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ANGEL CLUTTER AND THE ASR AIR TRAFFIC CONTROL RADAR. VOLUME I STUDY RESULTS

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16. Abstract
The goal of this study was to identify angel clutter reduction techniques which were cost-effective for the existing ASR-4, 5, and 6 radars. This report identifies a combination of techniques which can be implemented without major radar re-design and which improves the ASR surveillance capability. These techniques were developed by thorough analysis of ASR video and track radar data gathered during the Spring 1972 bird migrations at Milwaukee's General Mitchell Airport. The proposed angel clutter reduction (ACR) features operate on the three major differences observed between angel and aircraft signal characteristics: signal strength, pulse-to-pulse amplitude fluctuations, and velocity. These ACR features were chosen because they provide the highest level of effectiveness consistent with timely implementation and a reasonable degree of radar modification.

Chapter 1 summarizes all results. Chapter 2 discusses the impact of angel clutter on air traffic control operations. Chapter 3 describes angel and aircraft characteristics measured during the Milwaukee tests and compares them with previously-published information. Chapter 4 describes the recommended ACR system in detail. The Appendices provide a description of the field test instrumentation and supporting data and analyses.

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PREFACE

This study report contains the results obtained to date on the Angel Clutter Reduction Techniques Program conducted by the Applied Physics Laboratory, Johns Hopkins University, for the Federal Aviation Administration under Task II of Contract No. DOT FA-72WA-2705, issued on 8 October 1971.

The report includes the results published during the initial phase of effort in three interim reports (May, July, and August 1972) and the results of an extension phase which investigated the feasibility of applying pattern recognition techniques developed by Bendix Communications Division to reduce ASR Angel Clutter. Mr. O. E. McIntire of ARD-200 was the FAA Technical Representative for this effort. The support of Mr. K. E. Coonley of ARD-200, Mr. C. Chapman and others of the National Aviation Facilities Experimental Center (NAFEC), and of the FAA personnel at General Mitchell Field, Milwaukee, is gratefully acknowledged.

This study report is organized into two volumes. Volume I contains the Study Results. Chapter 1, Summary and Conclusions, contains all significant results and a recommended course of action leading to realization of an operational angel clutter reduction capability. Chapter 2 discusses the angel clutter problem, its sources, and its effect on air traffic control operations. Chapter 3 identifies differences in ASR signal return characteristics for angels and aircraft which were measured at Milwaukee airport during the spring bird migration period. Chapter 4 describes angel clutter reduction techniques which can exploit these differences in a manner which is cost effective for the ASR-4, 5 and 6 radars.

Volume II contains five appendices providing a summary of field test operations, supporting data, supporting analyses, a discussion of pattern recognition techniques and hardware design data for the suggested angel clutter reduction techniques.

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CHAPTER 1

SUMMARY AND CONCLUSIONS

The goal of this study was to identify angel clutter reduction techniques which were cost-effective for the existing ASR-4, 5, and 6 radars. Cost requirements dictate that these techniques be implemented as add-on devices which do not require major radar re-design. Effectiveness implies that the ASR surveillance capability be improved in angel clutter, with particular regard for small general aviation aircraft, which have small radar cross section and often lack beacon transponders.

This study identifies a combination of techniques which reduce the adverse effects of angel clutter on Airport Surveillance Radars (ASR) in a cost-effective manner. These techniques were developed by thorough analysis of ASR video and track radar data gathered during the Spring 1972 bird migrations at Milwaukee's General Mitchell Airport. The proposed angel clutter reduction (ACR) features operate on the three major differences observed between angel and aircraft signal characteristics: signal strength, pulse-to-pulse amplitude fluctuations, and velocity. These ACR features were chosen because they provide the highest level of effectiveness consistent with timely implementation and a reasonable degree of radar modification. Moreover, it is not clear at this point that even drastic radar re-design can provide a more effective solution at an acceptably low level of risk.

The major remaining task is to evaluate the performance of the recommended ASR modifications operating in concert against large concentrations of angels in real time. This test/demonstration will permit firm definition of design requirements leading to development of an operational angel clutter reduction system for the ASR radars.

CHAPTER 1

SUMMARY AND CONCLUSIONS

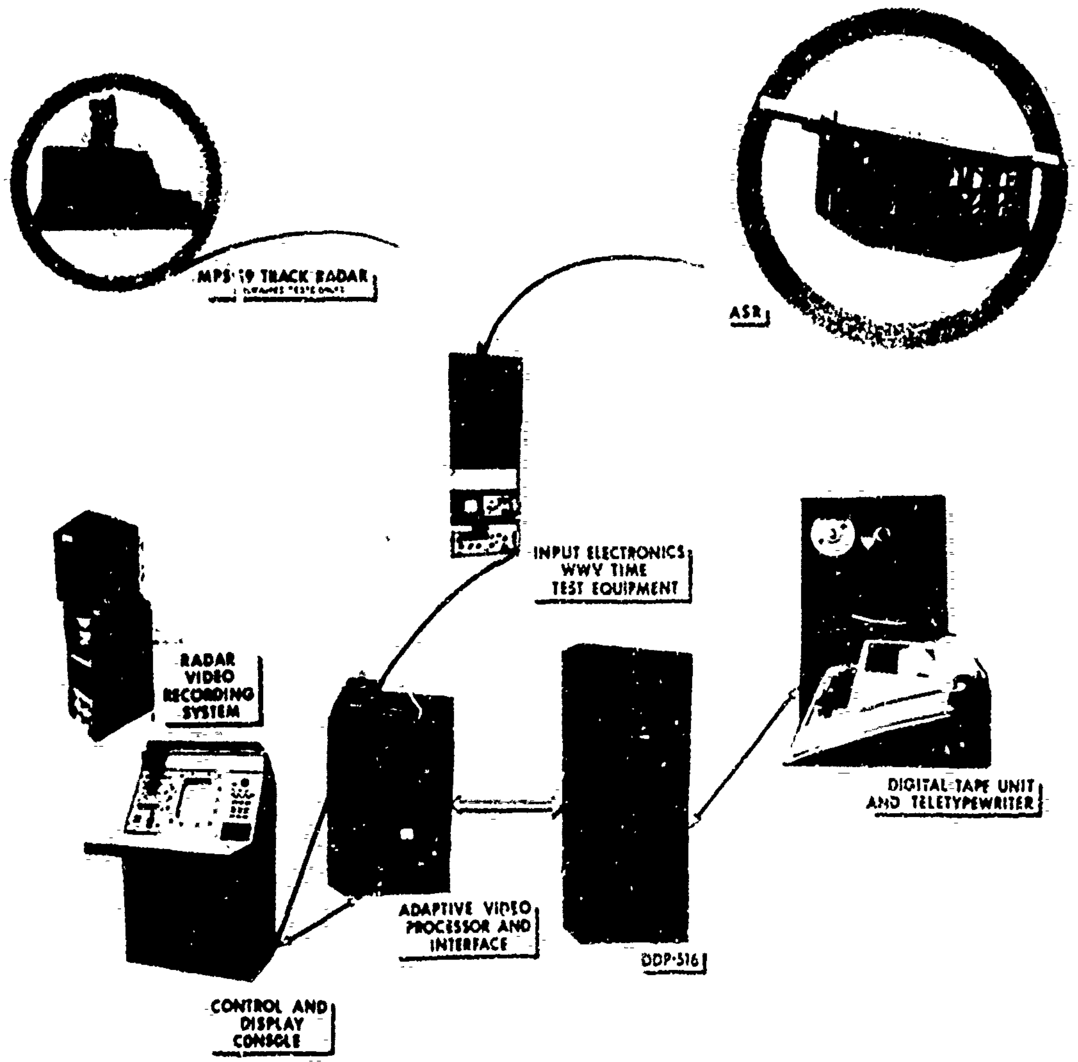
SUMMARY

1.1 Study Approach

Detections of angel clutter have been a persistent problem for ground-based surveillance radars which must provide short-range surveillance. In order to achieve good long-range surveillance, the Airport Surveillance Radar (ASR) has sufficient sensitivity to detect angel clutter out to ten to fifteen miles, even with MTI and sensitivity time control (STC). It also operates at S-band wavelengths where bird angel clutter is most pronounced. Several anti-angel features have been tested with the ASR in the past with relatively little success.

While much information has been published on the general nature of angel clutter, development of a successful angel clutter reduction capability for a specific radar requires knowledge of the detailed characteristics of angel and aircraft radar returns as well as an understanding of the physics of the radar/target interaction.

To gather the needed data, an appropriate instrumentation system was designed and constructed. The major components of the Data Acquisition Module are shown in Figure 1-1. This portable module interfaces with the ASR radar and a Track Radar Module which has radar parameters very similar to the ASR except for antenna beamwidth. Track radar data (target video amplitude, signal strength via AGC data, and position) can be digitally recorded via the DDP-516 computer for future analysis. ASR video amplitude data can be collected by using the track position to center a digital data collect matrix (1.4 nmi x 7^{o}) about the target of interest. Thus both continuous video data from the track radar and actual ASR video (at a four-second scan rate) are available for detailed analysis. The Data Acquisition Module can also automatically track and display all aircraft visible to the ASR (up to 255) as its major



DATA ACQUISITION MODULE EQUIPMENT

FIGURE 1-1

components were derived from the AN/SYS-1 Target Information Processing System developed by the Applied Physics Laboratory for the Navy. The Data Acquisition Module was also used to support the ARTS Enhancement program under Task I of this contract (Ref. 1).

While angel clutter consists of birds, insects, and meteorological echoes, the generally accepted opinion is that it is predominantly due to birds. However, the source of the clutter is not of principal concern for this problem, since the objective is the elimination of the radar clutter responses regardless of the source. This effort is directed toward determination of the characteristics of the clutter and to devise means which exploit the common characteristics to provide significant discrimination between aircraft and angel clutter which will be effective, in varying degrees, against all angel clutter.

Following preliminary tests with the Track Radar Module at NAFEC to gain experience in identifying bird angels, and a site survey to determine the most appropriate site, the major data collection operation was conducted during the spring bird migrations at Milwaukee. The data was returned to APL for analysis. Major concentration was placed upon processing the angel and aircraft azimuth patterns (amplitude of radar return pulses as the antenna scans past the target) to establish characteristic differences which could be exploited by appropriate video processing techniques. Techniques derived in this fashion were then simulated and evaluated with the data collected at Milwaukee. These results, plus additional analysis of ASR radar performance in angel clutter situations, form the basis for the conclusions summarized in the following sections.

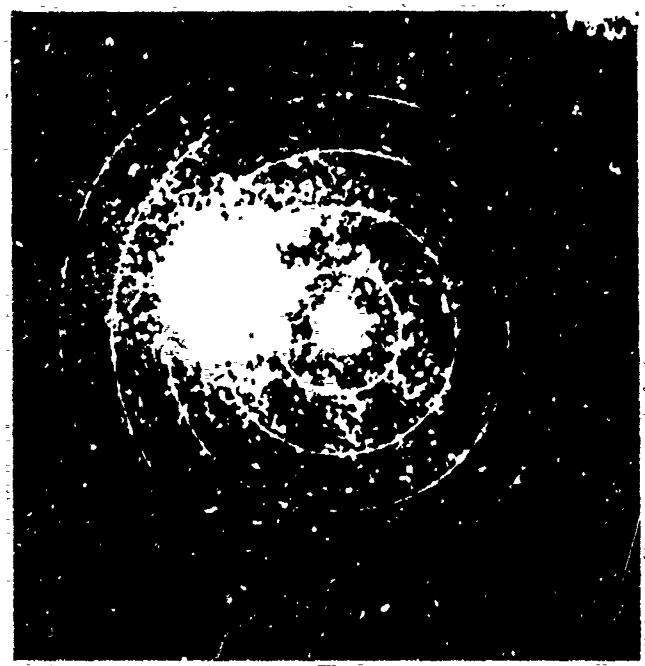
1.2 The Angel Clutter Problem (Chapter 2)

Angel clutter (AP in the air traffic control jargon) appears on the PPI as large masses of point targets which occur at locations in which there are no known aircraft or normally-expected sources of radar clutter (land and weather returns). The type and concentration of angel clutter observed at a given ASR site depends upon geographic location, season and time of day, and to a certain extent, upon the whims of Mother Nature. While angel clutter is rarely a daily problem, it can have serious effect on primary radar surveillance when present (Figure 1-2).

With the advent of ARTS III Enhancement and the enroute automation, angel clutter may become a serious limitation to the automatic tracking capability. Unless the angel clutter level can be sufficiently reduced, the number of declared targets may exceed the tracking capability. However, if the number can be reduced to a tolerable level, the tracking capability of ARTS can be used to further discriminate against angels based upon scan-to-scan properties, such as, velocity and trajectory.

Birds and groups of birds are a major source of angel clutter at many ASR sites, although insects, atmospheric irregularities, and even industrial pollution can produce returns that are classified as AP or angels. Based upon mean bird densities estimated for the United States, an ASR radar should have 200,000 birds populating its first ten miles of coverage. The maximum range for typical angel clutter is on the order of 10-15 nmi.

The present ASR features which are useful against angels (STC/CSS,MTI, and manual gain reduction) are not adequate. Over 700 bird angels were displayed within five miles of the Milwaukee radar using STC, MTI, and normal radar sensitivity. While birds differ in velocity from aircraft, they look very much like returns from small aircraft. The display observer therefore must contend with detecting aircraft in large masses of angels within 10-15 miles of the radar or operating at a lower (unknown) sensitivity at all ranges. An automated radar tracking system, such as the Enhanced Automated Radar Terminal System (ARTS), must be provided with appropriate processing to reduce angel clutter reports to a level that is compatible with the target tracking capability of the system.



1923 HRS, 28 OCT 71
2 MILE RANGE RINGS
MTI VIDEO

FIGURE 1-2 — ANGEL CLUTTER ON NAFEC ASR

Angel clutter, when present, can have a profound effect on air traffic control operations involving small, non-beacon, aircraft. In moderate angel clutter, it is usually possible to maintain visual track of a known aircraft as it transits the angel clutter region, if the aircraft load is light enough to permit adequate concentration. Large aircraft produce wide azimuthal returns that help identify them from angels. Detection of unknown aircraft (intruders) in angel clutter regions is much more difficult; strong angel clutter can lead to a suspension of primary radar services.

Bird hazards to aircraft are highest during landing and take-off, when the aircraft is at low altitude. Since angel clutter on the ASR provides the basis for suitable warning of such hazards with properly trained observers, angel clutter reduction features must be occasionally disabled to map angel clutter extent. Both the bird hazard problem and the ASR angel clutter problem can be helped by removing major bird attractions (dumps and other feeding or roosting areas) away from airports and their approaches; this has been accomplished with some success in the past.

1.3 Angel and Aircraft Return Characteristics (Chapter 3)

The detailed characteristics of angel and aircraft returns were measured with the ASR and with a track radar which had parameters very similar to the ASR. The results are summarized below.

Radar Cross-Section (RCS)

a) the long-term average RCS of tracked bird angels at Milwaukee varied from 0.005 m^2 to 2 m^2, with an average of 0.28 m^2. A Cessna 172 ranged from 2-25 m^2 on a trajectory that included crossing aspects.

b) RCS distributions from track radar data showed that the mean and median RCS of each angel were approximately equal and ranged from 0.02 to 0.7 m^2. The Cessna had a median RCS of 4.5 m^2 (large because of crossing aspects) and the mean was 2.4 times larger, indicating that large upward fluctuations in RCS are more likely for aircraft. The Cessna exceeded 1 m^2 about 80% of the time, while the largest angel exceeded 1 m^2 only 6% of the time.

c) RCS distributions from ASR video (including antenna scan modulations) showed the same mean/median ratio factor of 2.5 between birds and the Cessna. The distributions resembled the exponential distribution for the Cessna and fell between the exponential and Rayleigh distributions for angels, implying that the angels consisted of many more individual radar scatterers than the Cessna. Angels with large cross sections should therefore be more Rayleigh-like because they contain more birds. Using these models, an aircraft detection probability of 80% with a 95% angel rejection probability requires that the target RCS be 23 dB larger than an angel containing a few birds and 18 dB larger than an angel containing many birds and therefore having a larger RCS.

d) Azimuth autocorrelation functions of ASR video showed much faster decorrelation in azimuth for the bird angels (0.18° versus 0.6° for the aircraft) indicating that discrimination based on azimuth pattern fluctuations should be effective.

Range Attenuation Rate

Analog video recordings of ASR video indicated that angel clutter had the R^{-4} range/power relationship normally ascribed to point targets, indicating that an R^{-4} STC characteristic (like CSS-1) is appropriate for reducing angel clutter to an approximately constant value with range.

