defines this terminal area, then the cumulative distribution of Figure 3-1 shows that about 60% of the total traffic in view (indicated here by M) is within this area in New York. The curve in Figure 6-2 labeled M = 1,000 thus corresponds to a terminal area count of about 600 transponder equipped aircraft for a similar distribution. A terminal area count of about 600 aircraft, or M = 1,000,

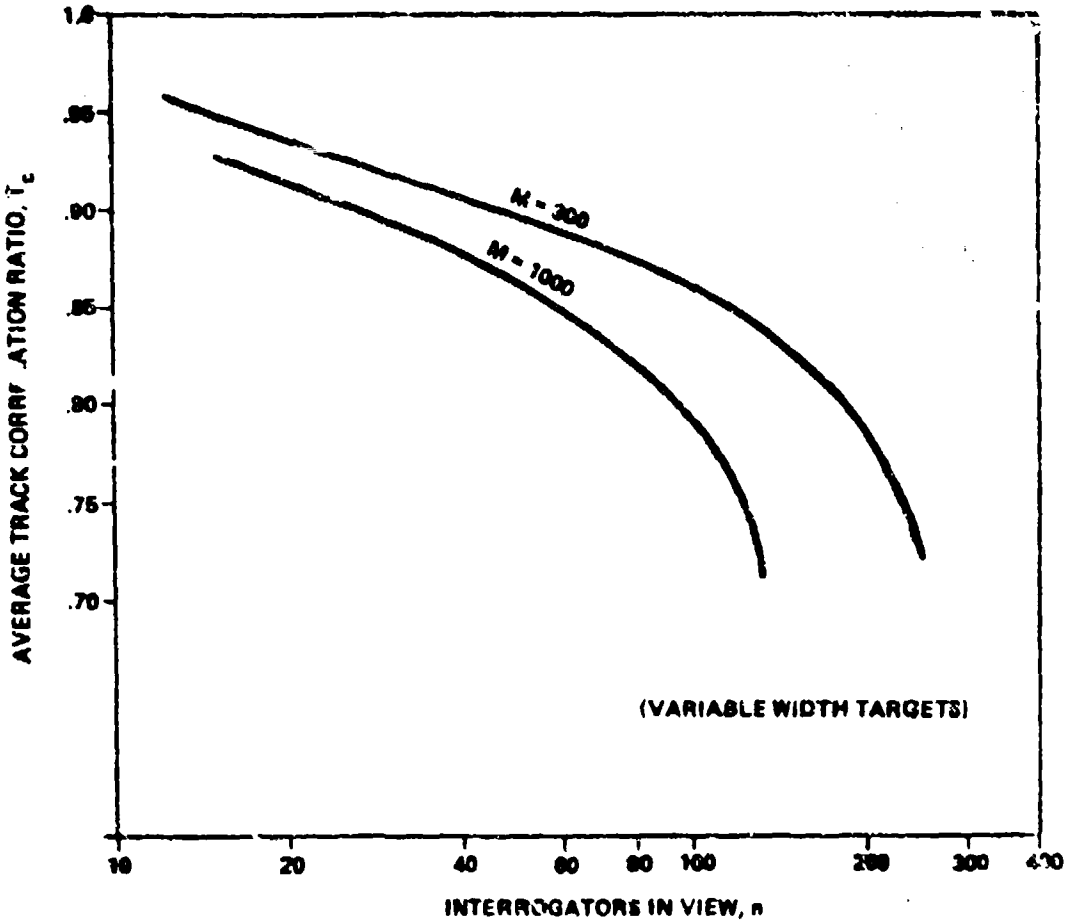

FIGURE 6-2
ARTS III PERFORMANCE VARIATION WITH SYSTEM LOADING

is expected in New York in 1995, in Chicago in 1980, and in Los Angeles within a year or so on the basis of the referenced forecasts.

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SUMMARY AND CONCLUSIONS

Mutually induced interference conditions in an ATCRBS terminal area have been examined on an integrated basis in this program. Synchronized measurements enabled the isolation of uplink and downlink interference phenomena along with simultaneous estimations of the sources of this interference. Average values of these measurements as well as many burst characteristics corroborated the results of an analytical model coupling the environmental features to their effects on the surveillance system. Parallel simulation efforts enabled an association of this environmental degradation with deterioration in performance of the ARTS III and TPX-42 processors. Subsequent combination of these results provided an overall assessment of the impact of system loading (interrogator and transponder equipped traffic populations) on the output characteristics of these ATC systems. These results should prove useful in forecasting and in system planning efforts.

Measured weekday afternoon conditions in the areas of New York and Boston are summarized below.

1. Mode 3A/C average interrogation rates of 110 interrogations/second have been measured at an altitude of 8K ft. in the vicinity of New York City. It has been estimated from FAA records that this uplink condition was produced by a visible population of approximately 40 interrogators. Similar measurements in the Boston area with an estimated interrogator count of about 25 have indicated a total interrogation rate of nominally 65 interrogations/second.
2. Average side lobe suppression rates monitored in the above environments were about one third the interrogation rates in New York and about equal to the interrogation rate in the Boston area, where many of the measurements were made in the immediate vicinity of several interrogators.

3. Monitored fruit rates near JFK averaged about 1,700 replies/second. Associated airborne counts of approximately 150 beacon equipped aircraft were radially distributed on a cumulative basis. Average fruit rates in the neighborhood of 300 replies/sec were recorded near Boston with a similar distribution of about 40 aircraft.

4. Average values of the above parameters were in reasonably good agreement, whether computed from measurements made over the 38ms beam dwell interval or from integration over the 7-second antenna scan period. These averages are based on smoothing intervals varying from 10 minutes to about one hour. Measured short term features are well represented by statistical models of the environment.

The following conclusions may be developed from an analysis of these results in terms of an analytical model of the interference environment.

1. Recorded traffic distribution associated with the fruit measurements indicate that the major portion of these unwanted replies were produced by traffic within the interrogator antenna minor lobes rather than from traffic located in the main beam.

2. The experimentally derived probabilities of reply garble associated with these fruit rates are closely approximated by a Poisson model with an event interval time of 25 to 35 μs. This factor is consistent with the detector degarbling characteristics employed in the data collection.

3. Initially measured transponder reply probabilities were some five percent lower than values expected on the basis of the probability of the transponder being busy with another reply or being suppressed when interrogated. Later measurements with a

modified decoder indicate that transponder response to uncounted interfering single pulses appear to have produced this effect. This performance degradation due to the random pulse susceptibility of the unit employed in the tests was more serious than was the degradation attributable to the measured interrogation rate.

4. SLS implementation and the power reduction program have reduced the uplink average interrogation rate and the average number of side lobe inhibits.

5. Average uplink and downlink interference conditions are closely represented by statistical models.

6. Measured average characteristics were in agreement with the theoretical model.

Simulation of the ARTS III and TPX-42 performance deterioration in an interference environment was accomplished by statistically representing the input conditions, rather than by the more commonly used traffic/interrogator model generators. This enabled parametric variation of the transponder reply probability and fruit rate in such a way that system sensitivity to critical conditions could be determined. Breakdown conditions thus determined could then be related to the environmental conditions through the experimentally measured results and use of the analytic model.

The following conclusions result from this assessment of the ARTS III performance properties:

1. The basic ARTS III system performance will degrade under conditions of increasing fruit and decreasing probability of reply. Under the assumptions of the study, which used the system parameters and logic of the Chicago ARTS III operational program as of

January 1972, it appears that tracking performance will degrade noticeably when the reply probability drops below .85 and fruit rate input to the defruiter is greater than 30K per second.

2. The quantitative results presented here are applicable only to the ARTS III detection and tracking parameters used for this study. More judicious choices of system parameters plus field tested logic improvements have been shown to improve system performance under field conditions.

3. In an environment of high reply probability and low asynchronous fruit the surveillance performance of basic beacon-level ARTS is limited by the existence of narrow-width targets engendere by antenna shielding and vertical lobing effects.

A comparison of the results of this study related to fixed and variable-width targets predicts that substantial benefits are to be gained through stabilization of the target widths. Not only would immediate improvement to current performance levels result, but also the susceptibility to future environmental degradations would be lessened.

Similar conclusions may be drawn from the TPX-42 study with the onset of rapid deterioration in the output quality for a reply probability of about 0.85. Performance is generally more critically dependent upon this parameter than upon any reasonably expected fruit rates. As with the ARTS III, the affect of weak targets is to accentuate this rate of performance degradation with interference.

A forecast of the ARTS III tracker output variation based on the results of this program indicates that a reduction in the interrogator population by a factor of almost two (e.g., 45 to 25) would be

required if the same level of performance was maintained for a traffic count within view which increased from 300 aircraft to 1,000 aircraft. This latter figure corresponds to about 600 aircraft in the terminal area.

Assuming approximately 45 interrogators and the current traffic forecasts, the results of the measurements, analysis, and simulation show that the ATCRBS reply probability and fruit rate will degrade the present ARTS III tracking in Los Angeles in a year or two, in Chicago in 1980, and in New York in 1995.

RECOMMENDATIONS

1. Further evaluation of the transponder reply probability should be undertaken. Particular attention in these efforts should be directed towards decoder recovery times and the influence of random single pulses on the unit's behavior. It is recommended that a survey of existing transponders be conducted to determine the extent of the problem uncovered by this program.

2. Further measurements should be conducted to obtain a greater sample of environmental situations. Tests in the Los Angeles area, with its continual report of abnormally high interrogation rates, would be worthwhile.

3. The results of the analytical methods developed in this task should be incorporated in a complete assessment of a congested area, such as Los Angeles, to predict when intolerable degradation would occur and what actions would be most effective in forestalling it. In this recommended study, in addition to the asynchronous interference treated here, the problem of synchronous interference should also be considered.

4. The results of this program show promise for utilizing the data collection and reduction features of the ARTS-III in the task of inferring the basic causes of system degradation. It is recommended that a short study be undertaken to assess the validity and utility of this approach, as part of the ATCRBS Monitoring Program.

5. Constraints on interrogator operation and proliferation should be maintained to assure adequate system performance because the number of interrogators has a greater impact on system performance than the number of aircraft.

6. Side lobe blanking should be considered as an alternative to synchronous defruiting, especially in terminal areas with concentrations of traffic near the interrogator. It is recommended that the program to investigate receiver side lobe suppression be re-emphasized.

7. Further analysis and experimentation is needed to quantitatively determine the effects of a degraded beacon environment on the controller. It is recommended that such a program be established using the simulation facility at NAFEC.

8. It is recommended that the various modeling efforts now being conducted by the FAA be compared with the approach used in this program to disclose advantages and limitations of each, and to reveal possible areas of simplification.

APPENDIX A

INTERROGATION ANALYSIS

The probability, p_b, of a transponder being busy replying to another interrogation when a desired reply is elicited may be expressed as

$$p_b = p(s|i)p_i \tag{1}$$

where

p_i = probability of another illuminating beam overlapping the desired illuminating beam

$p(s|i)$ = conditional probability that another interrogation in the same time interval will overlap the desired interrogation given that an overlapped beam illumination has occurred.

For asynchronously related interrogation repetitions at an average rate of $\bar{\nu}$, the conditional probability above may be estimated on a duty cycle basis with the result that

$$p(s|i) \approx \frac{a \times \tau_I}{\tau_\nu} \tag{2}$$

where

a = average number of overlapping beams, given that an overlapped condition has occurred.

τ_I = interrogation lock out time $\simeq$ 80 μs

τ_ν = interrogation repetition average period = $\frac{1}{\bar{\nu}}$

If λ is the average number of randomly related overlapping scanning beams, then

$$\lambda = n\, p_i \tag{3}$$

Substitution of these relationships into Equation (1) yields

$$p_b = \lambda\, \bar{\nu}\, \tau_I \tag{4}$$

which expresses the probability of a busy condition in terms of the average number of beams illuminating the target, λ, the response time for a reply, τ_I, and the average rate of interrogations over the network of illuminating units.

Now the probability that no beam will overlap the desired beam is just

$$p_o = 1 - p_i \tag{5}$$

From the Poisson distribution for an average number of overlapping beams given by λ, we may write

$$p(L) = \frac{\lambda^L e^{-\lambda}}{L!} \tag{6}$$

where p(L) is the probability of L overlapping beams. With L = 0, $p(0) = p_o$ and from the above,

$$p_o = e^{-\lambda} \tag{7}$$

The probability of no overlapping beam in a network of n independently related beams with an average width of ϕ degrees can also be expressed as

$$p_o = \left(1 - \frac{\phi}{360}\right)^n \tag{8}$$

Equating Equations (7) and (8) results in

$$\lambda = -n \ln \left(1 - \frac{\phi}{360}\right) \tag{9}$$

Values of ϕ are typically four degrees so that $\frac{\phi}{360} << 1$ and the relationship for $|Z| << 1$ given below may be used,

$$\ln (1 - Z) \simeq - Z - 1/2\ Z^2 - 1/3\ Z^3 \ . \ . \ . \tag{10}$$

Equation (9) then becomes

$$\lambda \approx n \left[\frac{\phi}{360} + 1/2 \left(\frac{\phi}{360}\right)^2 + \ . \ . \ . \right] \tag{11}$$

which is closely approximated by the first term only, or

$$\lambda \simeq n \frac{\phi}{360} \tag{12}$$

With this result in Equation (4), the probability of the transponder being busy is just

$$p_b \simeq n \frac{\phi}{360} \bar{\nu}\ \tau_I \tag{13}$$

This expresses the busy condition in terms of the illuminating interrogator network properties and the transponder response time. Neglecting other link characteristics, the transponder reply probability may be expressed in terms of this last relationship since in this case,

$$p_R = 1 - p_b \tag{14}$$

So,

$$p_R \simeq 1 - n \frac{\phi}{360} \bar{\nu} \tau_I \tag{15}$$

It is of interest to note the agreement between this formulation of the problem and the simpler one based on the assumption of random arrivals at a rate $\bar{\nu}_I$ which yields

$$p_R = e^{-\bar{\nu}_I \tau_I} \tag{16}$$

which, for $\bar{\nu}_I \tau_I \ll 1$, is approximated by

$$p_R \simeq 1 - \bar{\nu} \tau_I \tag{17}$$

Equations (17) and (15) are identical when $\bar{\nu}_I$ is interpreted as the average interrogation rate resulting from the n interrogators, or

$$\bar{\nu}_I \simeq n \frac{\phi}{360} \bar{\nu} \tag{18}$$

This development of the model has the advantage of providing estimates on the burst characteristics of the uplink condition, since the probability of any L overlapping beams may also be computed. The resulting impact on p_b is then just a straightforward extension of the procedure outlined above.

APPENDIX B

LIST OF SYMBOLS

a = Average number of looks by typical interrogator in time, T_S

ERP = Effective radiated power (dBW)

g = Average probability of clear look due to the influence of a single additional interrogator

G_R = Receive antenna gain

G_T = Transmit antenna gain

M = Total traffic count within view

MTL = Minimum threshold level

n = Number interrogators within view

p_c = Probability of clear reply

P_D = Probability of detection

p_g = Probability of garbled reply

$p(m|j)$ = Conditional probability of m, given occurrence of j

$p(n)$ = Average probability of clear look for n interrogators

p_R = Transponder reply probability

P_R = Receive power

P_T = Transmit power

$p(V|D)$ = Probability of code validation given detection

q = Average probability of illumination for a single unit

Q = TPX-42 performance index

r = Minor lobe range in miles

R = Mainbeam range in miles

T_c = ARTS III track correlation ratio

T_S = Scan period of instrumented interrogator

α = Fraction of air traffic within minor lobe range

η = Minor lobe volume efficiency factor determined by radiation

$\bar{n}$ = Average number of beams simultaneously illuminating target

$\bar{\nu}$ = Average repetition rate of interrogator population

$\bar{\nu}_t$ = Average truth rate (replies/sec)

$\bar{\nu}_I$ = Average uplink interrogation rate

$\bar{\nu}_R$ = Average reply rate of transponders (sum of Modes 3A and C)

$\bar{\nu}_S$ = Average SLS inhibit rate

$\bar{\nu}_T$ = Weighted sum of $\bar{\nu}_S$ and $\bar{\nu}_I$

T_o = Scan period of typical interrogator

σ_ϕ = Azimuth measurement jitter

t_o = Average beam dwell interval

t_R = Bracket pair interval

ϕ = Effective beamwidth of interrogators (in degrees)

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APPENDIX C

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APPENDIX D

ARTS III DEGRADATION

This appendix has been separately published as:
"Executive Summary: ATCRBS/ARTS III Performance in High Fruit and Low Probability of Return Environment", by J. E. Freedman, K. M. Levin, and J. A. Keenan III, MITRE MTR-6212, dated 13 July 1972

A more detailed description of this simulation task is given in the final report:
"ARTS III Detector and Tracking Performance as a Function of Degraded Beacon Environment", by J. E. Freedman and K. M. Levin, MITRE WP-8579, The program was directed in Department D-44 by J. A. Keenan, III.

EXECUTIVE SUMMARY

1. BACKGROUND

1.1 Study Objective

The objectives of the work documented by this paper have been:

1. To determine the range of sensitivity of the basic ARTS III performance to environment degradations.

2. Provide a family of parametric curves (over the range of sensitivity) relating key ARTS III performance measures to degradation in the environment.

3. To generally relate system degradation to increase workload experienced by controllers using the system.

To pursue these objectives the primary tool has been a set of computer programs collectively called the MITRE "Basic ARTS III Surveillance Model".

Terms used in this document are defined in Pezza, A. T., "NAS Glossary and Acronyms", MITRE Working Paper 8124, Revision 2, Washington, D. C., 29 September 1971. (U)

1.2 The ATCRBS/ARTS III System Combination

On a radar video display (plan view display) basic ARTS III adds alphanumeric identity and flight data to targets representing ATCRBS beacon equipped aircraft. This data reduces, for the radar controller in the Terminal Radar Control (TRACON) room, the workload associated with maintaining flight strips containing that same information. The association of identity data with one particular beacon target in the auto tracking area occurs automatically if the aircraft is utilizing a discrete (12 bit) beacon code, has flight plan information within the computer data base, and if that beacon target is unique. If any of these three conditions is not met, the association of alphanumeric data with a displayed target can be initiated manually by the controller (if the target is in the auto-tracking area). Furthermore, if the data and target become disassociated, a manual action is required to re-initiate if any of the three conditions are again or still not met.

Basic ARTS III automatically associates (Mode C) altitude data with any beacon target representing an aircraft transponding to altitude inquiries. The altitude data can be displayed as alphanumeric data automatically at the option of the controller. This capability can reduce both controller and pilot workload and substantially reduce the use of air-ground voice communications related to altitude (status) determination. The introduction of basic ARTS III has made possible a fuller utilization of ATCRBS capability than has been common in the TRACON prior to ARTS III, since the Mode C data has not been conveniently available to controllers without ARTS III. Further details of the ARTS III functional capability are found in Levin, K. M. "System Description--Automated Radar Terminal System III (ARTS III)", MITRE Technical Report [illegible], Washington, D. C., 3 August 1970. This document is available from the FAA as SPO-MD-600. (U)

An enhancement development is underway for ARTS III which is planned to implement additional functional and technical features onto the Basic ARTS III. Therefore, results in this paper which relate to Basic ARTS III represent a lower bound on expected ARTS III performance.

1.3 The Basic ARTS III Surveillance Model and Its Validation

A set of computer programs collectively referred to as the MITRE "Basic ARTS III Surveillance Model" has been used to support this study. It was developed to support system implementation engineering associated with ARTS III; it has been modified slightly to meet the needs of this study. The model architecture comprises the following five modules: an aircraft traffic generator; a target synthesizer; the ARTS beacon target detector; the ARTS tracker; and a statistical analysis package.

Verification of the Surveillance Model has included successful comparisons of model predictions with actual field test measurements performed during the ARTS III Engineering Performance Assessment Tests at Chicago in 1971. Further validation has included successful comparison of operational site (Chicago) tracking performance with model tracker performance using the same target data (which had been recorded by the ARTS III operational program data extractor). The detector and tracker models are regarded as reasonably faithful representations of the actual ARTS III functions.

The range of environmental conditions tested and used for model verification has been limited to a high-reply-probability, low-fruit environment typical for an ARTS III site. The emphasis in this study, however, has been to extrapolate the performance

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predictions to degraded environments (i.e., low reply probability, high fruit), a region where the model has not yet been validated. Since such environment degradations do not presently exist in practice, (and may never be as hostile as the limits tested), validation in this region is difficult. A rigorous verification would require the use of some special preprocessing equipments to randomly remove incoming target replies and insert random fruit replies to represent the full range of environmental conditions of interest. This type of model verification has not been done. Nevertheless, there is no indication that the model is not reasonably valid even in the extremely hostile environments used for parts of this study.

2. VARIABLES EXAMINED

Generally it is not possible in a system as complex as the ATCRBS/ARTS III combination to control any variables independently in the pure sense, thus considerable post-experimentation analysis has been required to separate and relate the dependent and independent variables. Independent Variables 3 and 4 (below) were identified as appropriate variables to consider after the study effort started and therefore are not explicitly identified in the original study objectives.

2.1 Independent Variables

The objective independent variables for this study have been:

1. Beacon Environmental Asynchronous Fruit Rate - The unwanted asynchronous beacon transponder replies [illegible] are received along with the desired true replies [illegible] system.

2. [illegible] Probability of Reply - The probability that the [illegible] will reply to a detected interrogation.

3. [illegible] Angular Width - The angular width over which both the transponder is capable of detecting interrogations and the ATCRBS receiver is capable of detecting the replies. A variable target width distribution, as shown in Figure 2-1, is used to approximate the present transponder and interrogator/receiver antenna combination. For certain simulation runs a fixed target width was used (4 degrees) to consider a limiting case if transponder and interrogator/receiver antenna improvements were made.

4. The ARTS III Logical Design and Parametric Operation - The performance of ARTS III under several conditions of different operational program logic design and of different operational parameter settings.

2.2 Dependent Variables

The objective dependent variables have been:

1. Probability of Detection - The probability that a received beacon signal will be detected by the ATCRBS/ARTS III combination detector.

2. Failure to Discern Mode C - The probability that a target which is transponding to Mode C interrogations will not be identified as a "Mode C" target.

3. Probability of Code Validation - The probability that at least two identical consecutive, ungarbled altitude or identity codes will be received from a target.

4. Probability of Erroneous Code Reports - The probability that an erroneous altitude or identity code will be reported for a target.

5. Fraction of Targets Classified Weak - The percentage of targets declared which have a run length below the weak-strong threshold setting. This characteristic is less important with the revised tracking logic which uses weak as well as strong targets for auto-acquisition and second pass recorrelation. This is included because of the results which are related to the earlier ARTS III logic design which did not so fully utilize weak targets.

6. Probability of Target Splits - The probability that a single target will be reported as more than one target.

7. Distribution of Azimuth Errors - The relationship of azimuth errors to an independent variable.

8. Processing Time Utilization - The percentage of available computing time used.

9. Track Correlation Ratio - The ratio of the number of scans a track correlates to the number of scans it is tracked (sometimes this has been called tracking blip/scan).

10. Probability of Track Loss - The ratio of the number of tracks which disassociated at least once to the total number of tracks.

11. Number of Aircraft Tracked - The number of aircraft actually tracked at least once during an experiment run.

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12. Controller Workload - The amount of work required of the controller to maintain status and tracking of aircraft under his control.

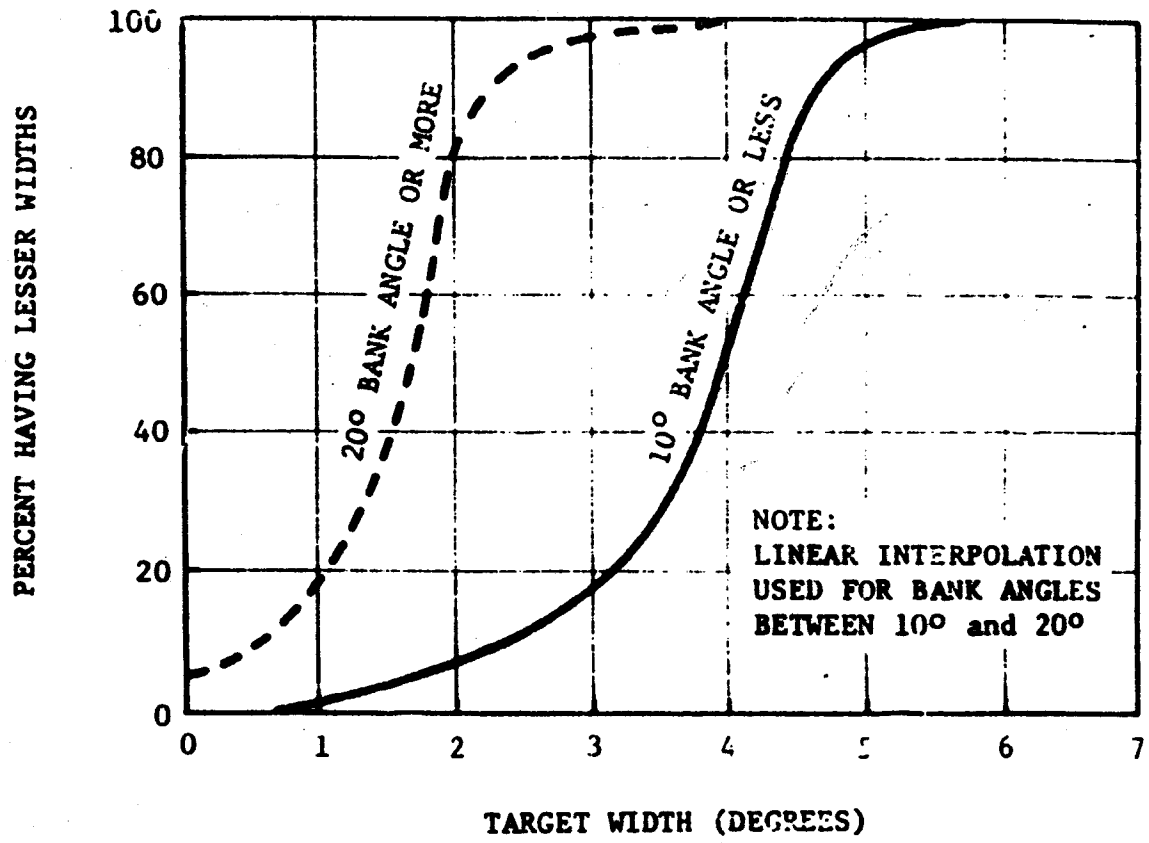

FIGURE 2-1
DISTRIBUTION OF TARGET WIDTHS USED IN SIMULATION FOR VARIABLE-WIDTH TARGETS

3. MAJOR RESULTS

3.1 Detector Performance Results

Of the eight detector performance measures examined (items 1 through 8 under 2.2) the two which were most affected by the postulated environmental degradations, hence those having the greatest adverse impact on the system performance, were the probability of detection and the probability of erroneous code report. It was found that degradations in the reply probability chiefly resulted in lowered detection probability (Figure 3-1) while the major effect of an increasing asynchronous fruit rate was an increasing number of erroneous code reports (Figures 3-2 and 3-3). Since the tracker requires both code and position correlation from the new report, a degradation of the tracking performance ensues from either or both of the above conditions.

The detector performance curves presented in portions of this paper pertain to performance attained when the base set of detector parameters are used (as was the case in July 1971). There has been and is an effort underway to refine system performance by improving the choice of parameters. This exercise has been completed at Chicago where the new parameters are now in operational use. The new settings selected for Chicago basically reflect the choice of a lower threshold in order to provide improved detection of weak targets (i.e., those incurring antenna shielding or vertical lobing effects) and a shorter processing window for improved azimuth resolution. The lowered thresholds were permitted by the low occurrence of false synchronous targets at this particular site.

To provide an example illustrating the impact of using the improved settings some additional simulation runs were made with these settings. The probability of detection curves for the different settings are shown in Figure 3-4. A comparison of the curves shows the improved settings (in use on January 1972) to have markedly less sensitivity to degradations in the reply probability. The use of the base set (i.e., those in use during July of 1971) of detector parameters in this study can therefore be considered as leading to pessimistic estimates of performance (when there are few synchronous target problems).

Note that in the portion of the curve descriptive of most actual field sites (e.g., PR=.95 to .99) the improvement is not spectacular. However, at the limits of system performance (e.g., PR=.75 to .85) substantial improvement can be seen. Based upon this observation, it can be said most of the detection performance

limiting characteristics identified in this report can be expected to improve as innovations and enhancements are implemented in the field.

3.2 Tracker Performance Results

The ARTS III Tracker is sensitive to environmental degradations. Two primary tracker performance measures, Track Correlation Ratio and Track Loss Probability will degrade with increases in fruit levels and decreases in the reply probability. The tracker is more sensitive to decreases in the reply probability than to increases in fruit rate. This occurs because, as probability of reply decreases, the probability of detection also decreases (See Figure 3-1); this in turn provides the tracker with less information (missing target reports). Increased fruit rates cause the declaration of targets with either erroneous or garbled codes. This error may or may not cause the tracker to fail to correlate.

For targets of fixed width (16 hits or 4°), it appears that the tracking system degrades most noticeably below .80 reply probability and above 40K fruit per second (See Figures 3-5 and 3-6). For this study fixed width target results represent a theoretical situation in which transponders and interrogator/receiver antennas have been substantially upgraded. Variable width targets (0°-6°) represent the current state of transponders and antennas. The distribution of target widths is based on a sample of targets from Chicago (See Figure 2-1). The tracking performance for variable target tracks is always below that for fixed target tracks (compare Figures 3-5 and 3-6 with Figures 3-7* and 3-8*). This is due primarily to the difference in probability of detection between fixed and variable targets. For variable targets, the performance appears to degrade most noticeably below .85 reply probability and above 30K fruit per second; this is true even when weak targets are utilized for recorrelation in the "process unused beacon" (PUB) routine of tracking (See Figures 3-9 and 3-10). Tables 3-1 and 3-2 show the increased number of aircraft tracked when weak targets, as well as strong, are used for auto-acquisition and recorrelation of discrete tracks. Figures 3-9, 3-10, and 3-11 plus tables 3-1, 3-2, and 3-3 show the general improvement in the tracking performance when improved logic and parameter settings are used. Thus, the results identified in this study as original July 1971 data should be considered as a lower bound on tracking performance.

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* The anomalies in these curves (specifically, the lower end of the 50K fruit curves) are due to the combination of sample size and reduced track life for the sampled tracks.

It does not appear that tracking-related processing time is adversely affected by environmental degradations. Lowered reply probability is expected to result in less tracking-related processing since there are less reports with which to correlate. Increased fruit levels are expected to require more tracking-related processing because of additional garble and code checks.

3.3 Controller Workload Effects.

It is felt that the predominant factor affecting controller workload, as the environment degrades, will be the manual acquisition or reacquisition required when tracks do not auto-acquire or when they disassociate. The idea of defining a system breakdown point as a function of environmental degradations has been found to be an exercise heavy with subjectively, unless extensive additional studies are performed. For the purpose of this study, it is suggested that the knee of the track loss probability curve be considered as an operating point beyond which substantial controller objection would be noted. This then becomes an operating condition to be avoided. As can be noted from Figures 3-9 and 3-10 this point is about .85 probability of reply for variable width targets (current environment) and about .80 for fixed width targets (the hypothesized improved ATCRBS environment). By noting the "number of aircraft tracked" columns in both Tables 3-1 and 3-2 it can be clearly seen that controller workload due to manual acuqisition is reduced if weak targets (as well as strong) are used in the auto-acquisition process. Again, these limits can be expected to improve (i.e., the knee move to lower probability of return conditions) as improvements are implemented in the next several years.