SUMMARY

Spatial Distribution Characteristics

a) The maximum height of the majority of angels at Milwaukee was 5000-6000 feet.

b) No angel returns were observed which substantially exceeded one radar resolution cell (410 feet by 1.5°).

c) Very few angel detections occurred beyond 10-15 nmi. Mean angel target densities vary widely; up to 700 detections were counted in the first five miles at Milwaukee with STC and MTI processing. Angel densities decrease with range due to radar detection capability; observed densities ranged from 4-16 angels/nmi^2 in the 0-2 nmi range interval to 0.03-0.4 angels/nmi^2 in the 6-8 nmi range interval. The majority of radar resolution cells (95% or more) within the angel clutter region are free of angels.

d) Six dB of video attenuation reduced the number of MTI angel detections in the first 10 miles at Milwaukee by a factor of two (670 to 325).

Velocity and Trajectory Characteristics

a) Milwaukee bird angel tracks had ground speeds of 10 to 59 knots, which is representative of most bird angels.

b) Trajectories and choice of altitude were influenced but not totally determined by wind conditions at the various altitudes.

c) During migration periods, the headings of most angels are approximately the same.

d) In multiple-scan photographs (for example, see Appendix A, Figure A-5) aircraft can be recognized by the longer trails they produce, so that a multi-scan PPI display will provide angel/aircraft velocity discrimination if input angel densities are not excessively high.

SUMMARY

Azimuth Pattern Characteristics

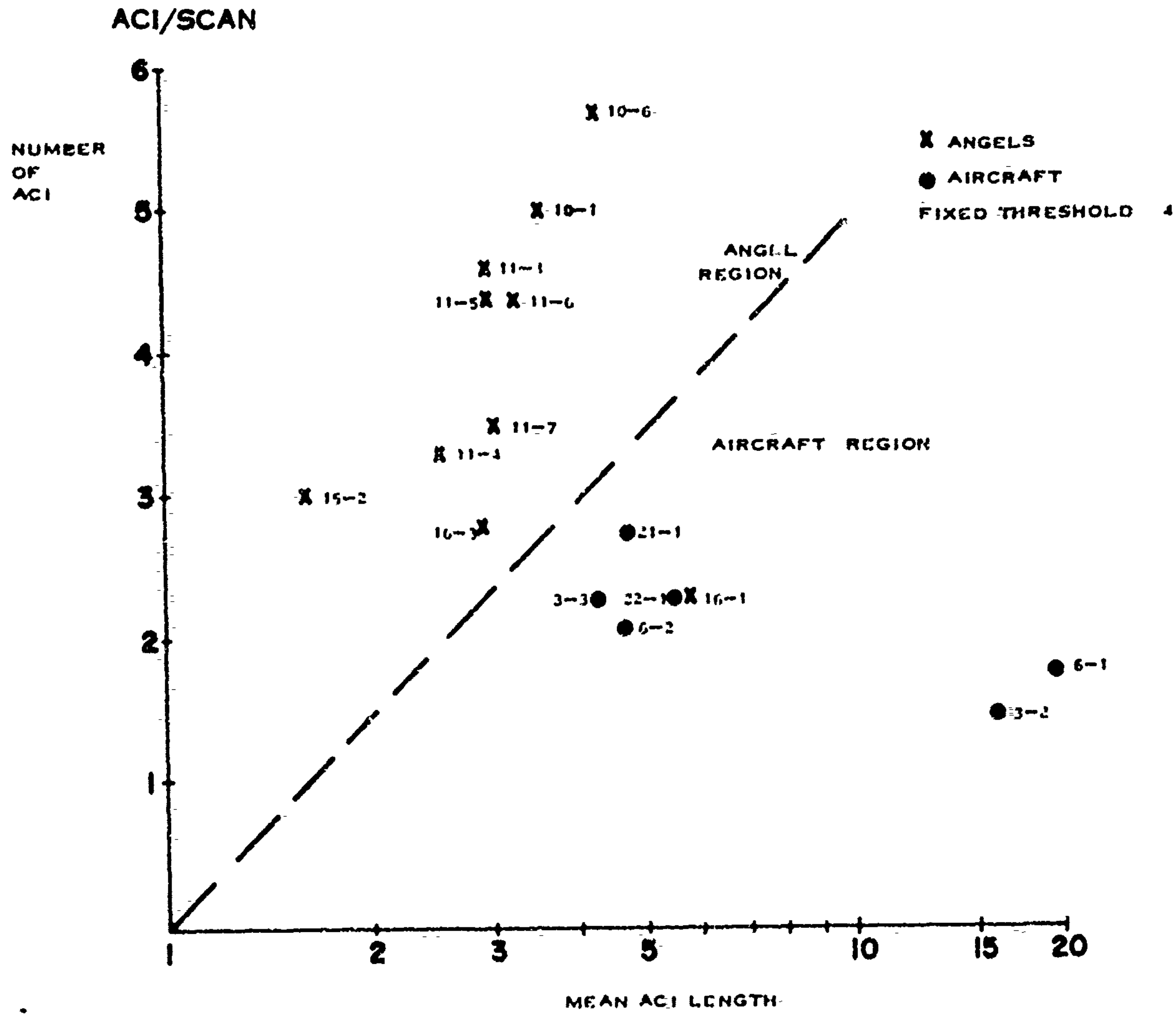
Azimuth patterns of angel and aircraft ASR returns were investigated in terms of Azimuth Correlation Intervals (ACI, groups of successive return pulses that exceed a threshold) and in terms of the performance of several Azimuth Pattern Processors designed to take advantage of differences noted through ACI analyses. The Azimuth Pattern Processors were implemented off-line in a digital computer. Input data was that collected with the ASR data collect matrix at Milwaukee; returned video amplitude was collected on every other radar pulse period for a total of 37 samples in azimuth. All angel data was for MTI video; aircraft data included both normal and MTI. Results were as follows:

a) The aircraft produced longer ACI lengths (number of consecutive samples above threshold) than angels; this difference was much less pronounced when only MTI aircraft tracks were considered.

b) The aircraft produced fewer numbers of ACI (groups of consecutive samples above threshold) than angels; this difference was maintained for both MTI and normal video aircraft data.

c) Figure 1-3 shows mean number of ACI versus mean ACI for each angel and aircraft analyzed, showing the potential of each as well as both measures for separating angels and aircraft.

d) Fluctuations in angel azimuth pattern tend to be less violent than for aircraft; aircraft patterns tend to fluctuate completely to zero while angels tend to fluctuate by a much smaller percentage of the mean amplitude. This result is consistent with previous findings that angels contain more individual scatterers than aircraft.



NUMBER OF ACI PER SCAN VERSUS AVERAGE ACI LENGTH

FIGURE 1-3

SUMMARY

Azimuth Pattern Processing Results

To explcit the differences in angel and aircraft azimuth patterns, it is necessary to develop practical techniques for processing the data. The digitized ASR azimuth pattern data collected at Milwaukee was processed with digital computer algorithms representing numerous detection schemes. The results of the five most promising schemes are shown in Figure 1-4 in terms of probability of detecting aircraft P(D/AC) and probability of rejecting angels P(R/AN) for all Milwaukee tracks. This performance curve is indicative of the best trade-offs between aircraft detection and angel rejection that can be achieved by varying the parameters (thresholds, etc.) of each processor. The shaded region denotes the region of degradation, i.e., the region where the unaided ASR could perform better than the processor. The ideal situation of P(D/AC) = 1 and P(R/AN) = 1 is unattainable because angels and aircraft are sufficiently similar that some mistakes are always made by the processor. Performance is essentially proportional to the complexity of the processors (Table I), and the results can be summarized as follows:

a) The M/M Azimuth Correlator is the simplest processor and operates on ACI length; an aircraft was declared if 2/2 or 3/3 of the alternate-pulse samples exceeded the threshold. Only modest angel clutter rejection (35%) is obtained before aircraft detection probability drops below 80%. However, the simplicity of this processor (it is essentially a binary video integrator) and its ability to provide an aircraft/angel decision rather rapidly (after 2 to 5 pulses are received) make it very attractive. Analog tapes of Milwaukee ASR MTI

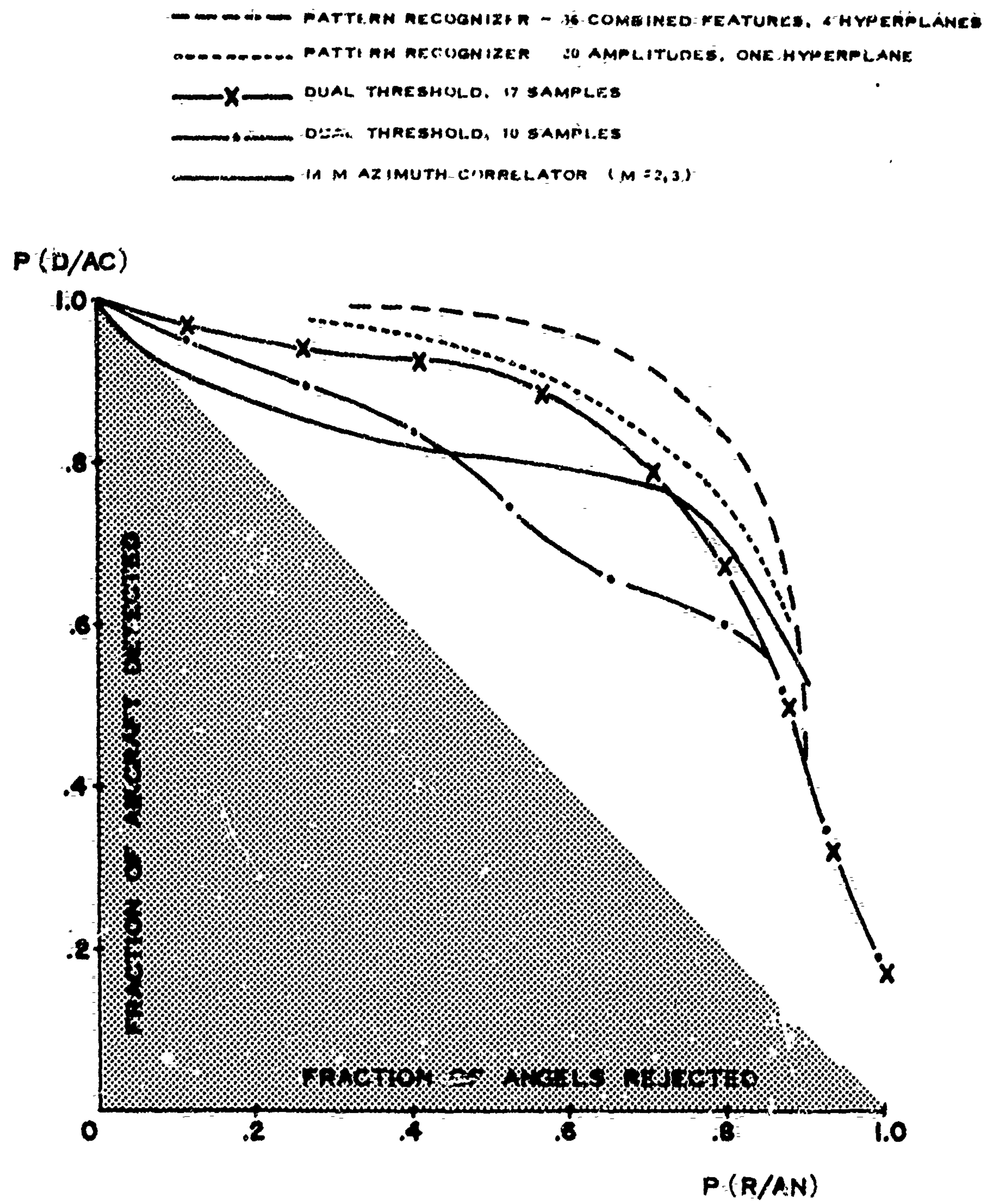


FIGURE 1-4 RELATIVE PERFORMANCE OF AZIMUTH PATTERN PROCESSORS

NOTE: The parameter varied for pattern recognizers was hyperplane orientation, for the dual threshold it was the threshold levels and for the azimuth correlator it was also an adjustable threshold.

TABLE I

ANGEL CLUTTER REJECTION OF AZIMUTH PATTERN PROCESSORS

	P(D/AC)		
	0.8	0.9	0.95
Pattern Recognizers			
I 36 Combined Features, 4 Hyperplanes	82%	73%	64%
II 20 Amplitudes, One Hyperplane	75	59	45
Dual Thresholds			
I 37 Alternate Dwells	70	54	20
II 10 Samples/37 Alternate Dwells	46	26	12
Azimuth Correlator			
m/m = 2/2 or 3/3	55	13	4

video were processed in the APL Data Acquisition Module, using a 5/5 criterion since the analog tapes provided data on every radar pulse rather than alternate pulses as used for the digital data. The resulting PPI photographs (Figure 3-21) showed favorable subjective performance on angels and aircraft targets of opportunity.

b) The Dual Threshold processor operates on the difference in number of ACI measured at high and low thresholds to take advantage of the deeper fluctuations observed for aircraft; aircraft produce lower differences in number of ACI at the two thresholds than angels. Figure 1-4 shows the performance curves for processing all 37 alternate-pulse samples and for processing each consecutive group of 10 samples (to reduce processor storage requirements). The 37-sample processor provides 10-15% better aircraft detection out to angel rejection probabilities of about 60%.

c) A Pattern Recognizer is a device which extracts a number of features from the azimuth pattern and subjects them to a set of weighting factors such that the value of the weighted output indicates whether the target is an angel or an aircraft. The weighting factors are derived from sample data sets of known angels and known aircraft. The curves in Figure 1-4 result from a feasibility investigation performed by Bendix Communications Division under subcontract to APL.

The two pattern recognizers represent two extremes of complexity. The 20-feature Amplitude Pattern Recognizer subjected 20 azimuth amplitudes to one set of weighting factors to perform the angel/aircraft decision. The Combined Features Pattern Recognizer was considerably more complex; in effect it consisted of 17 parallel processors examining 36 features: the 20 amplitudes, three amplitude statistics (mean, standard deviation, and maximum amplitude), three different M/M azimuth correlators, and ten different dual thresholds. Four successive sets of weighting factors were used to make the angel/aircraft decision. While the performance of this recognizer is excellent, the price paid in complexity is very substantial. Further study is required to select the minimum number of features required to achieve reasonable balance between performance and complexity. Present data indicates that certain of the dual thresholds were the most valuable contributors to the angel/aircraft decision and that amplitude samples must be included for recognizing the difficult cases.

1.4 Angel Clutter Reduction Techniques (Chapter 4)

While no single characteristic of ASR angel and aircraft returns permits unique separation of the two target classes, a combination of radar cross section (RCS), scan-to-scan motion (i.e., velocity as opposed to range rate), and azimuth pattern discrimination can be used to substantially improve ASR surveillance in angel clutter. A design concept consisting of add-on elements that perform these functions is described in Chapter 4 and is shown in Figure 1-5.

The design is conceptual for several reasons. First, the allowable cost of angel clutter reduction modifications varies from site to site depending upon the severity of the local angel

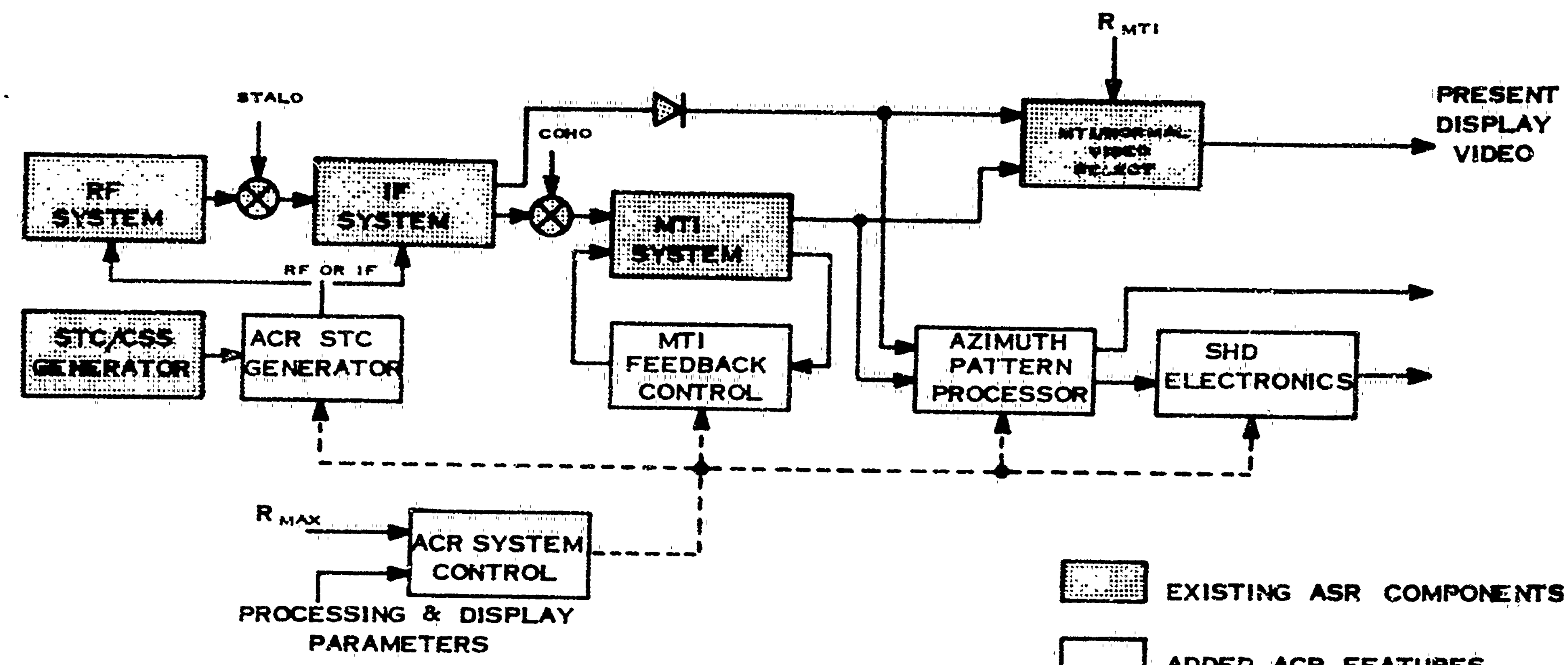


FIGURE 1-5 PROPOSED ASR ANGEL CLUTTER REDUCTION SYSTEM

clutter problem and on the number of annual air traffic operations. Second, the suggested techniques have not been evaluated when operating together since normal air traffic control activities at Milwaukee prohibited control of receiver gain and other radar parameters. The elements shown in Figure 1-5 constitute a modular system which can be pared down as necessary if dictated by individual airport priorities. Section 1.5 suggests an appropriate field test to refine this conceptual design so that firm design requirements of a suitable operational system can be provided.

Each of the angel clutter reduction modifications is discussed below. After a description of each element, the trade-offs in selection of a suitable Azimuth Pattern Processor and methods of displaying aircraft detections are addressed.

Angel Clutter Reduction (ACR) Modifications

The ACR STC Generator generates a modified STC characteristic which provides RF (or IF) attenuation that follows an R^{-4} law plus a controlled level of additional attenuation. It also measures MTI receiver noise in the radar dead time to permit generation of a video threshold which can be calibrated to reject angel targets whose signal strength is less than that of a selected minimum aircraft RCS. Since received signal strength is proportional to both RCS and position in the antenna elevation beamwidth, the desired attenuation is different for aircraft on the 3^{o} glide slope than for overflying aircraft. The passive receive horn modification being developed for the ASR will enable this form of discrimination to be used for overflying aircraft, while the normal antenna pattern is appropriate for landing and departing aircraft.*

The MTI Feedback Control is a simple switch which disables the present ASR MTI feedback connections in the angel

*The discrimination is not absolute, but high altitude targets are selectively rejected by the lower beam and vice versa.

clutter region. This eliminates the feedback-induced peaking of the MTI response in the 40-knot region where angel velocities predominate.

The Azimuth Pattern Processor contains the video processing required to perform azimuth pattern discrimination between angels and aircraft, elimination of very small angels via an RCS threshold calibrated to receiver noise, and efficient target detection. The latter function is performed by (1) an adaptive quantizer which compares each range cell against adjacent samples of the radar environment to provide good detection sensitivity at a constant false alarm rate and suppression of distributed clutter, and (2) a binary azimuth integrator which sums range-cell detections across the azimuth beamwidth to declare target detections. The results of the angel/aircraft azimuth pattern processing are used to eliminate or tag those detections which are declared to be angels. Selection of the appropriate form of angel/aircraft azimuth pattern discrimination is discussed separately below.

The Scan History Display (SHD) Electronics package consists of a target centroider which combines Azimuth Pattern Processor outputs into single target reports and a memory capable of storing up to eight scans of reports for 512 targets. This memory is read out onto the PPI display to show the motion of each target over the past eight scans; the length of the trail for each target is proportional to its velocity so that aircraft can be discerned from the angels remaining after previous angel reduction processing.

The ACR System Control contains an R_{MAX} control which is manually adjusted to the maximum range over which angel clutter reduction processing is desired. This avoids unnecessary losses in aircraft detectability beyond the angel clutter region. MTI video is always used in the angel clutter region since land clutter also appears at these ranges. Beyond R_{MAX}, the radar is returned to its normal processing configuration. The adaptive quantizer/binary integrator portion of the Azimuth Pattern Processor will still provide synthetic processed video if desired for improved long-range surveillance. The Scan History Display could also be used for full range coverage if angel clutter is light. The ACR System Control would also contain the minimum parameter adjustments necessary for proper ACR system operation and a switch to permit use of MTI feedback in the angel clutter region when angel clutter is adequately handled by other ACR system elements.

Choice of Azimuth Pattern Processors

The three azimuth pattern discrimination techniques provide three levels of effectiveness which are directly proportional to complexity. The following comparisons are in order:

a) The M/M Azimuth Correlator provides modest performance but is easily implemented using the same circuitry as a binary azimuth integrator.

b) The dual threshold provides better performance than (a) but requires storage of data over many more sweeps (20-40 alternate dwells). This delays the angel/aircraft decision until up to 6° after the radar sweep has passed the target.

c) The pattern recognizer is most promising but requires considerable refinement to select the best (and smallest) set of features that can be implemented in a practical processor of reasonable cost. A reasonable goal would be no more than five or six features which could be derived from a single-channel processor. The 20-amplitude, single hyperplane pattern recognizer is relatively simple and performs well.

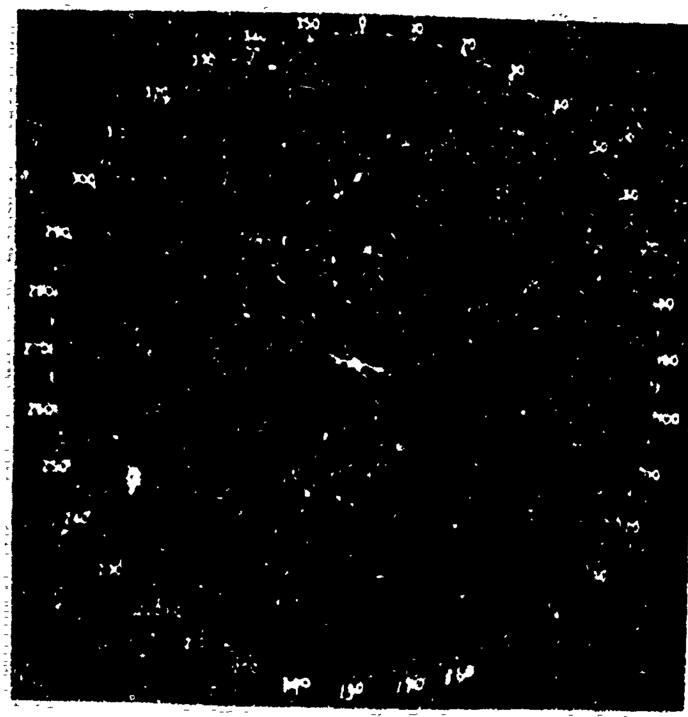
Choice of Display Format

Since the PPI display is the sole interface of the system with its users, display characteristics are a very important part of the system. Angel clutter reduction cannot be validly expressed in terms of the percentage of aircraft and angels remaining on the display, since the effectiveness of the display for surveillance purposes is subjective insofar as the perception of an operator is concerned. Not only is the number (as opposed to the percentage) of angels important, but also the subjective appearance of the residue over the surveillance region.

The Scan History Display (SHD) provides a unique PPI format which can be very useful for aircraft detection and angel discrimination. If the SHD outputs are displayed with a separate CRT gun, they can be continually refreshed independent of the PPI sweep. Target direction can then be indicated by sequentially displaying each stored scan so that each target trail appears to move in the direction of target motion. Intensity modulation (to simulate PPI persistence decay) could be used instead; the most appropriate format can be resolved only through evaluation with experienced operational air traffic control personnel.

The SHD provides an additional capability that has several distinct advantages for the proposed angel clutter reduction system. If the SHD memory is read out in bearing-range order from the previous eight scans and added at a higher intensity level to raw radar video, the PPI will show unprocessed raw video for the present scan plus eight dots showing past motion of targets designated as aircraft by the ACR system. This avoids any degradation of ASR video by the ACR system and permits existing PPI displays to be used, but the feasibility of using such dual-level video must be thoroughly evaluated.

Figure 1-6 shows the effect of a Scan History Display following a 5/5 Azimuth Correlator operating on analog video tapes recorded at Milwaukee.

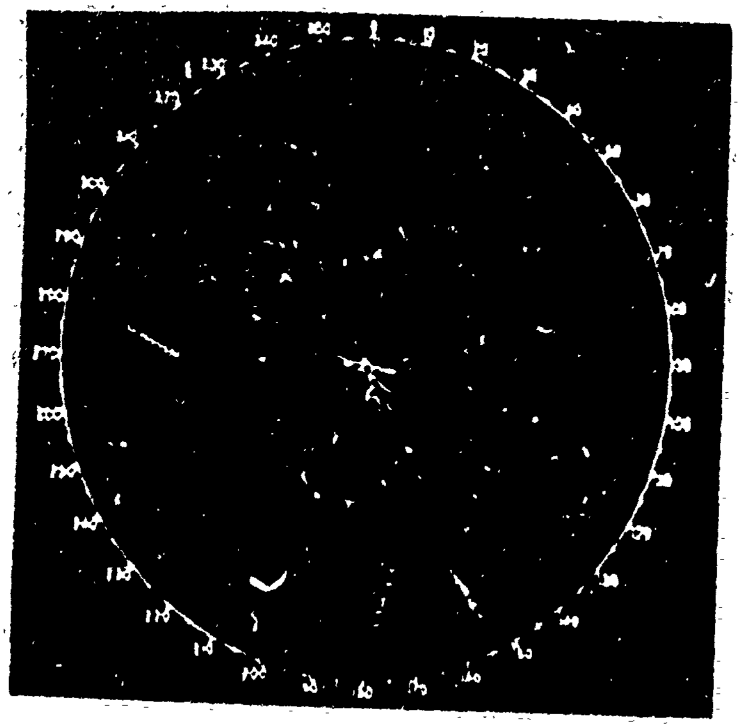


SHORT TERM MOTION
(3 SCANS)

FIGURE 1-6

SCAN-TO-SCAN MOTION OF ANGEL CLUTTER & AIRCRAFT

MILWAUKEE ASR, MTI & STC
5/5 AZIMUTH PATTERN PROC
10 MILE RANGE



LONG TERM MOTION
(9 SCANS)

FIGURE 1-6

SCAN-TO-SCAN MOTION OF ANGEL CLUTTER & AIRCRAFT

MILWAUKEE ASR, MTI & STC
5/5 AZIMUTH PATTERN PROC
10 MILE RANGE

1.5 Recommended Field Evaluation

Prior to definition of design requirements for an operational angel clutter reduction system, a field evaluation is required to establish the following:

a) the interaction of the four proposed angel clutter reducers, their relative effectiveness, and appropriate configurations for simplified systems.

b) the suitability of the calibrated radar cross section threshold for operational use with approaching, departing, and overflying aircraft.

c) the relative effectiveness of the three candidate Azimuth Pattern Processors on an expanded data base of real-time angel clutter (They have been tested only on a limited number of angel and aircraft tracks collected at Milwaukee).

d) minimization of parameter adjustments.

e) operational acceptability of the several possible display formats.

The ASR test site at NAFEC is appropriate for this evaluation because it experiences substantial angel clutter in the spring and fall (Appendix A) and because the radar parameters can be adjusted without regard for air traffic control surveillance requirements. NAFEC also has the necessary radar and air traffic control personnel to facilitate the type of tests required. These tests should be run in real time to provide a realistic demonstration of system operational capabilities as well as a means for evaluating the several alternative configurations. Following this demonstration, it will be possible to specify the detailed design requirements for cost-effective hardware development.

Hardware development, however, is not required for these tests. The cost of implementing the complete system in hardware can be avoided by implementing much of the azimuth pattern processing and scan history display in software. The Data Acquisition Module developed under this contract has the basic capabilities required to accomplish this task. The resulting system would be an adequate functional model of the complete system with sufficient flexibility to provide a valid test of the several system alternatives.

Prior to this field evaluation, simplification of the Pattern Recognizer algorithm should be accomplished. This can be performed with existing Milwaukee data and VQR (Video Quantizer Recorder) tapes of angel clutter which have recently been collected at NAFEC. The goal of this simplification study should be to select a few-feature recognizer that can be easily implemented in hardware and which has performance that is relatively independent of angel and aircraft types.

CHAPTER 2

THE ANGEL CLUTTER PROBLEM

The term "Angel" refers to a radar return which is seemingly anomalous, that is, one which occurs at a position which does not contain a normally-expected radar target, such as an aircraft or common forms of clutter (land and weather). Although the common Air Traffic Control term for angel clutter is "AP", an abbreviation for anomalous propagation, angel clutter often occurs under normal propagation conditions and, particularly during periods of high bird activity, angel clutter is not anomalous in the sense of being a departure from the general rule.

Angels have been observed since the early years of radar use; angels visually identified as birds were detected with an S-band (10 cm) radar in 1941 (Ref. 3). Angel returns vary in size from the threshold of detectability to larger than a large aircraft. Some appear to drift with the wind, others seem stationary, and still others are self-powered, moving relative to the ground and to the wind. Recognized sources of angels include birds, insects, unusual precipitation, smoke clouds, ionized regions, regions of irregular refractivity, and normally undetectable targets detected due to anomalous propagation (Refs, 4 and 5).

The following paragraphs consider the angel clutter problem in the context of FAA terminal Air Traffic Control. Sources of angel clutter are described in Section 2.1 with emphasis on aspects affecting Airport Surveillance Radars (ASR). The problem of identifying the source of specific angels is considered. The impact of angel clutter on terminal air traffic control in both the present system and in the Automated Radar Terminal System (ARTS) is then described, and the important connections with the bird strike problem are briefly discussed.

CHAPTER 2

THE ANGEL CLUTTER PROBLEM

2.1 Sources of Angel Clutter

2.1.1 Birds

Many experiments have shown that birds are major contributors to the angel clutter problem for ground-based radars. Eastwood (Reference 4) gives numerous examples. An estimated 10^{11} birds currently populate the earth. The corresponding world-wide mean density of 700 birds per square mile is a typical value given for the United States. With such a density, an ASR radar would have 200,000 birds populating the first ten miles of its coverage. In actual cases, the number normally present may even be much greater. For example, at Little Rock, Arkansas, some 5-50 million blackbirds roost within ten miles of the terminal radar. The radar cross sections of individual birds vary widely with species and aspect angle, typical values falling in the range from 0.001 to 0.1 square meters. Since the ASR is capable of detecting a 1 square meter (fluctuating) target at 45 nautical miles, it is capable* of detecting a single 0.0001 square meter bird target out to 4.5 nautical miles (Figure 2-1). An angel consisting of a group of birds simultaneously detected in the same radar resolution cell may present a cross section which is orders of magnitude larger than that of an individual bird; it may easily be as large as an aircraft cross section.

Ground speeds of birds range from zero to 60-80 knots. Winds affect bird ground speeds, usually increasing them; migrating birds are known to seek tail winds and avoid head winds. Although they rarely approach the speeds of even slow aircraft, bird velocities often lie outside the range of velocities cancelled by the ASR MTI. Consequently, the problem presented by bird clutter is distinct from that of ground clutter.

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*This is true only in the absence of ground clutter and when STC is not in use.