This study does not attempt to relate the workload required to determine which of several identified targets is the true target and which is a target resulting from synchronous fruit (side lobe, reflections, etc.). Since ARTS III identifies only one target, it any, the workload associated with this controller effort is not appropriate for this study.

TABLE 3-1

ARTS III Tracking Performance For Variable Width Targets, Zero Fruit

Considering The Utilization of Weak Reports (or not) in the tracking logic.

Reply Probability	Number of A/C Tracked	Track Correlation Ratio	Percent Track Lost
Case I, no weak targets used:			
.65	2	.04	100
.75	22	.28	64
.85	56	.67	20
Case II, weak as well as strong targets used:			
.65	58	.09	98
.75	58	.4[illegible]	52
.85	58	.74	7

TABLE 3-2

ARTS III Tracking Performance For Fixed Width Targets, Zero Fruit

Considering the utilization of weak targets (or not) in the tracking logic

Reply Probability	Number of A/C Tracked	Track Correlation Ratio	Percent Track Lost
Case I, no weak targets used:			
65	0		
70	3	.075	100%
75	17	.543	24%
80	44	.745	9.1%
85	57	.872	1.8%
90	58	.958	0%
95	59	.993	0%
100	59	.9991	0%
Case II, weak as well as strong targets used:			
65	49	.197	96%
75	58	.592	21%
80	58	.765	5.1%
85	58	.886	1.7%

TABLE 3-3

ARTS III Tracking Performance For Variable Width Targets, Zero Fruit

Considering new detection and tracking parameters and new tracking logic

Reply Probability	Number of A/C Tracked	Track Correlation Ratio	Percent Track Lost
Case I, Old tracking logic, tracking parameters and detection parameters			
.65	2	.039	100
.75	22	.282	64
.80	41	.526	37
.85	56	.666	20
.90	57	.802	9
.95	58	.878	5
1.00	58	.919	0
Case II, New tracking logic, tracking parameters, and detection parameters			
.75	53	.701	17
.80	54	.784	11
.85	57	.848	4
.90	57	.886	4
.95	58	.916	3

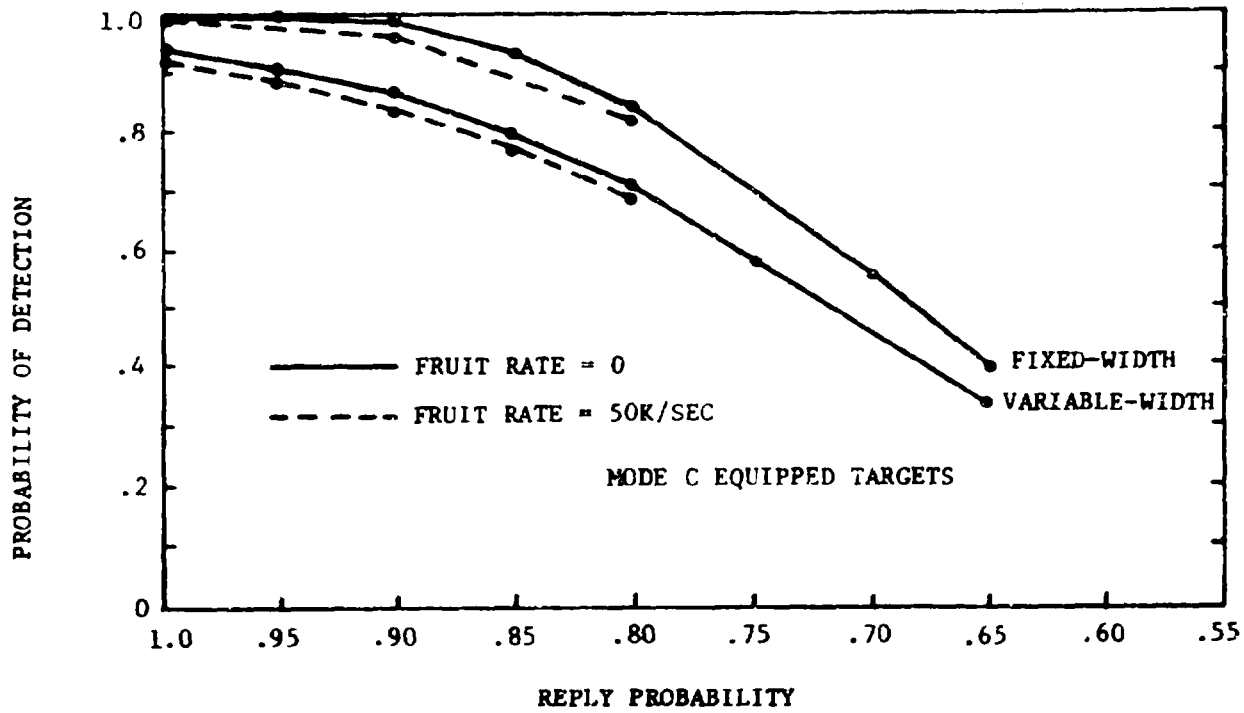

FIGURE 3-1
PROBABILITY OF DETECTION VS. REPLY PROBABILITY FOR TARGETS RESPONDING TO MODE C INTERROGATIONS

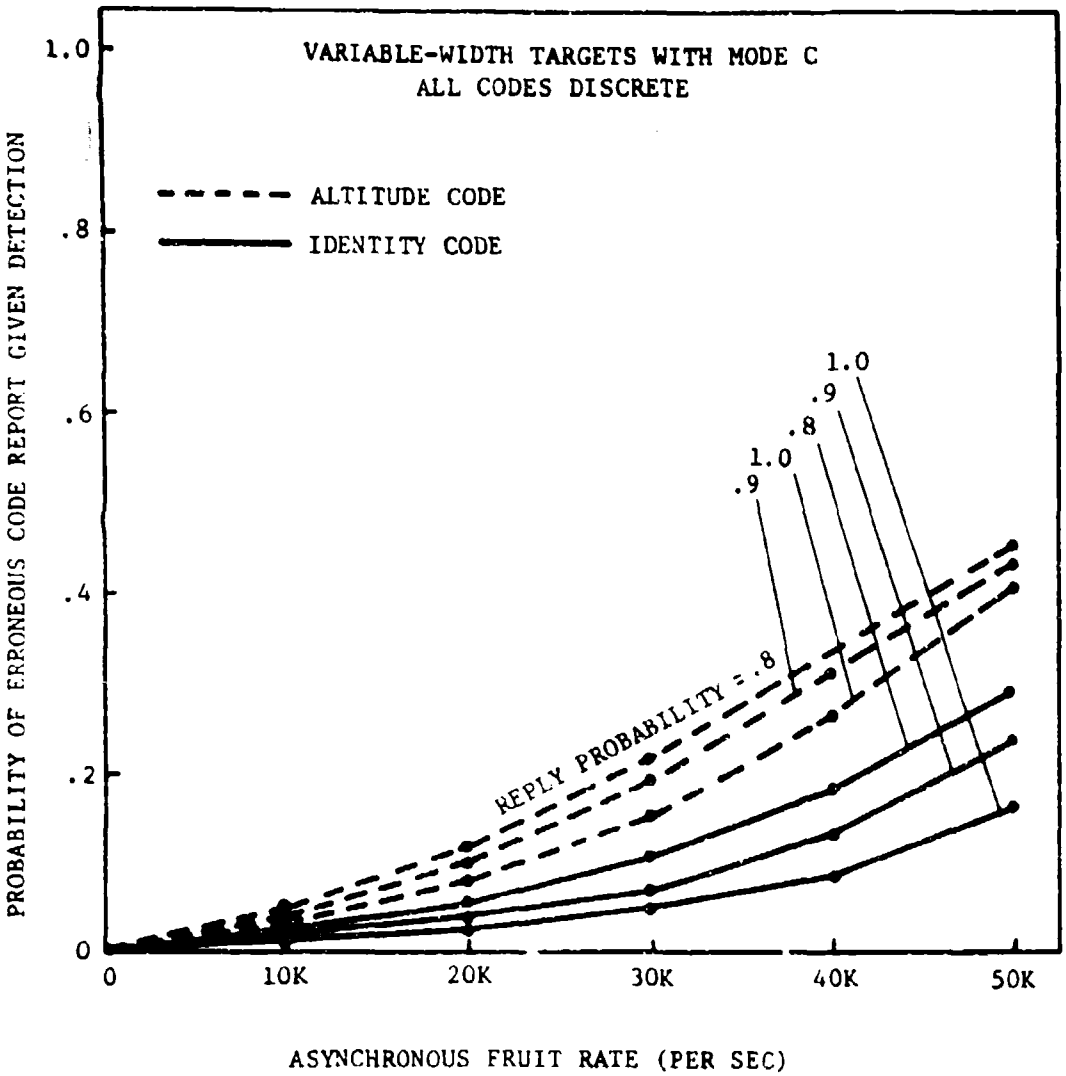

FIGURE 3-2
PROBABILITY OF AN ERRONEOUS CODE REPORT VS. FRUIT RATE AND REPLY PROBABILITY FOR VARIABLE-WIDTH TARGETS (INCLUDES ALL VALIDITY LEVELS)

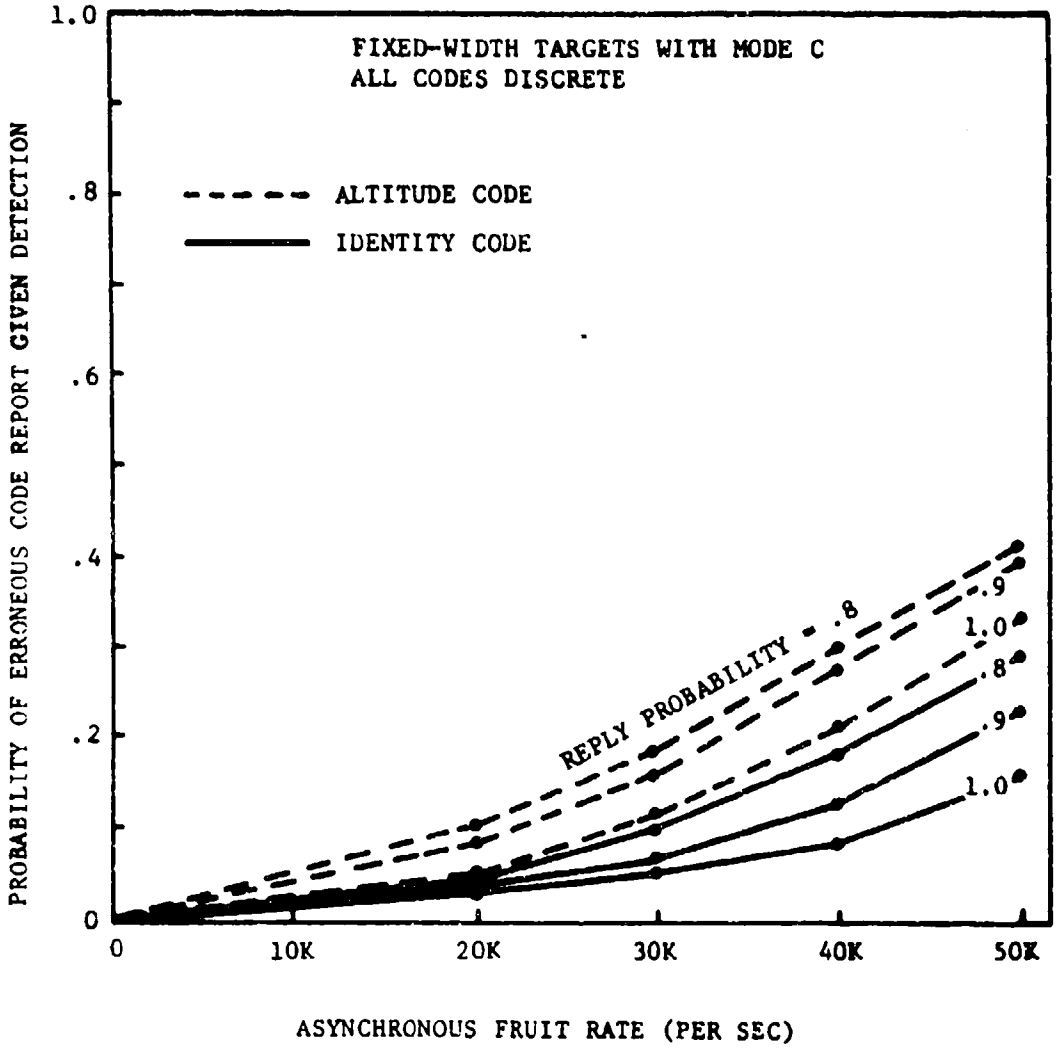

FIGURE 3-3
PROBABILITY OF AN ERRONEOUS CODE REPORT VS. FRUIT RATE AND REPLY PROBABILITY FOR FIXED-WIDTH TARGETS (INCLUDES ALL VALIDITY LEVELS)

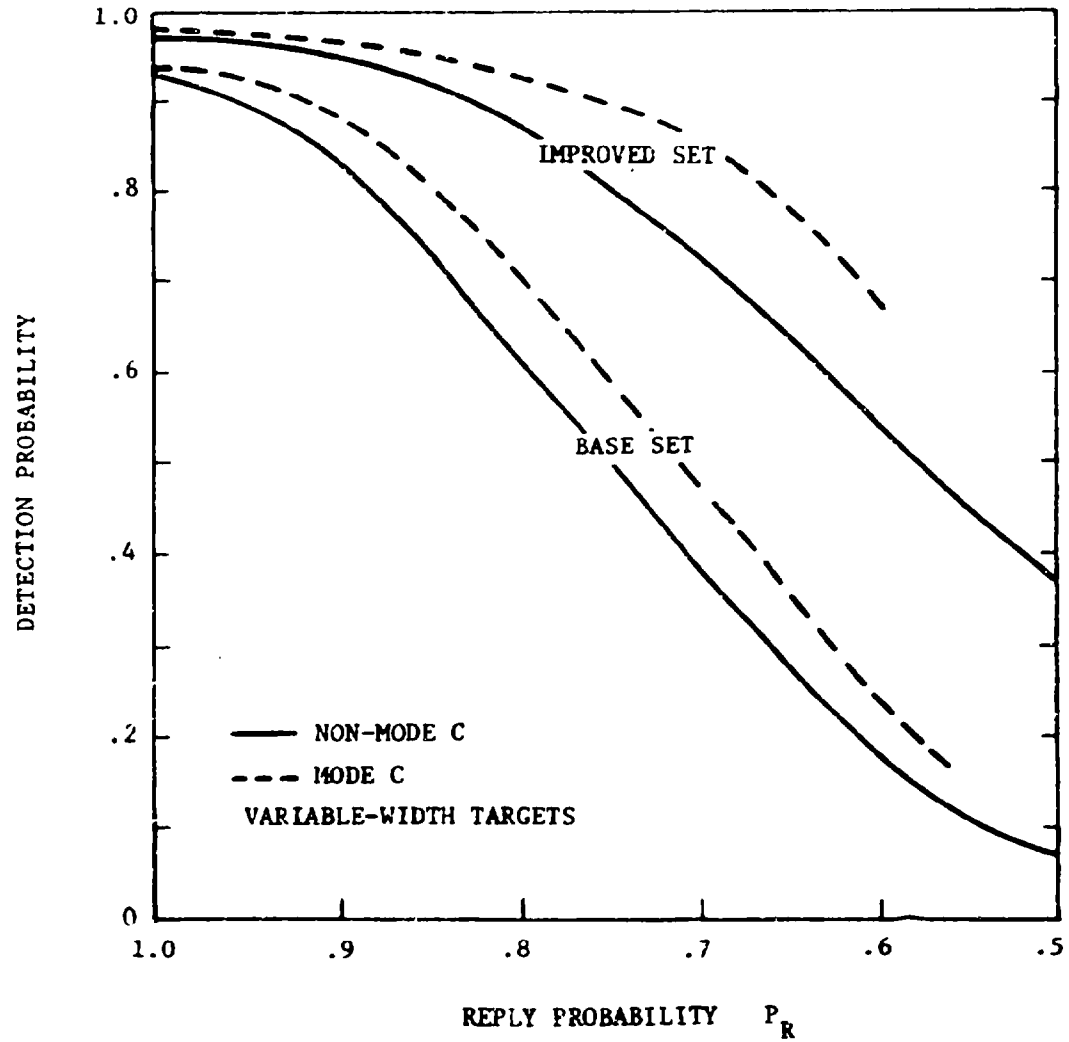

FIGURE 3-4
INFLUENCE OF CHOICE OF DETECTION PARAMETERS ON SENSITIVITY OF DETECTION PARAMETERS TO ENVIRONMENT DEGRADATION

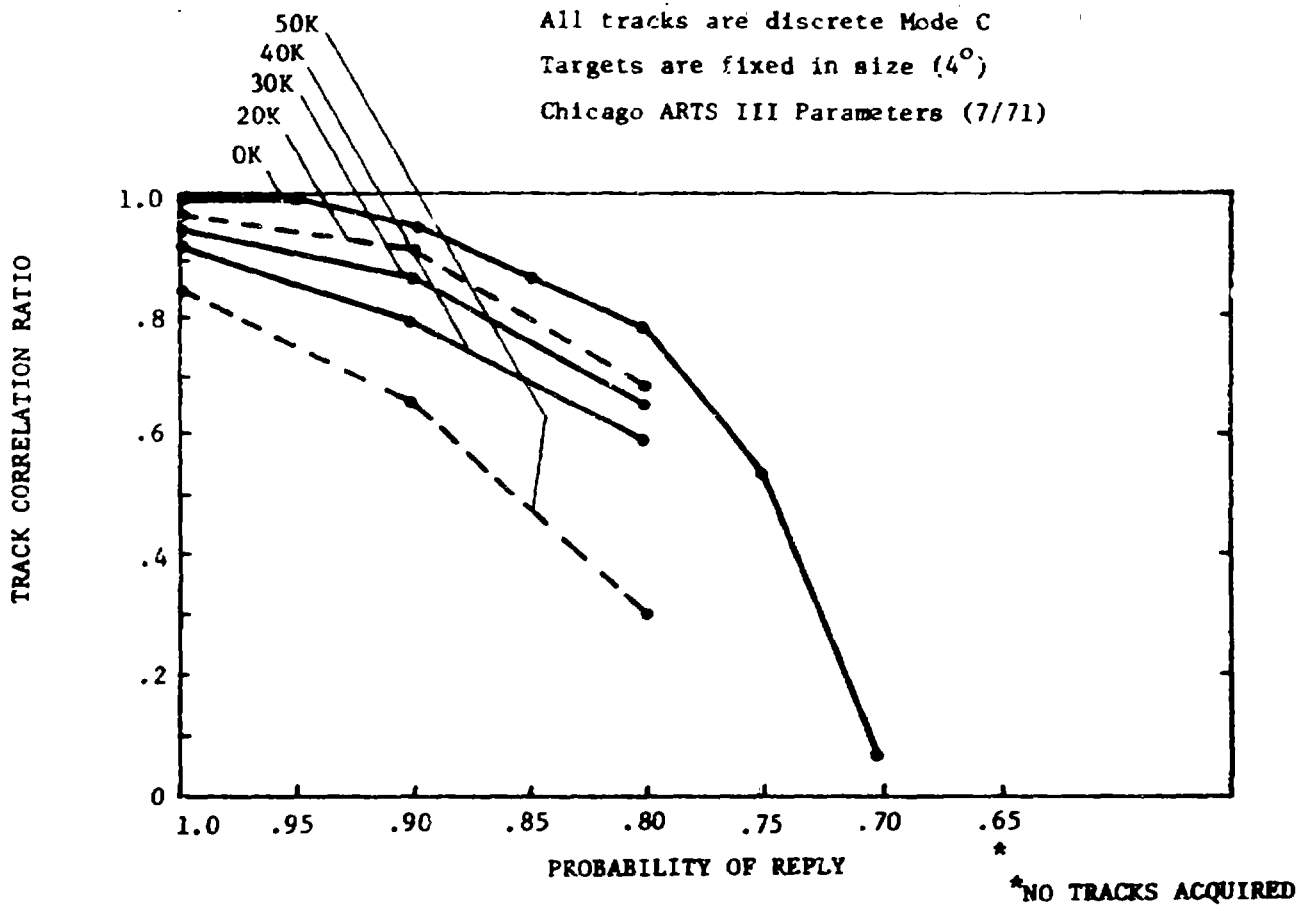

FIGURE 3-5
TRACK CORRELATION RATIO AS A FUNCTION OF BEACON PROBABILITY OF REPLY AND FRUIT PER SECOND

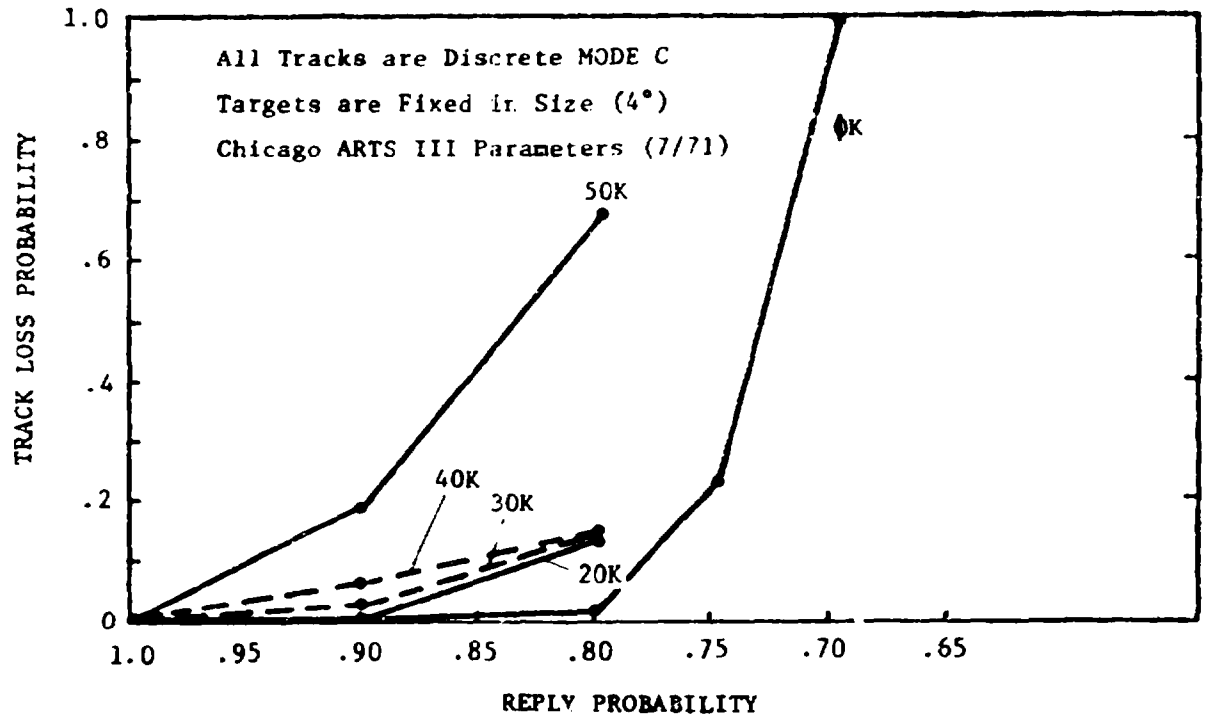

FIGURE 3-6
TRACK LOSS PROBABILITY AS A FUNCTION OF BEACON REPLY PROBABILITY AND FRUIT PER SECOND

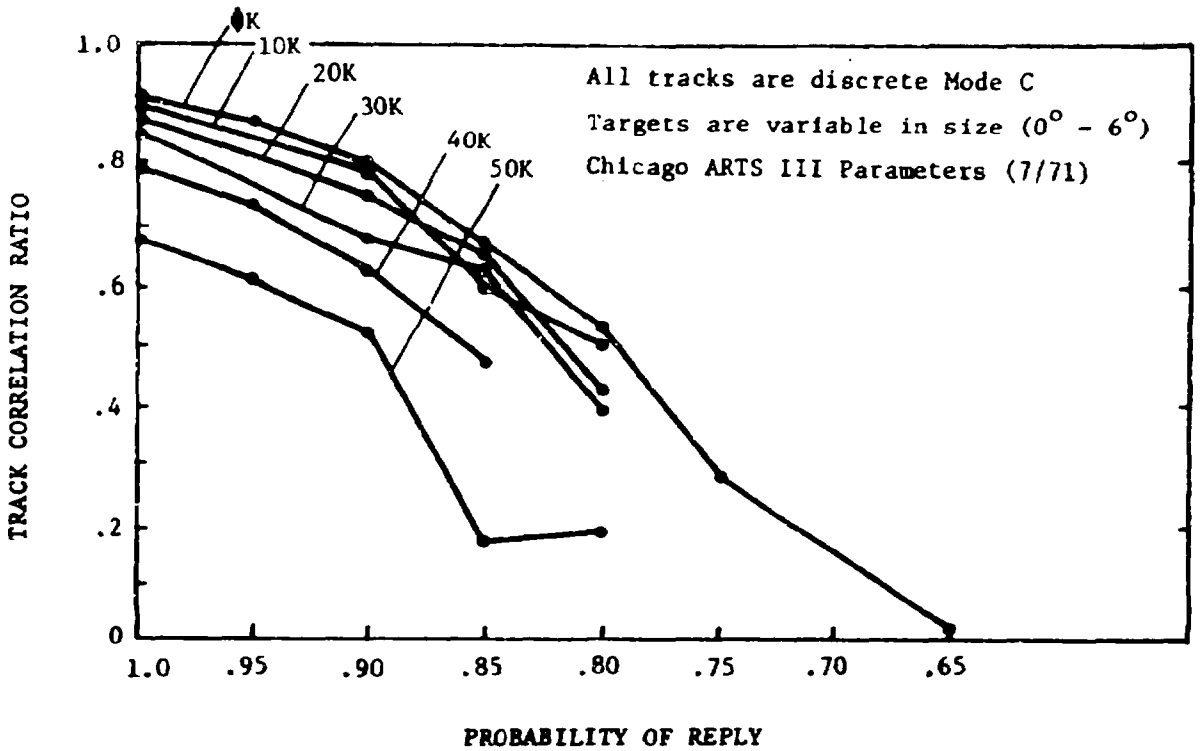

FIGURE 3-7
TRACK CORRELATION RATIO AS A FUNCTION OF BEACON PROBABILITY OF REPLY AND FRUIT PER SECOND

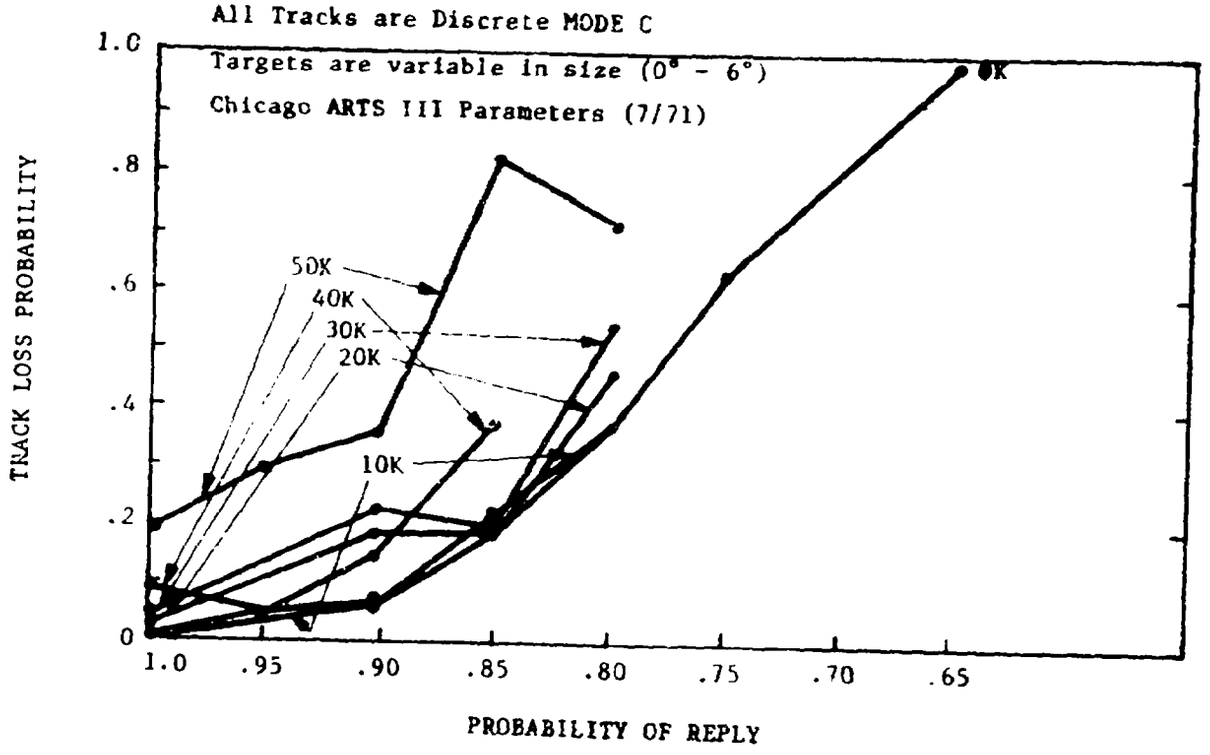

FIGURE 3-8
TRACK LOSS PROBABILITY AS A FUNCTION OF BEACON PROBABILITY OF REPLY AND FRUIT PER SECOND

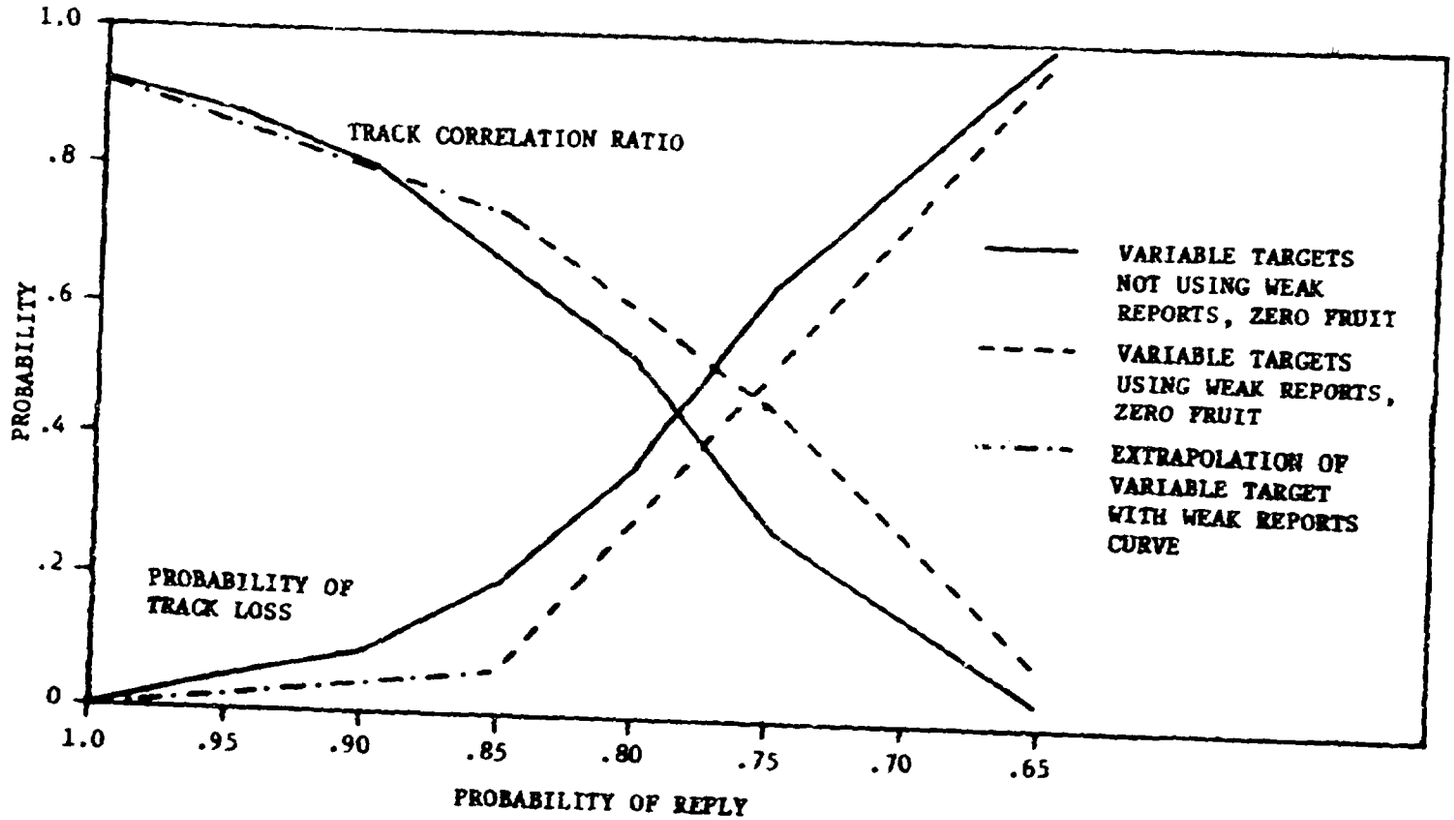

FIGURE 3-9
ARTS III TRACKING PERFORMANCE AS A FUNCTION OF THE UTILIZATION OF WEAK REPORTS

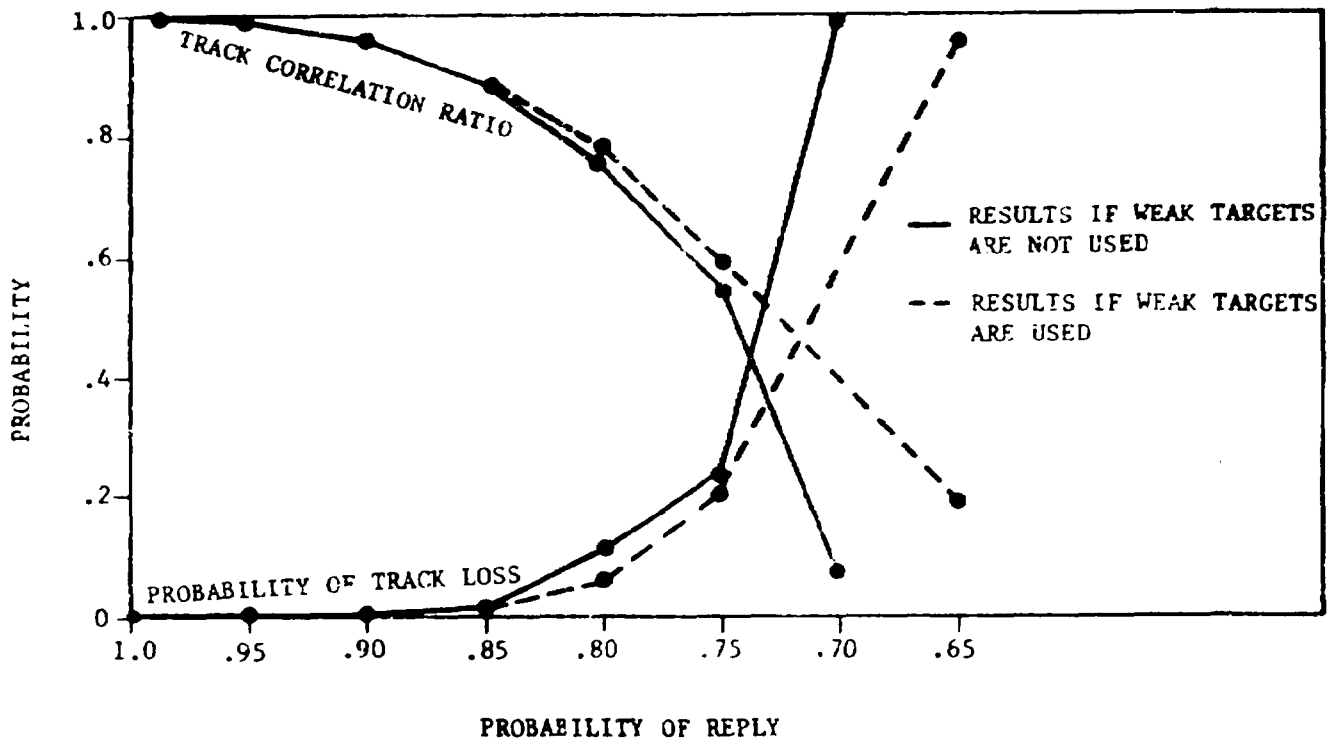

FIGURE 3-10
ARTS III TRACKING PERFORMANCE FIXED WIDTH TARGETS VERSUS STRONG/WEAK ACQUISITION CRITERIA

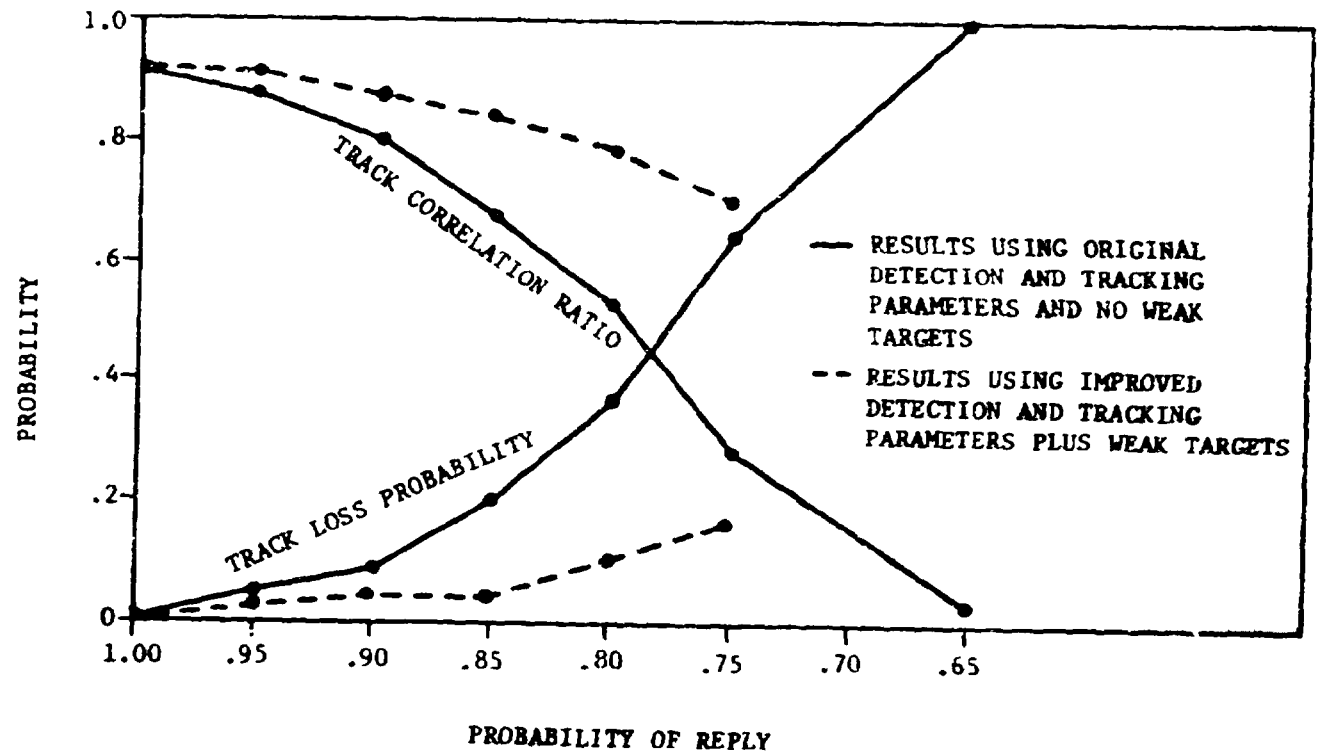

FIGURE 3-11
ARTS III TRACKING PERFORMANCE VARIABLE WIDTH TARGETS AND ZERO FRUIT WITH AND WITHOUT IMPROVED DETECTION, LOGIC AND TRACKING

4. CONCLUSIONS

1. The basic ARTS III system performance will degrade under conditions of increasing fruit and decreasing probability of reply. Under the assumptions of the study, which used the system parameters and logic of the Chicago ARTS III operational program as of January 1972, it appears that tracking performance will degrade noticeably when the reply probability drops below .85 and fruit is greater than 30K per second.

2. The quantitative results presented here are applicable only to the ARTS III detection and tracking parameters used for this study. More judicious choices of system parameters plus field tested logic improvements have been shown to improve system performance under field conditions.

3. In an environment of high reply probability and low asynchronous fruit the surveillance performance of basic beacon-level ARTS is limited by the existence of narrow-width targets engendered by antenna shielding and vertical lobing effects.

   A comparison of the results of this study related to fixed and variable-width targets predicts that substantial benefits are to be gained through stabilization of the target widths. Not only would immediate improvement to current performance levels result, but also the susceptibility to future environmental degradations would be lessened.

4. All measures of detector performance, with the exception of the target split probability, were found to be sensitive to environment degradations. However. processing time utilization and azimuth accuracy exhibited only minor sensitivity. Degradations in reply probability will primarily result in lower probability of detection. As fruit increases, the percent of erroneous codes increases. As the number of targets declared increases, detection processing utilization will increase linearly.

5. All measures of tracking performance are sensitive to environmental degradations as a result of the tracker's dependence on detector performance. The tracker performance is primarily dependent on probability of detection, on failure to discern Mode C, and on erroneous Mode 3/A code reports.

6. No statement can be made on the basis of this study with regard to system degradation due to: 1) synchronous fruit produced by side lobe replies or reflection replies or 2) with regard to synchronous garble.

7. No quantitative statement can be made about when system breakdown would occur due to controller workload increases. Subjectively, the knee of the probability of track loss (PTL) curve is believed to be a reasonable first order approximation of the point where substantial controller objection would be noted (i.e., .85 probability of return for the current target width characteristics and .8 for the fixed width targets).

5. RECOMMENDATIONS

1. Consider the expected impact of a degraded beacon environment on the enhanced ARTS III system which includes supplementary primary radar, improved beacon signal processing, and multi-sensor radar/beacon coverage plus improved algorithms and parameter settings.

2. Perform analysis and experimentation needed to determine quantitatively the effects of a degraded beacon environment on controller workload, stress, and traffic safety.

3. Study the effects of synchronous fruit (reflections and side lobe replies) and main beam synchronous garble on the performance of the ARTS III system.

J. A. Keenan J. E. Freedman K. M. Levin

APPENDIX E

TPX-42 DEGRADATION

This appendix is the Executive Summary from the Final Report: "AN/TPX-42 Target Processing Simulation Study", by S. M. Weinstein and A. Borelli, Hazeltine Corporation, Report #10773, November 23, 1971. The program was directed at Hazeltine by J. H. Gutman.

A. AN/TPX-42 System Description

The AN/TPX-42 Interrogator Set is a complete secondary surveillance radar ground interrogator, processor and display system. It can be used at both fixed and mobile ATC installations for the terminal control of aircraft equipped with beacon transponders. The Interrogator Set provides for the transmission, reception, and processing of signals as specified in the U. S. National Standard for the IFF Mark X (SIF)/ Air Traffic Control Radar Beacon System (ATCRBS). The AN/TPX-42 normally operates in association with a primary radar system and provides special beacon position symbols, and aircraft identity and altitude numerics on a traffic controller's PPI display.

Components of the Interrogator Set pertaining to the beacon processing function are the defruiter (interference blanker) and the Beacon Reply Processor (BRP). The defruiter only passes a reply pulse when it is synchronous with a reply received on the previous interrogator pulse repetition period for the same mode. The BRP accepts replies from the defruiter and processes these replies to produce a digital report for each aircraft on every scan of the antenna. This target report contains aircraft position coordinates (range and azimuth), identity code or codes and altitude data.

The AN/TPX-42 is capable of operating with the beacon/IFF modes 1, 2, 3/A, and C using a variety of interlace patterns. Operation with various primary terminal radars is expected to result in a minimum

of 9 and a maximum of 20 interrogations per scan on a target. The governing AN/TPX-42 specification (DOD-AIMS 65-527(B)) indicates that an average number might be 14 when operated at a pulse repetition frequency of 360 interrogations per second and a 4 second scan period (15 RPM). The specification requires operation in an environment containing a maximum of 128 targets within 200 NM of the radar. Furthermore, the equipment must be capable of processing up to 32 targets simultaneously within the beam of the beacon interrogator antenna.

B. Beacon Processing Functions

The AN/TPX-42 beacon processor uses a statistical decision device called a "sliding window" for the detection and azimuth center-marking of beacon targets. A sliding window is simply a shift register of fixed length (LW) into which a binary "one" is entered if a bracket decoded reply is present at the range of interest on a particular pulse repetition period (prp); otherwise a "zero" is entered. On successive prp's the ones and zeroes shift through the register. When the number of ones in the register reaches a preselected "leading edge" (LE) threshold, the target leading edge is declared at the associated prp. Trailing edge determination is made when the number of ones falls below a preselected trailing edge threshold (TE).

- o Target Detection is a function performed to determine whether or not a series of replies received within a given range limit on successive beacon interrogations (of all modes) constitutes a set of replies from a true target. The declaration of leading and trailing edge is one component of target detection. The other is confidence check.
- o Confidence Check is a function performed to screen and discard spurious false targets by requiring that a minimum number of bracket decodes (replies) be received out of the defruiter during a given scan across the target. The preselected confidence level (CL) must be met or exceeded in order to allow targets (whose leading and trailing edges have been declared) to be transmitted to the display processor.

- o Code Validation is a function performed to extract and report the most provable correct code value from the set of codes (of a given mode) received on a given scan across the target. The technique employed in the AN/TPX-42 processor to validate a code requires that two consecutive replies out of the defruiter (in the same mode) match and at least one must be garble-free. Target reports to the display processor will include the positional data on detected targets and validated code data only. Thus, failure to validate identity and/or altitude code will result in the absence of the associated information from the display.
- o Azimuth Centermarking is performed by averaging the leading and trailing edge measurement (including subtraction of an appropriate bias). Under certain conditions, the beacon processor may declare the presence of more than one target based on the sequence of replies from a single target. An azimuth split occurs when leading and trailing edges are declared more than once. This results in the reporting of two or more targets at the same range with slight azimuth separation. This condition generally results in incorrect azimuth centermarking of the single true target.

The following table shows the range of adjustment of the sliding window parameters of the AN/TPX-42 and the planned typical setting for government evaluation of production equipment.

PARAMETER	RANGE	TYPICAL SETTING
Window Length (LW)	8-12	8
Leading Edge Threshold (LE)	1-4	2
Trailing Edge Threshold (TE)	0-2	1
Confidence Check Level (CL)	0-16	0

C. Method of Analysis

The primary tool used in the analysis of the AN/TPX-42 is an existing, Hazeltine developed, computer model of the beacon processing functions. This model was exercised in a Monte Carlo simulation to study the impact of various environments on target detection, code validation and azimuth centermarking accuracy. The environmental factors

accommodated by the model are:

Transponder Reply Ratio - (TRR), the probability that a main beam interrogation will elicit a transponder reply. This probability is a function of many factors including the number and location of beacon interrogators, their coverage, transmitted power and interrogation rate, use of side-lobe suppression, aircraft antenna patterns and detailed transponder suppression characteristics.

Fruit Rate - The average rate at which asynchronous beacon reply trains occur at the interrogator of interest. These "fruit" replies are responses from transponders in the environment elicited by interrogators other than the interrogator of interest. This rate depends on the number and location of interrogators and transponders, the TRR of the transponders and the interrogators operating characteristics.

Hits Per Scan - the number of interrogations transmitted as the main beam of the interrogator scans the target. This depends upon the antenna rotation rate, interrogator prf and the "effective" antenna beamwidth (resulting from the detailed interrogator antenna pattern and side-lobe-suppression characteristics of the transponder).

Burst Errors - This is a form of interrogation link interference due to another interrogator operating in the coverage area having a prf nearly synchronous with the prf of the interrogator of interest. The interference manifests itself by the offending interrogator "capturing" the transponder for a number of successive pulse repetition periods, thereby denying service to the interrogator of interest. This burst error can be characterized by its period (in prp's) and the probability of its occurrence on a particular target scan.

Target Detector Parameters - the sliding window length (LW), the leading and trailing edge thresholds (LE, TE) and the confidence check level (CL) in the model are variable over the full range of possible AN/TPX-42 beacon processor settings.

Mode Interlace - the particular modes (1, 2, 3/A, C) used for

interrogation and the sequence in which they are used, constitute the mode interlace pattern of an interrogator. The modes elicit different types of coded information (e.g. barometric altitude on Mode C, identity code on Mode 3/A) from the transponder. The model can accommodate changes in the interrogator mode interlace as well as allow selection of the modes to which a transponder will reply.

The impact of the variation in these factors (representative of different environments) upon system performance (target detection, code validation, and azimuth accuracy) was examined by performing a parametric investigation. That is, a parameter was varied over its expected range (e.g. transponder reply ratio from 0.65 to 1.0) while others were held constant to evaluate sensitivity of system performance to each parameter of interest.

The model consists of two parts, a data generator program, and a beacon target processing program. The data generator provides (1) the target reply history (a sequence of coded replies/no replies based on transponder reply ratio) (2) a superimposed burst error condition and (3) embedded fruit replies and associated garble conditions. This is accomplished by a set of random number generators which are programmed to simulate the occurrence of events in accordance with the desired probability (in a manner consistent with detailed equipment characteristics). The beacon target processing program operates upon the generated data using a model of the sliding window to determine (1) whether these sequences result in detected targets, (2) whether codes are validated and (3) the azimuth centermark of the target.

The method of computer analysis is called a simulation since the statistical results are gathered by repeating an experiment. This experiment consists of sending a reply sequence from the data generator into the beacon processor and noting the result. This is repeated many times with varying reply sequences and the results are averaged to determine the probability of detection, etc. In designing the simulation experiment and in drawing conclusions from the data obtained, it is important to recognize the implication of using a particular number of iterations. The number used permits one to associate a certain degree of confidence with the data accumulated and hence on

the conclusions drawn from that data. The greater the number of iterations, the more confidence one can place in the results. However, computer costs and availability of computer time place an upper bound on these iterations. One hundred iterations were used in this program since it appeared to be a reasonable compromise between confidence in the results and the number of different cases which could be simulated within the available time period.

D. Major Results

MITRE representatives suggested that primary emphasis be placed on gathering statistics using the "most likely" settings for the sliding window beacon processor. Although definite settings will not be selected until completion of a planned government test program, it is our understanding that Air Force evaluation of the AN/TPX-42 will commence using a window length (LW) of 8, a leading edge threshold (LE) of 2, a trailing edge threshold (TE) of 1, and a confidence level (CL) of 0 with a CL=4 also being considered. A three mode interlace (2,3, C,1,3,C) would probably be used and between 9 and 16 hits per beamwidth are expected. Accordingly, the majority of computer runs was performed using these settings. The transponder reply ratio (TRR) was varied from 0.65 to 0.95 and fruit rates of 300 to 30,000 reply trains per second were simulated. Certain runs were made with 9, 16 and 30 hits per scan.

1. Acceptable Levels of Performance

The performance of the beacon system is ultimately judged by its ability to contribute to the process of aircraft separation and control. The air traffic controller is becoming increasingly dependent upon the ATCRBS for aircraft positional, altitude, and identity information. Accordingly, the ideal beacon system should display continuous, reliable, accurate information on all beacon equipped aircraft. This translates into a set of ideal beacon processing performance characteristics namely:

a. 100% probability of detection to ensure a beacon report on each target on each antenna scan (consistent with acceptable false-alarm rate).

b. 100% probability of code validation for each beacon mode on each antenna scan to ensure the presence of identity and altitude information for each target.

c. perfect azimuth centermarking; beamsplit azimuth standard deviation of zero degrees.

d. zero probability of target splits (range and azimuth) such that a single (rather than multiple) accurate position/code report is displayed for each beacon target.

Unfortunately, these ideal characteristics cannot all be met simultaneously in practice. This is due in part to the environmental effects (fruit and transponder reply probability), which force a compromise between detection probability and false alarm rate. The governing AN/TPX-42 specification (DOD-AIMS 84-527 (B)) does not specify the aforementioned beacon processing performance probabilities. Therefore, a set of nominal minimum (maximum) acceptable levels of performance are suggested for evaluation of AN/TPX-42 processing. These are based on (1) a review of specifications for certain classified beacon processors (2) the specification for the joint FAA/DOD Common Digitizer used to provide beacon data to the NAS Enroute Control Centers, and (3) Hazeltine's judgment predicated on years of exposure to the spectrum of beacon/IFF systems. The following table shows the specified Common Digitizer parameters and those suggested for use for AN/TPX-42 evaluation.

TABLE E-1

BEACON PROCESSOR PERFORMANCE PARAMETERS

Parameter	En-Route Common Digitizer[1]	AN/TPX-42
Probability of Detection[2]	90%	90%
Probability of Code Validation	95%	90%
Azimuth Accuracy[2,3],	±.26° 11 hits per mode ±.42° 23 hits per mode	{±1 to 2 prp's ±.25° to .5°}
Percent Azimuth Splits	0% (11 hits per mode) 1% (23 hits per mode)	1 to 2%

Note 1: At 0.76 transponder reply probability

Note 2: Target Detection Performed on Mode 3/A only

Note 3: 90% of targets must fall within these limits for the Common Digitizer. The value for AN/TPX-42 is about 68% (1σ)

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To the controller, a 90% probability of detection means that there is only a 1% chance of failing to get a target report on two successive antenna scans. Likewise, a 90% probability of code validation means a 1% chance of missing code (or altitude) information on two successive antenna scans. The occurrence of azimuth splits can be related to the total number of targets to be processed or to the number assigned to a controller. Thus, although 2% azimuth splits means about 2 to 3 splits per total 360° antenna scan (2% of 128 targets), a controller responsible for say 10 aircraft would, on the average, only see a target split every 5 antenna scans.

The reader is reminded that the values suggested for evaluating AN/TPX-42 performance are not government specified, but represent a Hazeltine judgment. They are used only to provide a basis for evaluation of results.

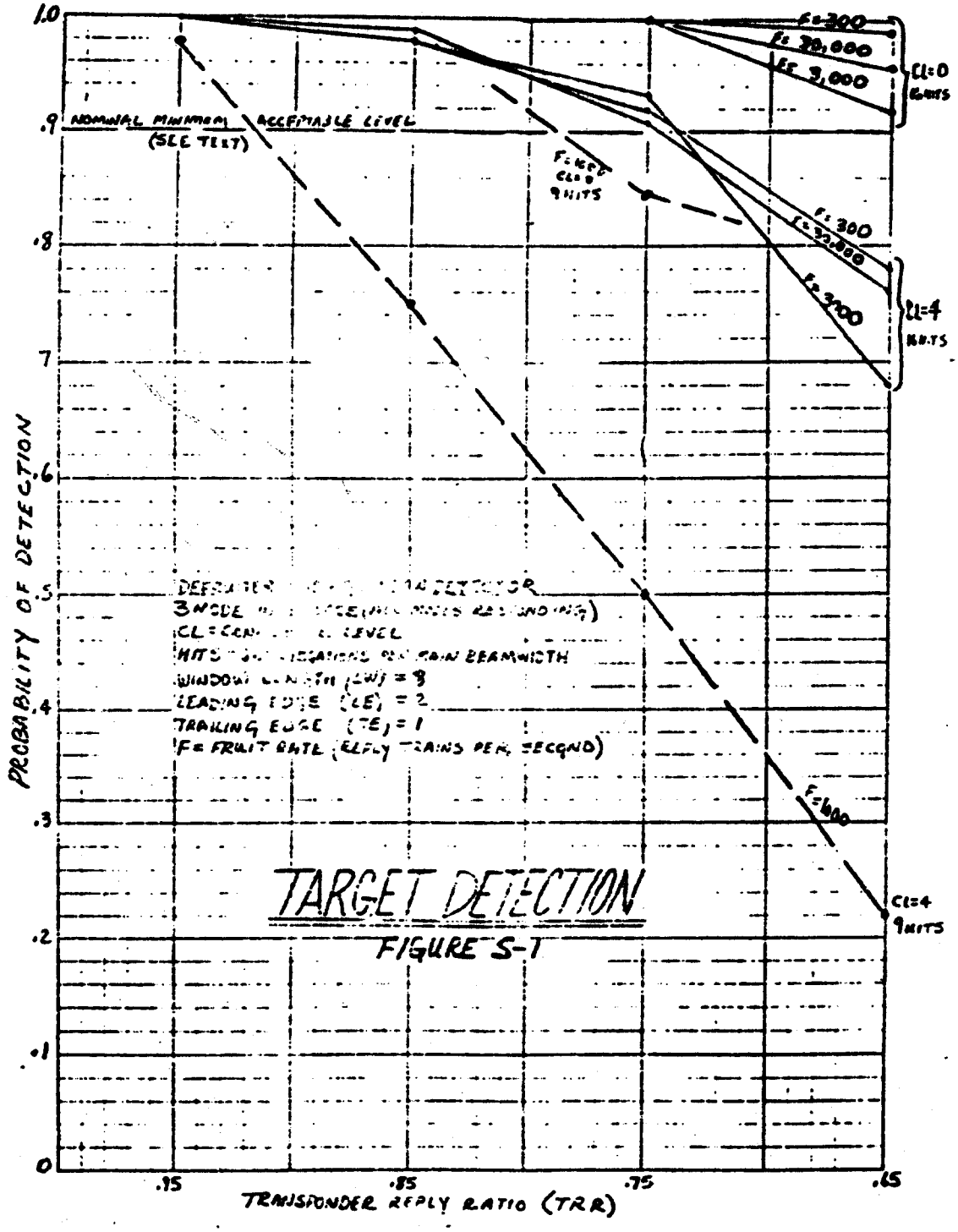
The results herein are based on 100 iterations for each data point. That is, in generating an estimate of an output parameter, data from 100 independent scans of the target was provided to the target detector.

2. Probability of Target Detection

The computer simulation was used to study the effects of transponder reply ratio, fruit rate, confidence level, and number of hits per scan on probability of target detection. Figure S-1 summarizes the major results. The suggested nominal minimum acceptable level for probability of detection is 90%.

a. With 16 hits on target and a confidence level of zero (CL=0), the probability of detection meets or exceeds 90% for fruit rates up to 30,000 reply groups per second and for transponder reply ratios as low as 0.65.

b. With 16 hits on target and a confidence level of four (CL=4) probability of detection meets or exceeds 90% for fruit rates up to 30,000 as long as TRR exceeds 0.75. Below TRR of 0.75, the probability of detection falls below 90% even for fruit rates as low as 300 reply groups per second.



TARGET DETECTION

FIGURE S-1

c. With only 9 hits on target and a fruit rate of 1000, the probability of detection falls below 90% when TRR is about .8 (for CL=0) and when TRR is as great as about .9 (for CL=4).

3. Code Validation

The computer simulation was run with a variety of conditions to study the code validation properties of the AN/TPX-42. The performance was generally poor (below 90% probability of code validation) for all cases at low (less than 0.8) values of TRR. Figure S-2 shows the results for the 16 hit case with the processor settings planned for use in the government test program (namely LW=8, LE=2, TE=1 and CL=0, three mode interlace). It is apparent that even for fruit rates as low as 300 replies trains per second, the probability of code validation falls below 90% for TRR below 0.85.

4. Azimuth Accuracy

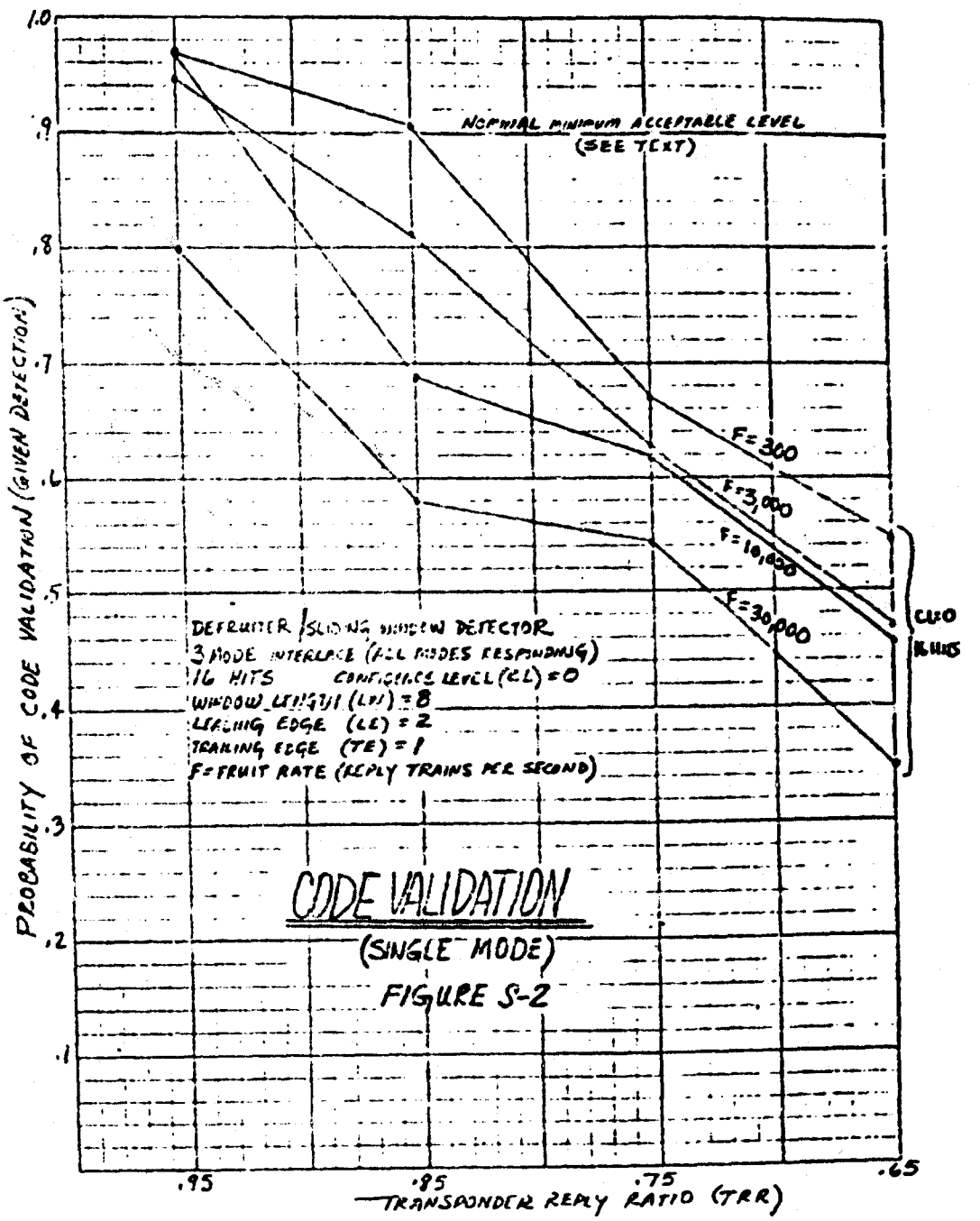
Target centermarking accuracy was studied as a function of hits per scan, confidence level, and fruit rate. The suggested nominal maximum acceptable level of standard deviation of reported target azimuth is 2 pulse repetition periods (2 prp's) which represents about 0.5° at a prf of 360 and a scan rate of 15 RPM. See Figure S-3.