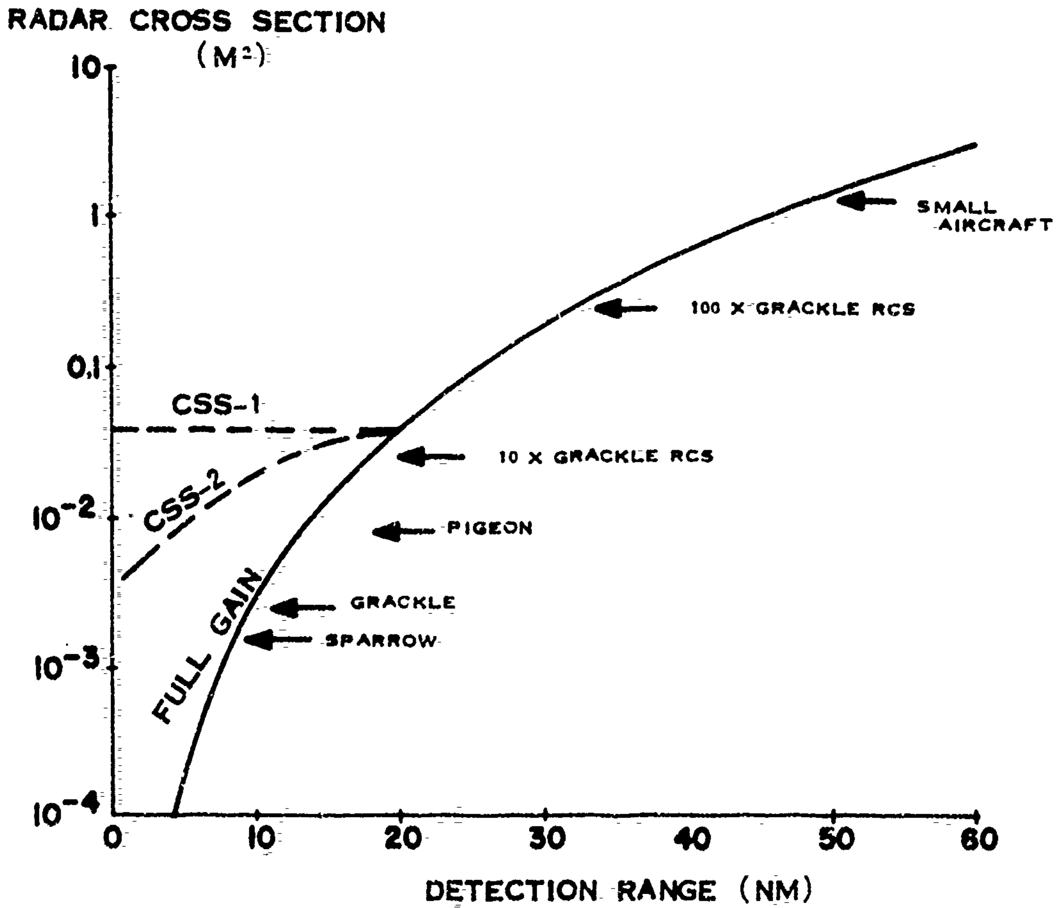


FIGURE 2-1 RADAR CROSS SECTION VS ASR DETECTION RANGE

2.1.2 Insects

Insects have been detected by radars at ranges of several miles (References 6, 7). Individual insect cross sections are extremely small, on the order of 10^{-5} square meters (Reference 8), but swarms have cross sections which are easily detected by ordinary radars. The limited data on airborne insect presence, densities, motions and numbers preclude their profitable consideration at this stage of clutter investigation. However, two likely types of insect clutter may be reduced by radar modifications aimed at better-known clutter varieties. Discrete clumps of insects may resemble bird flocks, inasmuch as the reflector is a collection of numerous similar-sized reflectors. Widespread dense swarms of insects may resemble weather clutter since both are extended arrays of small reflectors.

2.1.3 Atmospheric Anomalies

A third class of angels is produced by the atmosphere. Near large bodies of water, sea-breeze conditions and evening advection currents produce local regions in which the index of refraction is very inhomogeneous. A result is radar backscatter which may appear either as scattered discrete targets or as weather-like area clutter. The velocity of such angels may correspond to local winds or may be totally random. Other examples of atmospheric angels have been described by controllers as correlated with industrial gaseous discharges in Knoxville and Cleveland and with quarry dust in Chattanooga.

2.1.4 Identification of Angel Sources

Identification of the source of angels is highly desirable. When it can be done, then source characteristics determined by means other than radar may be useful in developing clutter reduction techniques. However, when birds are the suspected source, positive correlation with radar echoes is generally possible only in daytime with favorable visibility and target range. The two non-radar techniques for nocturnal bird observation are of limited value because of the special circumstances they require. These are the identification of low flying species from their audible calls and the estimation of bird densities from observed bird transits across the moon.

The frequent difficulty in positively identifying sources of angel clutter forces heavy reliance on circumstantial evidence. This includes time of day and of year, signal characteristics, angel positions, velocities, altitudes, headings, spatial distributions, correlation with local weather and weather changes, and finally, correlation with observed bird activity in the area. From a simultaneous evaluation of all these factors, a plausible identification of birds as the source of specific clutter may often be established. Among other types of angels, anomalous ground return due to ducting can usually be identified by its appearance and location. In cases of atmospheric and insect returns, evidence is usually limited and the source of clutter must often be left unidentified.

Although the identification of the source is desirable, it should be noted that inability to do so need not limit specific radar improvement efforts. Angels are evident to a radar through their RF and video characteristics. If these can be established, then radar improvement can proceed without knowledge of the specific biological or physical nature of the angel source.

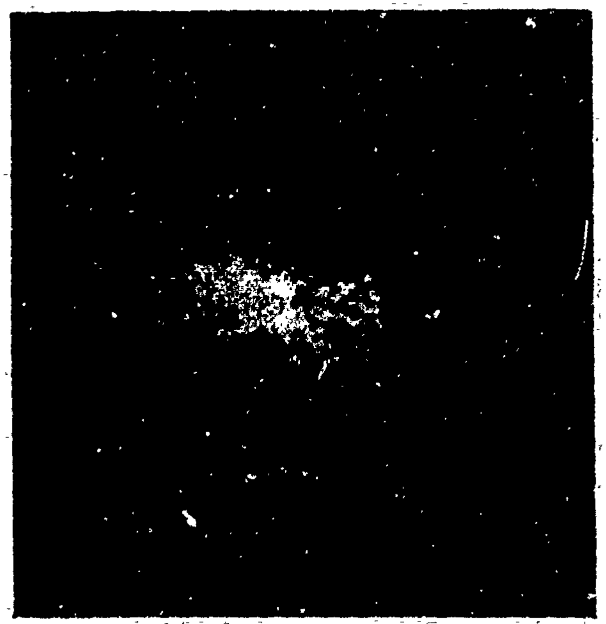
2.2 Effects of Angel Clutter on Air Traffic Control Operations

Angels interfere with radar-based air traffic control because they often look deceptively like aircraft returns and because they increase the effective clutter background in which controllers must detect and track controlled aircraft and monitor uncontrolled traffic. Valuable information on these effects was derived from intensive discussions with controllers, supervisors, maintenance technicians and administrative personnel at the terminals visited in the initial phases of this task, as well as from field observations made during test periods.

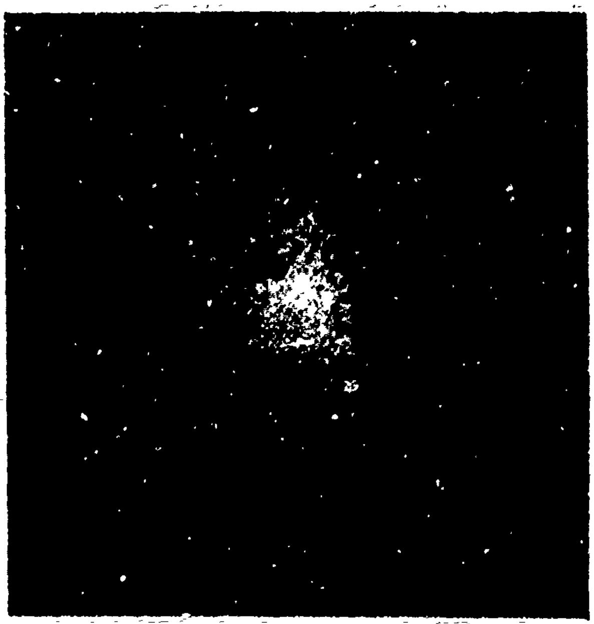
2.2.1 The Appearance of Angel Clutter on the ASR Display

The typical appearance of angel clutter from the Milwaukee ASR, as observed in April 1972, is shown in Figures 2-2 and 2-3. The photographs were made from playbacks of ASR normal and MTI video which had been simultaneously recorded on analog video tapes. Selection of STC or CSS modes was dictated by traffic control requirements rather than by the test conductor; CSS-2 (R^{-3} attenuation) was the usual choice when angels were present. In these photographs the initial mile of coverage is compressed because of the triggering scheme used in playback.

The figure-eight pattern shown in Figure 2-2A is expected when a large array of angels has a defined heading. Here, the mean angel velocity is westward, toward 290°. MTI cancellation is effective perpendicular to the direction of travel, where radial velocity is low, whereas the velocity along the 110° - 290° axis is high enough to prevent MTI rejection of the angels. Figure 2-2B shows similar angel clutter for which no well-defined heading exists. The MTI double canceller was in use in these and the following photographs.

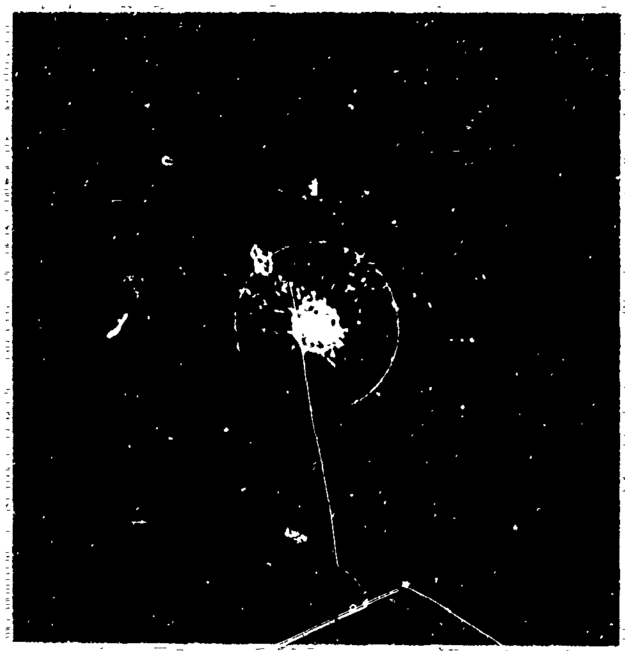


TIME: 2122 HRS, APRIL 15
VIDEO: MTI + CSS-2
RANGE RINGS: 2 MILES



TIME: 0620 HRS, APRIL 17
VIDEO: MTI (+ CSS-2?)
RANGE RINGS: 2 MILES

FIGURE 2-2
ANGEL CLUTTER ON MILWAUKEE ASR PPI



A——TIME: 0543 HRS., APRIL 17
VIDEO: MTI + CSS-2
RANGE RINGS: 2 MILES

B——TIME: 0549 HRS., APRIL 17
VIDEO: NORMAL + STC
RANGE RINGS: 2 MILES

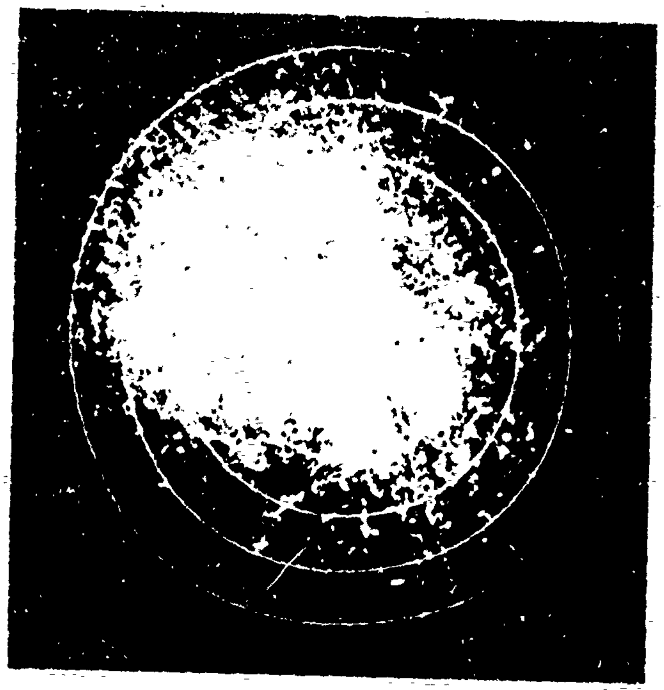
FIGURE 2—3

ANGEL CLUTTER RETURNS FOR
NORMAL & MTI VIDEO AT MILWAUKEE

MTI and Normal video are compared in Figure 2-3; the strength of combined angel and ground clutter is obvious in the normal video display. Comparison shows the very effective MTI cancellation of ground clutter and the notably lower effectiveness against angels due to their velocity. The relatively clutter-free area on the right half of the display is over Lake Michigan.

At Adams Field, Little Rock, in March 1972, similar echoes were observed. They could be correlated with high confidence with dense, extended flocks of blackbirds visible in the area. Under close scrutiny, many of the echoes could be tracked from scan to scan by eye for periods of a minute or more. Others appeared untrackable in that they would appear for one or two scans and then not reappear anywhere nearby. Controllers estimated the typical echo size as equal to that from a small single-engine general-aviation-type aircraft. Similar PPI clutter observed at NAFEC in October 1971, was also attributed to birds with high confidence (Figure 2-4).

The preceding photographs show angel characteristics associated with bird angels; velocities and altitudes measured by a tracking radar provided support to this identification for the angel clutter observed during the Milwaukee field tests. An apparently different type of AP is reported as occurring in the form of extended arrays of small echoes, "speckly clouds", more homogeneous in echo size and more uniform in spatial distribution than bird clutter. However, like bird clutter, this type also consists of well-defined discrete echoes, clearly distinguishable from typical continuous precipitation echoes. Figure 2-5 is an example from Little Rock showing a very well-defined figure-eight pattern. Reference 9 reports additional observations of this type. The source of such echoes is unknown; possibilities include insects, bats, and large, low-density swarms of birds at high altitude.

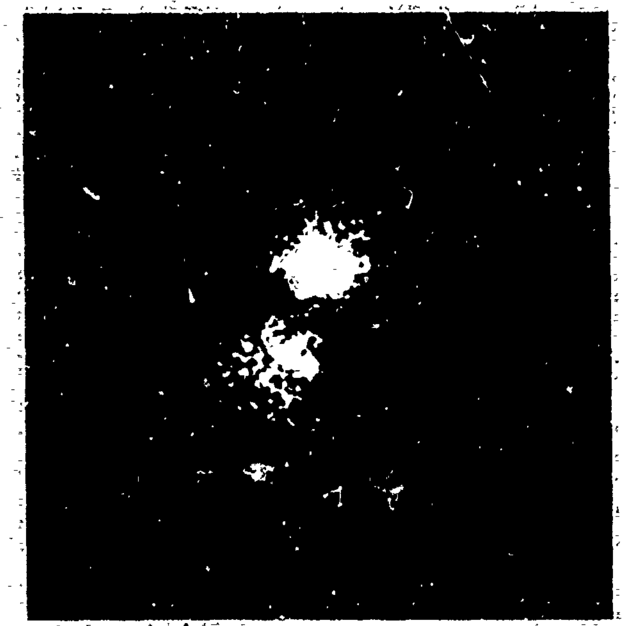


MTI VIDEO, NO STC, 10 SCANS

MTI VIDEO, STC, 15 SCANS

FIGURE 2-4

ANGEL CLUTTER DURING NAFEC TRACKING TESTS
OCTOBER 1971



A—2300 CST

FIGURE 2-5

ANGEL CLUTTER ON LITTLE ROCK ASR

(30 MILE RANGE, COURTESY OF
E. GRAHAM, FAA, LITTLE ROCK)

The distinction between the types of angel clutter considered in this report and true anomalous propagation is illustrated by Figure 2-6, which was also taken at Milwaukee. The nearly-radial lines at 020° and 040°, and the cusp-shaped return inside the 20 mile range ring between 040° and 115° are significantly different from the angels shown previously. They appear out to much longer ranges and therefore have much larger radar cross section than bird angels. These echoes are second-time-around returns from the distant shore of Lake Michigan, detected due to anomalous propagation over the lake. The positions and distorted shapes of the detected returns are explained by the range ambiguity resulting from the ASR PRF. With its usual staggered PRF, the ASR has a maximum unambiguous range of 61 miles in one pulse period and 74 miles in the next. When anomalous propagation occurs, returns may be received from targets normally undetectable due to their long range. Then, a target located between 61 and 74 miles appears on the PPI at its true range minus 61 miles in alternate PRF periods. In the intervening periods, it is detected at its true range, which is normally not displayed. A target beyond 74 miles appears at its true range minus 74 miles in one PRF period and at its true range minus 61 miles on the next. It is thus observable, distorted in the radial direction, at two false ranges. The range ambiguity which produces the second-time-around returns in Figure 2-7 is illustrated in Figure 2-7.

2.2.2 Controlling Aircraft in Angel Clutter

The problem of distinguishing aircraft and discrete angel radar returns, with their similar appearance on a PPI, is most acute for small, general aviation aircraft which lack beacon transponders. Radar returns from these aircraft are often weak, lacking the typical arc-like angular extent of large aircraft

A. TIME: 1346 HRS., APRIL 20
VIDEO: MTI + CSS-2
RANGE RINGS: 10 MILES

B. TIME: 1346 HRS., APRIL 20
VIDEO: NORMAL + STC
RANGE RINGS: 10 MILES

FIGURE 2-6

SECOND-TIME AROUND RETURNS OF LAKE MICHIGAN SHORELINE AT MILWAUKEE

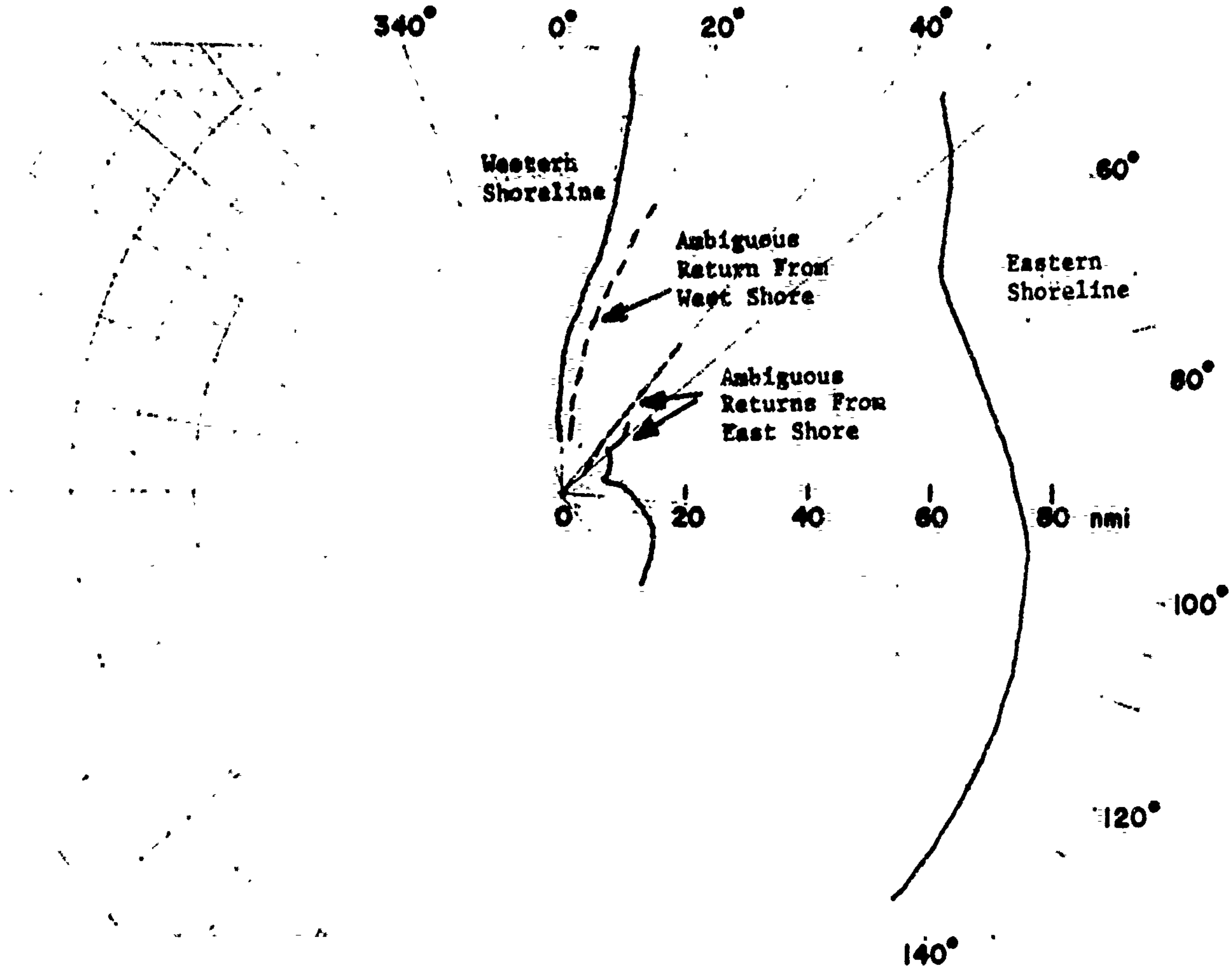


FIGURE 2-7 SECOND-TIME-AROUND RETURNS FROM LAKE MICHIGAN SHORELINE

returns. Also, primary radar returns are frequently unaccompanied by a beacon return; in late 1971 almost half of the general aviation aircraft were still without transponders (Ref. 10). Furthermore, small aircraft, far more commonly than large ones, operate under Visual Flight Rules (VFR) and appear in random locations on arbitrary flight paths, so position and track are of limited use as distinctive characteristics. The controller's problem then, is to decide whether a return is an aircraft or an angel when it resembles both. For low angel clutter densities, a controlled aircraft can often be visually tracked through angel clutter if the controller is able to concentrate on that particular aircraft. As the density of the angel clutter increases or the controller's assigned aircraft load increases, this becomes more difficult. The task of recognizing potential conflicts between controlled and uncontrolled aircraft in angel clutter can be a most formidable task for a busy air controller.

If receiver gain reduction is used to improve surveillance in angel clutter, it must be restricted to eliminating angels smaller than aircraft. If aircraft are eliminated along with the angels, area surveillance is directly degraded. When gain is properly reduced, the residual angels are just those which most strongly resemble small aircraft. The effect of this similar appearance is to reduce the controller's detection capability. With a high level of clutter, which here consists of angel returns which look like aircraft returns, either the rate of false alarms (calling angels aircraft) or the rate of misses (calling aircraft angels) will rise.

An operational view of this effect was presented by several controllers. Discrete angel clutter reportedly causes them, in some cases, to deliver false traffic advisories, warning pilots of possibly interfering traffic when no real threat exists. This typically occurs when the controller is unable to satisfy himself, to a high level of confidence, that a radar echo is in fact a harmless angel rather than an uncontrolled aircraft. The overall effect is an increase in unnecessary communications, a reduction of confidence in the surveillance system, and an increase in work-load for pilot and controller.

An equally important effect is the overloading of a controller's surveillance capability by large numbers of angels. For a controller to search for and detect aircraft in clutter in some area of a PPI, it seems necessary that he somehow examine all returns in that area and, for each, make a decision: aircraft or not aircraft. The examination and decision are clearly very fast but they are not instantaneous. If many returns appear in the area of interest, the total required examination and decision time becomes significant. Even if the controller can distinguish aircraft from angels, there is insufficient time available to do so in continuous surveillance over an assigned area. Then, aircraft become "lost in the clutter" and surveillance is degraded.

The impact of angel clutter is significantly increased by the limitation of the ASR radar to two-dimensional surveillance. Although, in general, angels may appear at altitudes up to 20K ft, they are likely to be limited in vertical extent at any particular time and place. For example, altitude distributions of migrating birds (Ref. 4) show that the majority are observed within a layer one to two thousand feet thick. The dense swarms of black-birds observed at Little Rock were concentrated well below one thousand feet. Refractive irregularities in the atmosphere often occur in thin layers (Ref. 11). In each of these cases, angel sources confined to a layer hundreds of feet high interfere with surveillance over the entire altitude range of interest, approximately twenty thousand feet. Only with elevation resolution can the effects of angels be limited to that surveillance volume which they occupy.

In summary, the impact of angel clutter on present air traffic control ranges from moderate distraction in controlling large aircraft to serious interference in operations involving small general aviation aircraft. Reducing IF gain to decrease angel amplitudes on the PPI also degrades ASR detection performance for small aircraft. Moderate levels of angel clutter may therefore significantly increase the likelihood of mid-air collision involving as one party a small non-controlled aircraft lacking a beacon transponder.

2.2.3 Effect on the Enhanced Automated Radar Terminal System (ARTS)

The prospect of automated processing of ATC radar surveillance data (as in the Enhanced ARTS system) suggests the possibility of rejecting angel clutter by velocity selection, that is, by using scan-to-scan motion to discriminate against slow moving targets. The technique would consist of tracking angels to establish velocity, as is done for aircraft, and then excluding from display all tracked targets with velocities less than some selected value (e.g. 60 knots). Most discrete angels, as well as surface vehicles and fixed clutter, would thereby be eliminated. It is often implicitly assumed that, given adequate computer capability, such tracking can be accomplished. The assumption becomes more tenuous as the density of discrete targets increases.

Tracking degradation occurs when aircraft position uncertainty due to measurement, tracking, and maneuver errors becomes comparable to the typical separation between targets of all types in the vicinity of the aircraft track. Clutter is then likely to appear in the tracking window. When it does, the action alternatives are to update the aircraft track with a relatively low probability of a correct update or to coast the track. As long as the aircraft return remains among dense angel returns, the likelihood of the multiple target situation resolving and only the aircraft appearing in the tracking window decreases with each scan. An array of angels extending for three miles, which is not uncommon, would force a coast of fifteen scans for a 180 knot aircraft; this is approximately twice the length of coast found practical at present (Reference 12). Thus, coasting is of limited value when angels extend over any significant area. On the other hand, an incorrect update (updating a track with a measurement on another target) is worse than no update at all since it is deceptive. The effect can be estimated as follows:

ASR one-sigma (σ) measurement errors are approximately 80 yards and 0.3° (Reference 1); these are assumed unbiased and Gaussian. An alpha-beta (α-β) tracker is assumed, with α=0.7 and β=$\alpha^2/(2-\alpha)$=0.38. The α-β relation is the optimum for present-value estimation (Reference 13), and the value of α is representative of those now used for continuing tracks of terminal area aircraft (Reference 12). The tracking window is taken to extend $\pm$ 2σ in each coordinate, centered on the predicted target position; σ is the coordinate measurement standard deviation. Then, in angel clutter of density five angels per square mile at a range of five miles, a moderate level observed in this task (Chapter 3), the probability of correctly updating a track is .36 on any one scan. The corresponding mean track duration, without coasting, is 6 scans. The probable end of the track is not an empty tracking window but an update of the track with an angel clutter measurement. Such an error may not be detectable for several scans.

The levels of discrete clutter density which can be tolerated in an operational tracking system are determined by the resolution of the radar and by the structure of the tracking algorithm, including prediction-detection correlation criteria, window size selection, coast and drop-track logic, and multiple target resolution procedures. A detailed analysis is outside the scope of the present task. However, the implications of the above for the developing ARTS radar tracking system seem clear. Discrete clutter density should be reduced by radar signal processing to a manageable level before the data reaches the tracking system. The observation that many angels are discrete, with well-defined velocities, does not imply that masses of these can be eliminated by velocity selection. Slow-moving targets, including surface clutter as well as angels, may be eliminated by the tracker, but only if their spatial density is low enough relative to the radar resolution cell and measurement accuracies to permit reliable tracking.

The above discussion is not intended to suggest that angel clutter renders automatic radar detection and tracking infeasible. In fact, the velocity discrimination provided by automated processing may be the only way to deal with angel returns that pass through single-scan aircraft/angel discrimination processors. However, it is essential that the angel clutter density be reduced as much as possible by single-scan processing and that the unique problems associated with angels be considered in the development of the automated tracking algorithms.

2.2.4 Angel Clutter and Bird Strikes

A serious flight hazard exists in some terminal areas from bird strikes, that is, mid-air collisions of birds with aircraft. The costs of bird strikes are high in terms of both risk to life and money (Ref. 14), and consequently, significant attention is being paid to reducing their frequency and their effects (Refs. 15-18). The two problems of radar bird angels and bird strikes are closely related in some important respects. First, they have a common source, predominantly those birds below several thousand feet and within five to ten miles of the terminal, although large birds have been identified at altitudes of tens of thousands of feet on major air traffic routes. Second, at any particular site, similar methods help define the local specifics of both problems, and these specifics point the way to locally-applicable solutions. Third, solutions which reduce the local bird density may reduce the incidence of both bird clutter and bird strikes. The existence of these common aspects suggests the possibility of mutual advantage and increased cost-effectiveness through some joint effort.

A technique for a terminal area ecological survey to define the extent and cause of local bird concentrations has been described in Ref. 19. Development of the method was motivated by Air Force bird strikes. Such a survey is complementary to an investigation of the bird clutter problem like the brief ones carried out at several sites in the initial phases of this project. Together, the two approaches can provide a comprehensive picture of the situation at a specific terminal; with such a picture, potentially effective environmental solutions can be determined.

After implementation of solutions, radar offers a convenient way to monitor their effectiveness over all of the area of interest except the square mile or so centered on the radar.

If a coordinated approach is taken to the two problems, multiple benefits can result with no increase in overall cost to the FAA. Without cooperative effort, it is possible that solutions to the bird strike problem may aggravate the radar clutter situation and, conversely, that radar improvements may increase the bird strike risk. As an example, displacing bird roosts from the airport to an area five miles away may clear normal flight paths of birds and thus eliminate a bird strike hazard. Yet, the radar clutter problem may be aggravated if the displaced birds, previously inside the minimum useful radar range, become detectable over, under or near a critical surveillance area.

An important precaution must be observed in using any radar angel clutter reduction technique. If this processing prevents most bird angels from being displayed, the controller cannot detect heavy bird concentrations and hence cannot warn pilots or divert them around the threat. This difficulty may arise for any angel clutter solution internal to the radar; it is essentially the same problem that arises when weather clutter is eliminated. Resolution requires a source of information on bird concentrations other than the traffic control PPI or a capability of disabling the angel clutter feature intermittently. Other possibilities include use of another sensor, such as a nearby weather radar, or an additional ASR processing subsystem for generating a real-time angel clutter map.

CHAPTER 3

RADAR RETURN CHARACTERISTICS OF ANGELS AND AIRCRAFT

Successful discrimination of aircraft from angels with the ASR radar requires exploitation of differences in the detailed radar return characteristics of these two classes of targets. While much general information regarding angel and aircraft characteristics can be found in the literature, it is not sufficiently specific to enable inference of the detailed characteristics of ASR returns which are necessary to develop techniques for discriminating between these two classes of targets with the ASR. Consequently, it was necessary to assemble test instrumentation (Appendix A) to collect the necessary ASR data.

Of the several different types of angel clutter, bird angels are particularly troublesome. This is partially due to the larger cross section of birds compared to other natural angels, and also due to high bird densities observed at airports near the spring and fall migration flyways. Bird angels also have a very desirable characteristic relative to field test operations: migration periods are fairly predictable and are therefore compatible with the necessary scheduling for economical data collection. For these reasons, bird angels were selected as the primary object for the field tests associated with this study.

CHAPTER 3

RADAR RETURN CHARACTERISTICS OF ANGELS AND AIRCRAFT

3.1 Field Test Operations

In all, four field operations were conducted to supply data for this study. The first was conducted during the spring 1971 bird migration period at the National Aviation Facilities Experimental Center (NAFEC), Atlantic City, New Jersey. Analog video tapes of ASR video were gathered to permit pre-contractual study of angel characteristics so that a proper instrumentation system could be devised for future tests.

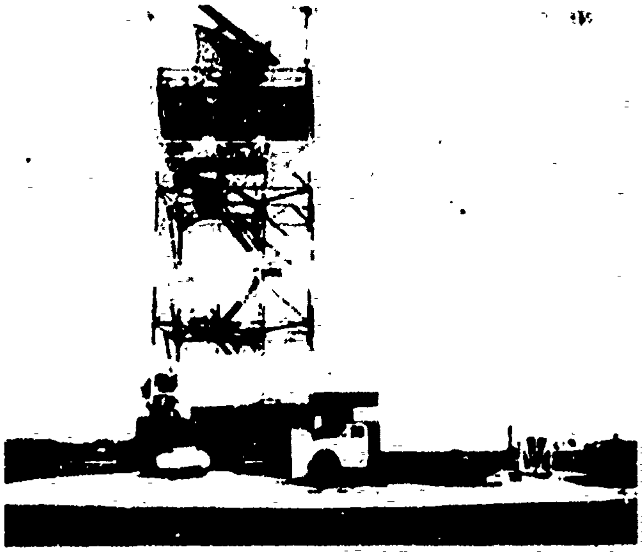
The second field test operation was conducted in October 1971, again at NAFEC, shortly after the contract for this effort was awarded. An MPS-19 tracking radar was used to track individual angels in order to gain experience in recognizing and tracking birds and again analog tape recordings were made. Appendix A-2 discusses the results of these tests.

The major field tests were conducted at Milwaukee's General Mitchell Airport in April and May 1972. These tests employed the full test instrumentation system, which consisted of three vans of portable equipment: the Tracking Radar Module, the Data Acquisition Module, and a motor-generator van. They are shown operating with the Milwaukee ASR-6 in Figure 3-1.

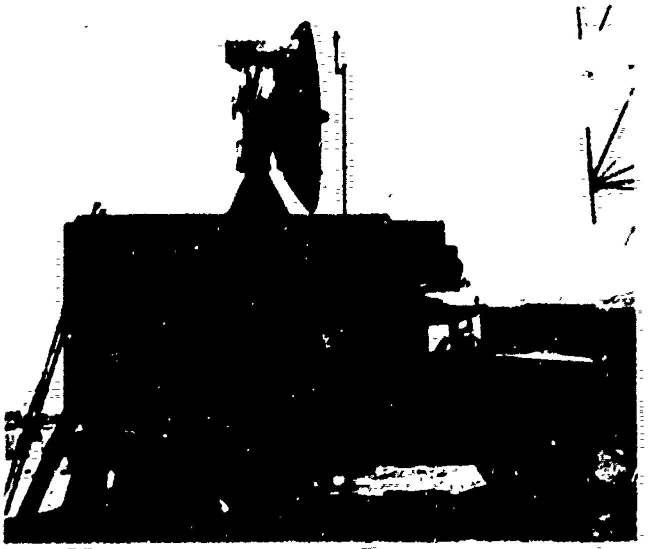
The final field test was performed at Baltimore's Friendship Airport to gather additional data on ASR return characteristics for aircraft.