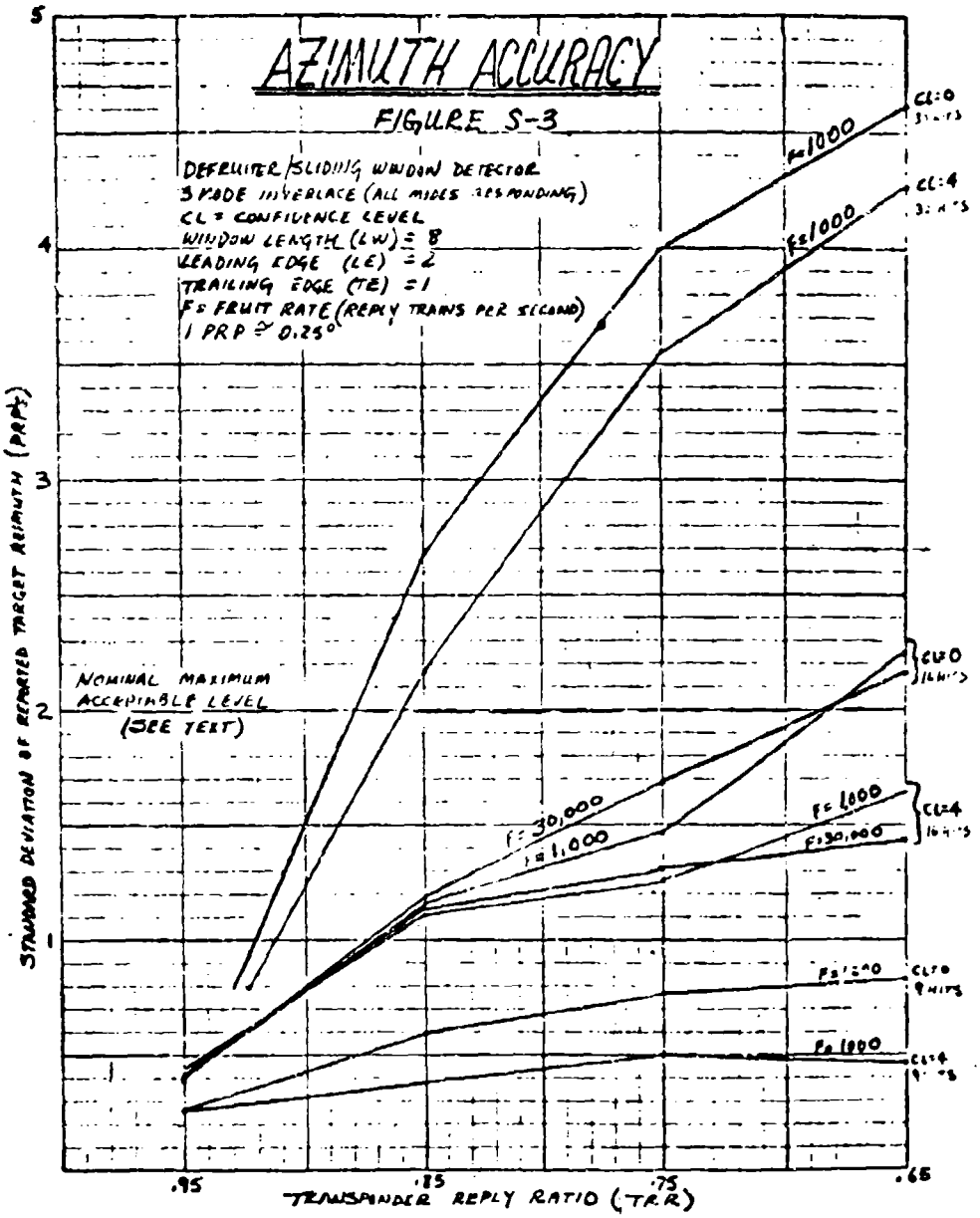
a. Azimuth rms error is acceptable (at or below 2 prp's) for the 16 hit case for fruit rates between 1000 and 30,000 for confidence levels of 0 and 4 even for transponder reply ratios as low as about 0.7.

b. With 9 hits the azimuth error is less than 1 prp for CL=0 and 4 for a fruit rate of 1000. (Recall however that with 9 hits, probability of detection is less than with the 16 hit case).

c. When the number of hits is increased to 30 (CL=0, 4, Fruit = 1000) the azimuth accuracy degrades (errors greater than 2 prps) with TRR as high as .85. When TRR falls to 0.65 the centermarking accuracy is about 4.5 prps (greater than 1 degree).

d. The occurrence of target azimuth splits with 16 hits on target was simulated with CL=0 and fruit rates between 300 and 30,000. For values of TRR below 0.8,


1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
PROBABILITY OF CODE VALIDATION (GIVEN DETECTION)
NOMINAL MINIMUM ACCEPTABLE LEVEL
(SEE TEXT)
F=300
F=3,000
F=10,000
F=30,000
CLEO
BLUES
DEFRUITER/SLIDING WINDOW DETECTOR
3 MODE INTERLACE (ALL MODES RESPONDING)
16 HITS CONFIDENCE LEVEL (CL) = 0
WINDOW LENGTH (LW) = 8
LEADING EDGE (LE) = 2
TRAILING EDGE (TE) = 1
F = FRUIT RATE (REPLY TRAINS PER SECOND)
CODE VALIDATION
(SINGLE MODE)
FIGURE S-2
.95
.85
.75
.65
TRANSPONDER REPLY RATIO (TRR)


AZIMUTH ACCURACY
FIGURE S-3
DEFRUITER/SLIDING WINDOW DETECTOR
3 MODE INTERLACE (ALL MODES RESPONDING)
CL = CONFIDENCE LEVEL
WINDOW LENGTH (LW) = 8
LEADING EDGE (LE) = 2
TRAILING EDGE (TE) = 1
F = FRUIT RATE (REPLY TRAINS PER SECOND)
1 PRP ≅ 0.25°
NOMINAL MAXIMUM ACCEPTABLE LEVEL (SEE TEXT)
F=1000
F=1000
CL=0
CL=4
CL=0
CL=4
F=30,000
F=1,000
F=1000
F=30,000
F=1000
F=1000
STANDARD DEVIATION OF REPORTED TARGET AZIMUTH (PRP's)
TRANSPONDER REPLY RATIO (TRR)
.95
.85
.75
.65
1
2
3
4
5

azimuth splits resulted for more than 2% of the targets as shown in Figure S-4. However, because of the small sample size associated with this particular estimator, no accurate probability of splits can be assigned.

e. When the TPX-42 performance was examined in an environment of 30 hits per scan in contrast with 16 (all other parameters remaining unchanged) azimuth accuracy and target split performance was significantly degraded.

5. Other Results

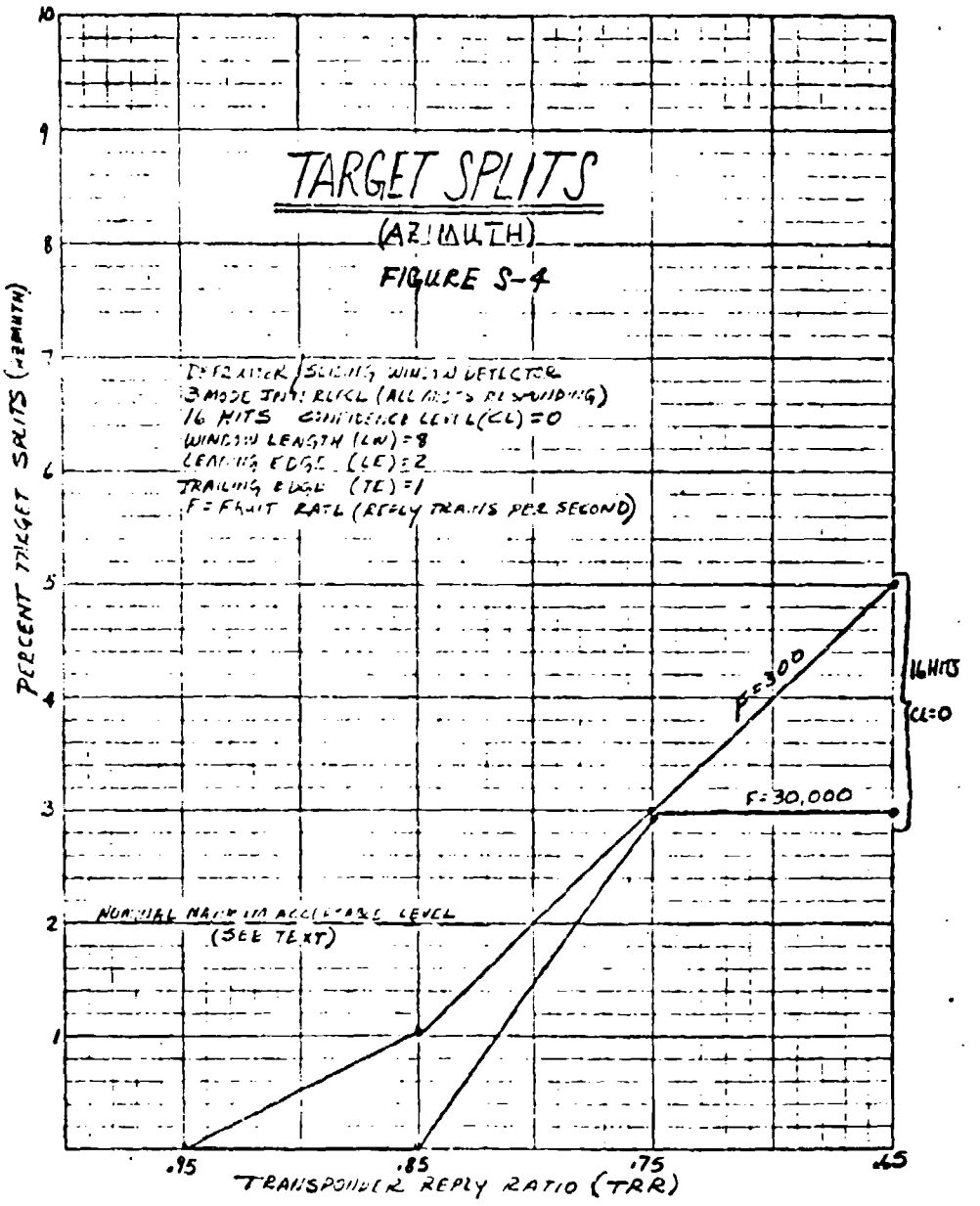
The computer simulation was also used to study the impact of both burst errors and transponders replying to only two out of three modes (missing mode) on system performance. In general, the results indicate that burst errors with probability of occurrence of 0.1 seem to have no more degrading effect than that experienced by an equivalent reduction in transponder reply ratio (TRR). The impact of a transponder with a missing mode was a reduction in probability of detection and azimuth accuracy at lower (0.65) values of TRR.

An analytic investigation of false alarm rate (false target) generation due to the presence of fruit was performed for the AN/TPX-42 beacon processor. A suggested acceptable level of performance used is one (1) persecond which is approximately the same as the Common Digitizer (CD), whose allowable false alarm rate is 0.4 per second (i.e., four per ten second scan). The analysis shows that with a confidence level of zero (CL=0) less than one false alarm per second occurred with a fruit rate of 20,000 trains per second and about 6 false alarms per second occurred at a 30,000 fruit rate. A confidence level setting of four (CL=4) resulted in satisfactory performance (less than 0.4 false alarms per second)with fruit rates up to 30,000 per second.

E. Conclusions

A Monte Carlo simulation of the AN/TPX-42 target detection and code validation operation was performed with the following nominal detector parameters:

- Sliding Window length (LW): 8
- Leading edge threshold (LE): 2
- Trailing edge threshold (TE): 1
- Confidence level (CL): 0
- Hits per target scan: 16


TARGET SPLITS
(AZIMUTH)
FIGURE S-4
3 MODE INTERLACE (ALL MODES RESOLVING)
16 HITS CONFIDENCE LEVEL (CL) = 0
WINDOW LENGTH (LW) = 8
LEADING EDGE (LE) = 2
TRAILING EDGE (TE) = 1
F = FRUIT RATE (REPLY TRAINS PER SECOND)
F=300
F=30,000
16 HITS
CL=0
NOMINAL MAXIMUM ACCEPTABLE LEVEL
(SEE TEXT)
PERCENT TARGET SPLITS (AZIMUTH)
TRANSPONDER REPLY RATIO (TRR)
.95
.85
.75
.65
1
2
3
4
5
6
7
8
9
10

Results of the simulation study indicate that under these nominal operating conditions, satisfactory performance (as measured by suggested criteria included herein) is obtained for all performance parameters of interest except code validation. With regard to code validation, performance is below acceptable levels when the fruit rate is as low as 300 per second and TRR is less than 0.85. Fruit rates of 30,000 reply trains per second can cause unacceptable performance (i.e. less than 90% probability of validation) even when TRR is as high as 0.95.

In addition to determining the levels of performance under nominal operating conditions and environment, the sensitivity of system performance to various environmental parameters was determined. Table S-2 gives a qualitative summary of these sensitivities. It can be seen from that table that transponder reply ratio (TRR)and number of hits per target scan have the greatest effect on performance. Probability of detection and code validation are the performance parameters most sensitive to changes in environment.

Parallel measurement programs and computer modeling efforts are under way to characterize the present and postulated ground and airborne environments. These programs, when coupled with the results presented herein, will provide a base for assessing beacon system performance as a function of actual operating environments.

TABLE S-2

SENSITIVITY OF PERFORMANCE PARAMETERS TO CHANGES IN ENVIRONMENT

ENVIRONMENT	INCREASING DETECTION PROBABILITY	INCREASING AZIMUTH ACCURACY	INCREASING CODE VALI-DATION PROBABILITY	INCREASING PERCENTAGE OF TARGET SPLITS
See Figures	2-2 thru 2-6	2-7 thru 2-10	2-13 thru 2-17	2-18 thru 2-20
INCREASING FRUIT	0	0	-2	0
INCREASING TRANSPONDER REPLY RATIO	+2	+2	+3	-2
INCREASING CONFIDENCE LEVEL	-2	+2	+1	-3
INCREASING BITS	+3	-3	+3	+3
INCREASING MODE REPLY RATIO	+2	+1	0	0

Sensitivity Ratings:

Plus (+) Positive correlation
Minus (-) Negative correlation

Sensitivity Levels:

0 Unaffected or mildly affected
1 Moderately affected
2 Strongly affected
3 Very strongly affected

APPENDIX F

DESCRIPTION OF EXPERIMENT

This appendix contains Sections II and III as well as part of Section IV from the Final Report:
"ATCRBS Measurement Program - Final Report (Measurements in the N.Y.C. Metropolitan Area)," by G. L. Glatfelter, W. P. Goldberg, R. Rubin, and I. R. Smith", MITRE MTR-2334, Vol. 1 & 2, 24 March 1972.

Other results from the experimental program are contained in:
"ATCRBS Measurement Program - Interim Report (Measurements in the Bedford Area)," by I. R. Smith, MITRE WP-4216, 18 February 1972 and,
"Trandponder Decoder Performance in an Interference Environment", by G. L. Glatfelter and I. R. Smith, MITRE WP-4332, 19 June 1972.
The last flight - P_R = 98%

The experimental effort was directed in Department D-81 by R. C. Renick.

Geographic Locale

To obtain data in a high air traffic density terminal area, the experimental measurements were carried out in the vicinity of John F. Kennedy Airport, New York City. Floyd Bennett Naval Air Station was chosen as the interrogator site because of its proximity to three major airports, John F. Kennedy, LaGuardia and Newark, and because of its favorable terrain, availability of primary power and facilities for securing the site. A map of Floyd Bennett Naval Air Station showing the interrogator location is given in Figure 2-1 and the relationship between the test site and the surrounding airports is shown in the map in Figure 2-2.

Interrogator Configuration

A block diagramatic representation of the interrogator/receiver is shown in Figure 2-3. The major equipment consists of two AN/UPX-6, transceivers, an antenna rotator AB/221-TPS-1D with dual rotary joint, directional antenna AT-309 and omnidirectional antenna AS-177. One AN/UPX-6 is used to transmit the sidelobe suppression pulse, P_2, via the AS-177 antenna and the second one is used to transmit the P_1 and P_3 pulses and to receive transponder replies via the directional antenna AT-309,

The UPX-6 transceivers are driven by a modified coder-decoder, KY-274 and KY-275, supplemented by a PRF and trigger generator. The combination of KY-274, KY-275 and PRF generator is capable of generating

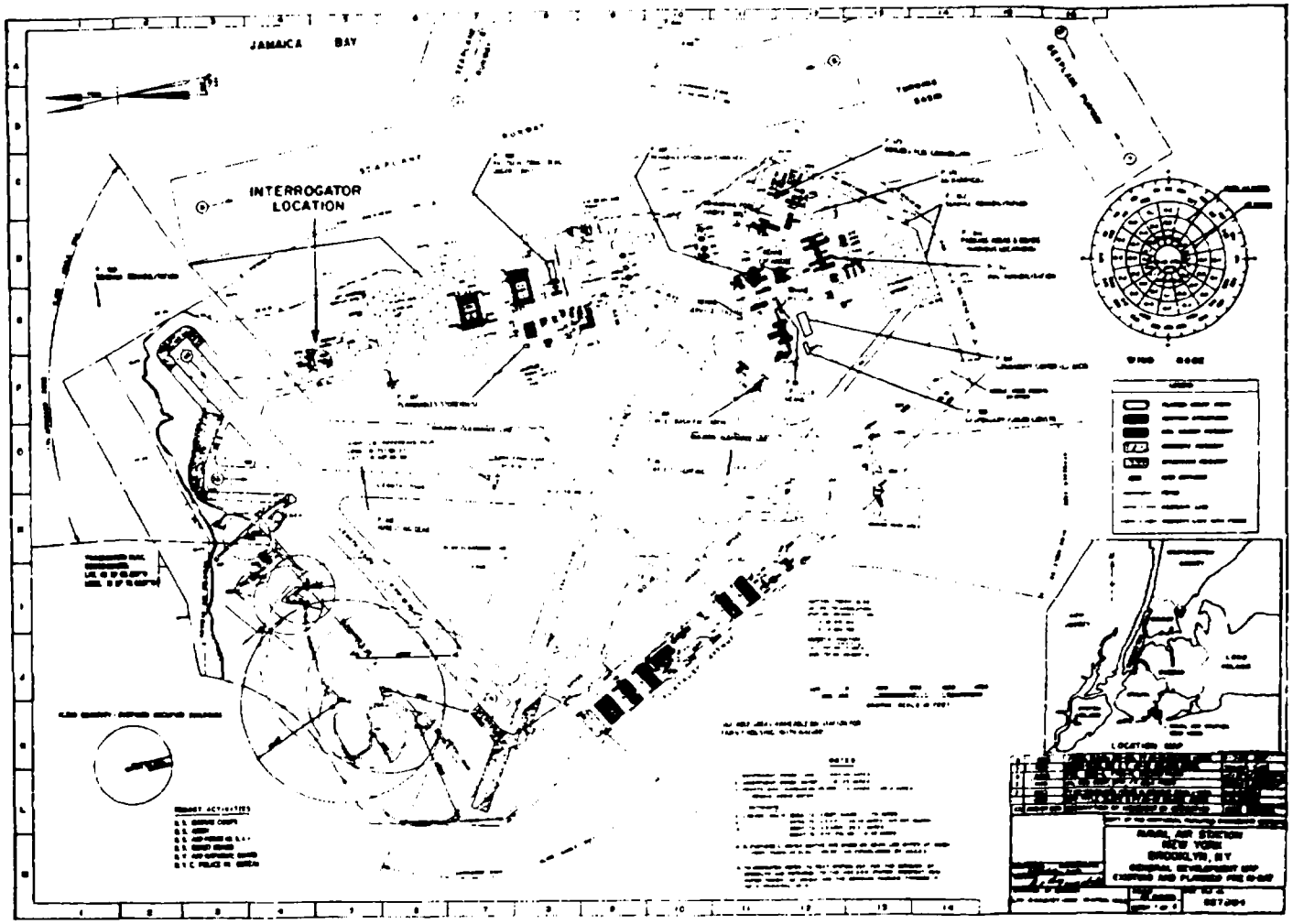


Figure 2-1 INTERROGATOR SITE AT FLOYD BENNETT NAVAL AIR STATION

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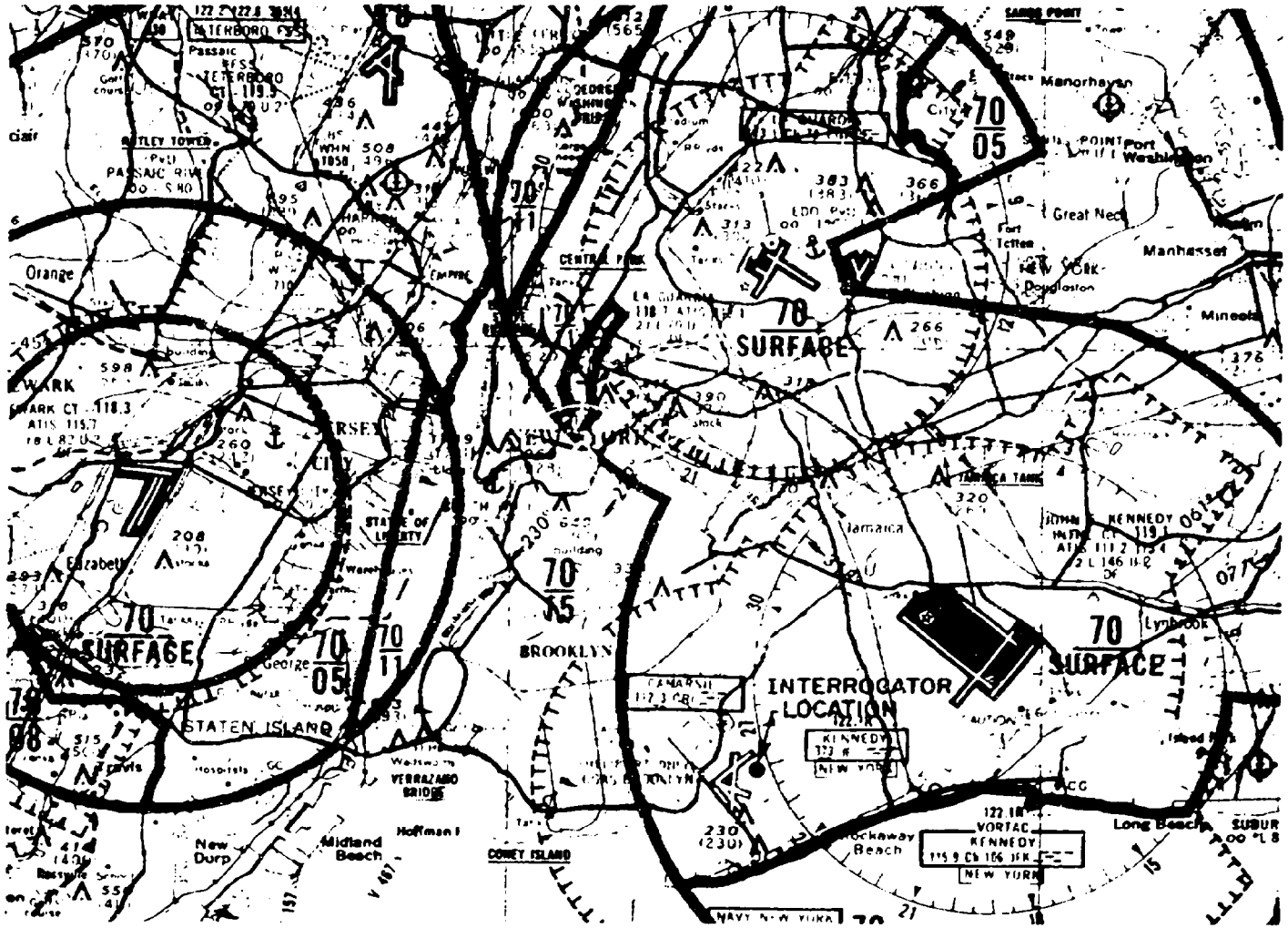

Figure 2-2 INTERROGATOR SITE LOCATION IN NEW YORK METROPOLITAN AREA

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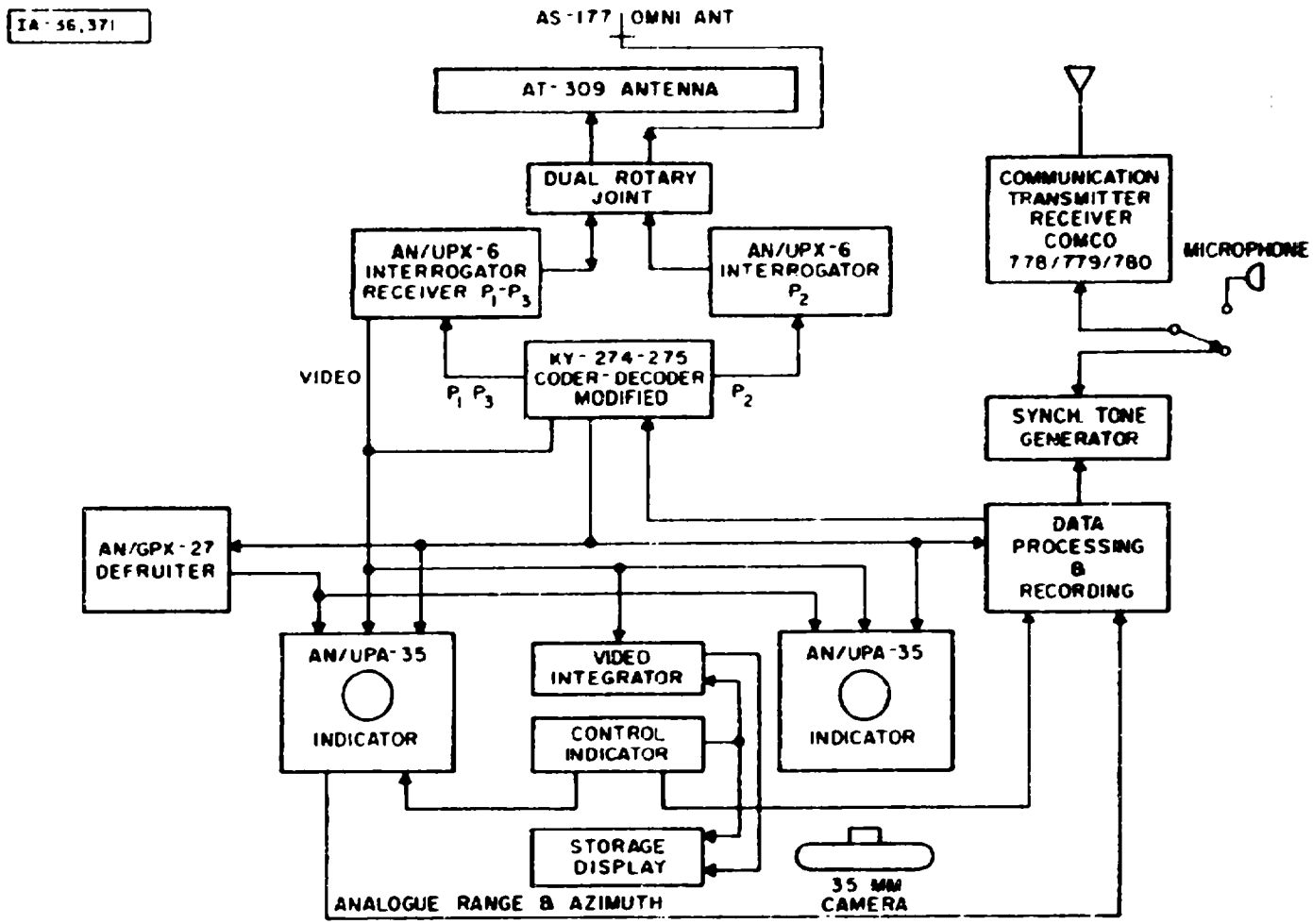

Figure 2-3 INTERROGATOR CONFIGURATION BLOCK DIAGRAM

Modes 3/A, C and D either separately, or interlaced in pairs on a one to one basis. Interrogations can be performed continuously or, under the control of the data processing equipment, in a burst transmission mode as the antenna beam passes the azimuth of the target. The video output of the decoder is processed by the data processing equipment and also displayed on two UPA-35 PPI displays. The unprocessed video output of the UPX-6 receiver is available for display as are various other signals and functions. In order to provide a clear display for photographic purposes, the output of the decoder is defruited by a Defruiter AN/GPX-27. Both the defruited and undefruited outputs are available for display. One UPA-35 is provided with a Control Indicator C-2055 which generates an area gate. The area, or tracking gate is displayed on the PPI displays and is used to generate various other gates and timing signals as described below.

To assist the operator in tracking the aircraft, the unprocessed video output of the UPX-6 receiver, that is received during the tracking gate, is integrated and presented on a slow sweep storage tube display. The storage tube also displays the gates generated by the data processing equipment showing the operator the relative position of the aircraft and the tracking gate.

Voice communications with the test aircraft is obtained by means of a VHF equipment manufactured by Comco and consisting of a 779 receiver, a 778 transmitter and a 780 power amplifier. The power output is 50 watts. The communication channel is used for both voice

communication and the transmission of synchronizing signals to the airborne portion of the measuring equipment. The synchronizing signals are a 400 Hz and a 2000 Hz tone which modulates the transmitter at appropriate times under the control of the data processing equipment.

The complete interrogator station is mounted in a 31 foot trailer as shown in exterior view and several interior views in Figures 2-4, 2-5 and 2-6.

Operational Considerations

Referring to Figure 2-3, it is instructive to trace some of the more important signal flows that occur during tracking operation. To avoid interfering with the normal operation of the ATC system, the FAA specified a repetition rate of 258 interrogations per second to be maintained throughout the tests. This repetition rate is generated by an adjustable PRF generator that forms part of the modified coder-decoder and is used as the basic timing signal throughout the system. The coder section of the KY-274 accepts the trigger pulses from the PRF generator and produces drive pulses for the P_1/P_3 transmitter and the P_2 transmitter in accordance with the mode selected by the Mode Selection Switch. Three modes are provided; Mode 3/A, Mode C, and Mode D with spacings between P_1 and P_3 of 8, 21, and 25 μs respectively. The P_2 pulse is always two μs after P_1. By means of a selector switch, the coder can be made to interrogate continuously or in a short burst, once per revolution of the antenna.