3.1.1 Site Selection

Milwaukee was selected after an extensive survey of possible sites. A site was required where angel clutter was a recognized operational problem, where significant angel clutter could be expected during the intended data collection period in April, and where a suitable location was available for the instrumentation vans. After a review of available reports of



ASR-6 & DATA ACQUISITION MODULE



TRACK RADAR MODULE
AN/MPS-19

FIGURE 3-1
MILWAUKEE TEST INSTRUMENTATION

ASR field problems, visits were made to FAA facilities at Adams Field (Little Rock, Arkansas) in the Southwest Region, to Minneapolis-St. Paul Airport, and to Mitchell Field (Milwaukee, Wisconsin) in the Great Lakes Region. An informal visit was also made to Memphis International Airport; angel clutter was reported as not a serious problem there with no significant bird activity. At the first three airports, discussions were held with the Airways Facilities Sector Chiefs, Tower Chiefs, Radar Unit Chiefs, controllers and maintenance personnel. The discussions centered on the existence of a local angel clutter problem, on the typical extent, frequency and duration of such clutter, on the expected occurrence of angel clutter during April, and on the feasibility of locating and powering the data acquisition instrumentation. In each city, contact was made with several authorities on the local avifauna to obtain estimates of the probable characteristics and level of local bird activity during the planned data collection period. In addition, discussions were held with a number of nationally-recognized authorities on ornithology to aid in selection of appropriate sites and test periods.

Following a review of all information collected, Milwaukee was chosen as the preferred site due to the reported frequency, variety, and operational impact of angel clutter there, and because of the expected availability of significant quantities of migratory birds during April and early May.

3.1.2 Data Collection

The data collection system assembled for this task consisted of three major components: an AN/MPS-19 Tracking Radar Module, a Data Acquisition Module containing data display, processing and recording equipment, and a power generator van. The MPS-19 radar is a mobile, automatic-tracking, conical-scan S-band radar, selected because its principal characteristics, except for beamwidth, closely resemble those of the ASR (Table I). The overall instrumentation system (described in detail in Appendix A) was installed and operating at Mitchell Field by early April 1972, with data collection continuing into May during periods of local ASR angel activity.

TABLE I

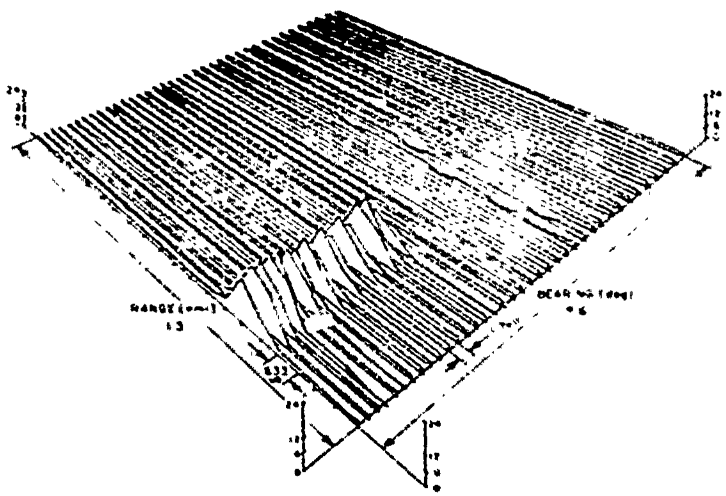
COMPARISON OF RADAR PARAMETERS

Parameter	Units	ASR	Track Radar Module
Radar Type	-	Search @ 15 RPM	Conical-scan track
Time-On-Target	seconds	0.017	Continuous
Frequency	GHZ	2.7-2.9	2.7-2.9
Peak Power	KW	400	137-250
Pulsewidth	µsec	0.833	0.8
PRR	Hz	1200	300-2000*
Beamwidth	degrees	1.5 x 30, csc^2	3^{o} x 3^{o}
Antenna Gain	dB	34	34
Polarization	-	vertical, circular	vertical
IF Bandwidth	MHz	2	2
Video types	-	MTI, Linear Normal	Linear Normal

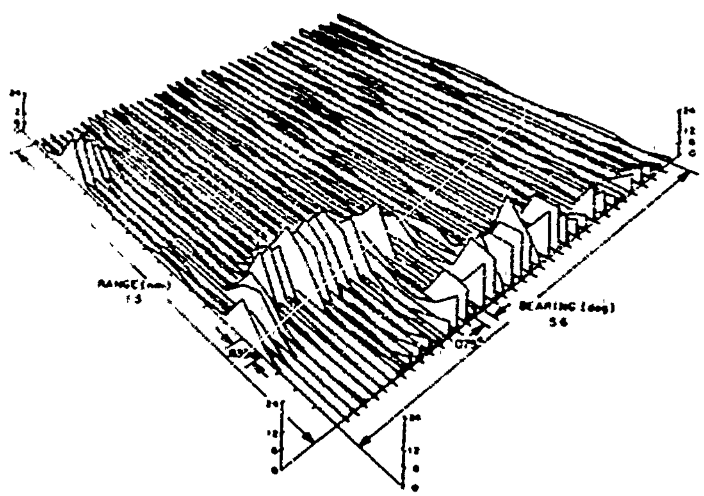
*PRF was synchronized to 1/2 the ASR PRF for these tests.

RETURN CHARACTERISTICS

The data collected at Milwaukee consisted of analog ASR video tape recordings and digital data derived from the ASR and MPS-19 radars. The MPS-19 provided continuous angel and aircraft video returns (at half the ASR pulse repetition frequency). Video amplitude and Automatic Gain Control (AGC) voltages were recorded in digital form in the Data Acquisition Module. ASR video data was collected with an automatic detection and tracking system in the Data Acquisition Module; the MPS-19 track position was used to center a range-bearing window (the data collect matrix) in which digitally-quantized ASR video was collected on aircraft and angel targets of interest (Figure 3-2). All of this data was returned to the Applied Physics Laboratory for processing and evaluation. The following sections describe the characteristics of the angel and aircraft targets investigated in these tests.



CESSNA 172 AIRCRAFT



ANGEL CLUTTER

FIGURE 3-2 ASR DATA COLLECTION MATRIX

3.2 Radar Cross Section

Since bird angels are much smaller in physical size than aircraft, the radar return from an angel that contains a small number of birds should be smaller than the return from an aircraft. For a given radar, the strength of radar returns for different targets is proportional to the equivalent radar cross section (RCS) of the targets. RCS can be defined as the area of a perfectly-conducting isotropic reflector which produces a radar return of the same power as the target. RCS is usually expressed in square meters (m^2). Since most radar targets produce a radar return which fluctuates with time, a single RCS value is appropriate only as a long-term measure of RCS and statistical measures are required to develop a reasonable model for short-term RCS fluctuations.

RCS data from the literature and from the Milwaukee tests is discussed below.

3.2.1 Published Radar Cross Section Data

Mean RCS Data

It has long been recognized that the radar cross section of birds and insects is generally smaller than the cross section for most aircraft. Radar cross section data from the literature for single birds of several species and for several classes of aircraft are given in Table II (Reference 25). The mean cross section for a pigeon is about 0.008 m^2 and about 0.0016 m^2 for a sparrow. It is also shown that the cross section varies with frequency and is a maximum for S-band, which is a resonance region for typical bird sizes. For small aircraft the radar cross section varies from less than one to tens of square meters, depending upon the orientation of the aircraft relative to the radar.

TABLE II

MEDIAN RADAR CROSS SECTION OF AIRCRAFT, SINGLE BIRDS, AND INSECTS (decibels relative to 1 m^2)

Type	Aspect	UHF	Frequency Band L	S	C	X
Large Jet (707-DC8)	Nose		15	16	10/16	14
	Tail		12/18	24		14/27
	Broadside		27	27		25
	Average	10	14/16	14/16		18
Medium Jet (727-DC9)	Nose	0/14	8/13			6
	Tail	8	13	13		
	Broadside	23	25	24		29
	Average		11	11		10
Small Jet (Learjet-F4)	Nose	8	-5/9	-7/10	-2/3	0
	Tail	5	3	-2/12		
	Broadside		7/20	15/25		13/18
	Average		-2/2	0/3		0/7
Sparrow	Head					-46
	Broadside					-32
	Tail					-47
	Average	-56		-28		-38
Pigeon	Head					-40
	Broadside					-20
	Tail					-40
	Average	-30		-21		-28
Duck	Head	-12				
Grackle	Average	-43		-26		
Hawkmoth, 5.0 cm	-	-54		-30		
Worker Bee, 1.5cm	-	-52		-37		
Dragonfly	-	-52		-44		

Figure 3-3 was derived from an empirical model developed by Pollin (Reference 24) to estimate bird RCS as a function of radar wavelength and bird weight. The model was based on the results of data taken by several experimenters at several radar wavelengths (including the data in Table II); values predicted by this model are lower than the bird RCS values in Table II by a factor of four (6 dB).

While the average RCS of single birds is quite small compared with aircraft, groups of birds that fall within a single ASR resolution cell (410 feet in range by 1600 feet in bearing at 10 nmi) all contribute to the net RCS returned from that cell. In the absence of a typical flock size, which varies with species, estimates of the average cross section of bird flocks are much more difficult. A rough estimate can be obtained by assuming that no more than 10 birds are contained within the ASR resolution volume at close ranges. Since the individual radar returns from each bird add incoherently, the effective cross section is equal to the cross section per bird times the number of birds. In this case, the flock cross section would be ten times the bird cross section or about 0.01 to 0.1 m^2. It will be shown that while the actual cross sections vary considerably, this rough estimate is close to the average value measured during the Milwaukee tests.

At 10 nmi, the ASR resolution cell is about .02 nmi^2. Based upon data published in Reference 20, ten birds in this area would correspond to the 93rd percentile of bird density distribution over all of North America during the October (1952) bird migration period.

3.2.2 RCS Data From Track Radar AGC

RCS of angels (groups of birds within the ASR resolution cell) was measured with the Tracking Radar Module during the Milwaukee tests. This was done by locating a particular angel on the ASR PPI

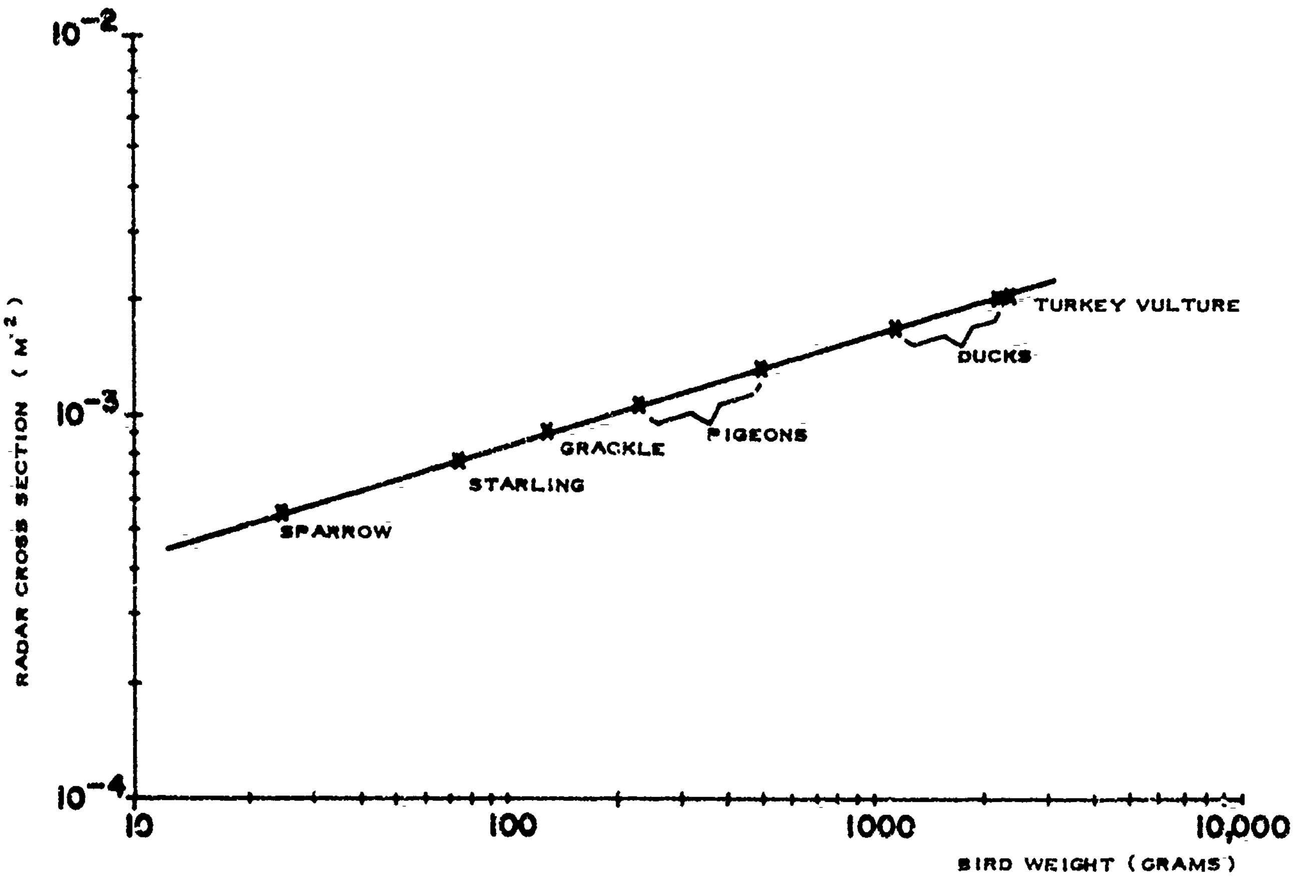


FIGURE 3-3 MODEL FOR BIRD RCS AT S-BAND BASED ON WEIGHT

and designating it to the track radar, which then acquired and tracked the angel. Since the track radar Automatic Gain Control (AGC) voltage had been calibrated in terms of RCS, strip chart recordings of the AGC and range annotations permitted the calculation of angel RCS.

Average RCS Data

Figure 3-4 shows the long-term average RCS values from the Track Radar AGC for several angel tracks and a Cessna 172 test aircraft, which is typical of small general aviation aircraft. The aircraft was flown on trajectories providing various target aspects to the radar (Appendix A), so the resulting RCS values are somewhat larger than the minimum expected nose-on cross section, which may be as low as 0.2-0.5 m^2 for short periods of time.

While the smallest angel RCS (0.005 m^2) is consistent with the RCS expected for a single small bird, angel RCS values extended upward over three orders of magnitude. The average tracked angel RCS is 0.28 m^2, which is comparable to the minimum nose-on RCS for a small general aviation aircraft. Note that the Cessna 172 RCS values in Figure 3-4 range from about 2 to 25 m^2.

These results show that birds and flocks of birds present an RCS which is often less than the RCS of small aircraft. Discrimination based on radar cross section, to the extent that RCS can be inferred from received signal amplitude, can therefore be an effective technique for substantially reducing angel clutter returns. However, the RCS discrimination threshold must be set low enough to preserve reasonable blip-scan ratios on small aircraft. Consequently, RCS discrimination can be used to reduce the number of reports due to angels with small RCS values, but other techniques are required to reduce those angel clutter returns which have RCS values approaching or exceeding those for small aircraft.

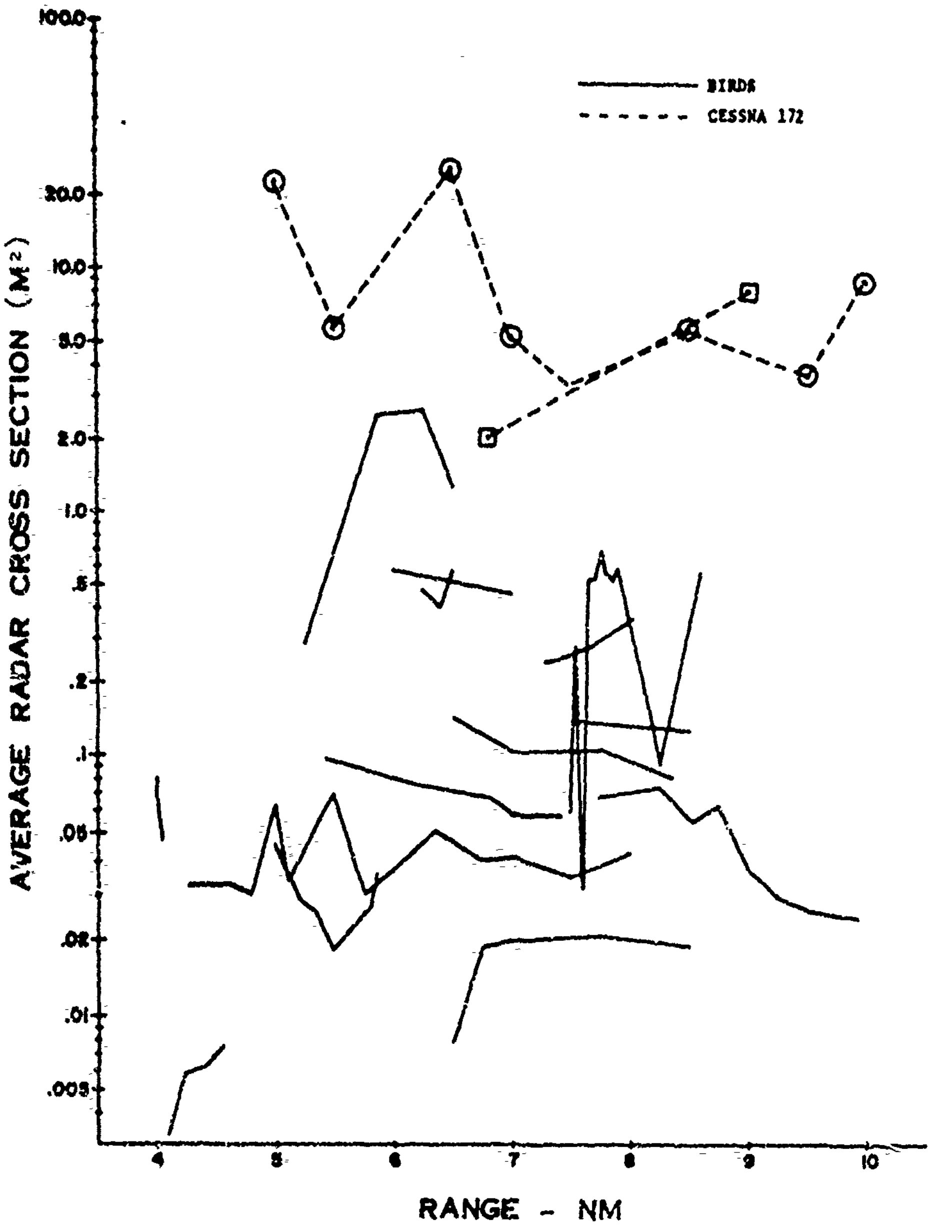


FIGURE 3-4 MEASURED RADAR CROSS SECTIONS

RCS Distributions

The data concerning the RCS of angels presented previously was based upon a long-term average reading of the track radar AGC. In addition, samples of the recorded AGC voltage were taken at one second intervals with the target at essentially constant range, and the cumulative probability distribution function of these samples was computed.

The resulting radar cross section distributions for seven angel tracks and the Cessna 172 aircraft are plotted in Figure 3-5. A straight line on the figure would correspond to a log-normal probability distribution. Such a distribution can be characterized by its mean-to-median ratio (ρ); Table III summarizes the maximum, minimum, and median values of measured RCS along with the value of ρ for each track.

TABLE III

RCS STATISTICS DERIVED FROM TRACK RADAR AGC DATA, ONE SECOND SAMPLES

			Radar Cross Section				
Target	Run	Range	Maximum	Mean	Median	ρ	# Samples
Cessna 172	-	21 nmi	49 m^2	10.9m^2	4.5m^2	2.4	51
Angels	10-3	7.0 nmi	0.9m^2	.52m^2	.5m^2	1	50
	12-1	7.7	1.4	.7	.7	1	40
	12-1	7.9	1.2	.56	.5	1	50
	12-2	5.0	.04	.025	.025	1	50
	12-2	5.5	.05	.023	.02	1.2	50
	17-1	4.4	.05	.031	.03	1	50
	17-1	5.5	.09	.048	.04	1.2	50

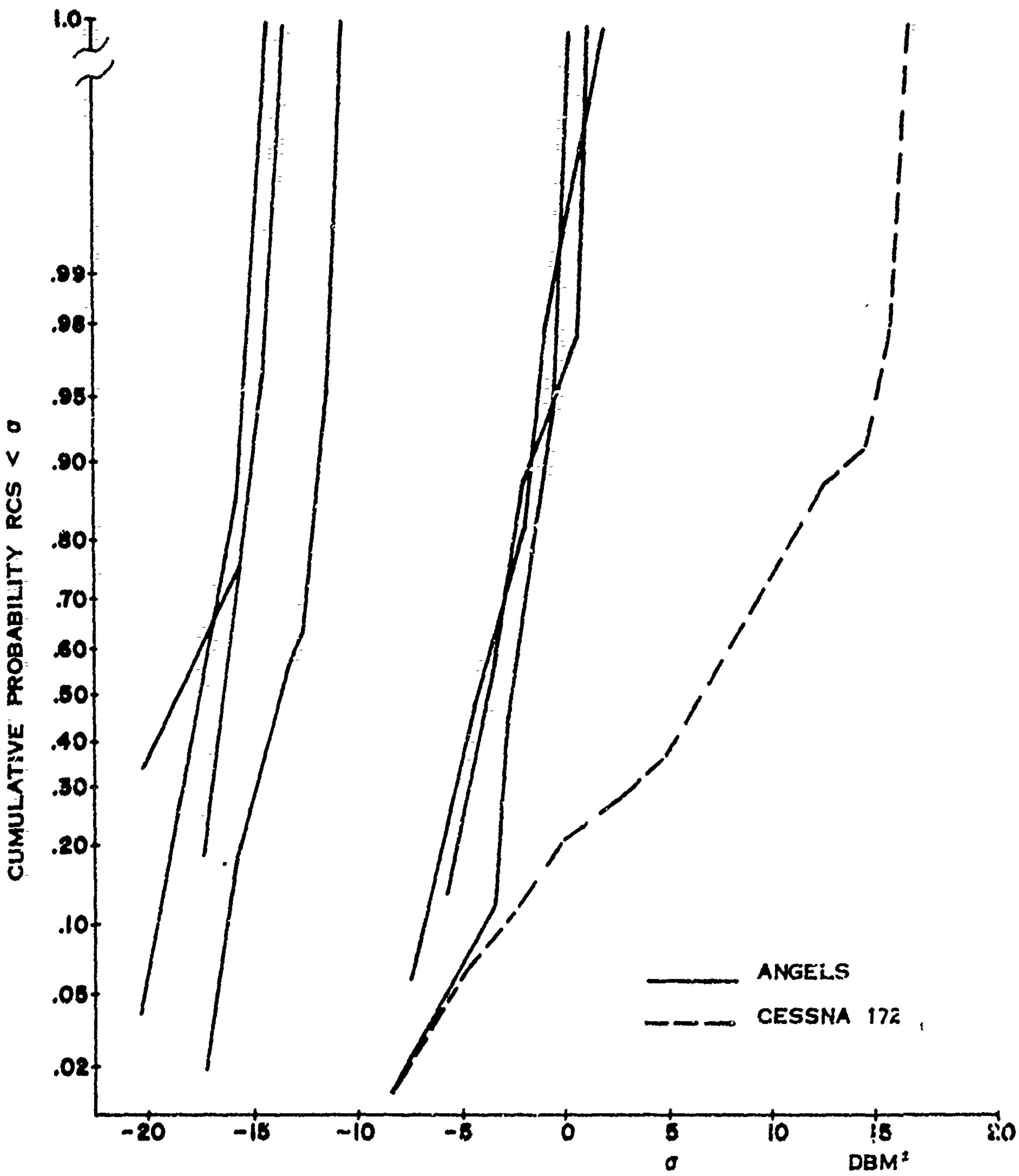


FIGURE 3-5 DISTRIBUTION FUNCTIONS FOR ANGELS AND AIRCRAFT

In general, the aircraft RCS is much larger than the angel clutter. However, both targets fluctuate and the aircraft occasionally appears smaller than the birds. This indicates that RCS or received amplitude is a good, but not absolute,discriminant between angels and small aircraft.

Figure 3-6 shows the effect on aircraft detection and angel rejection of an RCS threshold for the data shown in the previous figure. The format of Figure 3-6 is one which will be used throughou this chapter to judge the effectiveness of angel clutter reduction techniques.

We define:

P(D/AC) = probability of detecting a target, given to be an aircraft

P(R/AC) = probability of rejecting a target, given to be an aircraft, by incorrectly identifying it as an angel

P(D/AN) = probability of detecting a target, given to be an angel, by incorrectly identifying it as an aircraft

P(R/AN) = probability of rejecting a target, given to be an angel.

We have:

$$P(D/AC) + P(R/AC) = 1$$

$$P(D/AN) + P(R/AN) = 1$$

Perfect system performance, that is, no errors in identifying aircraft or angels, is given by:

$$P(D/AC) = 1$$

$$P(R/AN) = 1$$

which is the upper right-hand corner of the plot. A system which provides no improvement in aircraft/angel identification has

$$P(D/AC) \leq P(R/AN)$$

which is represented by the shaded region as in Figure 3-6. Systems which have P(D/AC) < P(R/AN) lie below this dotted line and such systems worsen, rather than improve, performance.

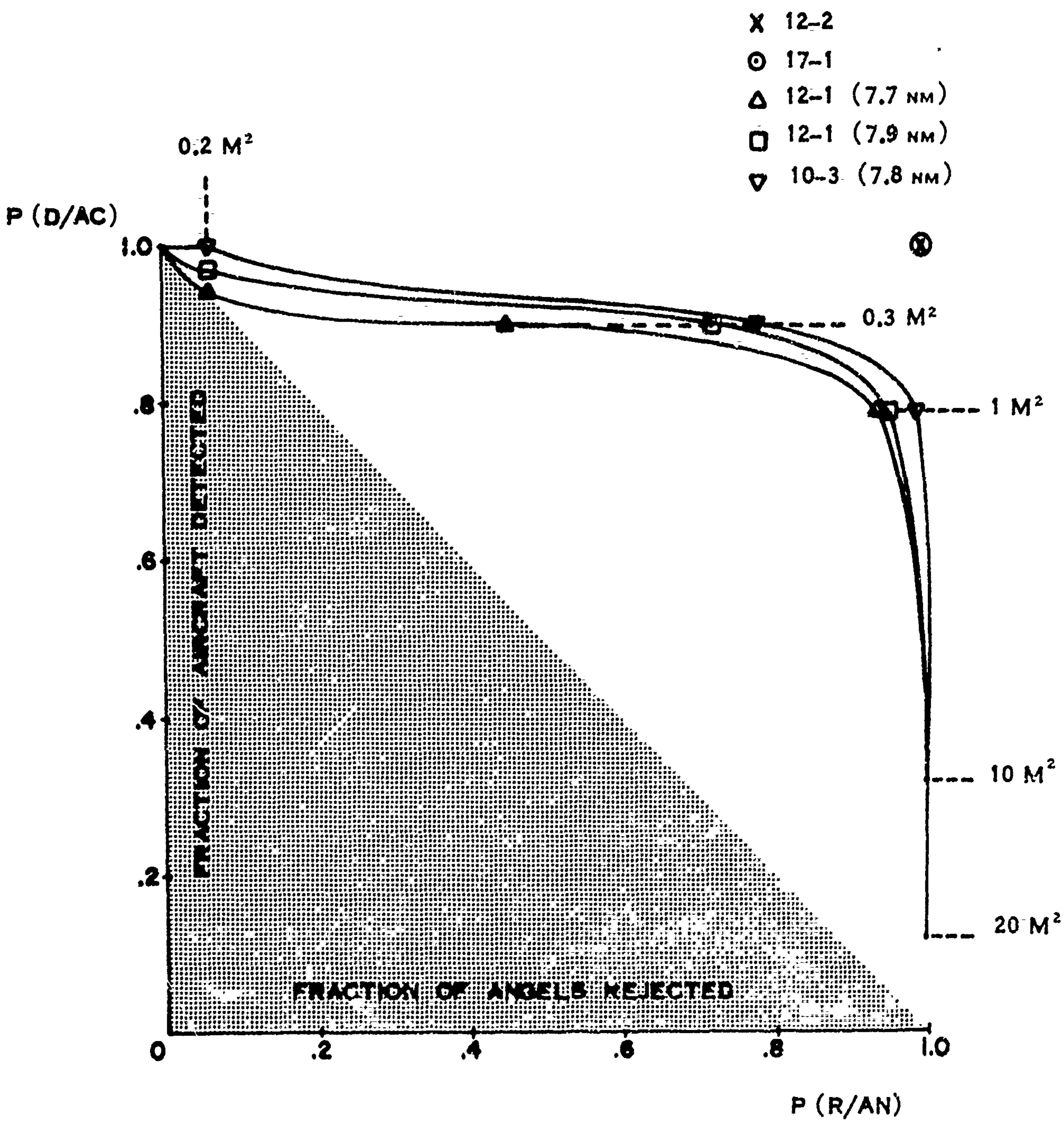


FIGURE 3-6 PERFORMANCE CURVE FOR RCS DISCRIMINATION

For a particular discrimination technique, P(D/AC) is the fraction of scans on which aircraft are correctly identified (detected) and a particular P(R/AN) is the fraction of scans on which the particular angel targets are correctly identified (rejected). In general, all practical systems will have some error in identifying angels and aircraft so that the error probabilities P(R/AC) and P(D/AN) are non-zero. In most cases, the discrimination technique has variable parameters which trace out a performance curve in the P(D/AC), P(R/AN) plane as these parameters are varied.

In Figure 3-6, a 1 m^2 RCS threshold would have correctly identified the Cessna 172 about 79% of the time and would have correctly rejected the most difficult angel target 94% of the time. This performance is somewhat misleading because:

a) the Cessna misses would occur more frequently when its trajectory presented low RCS values, such as the 0.2 m^2 nose-on value previously quoted.

b) the angel tracks analyzed may not be representative of a more general angel population (different sites, times, etc.)

c) RCS is not directly measurable via the ASR but rather must be inferred from signal amplitude, range, and antenna elevation pattern.

Nevertheless, these data suggest that a proper Sensitivity Time Control (STC) profile and a fixed threshold based upon expected radar video return amplitude can provide an appropriate means of eliminating many of the smaller angel returns.

3.2.3 ASR Video Matrix Amplitude Distribution Functions

ASR video amplitudes from the Data Collect Matrix (previously shown in Figure 3-2) were analyzed. The resulting probability distribution functions are different than the usual target distribution functions quoted in the literature because the effects of antenna scanning modulation are included and the entire data collect matrix (1.3 nmi x 5.6^{o}) is analyzed, rather than only the target return.

Figure 3-7 shows typical results for three angel tracks and two aircraft tracks. Over 90% of the returns in the Data Collect Matrix are receiver noise and MTI residues with amplitudes of 1 and 2. Therefore, the data in the figure was truncated by a lower threshold of 3 out of the 31 amplitude levels which corresponded to the full ASR video dynamic range. (Amplitudes for the Cessna 172 exceed 31 because range normalization was used to eliminate amplitude dependence on Cessna 172 range over the run). The figure is scaled so that a Weibull distribution will produce a straight line; data in the Appendix considers Log Normal distributions as well. The slopes of the plots permit estimation of the parameters of the respective distributions for angels and aircraft.

The need for truncation to eliminate receiver noise and MTI residue leads to loss of low-amplitude target data, which complicates assignment of specific distributions to the data. However, some information on the differences in angel and aircraft video amplitude matrix data can be inferred. For the Weibull plots, the Weibull parameter β lies between 0.9 and 1.4 for the aircraft and between 1.1 and 1.7 for the angels. Since $\beta = 1$ corresponds to the exponential and $\beta = 2$ corresponds to the Rayleigh distribution, these curves indicate that the aircraft video matrix data is somewhat closer to exponential than the angels, which lie between the exponential and the Rayleigh. The tails of the exponential distribution (the high-amplitude region) are larger than the Rayleigh distribution, hence one would infer that the aircraft is more likely to produce a wider spread of amplitudes than the angels.