The azimuth at which the interrogation burst occurs is determined by the position of the azimuth cursor on the PPI display. The position

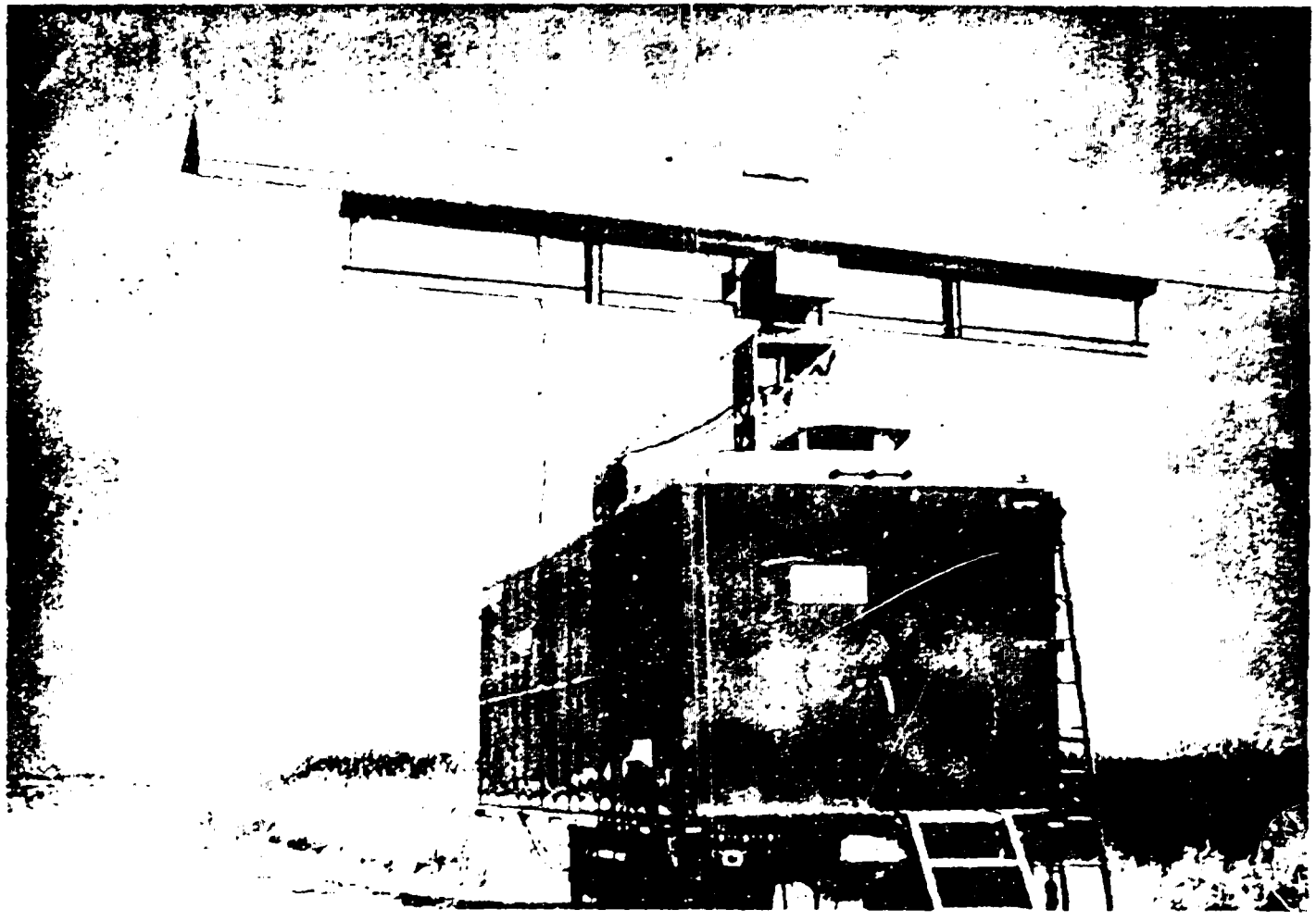

FIGURE 2-4 EXTERIOR VIEW OF INTERROGATOR TRAILER

FIGURE 2-5 INTERIOR VIEW OF INTERROGATOR TRAILER

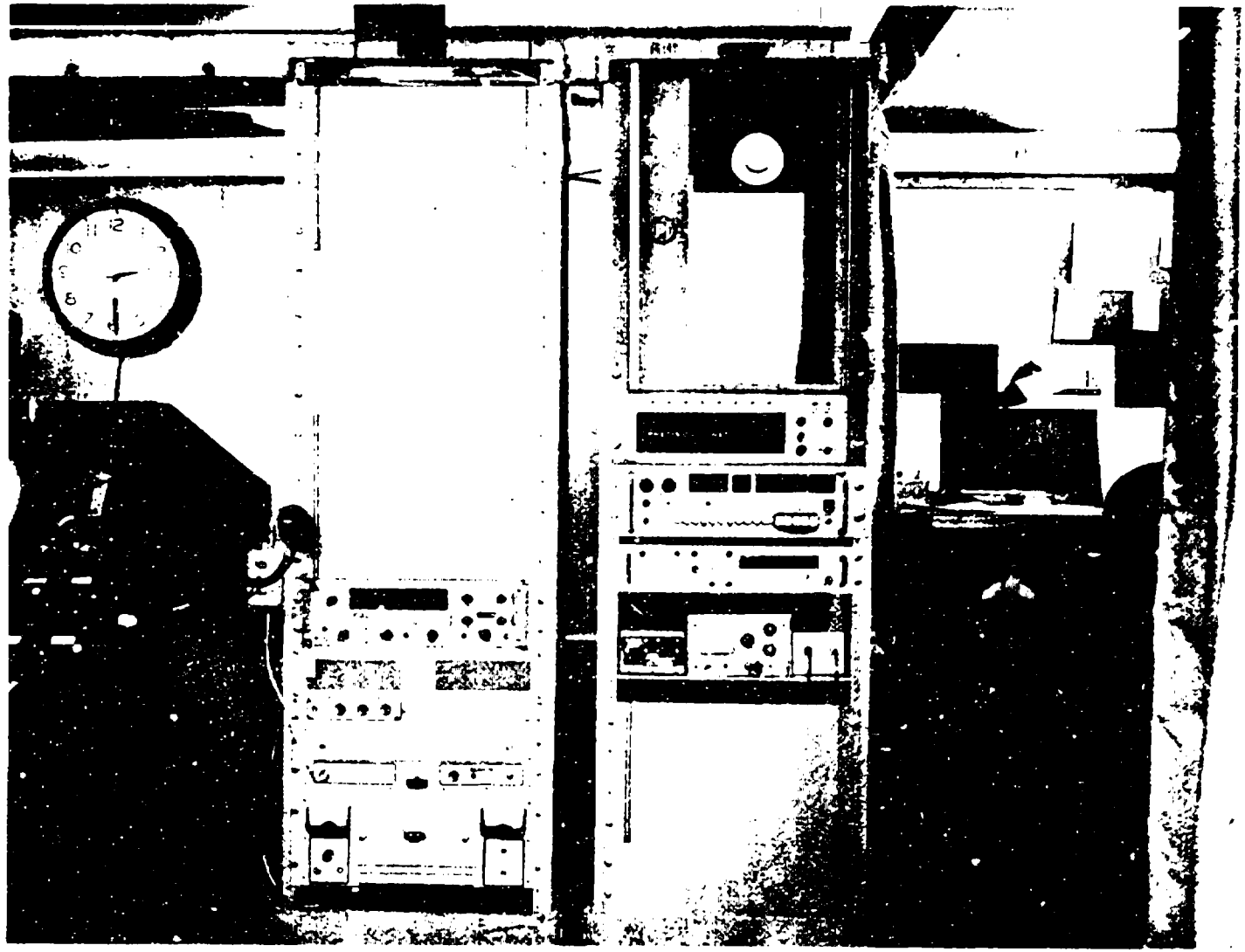

FIGURE 2-6 COMMUNICATIONS, DATA PROCESSING AND RECORDING EQUIPMENT

of the cursor is controlled by means of a joystick which also controls the range of a range gate. The joystick azimuth and range information are inserted into the Control Indicator which combines then to produce an area gate. The area gate consists of a sequence of approximately 30 range gates each about 40 μs long, spaced at the reciprocal of the PRF. The length of the range gates and the number of range gates are both adjustable by means of range and azimuth gate width controls in the Control Indicator. Since the area gate tends to have a somewhat slow rise and fall time on its leading and tracking edges, it is processed further by the data processing equipment before use as a final tracking gate. The data processor also reproduces a set of pre-triggers which are returned to the KY-274 coder to produce the burst interrogations. For these tests, the burst interrogations and interrogations used for acquisition purposes were always on Mode D.

Replies from the target aircraft are received by the P_1/P_3 receiver and decoded by the KY-275. Reply Code 4000 that is not normally used in the N.Y. area was employed to segregate the target aircraft Mode D responses from all others. The decoded replies are displayed on the PPI and also passed to the data processing equipment for further processing, as described below. The signals displayed on the PPI are the primary means by which the tracking operator keeps the area gate centered on the target. To further assist in maintaining a good track, the operator is also provided with second display which, in effect, expands the azimuth scale. The raw video from the

P_1/P_3 receiver is gated by the area gate, integrated and presented on a slow sweep storage tube along with the tracking gates generated by the data processing equipment. The resulting display shows the operator the relationship between the target and the gate and permits him to make appropriate, small, azimuth corrections.

The decoder output consists of two types of signals: each pair of bracket pulses spaced at 21.3 μs produces a narrow pulse output; the correct code produces a wide pulse output. The data processor recognizes narrow pulses as fruit and wide pulses as legitimate replies to Mode D interrogations. Since the Mode D reply code is not used by any other aircraft, the ratio of Mode D replies to Mode D interrogations gives a measure of round reliability.

At periodic intervals during the test, a traffic count is recorded photographically. This is accomplished by interrogating on Mode A over several complete scans and photographing the PPI display scope. To make the task of counting traffic on these photographs somewhat easier, the fruit is eliminated from the PPI by passing the decoder output through a defruiter before display.

In the data processor, the Mode D replies are gated by the processed area gate. The data processor, in effect, splits the azimuth portion of the area gate into an early gate, a dwell gate and a late gate. It accomplishes this digitally by counting PRF triggers. The number of triggers contained in the early-late gates and the dwell gate are adjustable by means of thumb-wheel switches. The purpose

of this arrangement is to provide guard gates around the dwell gate to insure that the data in the dwell gate is valid, i.e. that the interrogations and replies occured on the peak of the antenna beam and not on the steep sides of the beam, where the data could be invalidated by low signal strength either in the interrogation or the response. As an illustration, assume the antenna rotation rate is 10 r/min. Since the nominal beam-width is 2.5° and the repetition rate is 258,

$$\frac{60}{10 \times 360} \times 258 \times 2.5 \approx 10 \text{ interrogations per beam-width.}$$

are produced. The azimuth gate is then set wide enough to provide 30 interrogations and the early-late gates and dwell gate are set for 10 interrogations each. A tracking criterion is then set in the data processor, by means of a thumb-wheel switch, whereby the early-late gates must have some specified number of replies, e.g. two out of the ten interrogations (m out of n), before the data in the dwell gate is accepted. If two replies are not present in the early-late gate, the dwell gate data is tagged as invalid. This system insures that poor tracking will not be mistaken for poor round reliability. If the tracking operator does not keep the tracking gate centered on the target, there may be missing replies in the dwell gate due to low signal strength, however in that case, the early or late gate will not pass the tracking criterion, two hits out of ten, and the data will be tagged as invalid.

In Figure 2-8, the timing relationships between the various waveforms are shown for the case where the cursor is centered on the target. In Figure 2-8(b) the azimuth part of the area gate, or sector gate is shown. For an antenna speed of 10 r/min, this waveform is about 120 milliseconds long. The early, late and dwell gates produced by the data processor are shown in (c), (d) and (e) and the relationship to the burst interrogations is shown in (f). The reply from the target is shown in (g) and the integrated video displayed on the slow sweep storage tube is shown in (h).

Ground Station Data Processor

A simplified functional block diagram of the ground station data processor is shown in Figure 2-7. This data processor generates the gates which are required to qualify, count, and record the data collected during an interrogator scan. In addition, the data processor generates programmed interrogation pretriggers which are sent to the interrogation coder input. These triggers are used to generate Mode D interrogations over a controlled angular scanning sector.

Sector and Early-Late Gate Logic

The time relationships of the various signals generated by the data processor are shown in Figure 2-8 for the case where the manual tracking cursor is centered on an aircraft transponder reply signal. The corresponding angular relationships are depicted in Figure 2-9 showing the plan position indicator (PPI) tracking presentation.

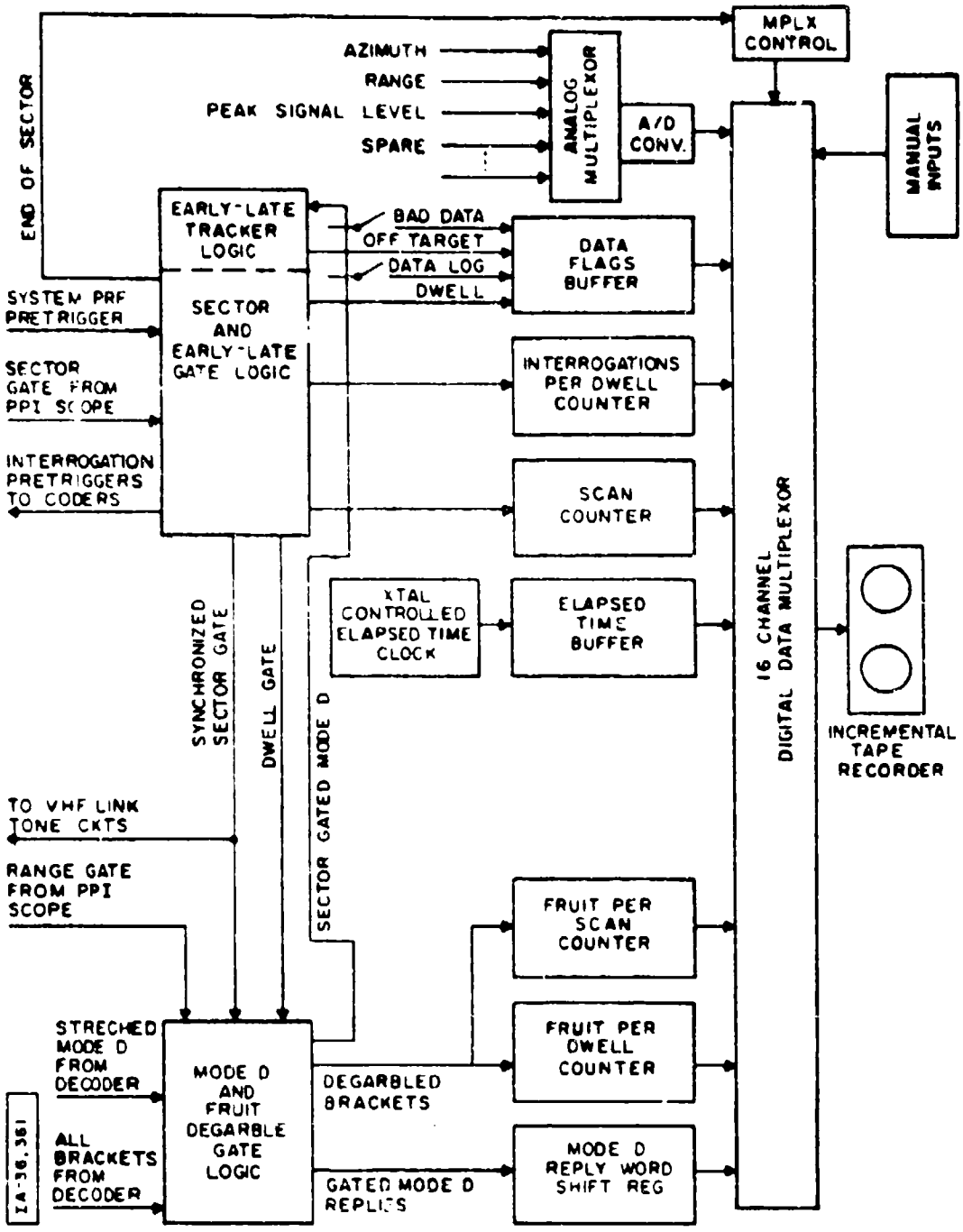

Figure 2-7 GROUND STATION DATA PROCESSOR SIMPLIFIED BLOCK DIAGRAM

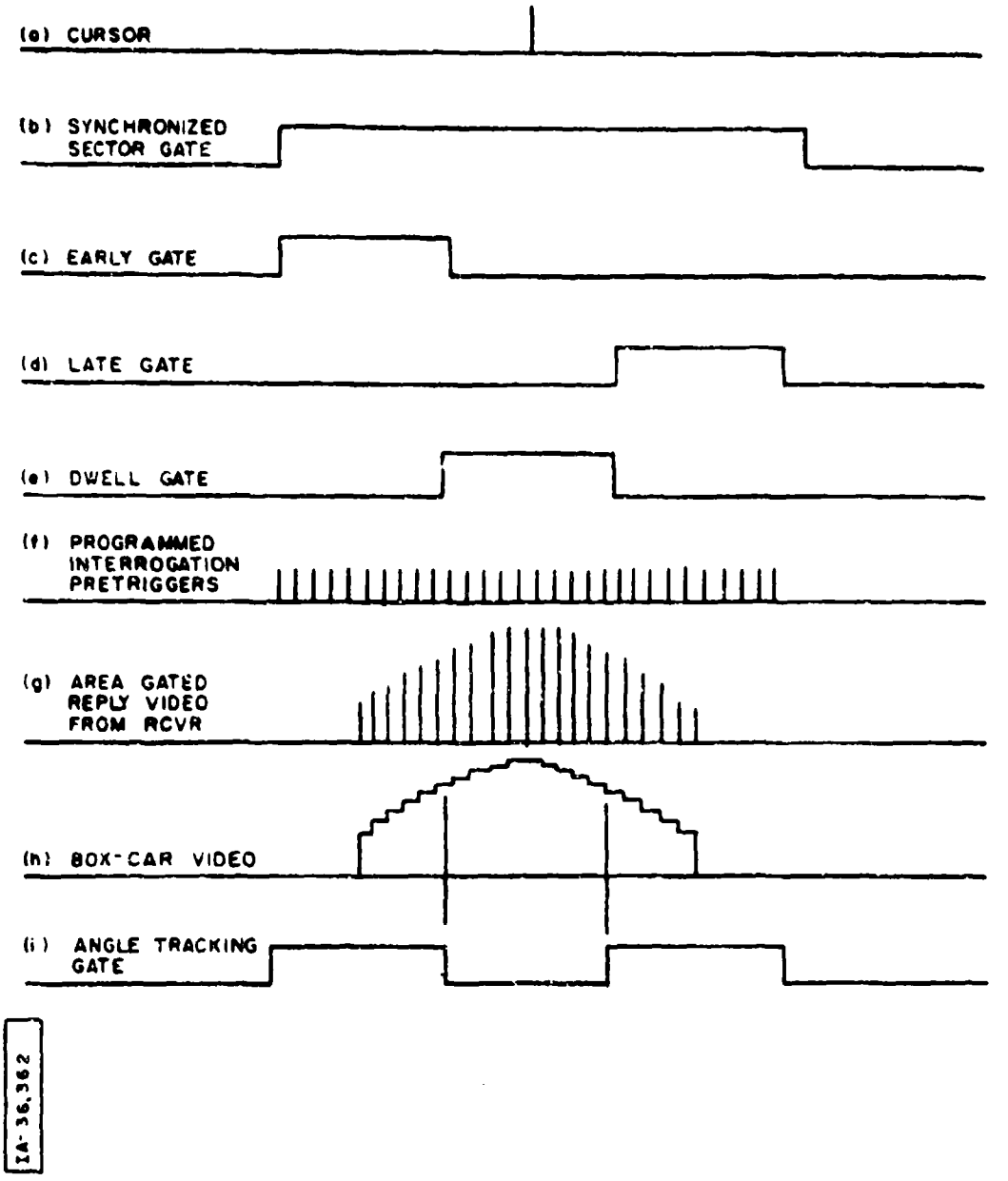

Figure 2-8 GROUND STATION TIMING DIAGRAM

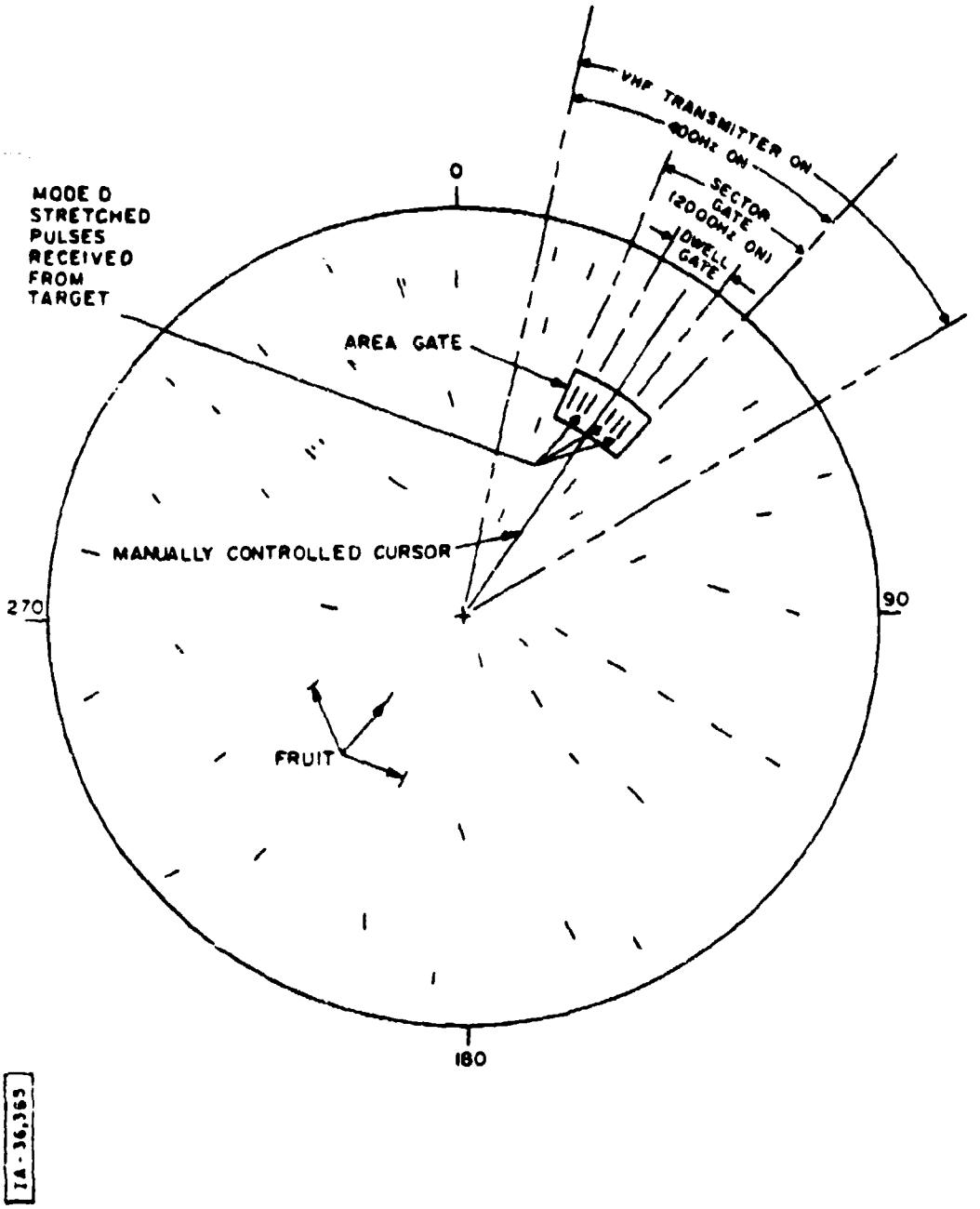

Figure 2-9 P.P.I TRACKING SCOPE DISPLAY

In Figure 2-8 the beginning and end of the sector gate is synchronized with the system PRF pretriggers to produce a synchronized sector gate. This gate is centered about the tracking cursor. Subsequent pretrigger pulses are used in counters to divide the sector gate into a precision early gate, dwell gate, and late gate. The widths of these gates can be set to an integral number of PRF periods by using front panel thumbwheel switches. The beginning and end of all gates coincide with the system pretrigger and therefore will not split synchronous responses from the aircraft transponder. Adjustment of the relative widths of the early, late, and dwell gates determines the total number of programmed interrogations during the sector, Figure 2-8(f), as well as the number of interrogations which occur in each gate. The gate widths are normally adjusted for a given antenna scan rate so that the dwell gate spans the 3 dB points of the beam while the early-late gates are adjusted so as to provide tracking and data qualification information to the data processor and tracking operator.

Figure 2-8(g) shows the area gated reply video (range and angle gated) from a target centered on the tracking cursor. This video is box-carred as shown in Figure 2-8(h) and displayed along with the angle tracking gate, Figure 2-8(i), on a storage scope. This display, along with the PPI scope is used for tracking operator information.

Ground Station Data

The ground station functional block diagram, Figure 2-7, indicates the type of data which is collected during one interrogator antenna scan. All data is converted to digital data and is sent via a digital multiplexer to an incremental magnetic tape unit. The data are written in a fixed format on a seven track IBM compatible tape at 200 bits per inch. This tape is compatible with most computer systems.

Data recording is initiated by the end of the sector gate. All of the data is recorded for every scan. Various flags are used to mark data and/or qualify it for subsequent data reduction programs. The data are described briefly below:

Manual Inputs - This data is written as a header on the tape and consists of the date, time, and various system operating parameters.

Analog Inputs - Coarse range and azimuth analogs are derived from the UPA-35 PPI scope tracking circuits. Peak signal is the maximum level of the box-carred video that occurred in the sector gate.

Data Flags - The Bad Data and Data Log flags can be manually set by an operator. They are used to mark data for subsequent action by data reduction programs.

The Off Target flag is automatically set by the early-late gate logic when the dwell gate is not centered on the target so as to meet a fixed tracking criteria. This criteria consists of m replies out of n interrogations in both the early and late gates.

Interrogations Per Dwell - The number of interrogation during the dwell gate.

Scan Counter - Counts the number of antenna scans and is used for data indexing.

Elapsed Time - Recorded as hours, minutes, and seconds to the nearest second. The clock used in the tests is stable to better than one second per day. It is started and synchronized with a similar clock in the aircraft at the beginning of a flight.

Fruit Per Scan - The fruit per scan is derived from the bracket output of the decoder. The brackets are deghosted and degarbled as shown in the examples of Figure 2-10. In Figure 2-11 the resetable one shot multivibrator does not begin its output until the trailing edge of the input pulse and is retimed with each new input pulse. The 1 μs one shot multivibrator is also used as a ghost window. The output from this logic is counted as fruit.

Fruit Per Dwell - The degarbled and deghosted fruit is gated by the dwell gate to produce fruit per dwell.

Mode D Reply Word - The Mode D replies are processed by a 36 bit shift register. The register is shifted once per interrogation. A dwell gated Mode D reply during the PRF period sets a ONE while no reply sets a ZERO. Thus the pattern of replies is recorded during the dwell gate on a per scan basis. This data is qualified by the applicable flags described above.

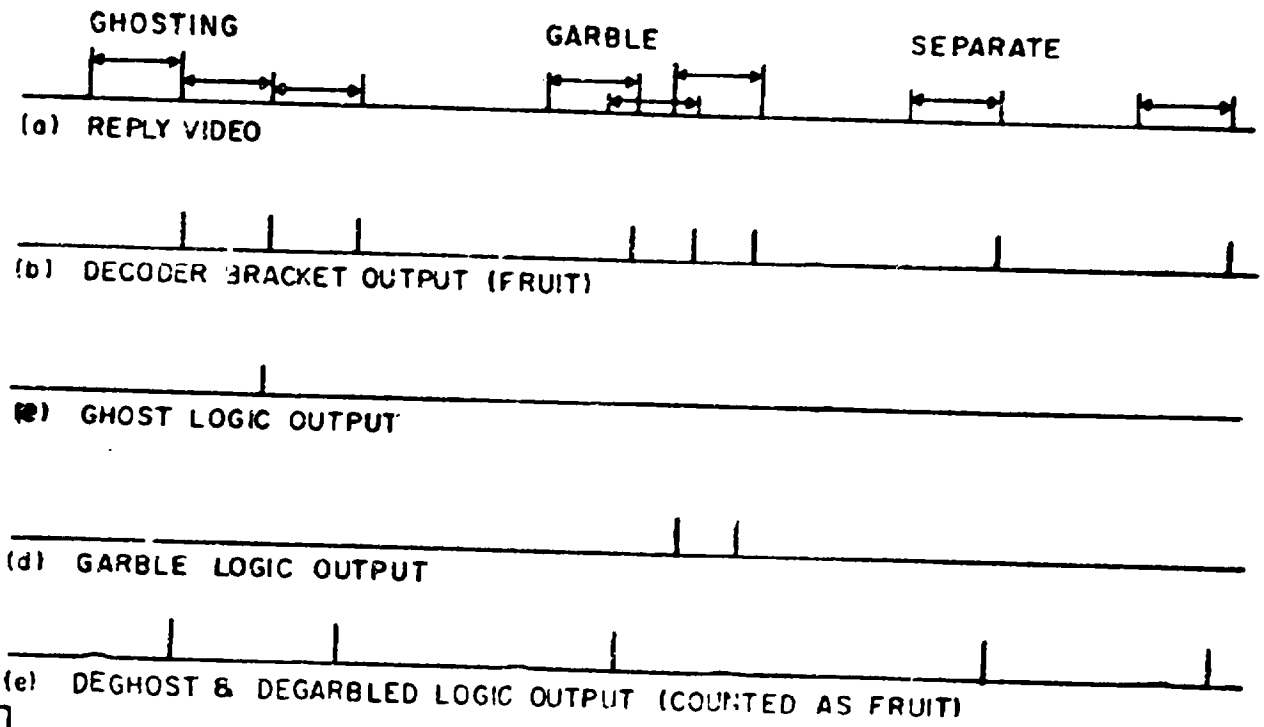

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Figure 2-10 EXAMPLES OF FRUIT TIME RELATIONSHIPS

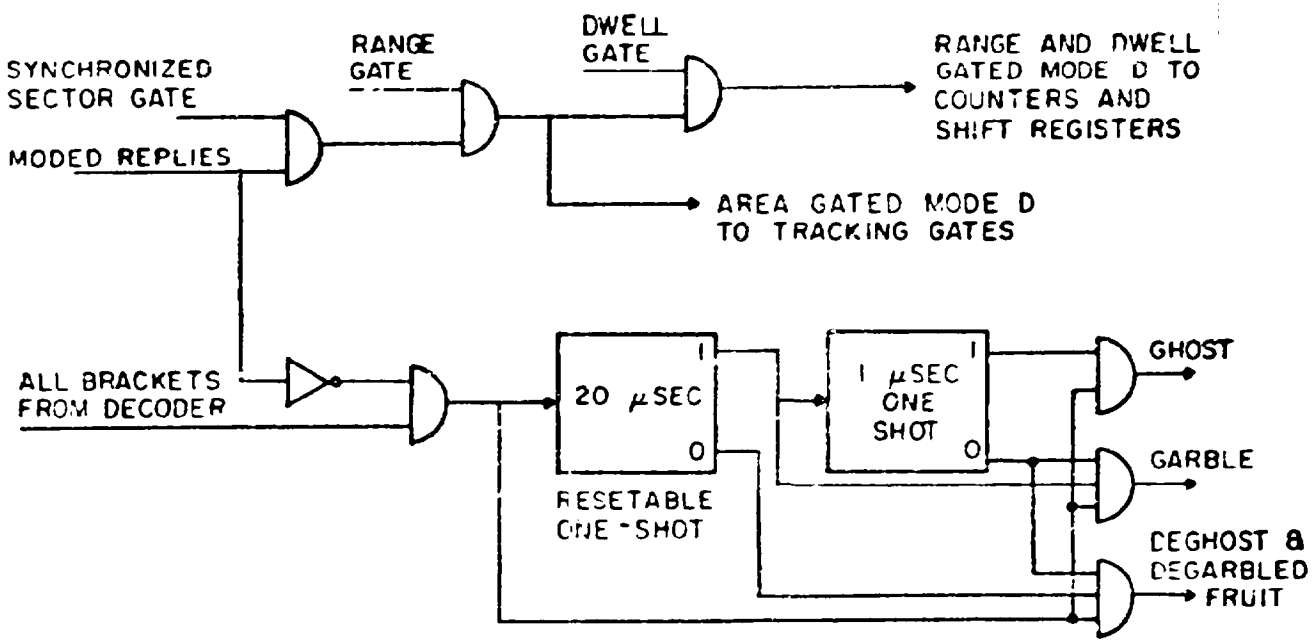


Figure 2-11 SIMPLIFIED MODE D AND FRUIT LOGIC GATES

Airborne Equipment Configuration

The test aircraft employed is a twin engine Cessna 310, N6839T. It carries a full complement of navigation and communication gear and is normally equipped with a standard ATC transponder. For these tests, the aircraft's transponder was replaced with a modified unit to respond to Modes 3/A, C, and D. The ATCRBS antenna already on the aircraft was used.

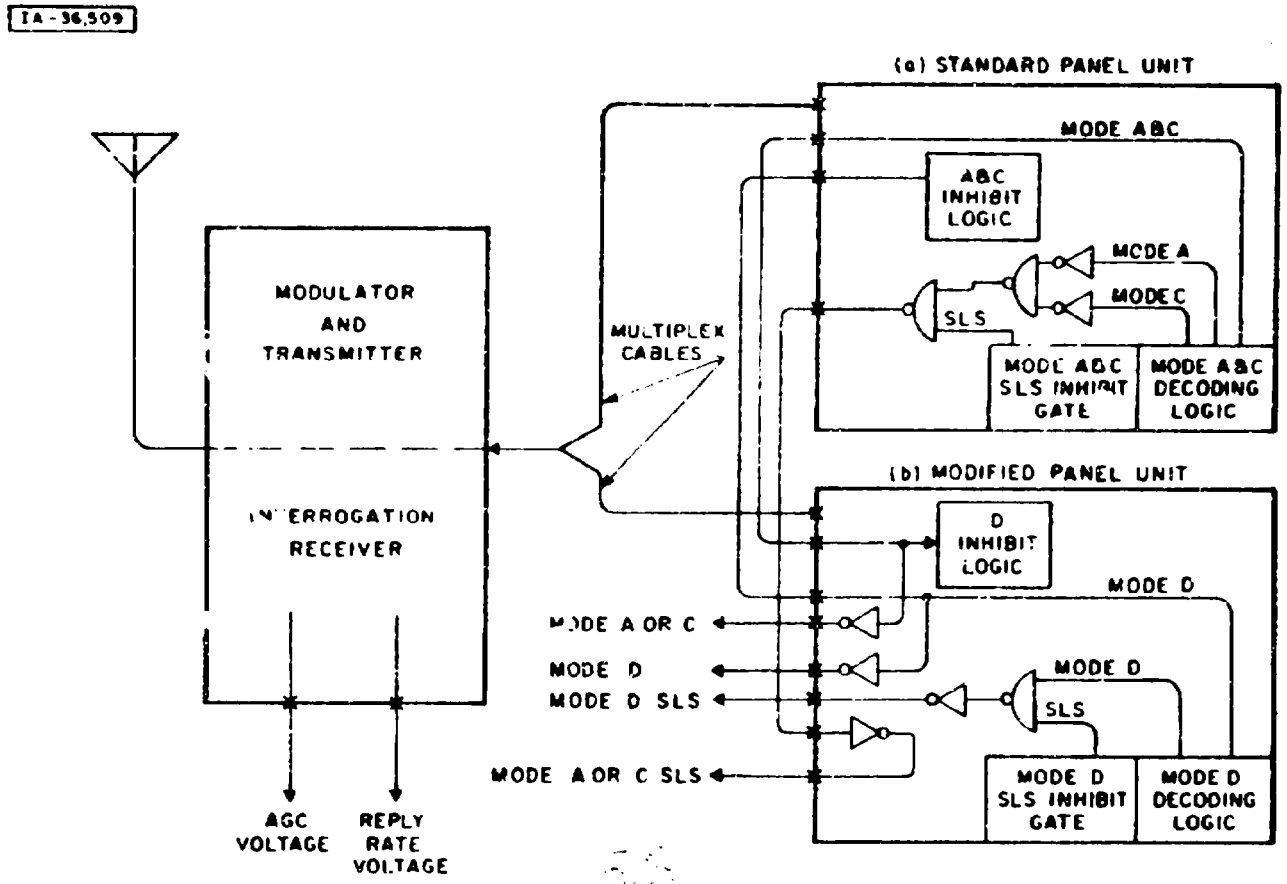
Transponder

The aircraft transponder selected for this program is a NARCO Model AT6-A transponder with an extra coder-decoder panel unit. The transponder has passed Technical Standard Orders (TSO) tests by designated testing agencies and was selected for the experiment because of its ease of modification and ready access to certain signal circuits required for the purposes at hand.

A simplified functional diagram of the modified transponder configuration is shown in Figure 2-12. It is seen to consist of a standard remote unit (RF and video circuitry) a standard panel unit, and a modified panel unit.

The remote unit was not modified except to pick off the AGC and reply rate analog signals.

The standard panel unit decodes and responds to normal Mode A or Mode C interrogations with Mode A identity code set in on its panel switches. This unit was modified by adding the gates shown in



LOGIC GATES SHOWN WERE ADDED TO A NARCO AT-6A TRANSPONDER

Figure 2-12 AIRCRAFT TRANSPONDER CONFIGURATION

Figure 2-12 to pick off data and to inhibit its own operation when the other panel unit was replying to a Mode D interrogation. Otherwise its operation is normal.

The second panel unit was modified to decode and respond to a Mode D interrogation. This was accomplished by disabling the Mode A decoding circuitry and changing the Mode C (21 μs) decoding circuitry to decode Mode D (25 μs). The Mode D response was then changed so that it replies with the disabled Mode A identity switch setting. Other changes include adding the logic gates shown in Figure 2-12 to pick off data and to inhibit its own operation when the standard panel unit responds to Mode A or Mode C.

With the exception of the cross-inhibits both units function in their normal manner, the standard unit replying to Mode A or Mode C interrogations normally while the modified unit replies only to Mode D interrogations with its own identity code. The added [illegible] es only to pick off the required signals which are sent to [illegible] rne data processor and in no way interferes with normal panel unit logic operation.

The modified transponder and the data processing and recording equipment are mounted in a single carrying case to permit rapid and easy installation. A photograph of the aircraft is shown in Figure 2-13. The airborne equipment is shown in Figure 2-14 and installed in the aircraft in Figure 2-15.

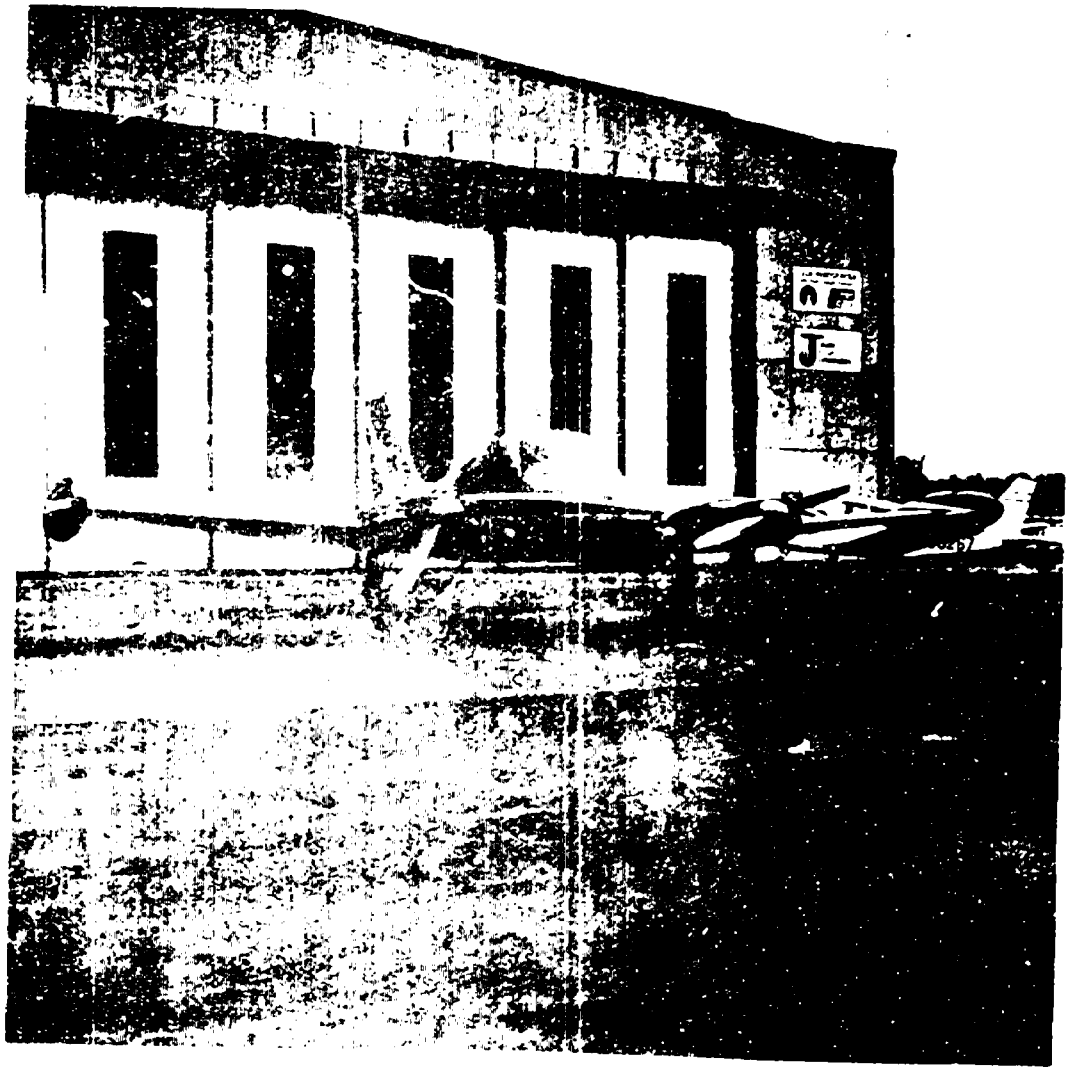


FIGURE 2-13 TEST AIRCRAFT

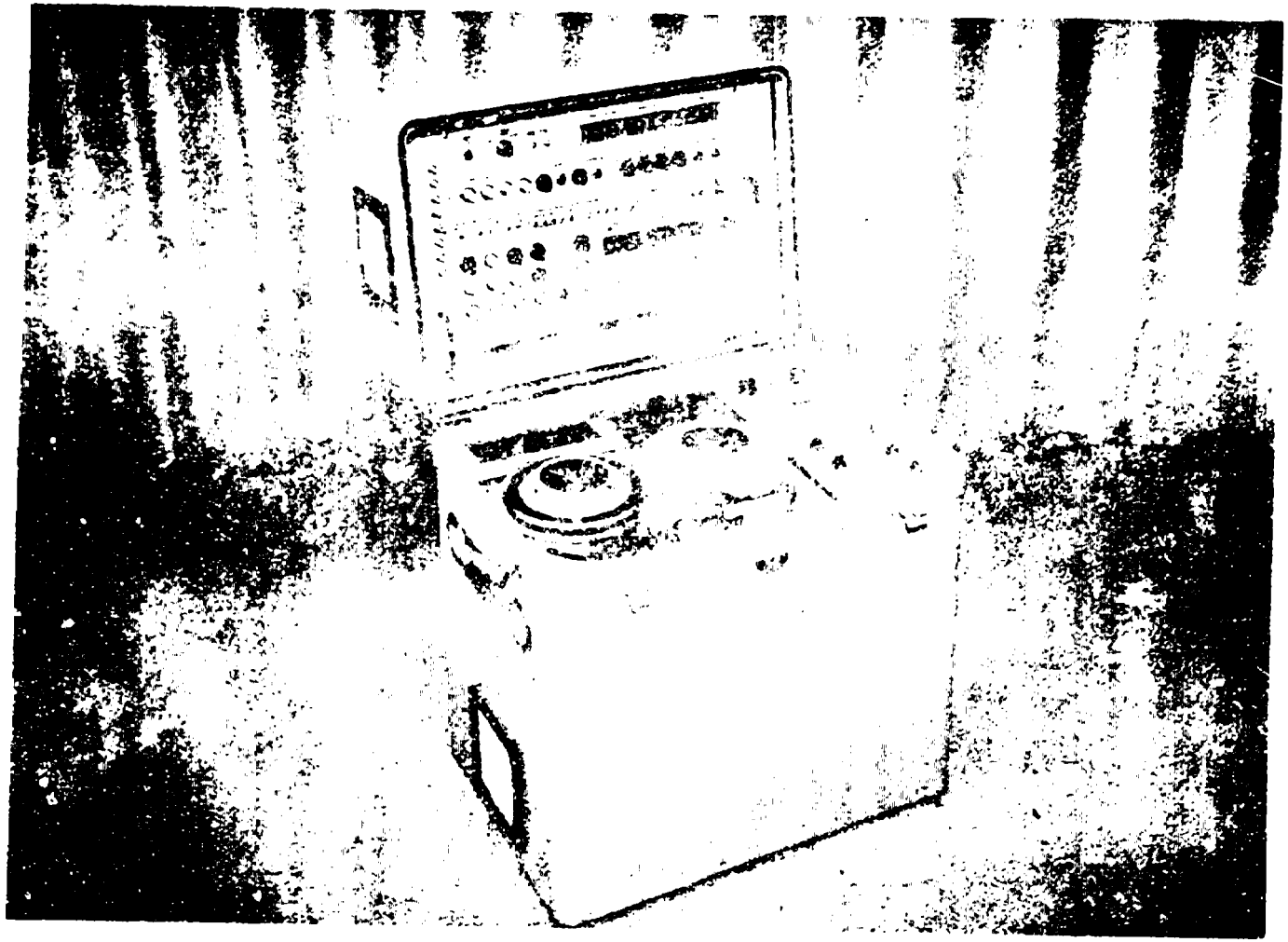


FIGURE 2-14 AIRBORNE EQUIPMENT

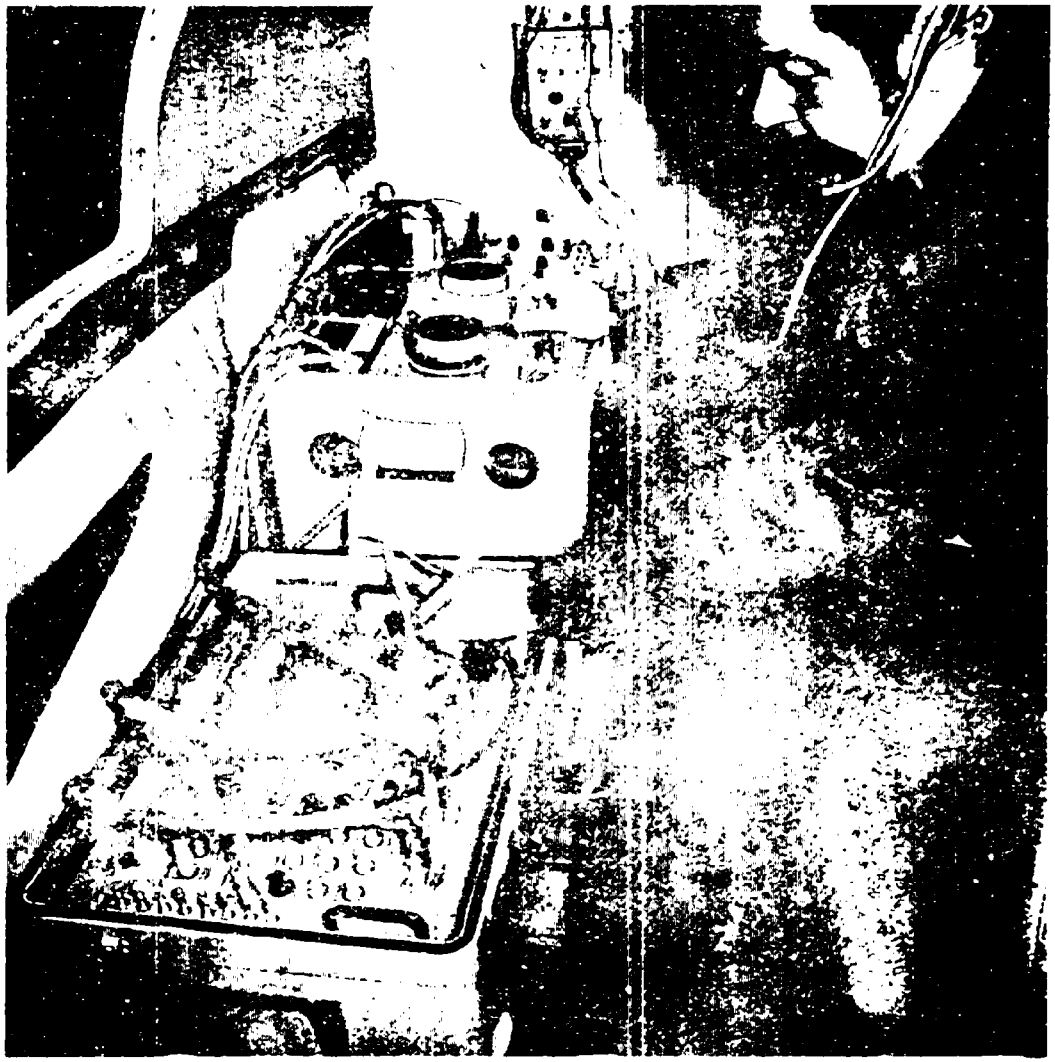


FIGURE 2-15 AIRBORNE EQUIPMENT INSTALLATION

Airborne Data Processor

A simplified block diagram of the airborne data processor is shown in Figure 2-16. The purpose of this unit is to collect, qualify and record data which are derived from the airborne transponder. Comparison of Figure 2-7 with Figure 2-16 shows that the ground and airborne data processors are similar in their operation. The purpose here is to synchronize the airborne data with that taken on the ground so that interrogation-reply comparisons can be made.

Airborne Sector and Early-Late Gates

The airborne timing diagram is shown in Figure 2-17. It is required that the airborne dwell gate, Figure 2-17 (e), be exactly aligned with the ground station dwell gate shown in Figure 2-17(a). In this manner both data processors collect and qualify data on a pulse by pulse basis from the same section of the scanning antenna pattern.

Sector gate and early-late gate circuit operation in the airborne unit is identical with that on the ground except that the airborne gates are derived from a pulsed 1 ms clock. This clock is pulsed on by a sector gate which is derived from a two-tone signal sent to the aircraft via a dedicated channel on the VHF communication link. The airborne dwell gate width is set to equal the ground dwell gate width. However, the airborne early-late gate width is slightly shortened as shown in Figure 2-17(c) so as to account for various circuit delays through the synchronizing channel. Experience has

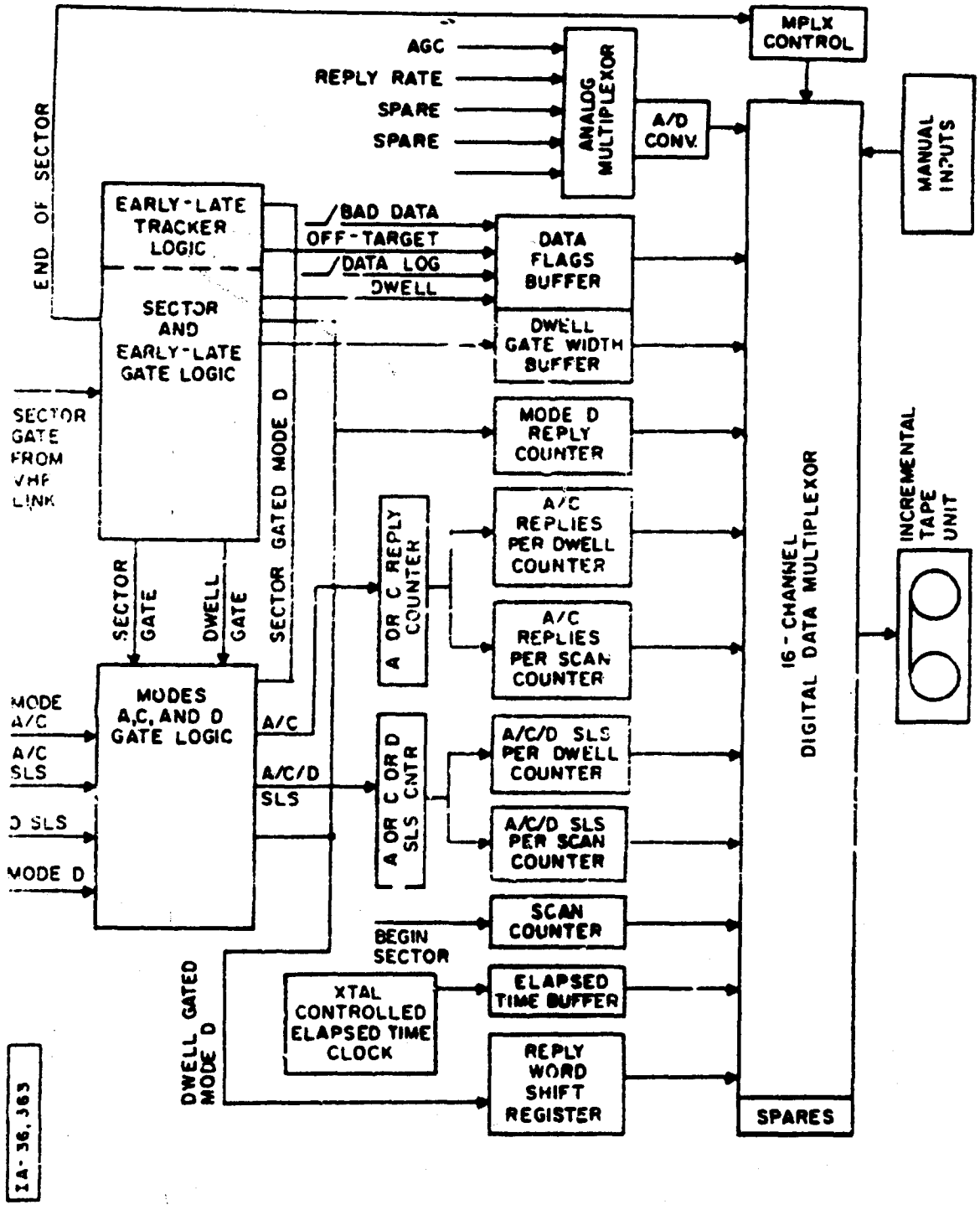


Figure 2-16 AIRBORNE DATA PROCESSOR SIMPLIFIED BLOCK DIAGRAM

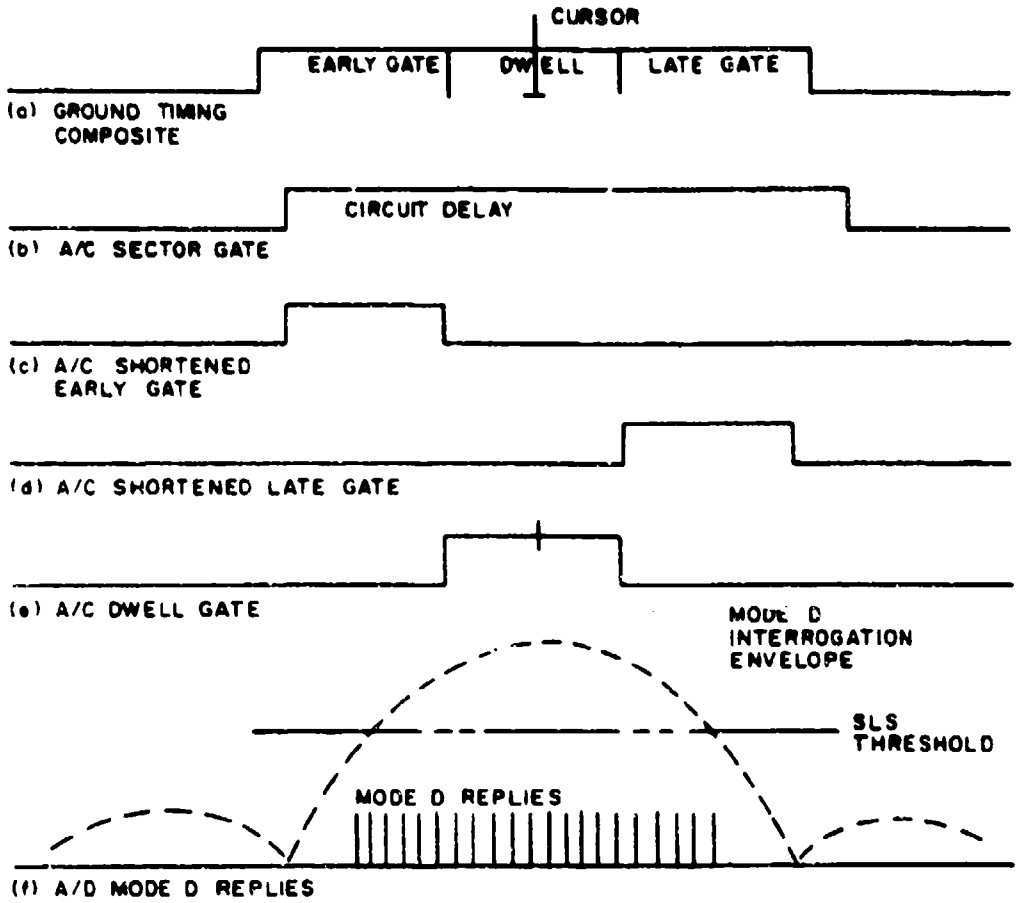


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Figure 2-17 AIRCRAFT TIMING DIAGRAM

shown that ground to air dwell gate alignment can be maintained (within ± 0.25 ms) over the useful dynamic range of the synchronization link.

Similar to the ground station, track qualification is accomplished by counting the number of Mode D reply pulses which occur in the tracking gates. Qualification requires m out of n replies in the early gate and also the late gate. Therefore, the airborne data may be disqualified by the ground tracking operator being off target, low signal level or it will be disqualified due to false airborne sector gates being generated by interference on the communications channel.

Airborne Data

Airborne data are derived from the outputs of the special airborne transponder. As noted, the transponder is a NARCO Model AT6-A suitably modified to respond to normal interrogations as well as Mode D interrogations. All data is converted to digital form and recorded on a high environmental incremental magnetic tape unit via a digital data multiplexer. The data is recorded in a fixed format on a seven track IBM compatible tape at 200 bits per inch.

All data is recorded for every scan and is described below.

Manual Inputs - Used as a header on the tape for data, time and various operating system parameters.

AGC and Reply Rate - These are analog voltages corresponding to the transponder reply rate. The AGC is derived from the reply rate

voltage in the NARCO AT6-A transponder and is not necessarily a function of signal strength.

Data Flags - Bad Data and Data Log flags can be manually set by an operator. The airborne off-target flag is used to qualify data against ground tracking or synchronization link interference. All of the data flags are used to edit data by subsequent data reduction programs.

Dwell Gate Width - Records dwell gate width in milliseconds-used as a check against the ground station dwell gate and communication link interference.

Mode D Reply Counter - Counts the Mode D replies during the airborne dwell gate.

A/C Replies Per Dwell - Counts the Mode A or Mode C replies during the airborne dwell gate.

A/C Replies Per Scan - Counts the Mode A or Mode C replies between airborne sector gates (corresponds to one scan less the sector width).

A/C/D SLS Per Dwell - Counts Mode A or Mode C or Mode D sidelobe suppressions during the airborne dwell gate.

A/C/D SLS Per Scan - The above for one scan.

Scan Counter - Counts the number of sector gates (scans) used for bookkeeping and communication interference checks.

Elapsed Time - Time into the flight is derived from a crystal controlled digital clock accurate to better than one second per day. The airborne clock and ground station clocks are started and synchronized at the beginning of a flight. Time is recorded in hours, minutes, and seconds to the nearest second.

Reply Word Shift Register - Records the Mode D reply word.

Two-Tone Ground to Air Synchronization Signals

The purpose of the ground to air tone signal is to synchronize data taken by the airborne data processor with that taken by the ground data processor. The data from the two sources are compared on a interrogation to response basis in subsequent data reduction programs.

The ground to airborne timing relationships for the case where the ground tracking cursor is centered on an aircraft response are shown in Figure 2-18. The VHF transmitter is turned on about 0.2 seconds before the ground sector gate and is turned off about 0.2 seconds after the sector gate. Two tones are used to modulate the VHF carrier as shown in Figure 2-18(b), a 400 Hz tone which is used as an interference protection gate for the synchronizing signal and a 2000 Hz tone which is the synchronizing signal.

The two tones are separated in the airborne unit by filter circuits whose outputs are shown in Figure 2-18(c) and (d). The 400 Hz filter circuit has a 28 Hz bandwidth followed by a 0.1 second post detection integrator. The equivalent narrow bandwidth of this

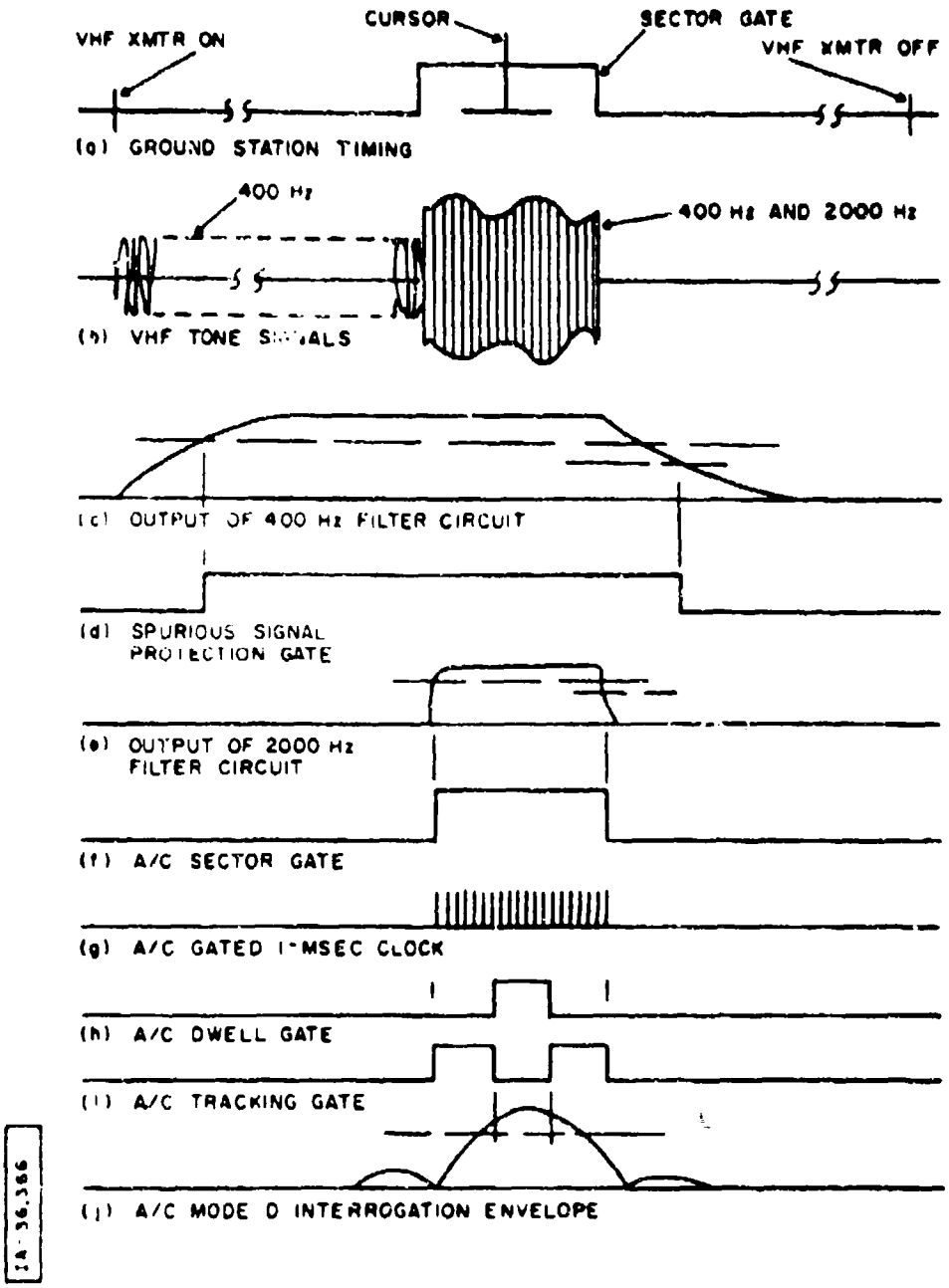

Figure 2-18 GROUND TO AIRCRAFT TIMING RELATIONSHIPS

filter is used to protect against interference and impulse noise on the VHF communication link. The 2000 Hz signal has an equivalent bandwidth of 1000 Hz with a 400 Hz notch. Its output is used to derive the airborne sector gate. This signal is gated by the 400 Hz protection gate. The various signal levels and the filter thresholds are adjusted so that if the 400 Hz output gate is present, the airborne sector gate will not vary more than $\pm$ 0.25 ms due to signal to noise ratio over the useful dynamic range of the VHF link. Continuous audio monitoring and gain control adjustment by an airborne operator throughout these experiments provided reliable operation of this critical synchronizing link.

The airborne sector gate is used to pulse a 1 ms clock in the airborne data processor. Early-late tracking gates and the dwell gate derived from this clock are used to track, collect, and qualify data in the airborne processor.

Equipment Parameters

Table 2-1 lists the nominal parameters of the airborne and ground radar equipment. Figure 2-19 shows the sidelobe suppression characteristic of the transponder as a function of input level and Figure 2-20 gives the effective bandwidth of the transponder.

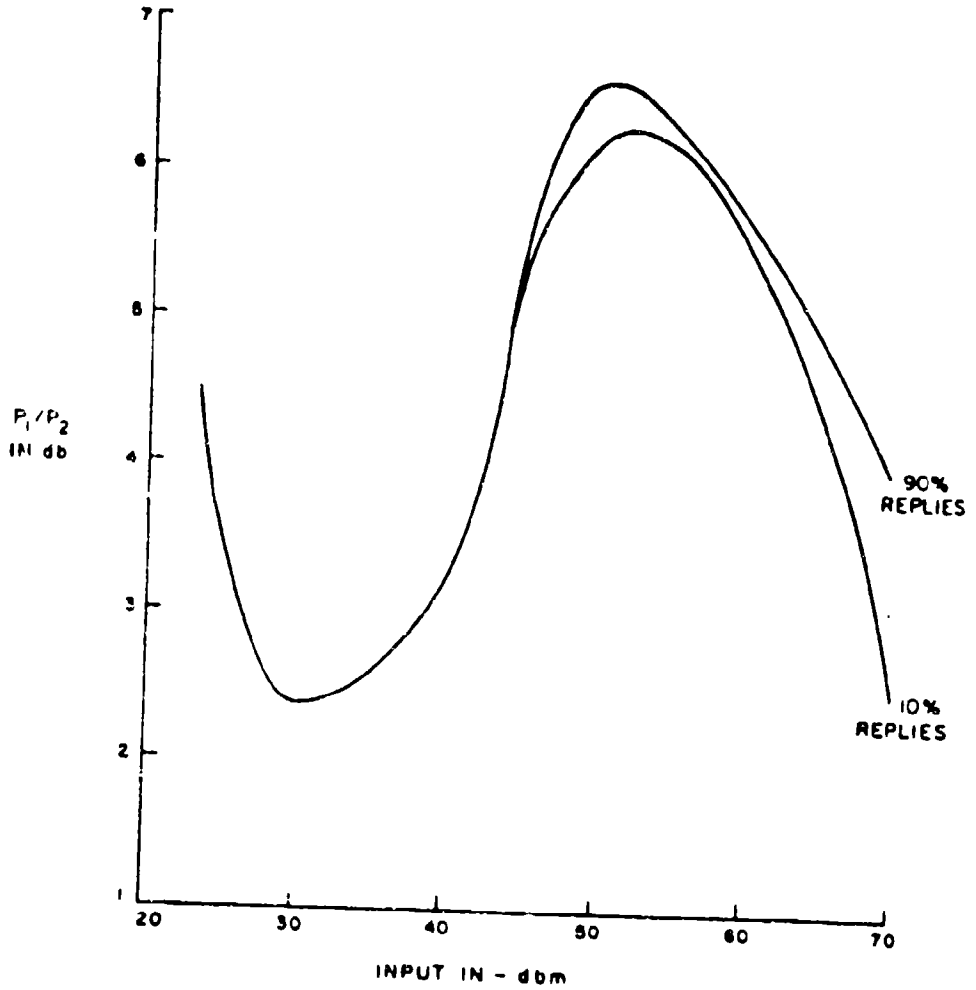

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Figure 2-19 SLS CHARACTERISTICS FOR NARCO AT-6A TRANSPONDER SERIAL # 54JQ6

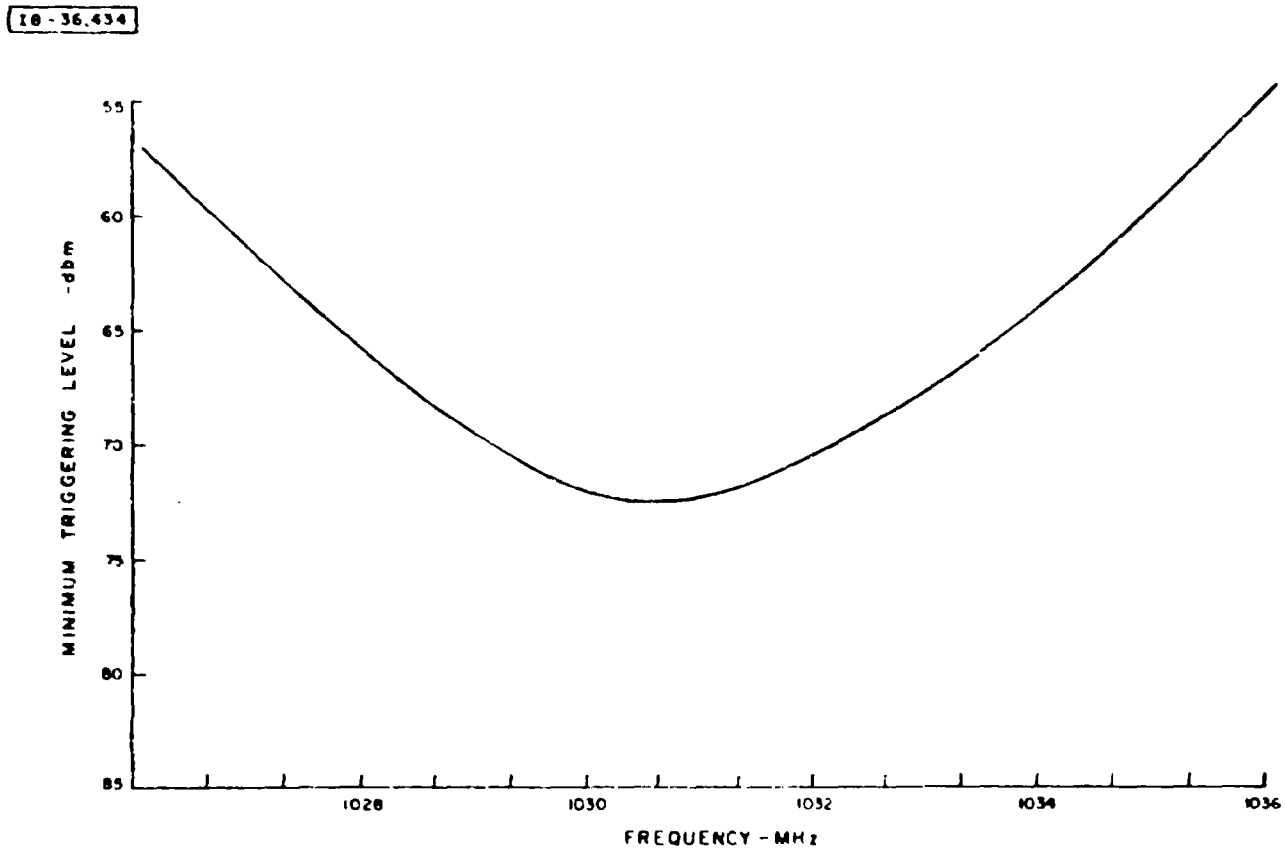

Figure 2-20 MODE D TRANSPONDER RECEIVER BANDWIDTH

Table 2-1

TRANSPONDER

Minimum Triggering Level	-72 dBm
Power Output	240 watts peak
SLS Dead Time	35 μs
Mode 3/A, C & D Inhibit Time	58 μs, 70 μs, 94 μs
Transmitter Frequency	∿ 1091 MHz
Response Delay - Leading Edge of P_3 to Leading Edge of F_1	3 μs

INTERROGATOR

P_1/P_3 Transmitter Frequency	1030 MHz
P_2 Transmitter Frequency	1030 MHz
P_1/P_3 Power	1200 watts peak
P_1/P_3 Pulse Width	0.9 μs
P_2 Power	1600 watts peak
P_2 Pulse Width	0.9 μs
Repetition Rate (Specified by FAA)	258 Hz
VSWR P_1/P_3 Line	1.15
VSWR P_2 Line	1.10
P_1/P_3 Receiver Sensitivity	-91 dBm
P_2 Receiver Sensitivity	-90 dBm
P_1/P_3 Receiver Plus Decoder Sensitivity	-84 dBm

SECTION III

FLIGHT PLANS

Experimental Requirements

The selection of appropriate flight patterns for ATCRBS performance data acquisition is governed by a number of considerations. Air constraints in the New York metropolitan area, including the newly implemented Terminal Control Area (TCA) concept, motivated the selection of VFR flights to provide a sufficient degree of flexibility in flight planning. Implicit in the selection of VFR flights is the requirement of avoiding the penetration of the TCA volume during the flight tests. To simplify target tracking and to obtain a relatively stationary signal amplitude, constant speed, experimental interrogator centered, circular flight patterns were selected as being most appropriate. To avoid severe loss of signal caused by antenna pattern vertical lobe nulls (destructive interference of direct and multi-path reflected signals), flight radius and altitude combinations were chosen corresponding to the vertical lobe peaks.[4] To complement the circular flight contours, radial flight paths were added to the flight plans. The directions of the radial segments were selected to be parallel to the existing approach and departure corridors of the nearby JFK airport to maximize the mainlobe fruit collected. Horizon coverage and transponder antenna aspect angle considerations were taken into account in the selection of the range, altitude and speed of the test flights. Two major flight pattern geometries were chosen.

One geometry consisted of flights beyond the maximum radius of the TCA at a range of 36 n.mi. and at an altitude of 7500 feet. The second geometry required flying above the top of the TCA at an altitude of 9000 feet at a range of 18 n.mi. In the latter flight regime several active interrogator sites SLS coverage regions are penetrated during the flight. These are regions within which detectable sidelobe interrogations are likely.

Aircraft Considerations

From a data acquisition viewpoint it is desirable to collect as many measurement samples as possible during an interval in which the ATCRBS environment is essentially stationary. It can be shown that significant changes in the angular distribution of air traffic occur in intervals of from 5 to 10 minutes. A vehicle which could follow the centroid of a localized cluster of air traffic would be ideal from the standpoint of parameterized data collection i.e. data collection over intervals where one or more system parameters are held steady to observe the effects of the remaining parameters. Although it is not possible, in an uncontrolled experiment, to predict the details of general air traffic movement it was felt that an experiment aircraft which could keep pace with the traffic would be adequate. A four seat Cessna 310, capable of cruising at 150 knots with dual controls and space for the logging equipment and a technician, was selected for this experiment. The operating ceiling, for the Cessna, which is unpressurized is approximately 12 to 14 kilofeet

above sea level. Flight altitudes were chosen on the basis of vertical lobing considerations rather than the maximum attainable altitude. Due to fuel capacity, maximum tracking range and flight origin constraints it was felt that a maximum of 2 to 2 1/2 hours of recorded flight data could be obtained during each flight.

Detailed Flight Patterns

Figures 3-1, 3-2 and 3-3 depict the time-position history or trajectory of the experimental aircraft during the three flights in the New York metropolitan area. The numbers along the trajectories correspond to the time (hours, minutes and seconds) into the flight test. The first flight occurred on Wednesday February 9, 1972. Its trajectory, flight pattern A, consisted of a 18 n.mi. semi-circular arc with radial extensions parallel to JFK airport - runway 22 as shown in Figure 3-1, at an altitude of 7500 feet that was flown first in the counterclockwise direction then retraced in the clockwise direction. On Friday February 11, 1972 the second flight occurred. Its trajectory, flight pattern B, consisted of a 36 n.mi. 200 degree circular arc, with radial extensions, at an altitude of 8500 feet, as shown in Figure 3-2. The third flight occurred on Wednesday February 16, 1972. Its trajectory flight pattern C, as shown in Figure 3-3, consisted of a combination of the previous two flight patterns. Two semi-circular arcs were flown in the third flight, one at a 18 n.mi. radius the other at a radius of 36 n.mi. In

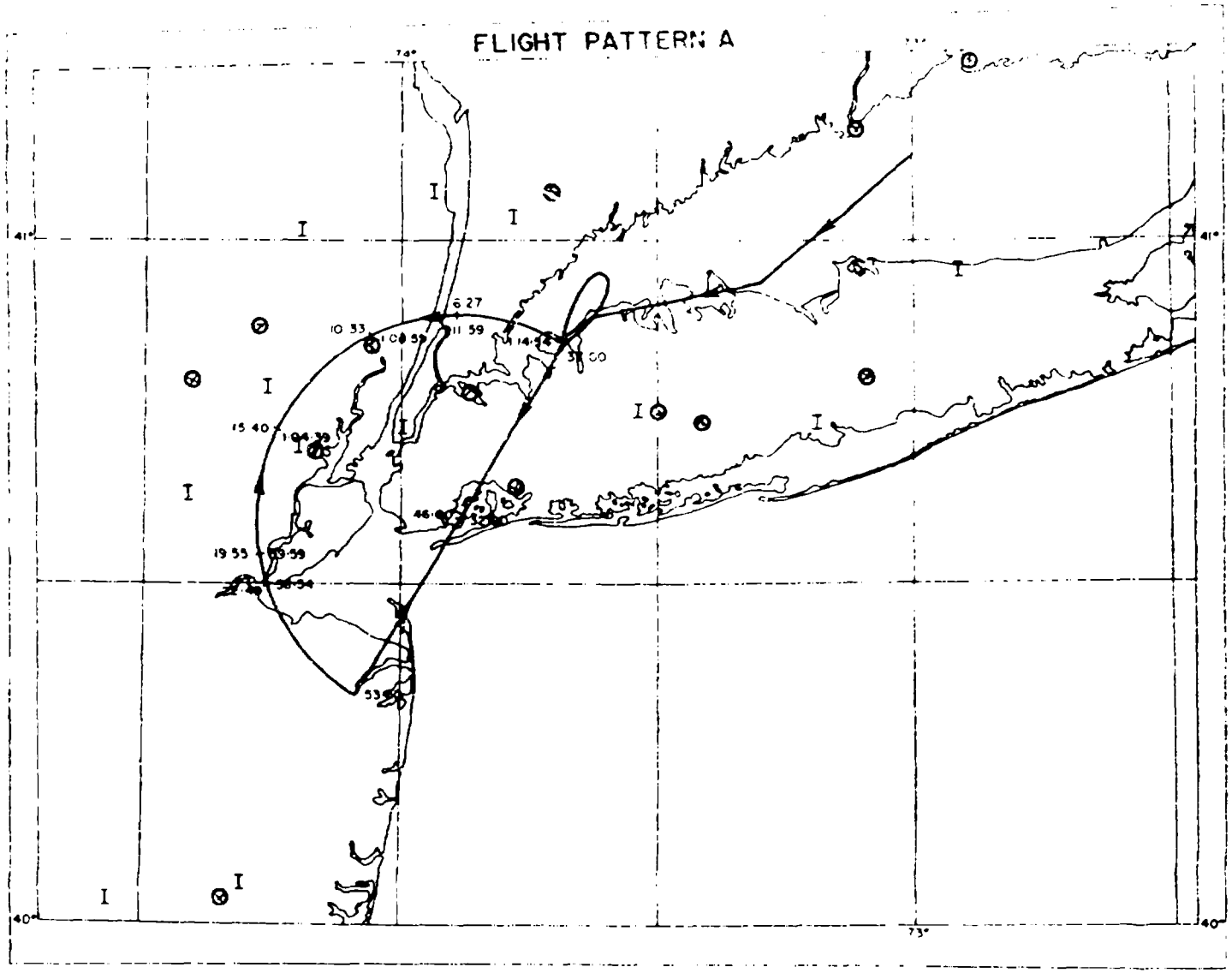

FIGURE 3-1 FLIGHT PATTERN A, FLIGHT OF 2/9/72

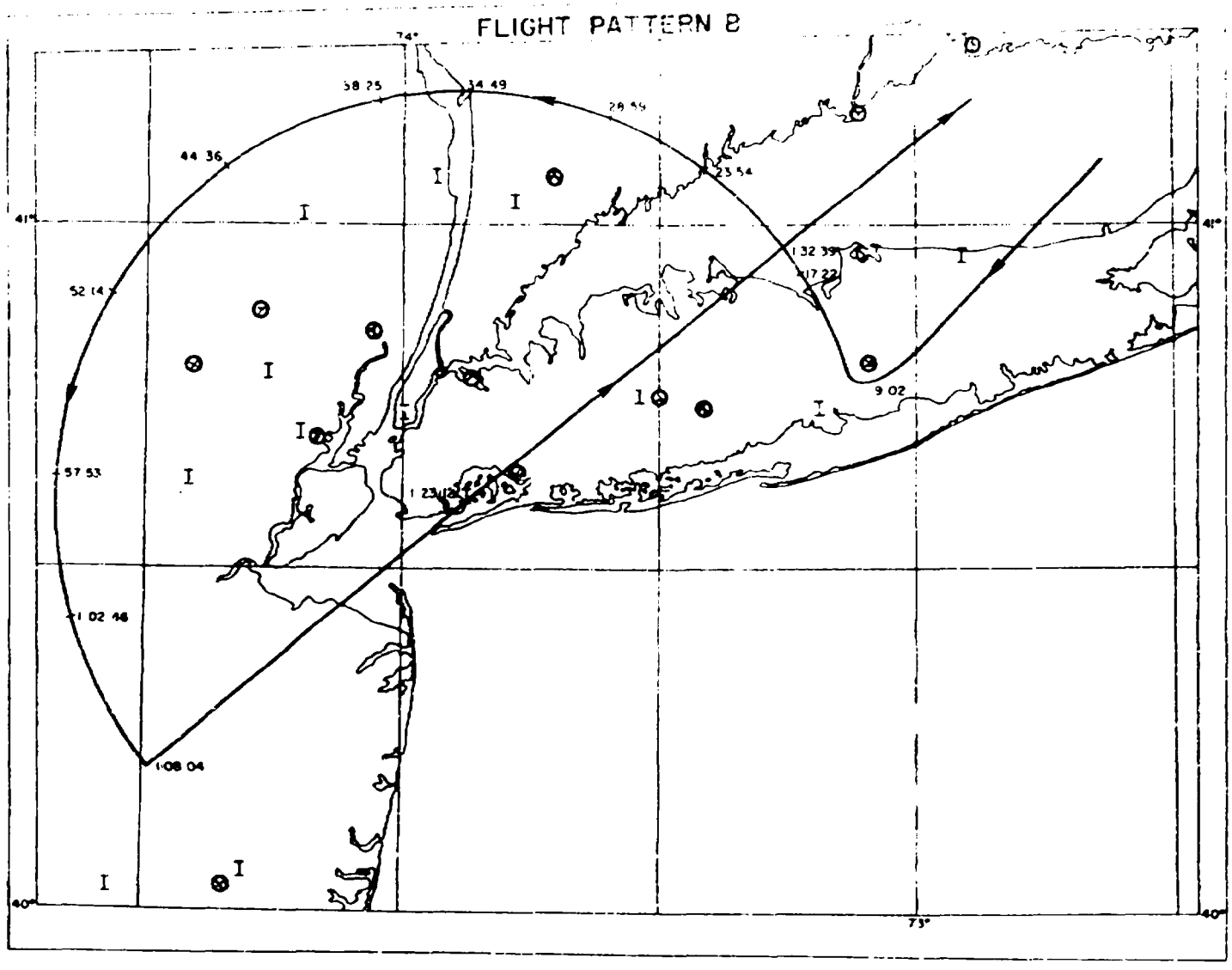

FIGURE 3-2 FLIGHT PATTERN B, FLIGHT OF 2/11/72

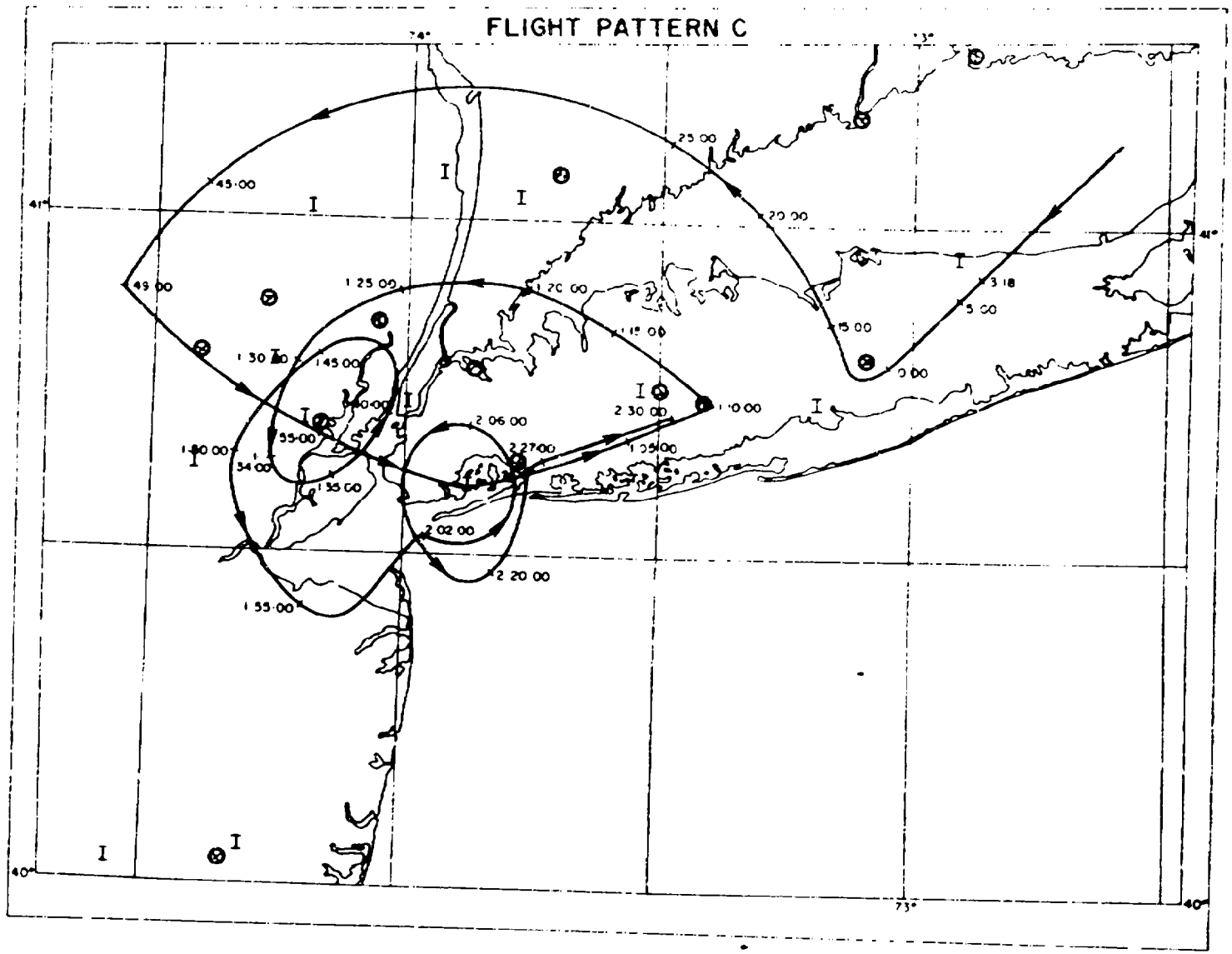

FIGURE 3-3 FLIGHT PATTERN C, FLIGHT OF 2/16/72

addition two circuits around two known active interrogator sites, Newark airport and Floyd Bennett field, were included in the flight plan to investigate the characteristics of SLS interrogations taken at close range.

SECTION IV

DATA COLLECTION, REDUCTION AND ANALYSIS

Data acquisition events were scan ordered in a periodic fashion. For 24 consecutive scans, burst-like sequences of Mode D interrogations were transmitted at a PRF of 258 ips during the interval when the interrogator beam and the aircraft target crossed. Every 25th scan was devoted to the collection of fruit data in 17 twenty degree angular sectors. In the eighteenth sector, which contains the target sector, fruit collection is omitted since fruit per dwell measurements are made in that sector. In the sequence of 24 consecutive scans the Mode D interrogation bursts are subdivided into three sets of 10 interrogations each. The three time intervals containing these sets of interrogations are referred to as the early, dwell and late gates, respectively. Replies to the Mode D interrogations occurring in the early and late gates are subjected to m out of n threshold tests both at the van and in the aircraft to establish the validity of dwell gate centering within the mainlobe-target crossover interval. Scans in which early and late gate threshold tests are failed in either the van record, the air record or both are deleted from the processed records. The recorded data which relates to events occurring during the dwell gates include:

Van Tape

Mode D interrogations per dwell
Fruit per dwell
Van track status flag
Target range
Target azimuth
Peak interrogator receiver video
Interrogator reply word sequence (presence or absence of individual replies)

Aircraft Tape

AGC Voltage
Transponder Mode D replies
Mode 3A/C replies per dwell
Sidelobe suppressions per dwell
Airborne track status flag
Dwell gate width
Transponder reply word sequence (asynchronous)

In the interval between successive dwells the following scan related data are recorded:

Van Tape

Fruit per scan
Scan number
Elapsed time in hours, minutes and seconds

Air Tape

Mode 3A/C replies per scan
Sidelobe suppressions per scan
Scan number
Elapsed time in hours, minutes and seconds

In the 25th scan following the sequence of 24 consecutive Mode D interrogation scans the van tape recorder records,

Fruit per angular sector
Sector azimuth
Data Status flag
Elapsed time in hours, minutes and seconds

The raw van and air tape recordings which are written in a mixed binary and BCD format with an irregular packing density are unpacked from the tapes with a compatible assembly language routine. A PDP-8 minicomputer listing of the raw data tape recordings is made initially for quick-look analysis and establishing the segments to be subjected to further processing on the IBM 370/155 central processor. The sequence of major IBM-370/155 processing steps includes; assembly language unpacking of dual tapes, sorting of sector data for angular fruit distribution analysis, filtering out poor and erroneous dwell data based on track criterion thresholds, data quality flags, time correspondence and spurious air tape frames. Spurious air tape frames are occasionally generated by communications channel interference which cause the false triggering of the data logging units. A sample of filtered data is shown in Table entitled Van Data Elements and in Table 4-2 entitled Airborne Data Elements. After the data filtering operation a series of statistical analysis operations are performed which produce sample cumulative probability distributions, sample statistical moments (means, standard deviations, etc.), correlation coefficients and linear least mean square regression analysis for each of the following eleven measured or derived ATCRBS variables:

Transponder reply ratio (up-link performance parameter)

Round reliability (two way overall performance parameter)

Interrogator population count

Mode 3A/C replies per scan

AZIMUTH	RANGE	SIGNAL	SPEED	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	FLAG
-2047.0	270.0	2047.0	2.0	10	757	[illegible]	12661		000[illegible]FF0002	01
-2047.0	270.0	2047.0	3.0	10	758	[illegible]	12494	[illegible]	000[illegible]FF0002	01
5.0	269.0	2047.0	2.0	10	759	[illegible]	11103	[illegible]	000001F30002	01
5.0	269.0	2047.0	3.0	10	760	[illegible]	10364	[illegible]	000003FF0002	01
2047.0	268.0	2047.0	2.0	10	763	[illegible]	9043	[illegible]	000003FF0002	01
2047.0	268.0	2047.0	2.0	10	764	[illegible]	11788	52	000003FF0002	01
2047.0	268.0	2047.0	2.0	10	767	884	10359	71	000003FF0002	01
2047.0	265.0	2047.0	2.0	10	770	905	11923	118	000003FF0000	01
2032.0	265.0	2047.0	3.0	10	772	918	10162	81	000003FB0000	01
2017.0	265.0	2047.0	2.0	10	773	924	11411	111	000003FF0000	01
1999.0	265.0	2047.0	2.0	10	774	931	9707	74	000003FF0000	01
1992.0	265.0	2047.0	3.0	10	775	938	10371	86	000003FD0000	01
1976.0	265.0	2047.0	2.0	10	776	[illegible]	12975	121	0000C3DF0000	01
1966.0	265.0	2047.0	3.0	10	777	952	11278	50	000000FF0000	01
1958.0	265.0	2047.0	2.0	10	778	959	9355	91	0000037F0000	01
1946.0	265.0	2047.0	2.0	10	779	966	11136	60	000001FF0000	01
1925.0	265.0	2047.0	2.0	10	781	980	9518	61	000001FF0000	01
1912.0	265.0	2047.0	3.0	10	783	984	12948	72	000003FD0000	01
1894.0	265.0	2047.0	3.0	10	784	1001	9457	117	000003FF0000	01
1863.0	265.0	2047.0	2.0	10	787	1022	12271	56	000001EE0000	01
1834.0	265.0	2047.0	2.0	10	789	1036	11962	141	000003FB0000	01
1819.0	265.0	2047.0	2.0	10	790	1043	14297	100	0000016D0000	01
1810.0	265.0	2047.0	2.0	10	791	1050	10392	54	0000030F0000	01
1799.0	265.0	2047.0	2.0	10	792	1057	9602	66	000003FF0000	01
1776.0	264.0	2047.0	2.0	10	794	1071	10657	84	0000037F0000	01
1767.0	265.0	2047.0	2.0	10	795	1078	9992	73	000003FB0000	01
1753.0	264.0	2047.0	2.0	10	796	1084	11366	87	000003FF0000	01
1720.0	265.0	2047.0	2.0	10	799	1106	11244	99	000003FF0000	01
1708.0	265.0	2047.0	3.0	10	800	1112	11452	67	000003FD0000	01
1704.0	264.0	2047.0	3.0	10	801	1119	10722	60	000003EF0000	01
1687.0	265.0	2047.0	3.0	10	802	1126	11057	106	0000038F0000	01
1680.0	265.0	2047.0	2.0	10	803	1133	12034	57	0000038F0000	01
1667.0	265.0	2047.0	3.0	10	804	1140	10510	45	000001FF0000	01
1652.0	264.0	2047.0	3.0	10	805	1147	11422	54	000003FF0000	01
1648.0	265.0	2047.0	2.0	10	806	1154	11753	53	000003DE0000	01
1632.0	265.0	2047.0	2.0	10	807	1160	10712	53	000003FF0000	01
1550.0	265.0	2047.0	3.0	10	815	1215	14004	78	0000018F0000	01
1536.0	263.0	2047.0	2.0	10	816	1222	13290	85	000003FF0000	01
1526.0	261.0	2047.0	3.0	10	817	1228	10594	72	000003D80000	01
1496.0	261.0	2047.0	2.0	10	820	1249	10378	72	000003FE0000	01
1484.0	261.0	2047.0	2.0	10	821	1256	10759	62	000000FF0000	01
1479.0	261.0	2047.0	2.0	10	822	1262	14487	79	0000038F0000	01
1328.0	261.0	2047.0	3.0	10	836	1357	10676	81	000003BF0000	01
1310.0	261.0	2047.0	2.0	10	837	1363	12571	106	000003F00000	01
1304.0	261.0	2047.0	2.0	10	838	1370	9854	51	000003760000	01
1288.0	261.0	2047.0	3.0	10	839	1377	12119	29	000003FF0000	01
1273.0	261.0	2047.0	3.0	10	840	1384	11104	119	000003FF0000	01
1258.0	261.0	2047.0	3.0	10	841	1391	11147	65	000003FF0000	01
1236.0	261.0	2047.0	2.0	10	844	1411	12686	76	000002FD0000	01
1224.0	261.0	2047.0	3.0	10	845	1418	10322	77	000003F70000	01
1210.0	261.0	2047.0	3.0	10	846	1425	12617	42	000003FF0000	01
1174.0	261.0	2047.0	3.0	10	849	1444	13364	128	000001FF0000	01
1133.0	261.0	2047.0	2.0	10	852	1464	13824	120	000003F70000	01
1120.0	261.0	2047.0	2.0	10	853	1471	12457	53	000003AF0000	01
1108.0	261.0	2047.0	2.0	10	854	1477	11181	96	000003FF0000	01
1098.0	261.0	2047.0	3.0	10	855	1484	12854	110	000003FF0000	01
1092.0	261.0	2047.0	2.0	10	856	1491	13446	67	000003FF0000	01
1078.0	261.0	2047.0	2.0	10	857	1498	11258	106	000003FF0000	01

Table 4-1 VAN DATA ELEMENTS

BEST AVAILABLE COPY

[illegible]	GATE WIDTH	ALTITUDE	[illegible]	MODE (DWELL)	[illegible] SCAN	[illegible]	[illegible] EN	[illegible]	TIME (SEC)	REPLY WORD	FLAG
1505.0	38.0	4095.0	9	3	939	[illegible]	18	[illegible]	816	00191111	01
1700.0	38.0	4095.0	10	8	1463	[illegible]	56	[illegible]	821	00911111	01
1673.0	38.0	4095.0	9	18	1479	0	43	[illegible]	830	00101111	01
1574.0	38.0	4095.0	10	18	1464	0	21	[illegible]	837	00911111	01
1472.0	38.0	4095.0	10	16	1906	0	13	227	857	00911111	01
1958.0	38.0	4095.0	10	1	930	0	26	228	864	00991111	01
1958.0	38.0	4095.0	10	0	982	0	91	231	884	00991111	01
1755.0	38.0	4095.0	9	0	1961	0	190	233	904	00891101	01
1961.0	38.0	4095.0	9	0	1275	0	33	235	918	00991111	01
1564.0	38.0	4095.0	10	15	836	0	37	236	924	00891111	01
1960.0	38.0	4095.0	10	0	1584	1	98	237	931	00111111	01
1916.0	38.0	4095.0	10	13	1616	0	17	238	938	00991111	01
1595.0	38.0	4095.0	10	12	1339	0	26	239	945	00991111	01
1683.0	38.0	4095.0	9	10	1422	0	38	240	952	00811111	01
1744.0	38.0	4095.0	9	8	1652	0	39	241	959	00881111	01
1663.0	38.0	4095.0	9	11	1968	0	60	242	966	00091111	01
1716.0	38.0	4095.0	10	14	1705	2	58	244	980	00891111	01
1778.0	38.0	4095.0	9	0	1584	0	51	245	994	00891111	01
1585.0	38.0	4095.0	10	6	1821	0	53	246	1001	00891111	01
1952.0	38.0	4095.0	9	7	1759	0	81	247	1022	00991101	01
1533.0	38.0	4095.0	9	22	1902	0	112	248	1036	00911111	01
1952.0	38.0	4095.0	7	9	1628	0	64	249	1043	00081111	01
1723.0	38.0	4095.0	9	8	1583	0	24	250	1050	00891011	01
1736.0	38.0	4095.0	10	0	1740	0	161	251	1057	00891111	01
1642.0	38.0	4095.0	10	10	1578	3	74	253	1071	00891111	01
1712.0	38.0	4095.0	9	9	1771	0	168	254	1078	00891111	01
1587.0	38.0	4095.0	10	12	1579	7	70	255	1084	00911111	01
1498.0	38.0	4095.0	10	19	1604	0	185	258	1105	00891111	01
1491.0	38.0	4095.0	9	18	1381	0	50	259	1112	00891111	01
1513.0	38.0	4095.0	9	6	1956	0	64	260	1119	00891101	01
1587.0	38.0	4095.0	10	22	1724	0	30	261	1126	00891111	01
1696.0	38.0	4095.0	9	8	1342	0	12	262	1133	00890111	01
1744.0	38.0	4095.0	10	0	1854	0	11	263	1140	00891111	01
1800.0	38.0	4095.0	11	18	1676	0	58	264	1146	00919111	01
1618.0	38.0	4095.0	9	12	1360	0	29	265	1153	00891111	01
1580.0	38.0	4095.0	10	11	1784	0	63	266	1160	00931111	01
1757.0	38.0	4095.0	9	12	1882	0	142	273	1215	00091111	01
1948.0	38.0	4095.0	10	0	1476	0	62	274	1222	00991111	01
1707.0	38.0	4095.0	9	8	1806	2	86	275	1228	00991111	01
1694.0	38.0	4095.0	10	18	1861	1	51	278	1249	00891111	01
1956.0	38.0	4095.0	9	8	1929	0	50	279	1255	00811111	01
1960.0	38.0	4095.0	9	0	1364	0	37	280	1262	00910111	01
1957.0	38.0	4095.0	9	10	1577	5	139	294	1356	00890111	01
1445.0	38.0	4095.0	9	18	1421	1	132	295	1363	00891111	01
1960.0	38.0	4095.0	8	0	1073	0	40	296	1370	00881111	01
1390.0	38.0	4095.0	10	0	1627	6	87	297	1377	00891111	01
1641.0	38.0	4095.0	10	7	1383	0	116	299	1384	00891111	01
1716.0	38.0	4095.0	10	8	788	0	42	300	1391	00891111	01
1825.0	38.0	4095.0	9	13	682	0	34	302	1411	00811111	01
1947.0	38.0	4095.0	9	11	1201	0	16	303	1418	00891110	01
1955.0	38.0	4095.0	10	0	1379	0	83	304	1424	00911111	01
1856.0	38.0	4095.0	9	21	2802	9	105	306	1444	00091111	01
1952.0	38.0	4095.0	10	0	3241	0	214	308	1464	00911111	01
1948.0	38.0	4095.0	9	0	796	0	87	309	1471	00891101	01
1536.0	38.0	4095.0	10	6	1063	0	32	310	1477	00911111	01
1909.0	38.0	4095.0	10	2	1275	0	20	311	1484	00891111	01

Table 4-2 AIRBORNE DATA ELEMENTS

Sidelobe suppressions per scan

Fruit per dwell

Mode 3A/C replies per dwell

Sidelobe suppressions per dwell

Effective interrogation rate

Garble (down-link interference)

Fruit per scan

The interrogator population data, are generated from a geometric analysis subroutine which identifies and sums the number of interrogators within the horizon coverage of the aircraft at all positions of interest. The effective interrogation rate is another derived ATCRBS variable which is extracted from a sampled transponder AGC system voltage level (called the reply rate voltage) which has been calibrated previously against uniform interrogation rate test signals during initial transponder laboratory bench tests. The garble variable is inferred, rather than directly measured, as the difference between transponder Mode D replies and interrogator Mode D decoded replies per dwell. A comparison of interrogator, transponder and garble (derived) reply word sequences for a segment of the 2-9-72 flight is made in Table 4-3.

Further statistical analysis of measured data is performed in the form of hypothesis testing procedures which determine whether a given ATCRBS variable may be characterized by a known stochastic process. Three hypothesis distributions are used in these tests:

TABLE 4-3

COMPARISON OF AIRBORNE, VAN AND GARBLE REPLY WORD SEQUENCES

FLIGHT: 2-9-72 TIME SPAN 0:16:08
0:27:24

VAN REPLY WORD	A/C REPLY WORD*	GARBLE*
1110110110	111110111	001000001
1111111111	111111111	000000000
1111110101	111111101	000001000
0011111111	011111111	000000000
1111111111	111111111	000000000
0010001011	010101011	000100000
1110111111	111111111	001000000
0010111011	111111111	101000100
0011110111	011110111	000000000
1110111101	110111111	000000010
1111011011	111111111	000100100
0111110110	111111111	000001001
1111111101	111111101	000000000
1111111011	111111011	000000000
1111111101	111111111	000000010
0111111111	111111111	000000000
1111100111	111100111	000000000
1011111101	111111101	100000000
0111101101	111101101	000000000
1011111001	011111101	000000100
1111111111	111111111	000000000
1111111110	111111111	000000001
1110111011	111111011	001000000
0111111111	111111111	000000000
0101010110	101010111	000000001
1111111111	111111111	000000000
1111111101	111111101	000000000
1111111110	111111111	000000001
1001111110	011111110	010000000
0101011111	101011111	000000000
1110111111	110111111	000000000
1111111111	111111111	000000000
1111111111	111111111	000000000
1111100110	111100110	000000000
0011110111	011110111	000000000
1111111111	111111111	000000000
1111111110	111111111	000000001
0111111111	111111111	000000000
1110011010	110011010	000000000
1010101011	010101011	000000000

*A/C and Garble words show last nine bits of a possible 10 bit sequence due to an offset.

the normal distribution, the Poisson distribution and the binomial distribution. Hypothesis testing results reported on in this paper can be a significant aid in ATCRBS simulation and modelling studies.

ATCRBS Physical Environment

At 10 minute intervals during the recorded protions of each of the three test flights the sequence of unique Mode D interrogation bursts was interrupted and Mode 3A and C interrogations were generated continuously for several scans. During these intervals two photographs of the PPI scope display, showing the defruited replies to the Mode 3A/C interrogations, were taken. Periodic photographs were taken both at the Floyd Bennett Field test interrogator site and at the display console in the JFK International Airport tower. The JFK airport tower display is derived from the defruited output of the JFK interrogator. Two range scales were used on the van PPI scope photographs, one covering a range of 50 n.mi. with five 10 n.mi. rings, the other covering 160 n.mi. with eight 20 n.mi. rings. The JFK display covered 50 n.mi. with no scale markings. A comparison of the Mode 3A/C beacon-equipped air traffic, targets, as seen by each 0-50 n.mi. interrogator display is shown in Figure 4-1 for the flight of Wednesday, February 9, 1972. The origin of the time scale corresponds to 1345 EST.

The radial distributions of air traffic in the 160 n.mi. radius, which were monitored on the van interrogator PPI display, during four periods, each of which was approximately two hours long, on Wednesday

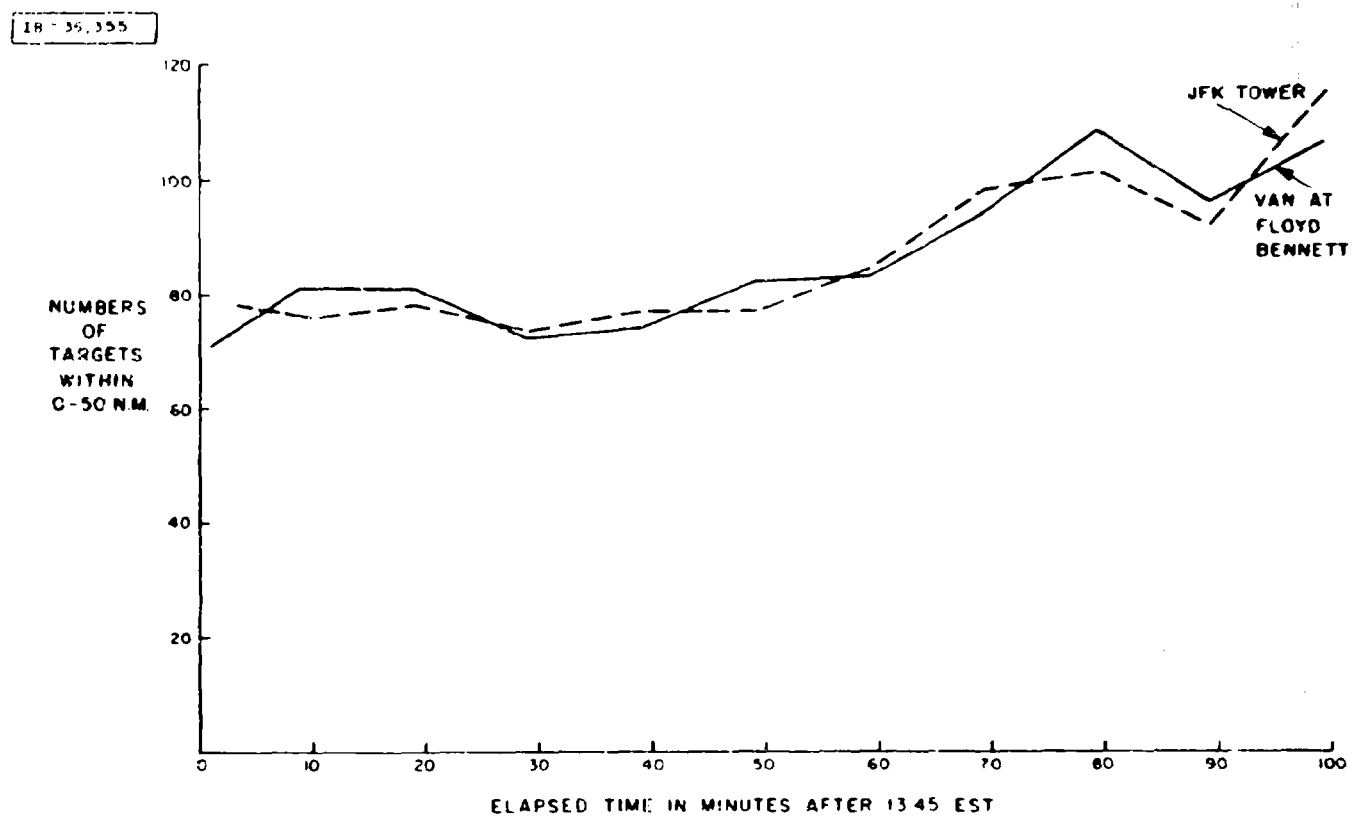

Figure 4-1 BEACON EQUIPPED TRAFFIC COUNT TAKEN ON FEB 9, 1972

February 9, 1972, Friday February 11, 1972, Wednesday February 16, 1972 and Tuesday February 22, 1972 are shown in Figures 4-2, 4-3, 4-4 and 4-5. There exists a marked similarity among these graphs in that the median range is about 50 n.mi. on each plot. Equally significant is the observation that 30 to 40 percent of the air traffic is contained within a 30 n.mi. radius of Floyd Bennett Field, which is the region from which fruit replies, occurring in the antenna sidelobes, originate. Although most of the air traffic lies outside of this region it is more likely that the observed peaks in the angularly sampled asynchronous fruit replies, collected by the interrogator receiver (see Figures 111 through 121 in Appendix III), are caused by the chance multiple illumination by other interrogators of the targets within the sidelobe region of the experimental interrogator than by the simultaneous illumination by several interrogator beams of the same target region.

With a data bank of known interrogator geographic positions it was possible to write a computer program to determine the number of interrogators which are within the horizon coverage of the instantaneous experimental aircraft position. Aircraft position is determined from the recorded altitude, range and azimuth. The latter two quantities are extracted from the tracking range and azimuth gate positions on a scan-by-scan basis. Due to problems with the azimuth encoder, shaft coupling slippage, only the 2-16-72 flight contained reliable azimuth estimates and hence reliable interrogator population counts and reliable angular fruit distribution measurements. Interrogator

IA-36,359

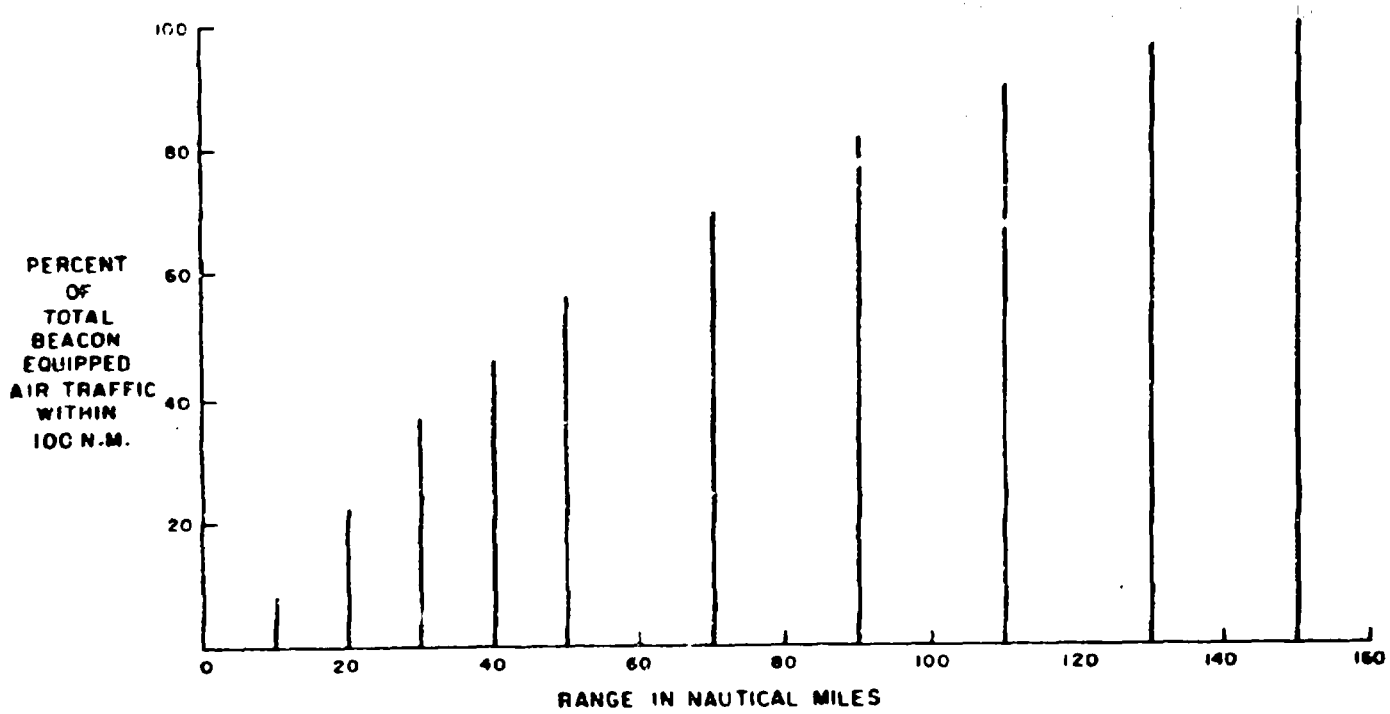

Figure 4-2 CUMULATIVE DISTRIBUTION OF AIR TRAFFIC VERSUS RANGE (FLIGHT OF 2-9-72)

IA 36,358

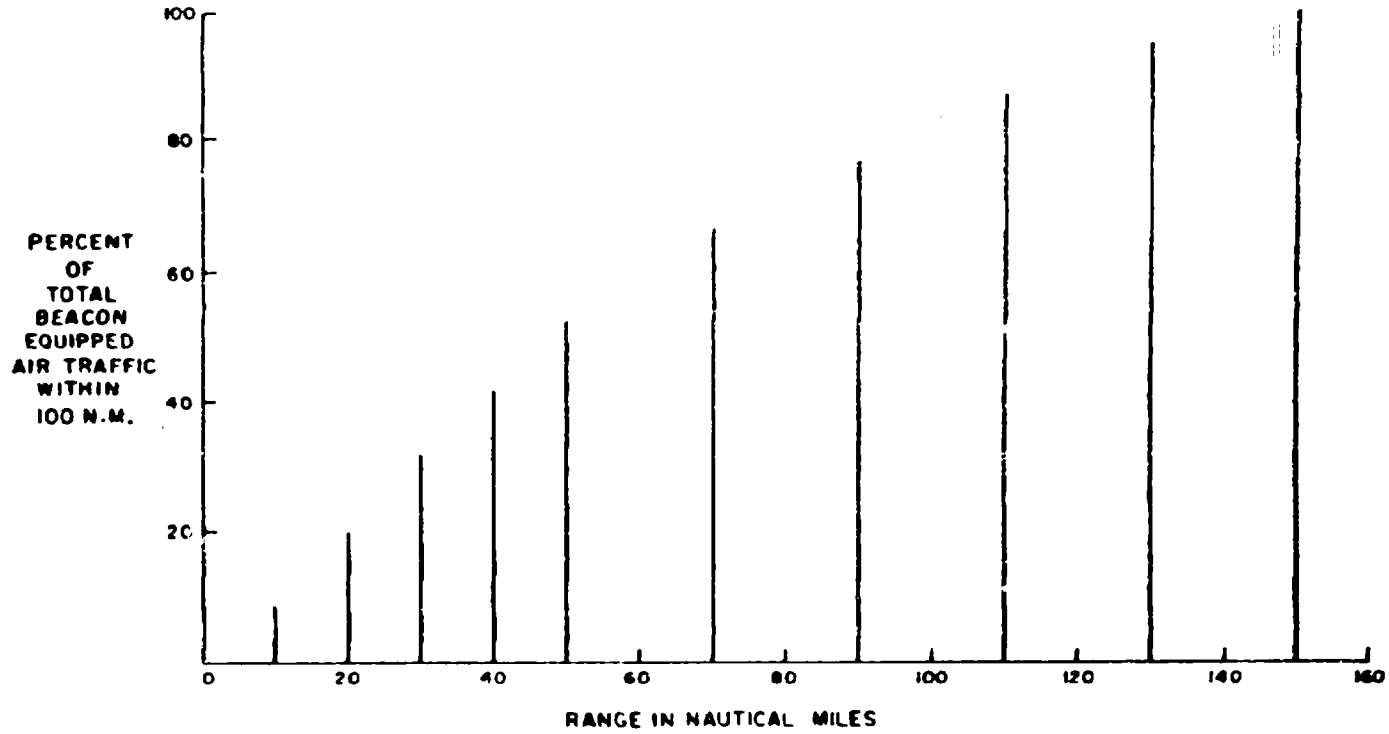

Figure 4-3 CUMULATIVE DISTRIBUTION OF AIR TRAFFIC VERSUS RANGE (FLIGHT OF 2-11-72)

IA-36,357

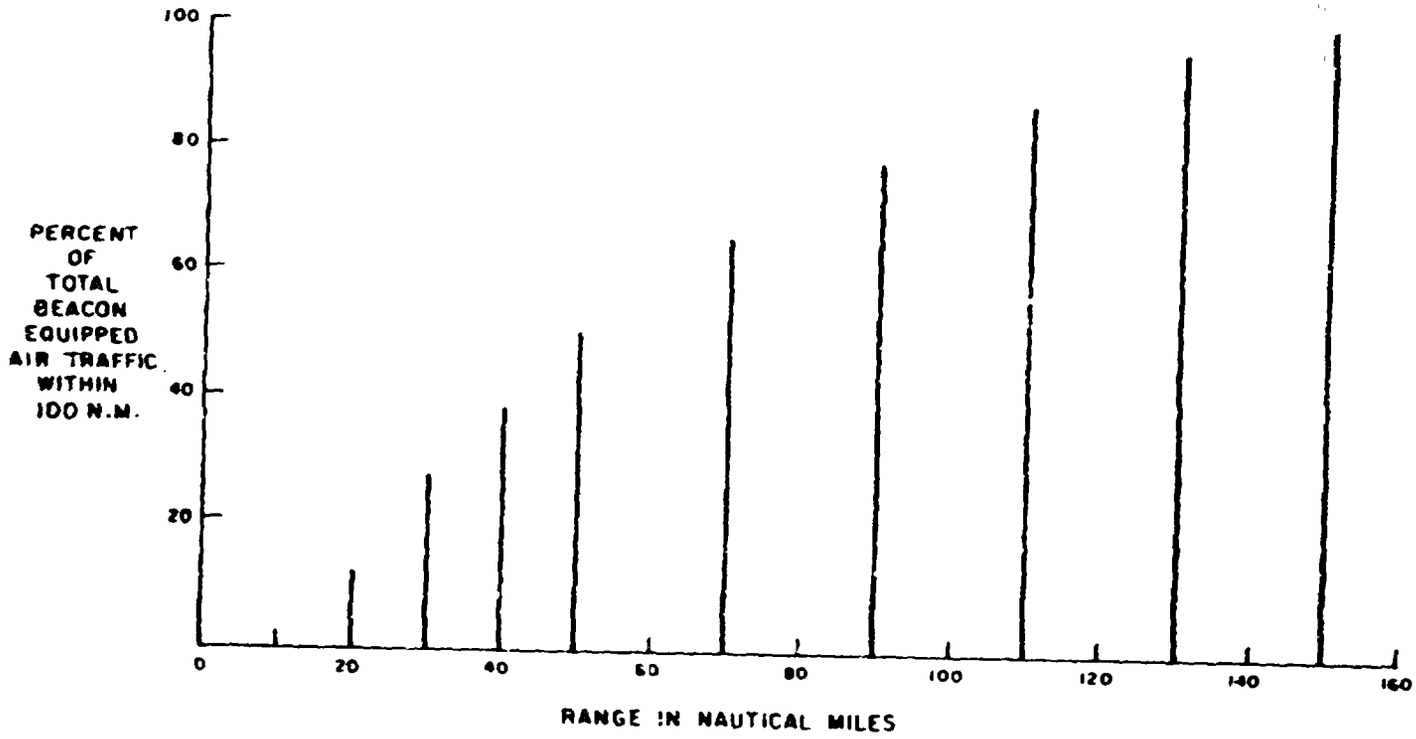

Figure 4-4 CUMULATIVE DISTRIBUTION OF AIR TRAFFIC VERSUS RANGE (FLIGHT OF 2-16-72)

IA 36,356

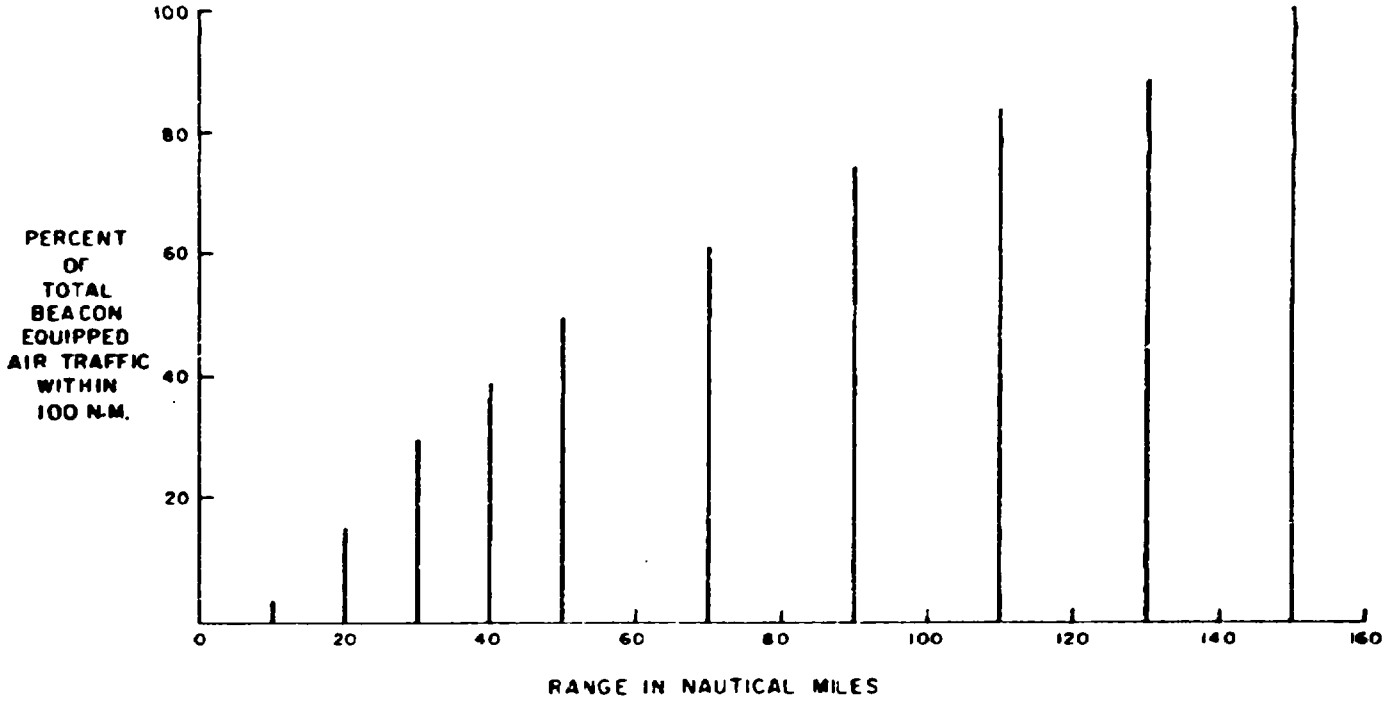

Figure 4-5 CUMULATIVE DISTRIBUTION OF AIR TRAFFIC VERSUS RANGE (FLIGHT 08 2-22-72)

population counts averaged over 10 minute intervals during the 36 n.m.i. semi-circular portion of the 2-16-72 flight were between 34.1 and 48.9

The random spacing and interference of the ensemble of Mode 1, 2, 3A/C interrogation pulse trains present at the transponder antenna input terminals occasionally simulate Mode D interrogations which are otherwise unique in the environment. The transponder decoder which is programmed to respond to any pair of pulse-like signals with a 25 μs, Mode D, P1 to P3 pulse separation, is likely to erroneously indicate the presence of a Mode D interrogation when a pair of spurious pulses caused by TACAN or other L-band transmissions arrive at the transponder with the proper spacing. The time history of the excess Mode D replies due to spurious Mode D interrogations collected during the filtered antenna dwell periods for the three flights in the New York area is summarized in Table 4-4.

TABLE 4-4

MODE D SPURIOUS OCCURRENCES

2-9-72 Flight			2-11-72 Flight			2-16-72 Flight		
Segment No. *	Scans per Segment	Mode D Spurious **	Segment No. *	Scans per Segment	Mode D Spurious *	Segment No. *	Scans per Segment	Mode D Spurious **
1	31	0,0	1	65	1,1	1	75	1,0
2	41	0,0	2	66	1,0	2	75	0,0
3	41	2,0	3	65	1,0	3	76	1,0
4	60	3,0	4	76	1,0	4	80	0,0
5	67	0,0	5	71	3,7	5	58	0,0
6	54	1,0	6	50	7,23	6	68	1,0
7	67	1,0	7	48	2,6	7	75	0,0
			8	41	1,0	8	55	0,0
			9	36	1,0	9	60	3,0
			10	88	3,2	10	44	1,0

*Each flight's test data was processed in limited length segments for convenience in analyzing the data.

**Mode D spurious events of one and more than one per dwell are indicated by the pairs of numbers in these columns.

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