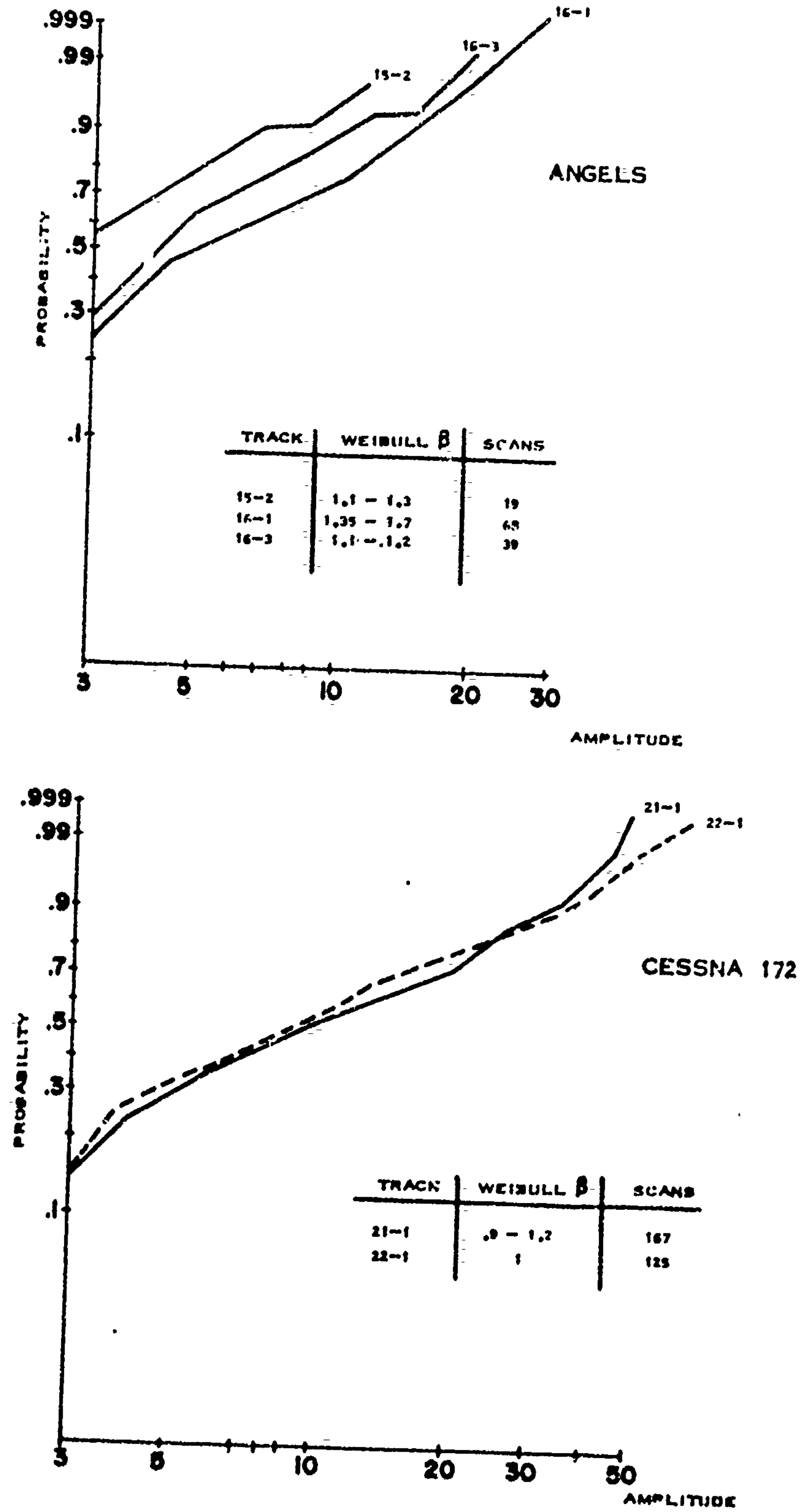


FIGURE 3-7 ASR MTI VIDEO AMPLITUDE DISTRIBUTIONS

The Log Normal distribution parameter is the mean-to-median ratio ρ. For the Cessna, ρ was about 2.5 times larger than ρ for the angels, again showing the influence of fluctuation to higher relative values for the aircraft.

These results suggest that the angel targets tended to behave more like a many-scatterer target than the aircraft, that is, each angel consisted of more independent radar reflectors than the aircraft. This is consistent with the very reasonable supposition that each angel consisted of a number of birds. As the number of birds in an angel target increases, one would expect a distribution which is more Rayleigh. Thus, angels having large RCS values (i.e. consisting of many birds) would also have a more limited spread of RCS variations.

While the straight-line fits to the Weibull distributions are not as good as one would like, it is interesting to quantify the implications of the exponential-target model and an angel model lying between Rayleigh (many birds per angel) and exponential (few birds per angel). We would like to know by how much the target RCS must exceed the angel RCS for a given level of discrimination performance, measured in terms of the probability of correctly identifying the aircraft, P(D/AC), and the probability of correctly identifying the angel, P(R/AN). For the many-bird per angel model (Rayleigh), 95% of the angels are rejected if an amplitude threshold is set 5.8 dB above the mean angel RCS. For the few-bird (exponential) model, the threshold must be 3.7 dB higher (9.5 dB above the mean). From these thresholds, we can compute the ratio of target RCS to mean angel RCS required to give any value of correct target identification probability, P(D/AC), and the results are shown in Figure 3-8. Clearly, very high target-to-angel RCS ratios are required for high system performance (25-30 dB for P(D/AC) = 0.9).

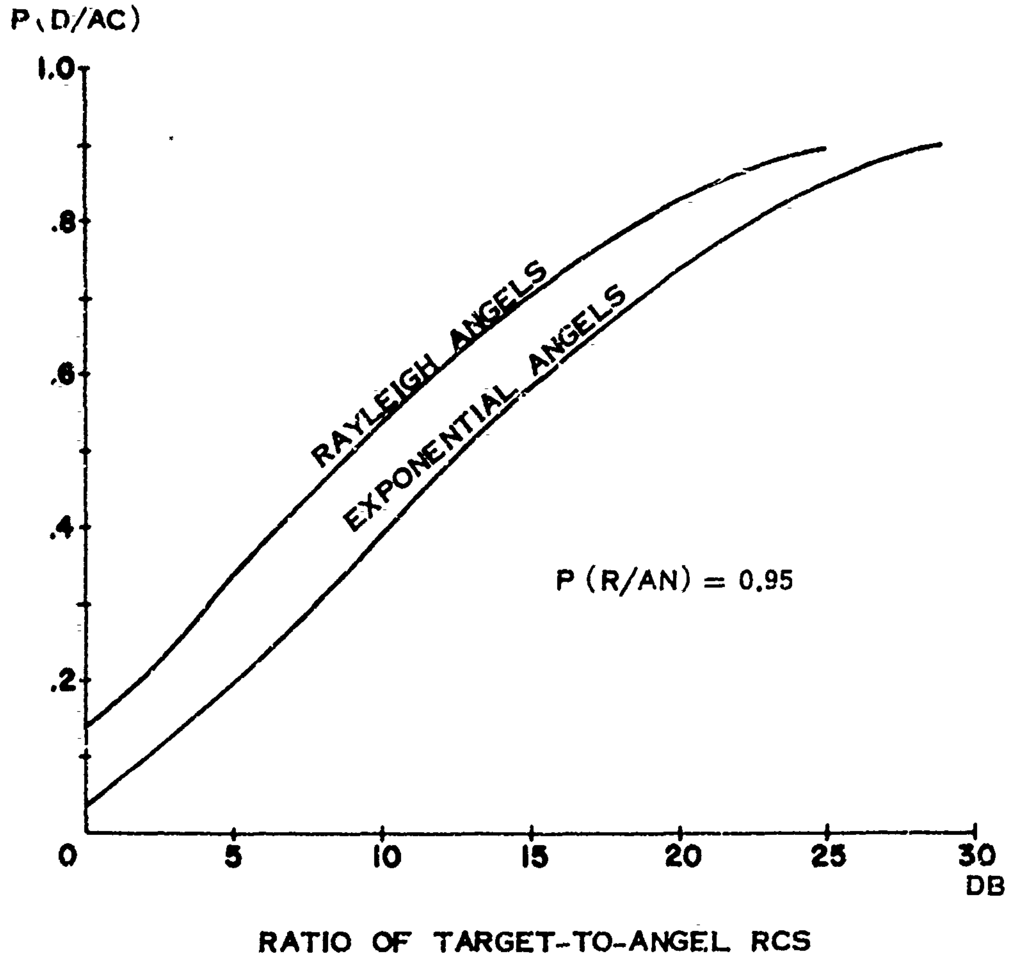


FIGURE 3-8 DETECTION PROBABILITY FOR EXPERIMENTAL AIRCRAFT MODEL IN ANGEL CLUTTER

For a 1 m^2 target following the exponential model, Table IV shows the highest values of mean RCS that can be rejected for several values of P(D/AC) and P(R/AN) and for the two angel models. Note that there is little difference in the Rayleigh and exponential models at P(R/AN) = 0.75, and that P(D/AC) = 0.9 requires much smaller mean RCS values for the angels. These data imply that, if the radar performance requirement were P(D/AC) = 0.9 on a 1 m^2 target, the RCS threshold should be set at .11 m^2 (exponential angel model) and the angel rejection probability would range from 95% to 75% as the angel RCS varied from .001 to .006 m^2.

It should be noted that these calculations do not include the effects of pulse-to-pulse processing (e.g. integration) of the radar returns. As a result, the angel RCS values in Table I are lower than would be required if the aircraft are more highly correlated from pulse-to-pulse than angel returns.

TABLE IV

PERFORMANCE OF AMPLITUDE THRESHOLD
FOR EXPONENTIAL/RAYLEIGH ANGEL MODELS

Aircraft: Mean RCS = 1 m^2, exponential model

P(D/AC): Probability of correct aircraft detection

P(R/AN): Probability of correct angel rejection

P(D/AC)	P(R/AN)	Mean Angel RCS	
		Many Birds per angel*	Few Birds per angel**
0.5	0.95	.13 m^2	.05 m^2
	0.90	.16	.09
	0.75	.27	.25
0.9	0.95	.003 m^2	.001 m^2
	0.90	.004	.003
	0.75	.006	.006

*Rayleigh Model

**Exponential Model

3.2.4 Azimuth Autocorrelation Functions

The amplitude distribution functions presented in the previous section were calculated over many scans of ASR video data. This information is appropriate to determining amplitude thresholds for separating angels and aircraft when the angels are somewhat smaller than the aircraft. The next logical question is, "what can be done when the angels and the aircraft are roughly the same size?" In this case, the sweep-to-sweep (pulse-to-pulse) correlation of angel and aircraft returns plays the important role.

Azimuth autocorrelation functions of the Data Collect Matrix for angels and aircraft are presented in Appendix B-1. The results show that aircraft have more sweep-to-sweep correlation than angels. If we define the decorrelation interval as the azimuth over which the azimuth autocorrelation function decreases by half its amplitude, the aircraft decorrelated at $0.6^{o} \pm 0.2^{o}$ while the angels decorrelated three times as fast (0.18^{o}). This implies that, for a sufficiently high threshold, the number of aircraft pulse returns above the threshold will be approximately three times as great as for angels, and therefore this approach should be an effective means of discrimination. This type of discrimination will be discussed in detail in Section 3.6. A second implication is that the amplitude threshold data presented previously in Table IV is conservative if video integration is employed, since the aircraft will experience more integration gain than angels due to higher pulse-to-pulse correlation.

3.3 Range Attenuation Rate of Angel Clutter

The range attenuation rate of ASR angel clutter is a significant factor in determining the form of sensitivity time control (STC) which may be required. In order to determine this rate, analog tape recordings of ASR MTI video were played back onto a storage oscilloscope and the video for each sweep was displayed and stored. The envelope of the video traces was then an indication of the attenuation rate with range for the detectable angel clutter. The results are presented in Figure 3-9 for two different data runs during which no STC or CSS was being used. The central curves in the figure represent the video amplitude displayed on the storage scope and obtained from photographs. It is seen that the attenuation rate is approximately proportional to the fourth power of range (R^{-4}). This is as would be expected for point targets (including aircraft) in the main portion of the antenna pattern. For lower elevations relative to the antenna beam axis, the rate of attenuation would be larger than R^{-4}, but such is not evident in this limited data. This is probably due to the fact that angels on the peak of the antenna beam tend to dominate the angel returns at a given range.

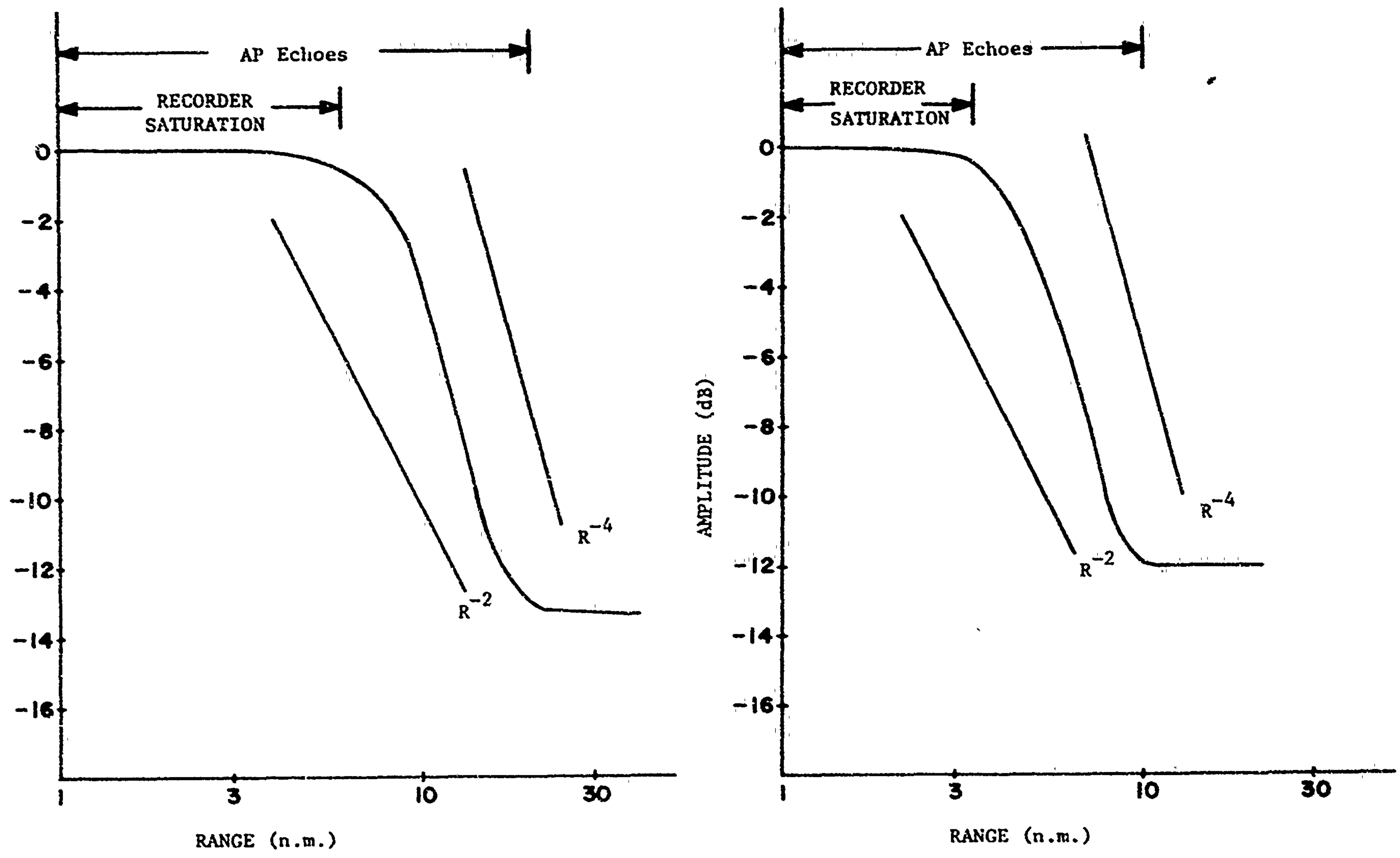


FIGURE 3-9 ANGEL CLUTTER ATTENUATION WITH RANGE

3.4 Spatial Distribution Characteristics of Angel Clutter

The spatial distribution of angel clutter relative to the ASR beamwidth and pulsewidth determine the capability of the system to resolve aircraft from surrounding angel clutter. Items of interest include the density of angels per unit area, their height distribution, and whether or not angel returns exceeed one radar resolution cell (1.5° by 410 feet).

3.4.1 Height Distribution of Angels

Altitudes of bird angels can vary widely with bird species, radar location, season, and time of day. Bird distribution in altitude at night has been described in the literature by an exponential density model with a scale height of 2500 feet; the model has some limited experimental support. The model implies that the mean bird altitude at night is 2500 ft. and 63% of birds fly below that level. Daytime migrating activity tends to be more stratified with preferred altitudes dictated by wind conditions. (Tailwinds are preferred). Local, resident bird activity is concentrated below one or two thousand feet and is also strongly influenced by wind.

Angel altitudes measured in Milwaukee using the MPS-19 radar were consistent with this model (Figure 3-10). The maximum altitude observed was approximately 6K ft and the minimum several hundred feet. The 7 mile maximum range shown in the figure is largely due to the small radar cross-section of the angels.

For the Milwaukee ASR, the angel altitude relative to the peak of the elevation antenna pattern ($\approx 3^{\circ}$) and their relatively low RCS limited detection ranges to less than about 15 miles, with the vast majority of angel returns occurring within the first ten miles of radar coverage. This has several important implications:

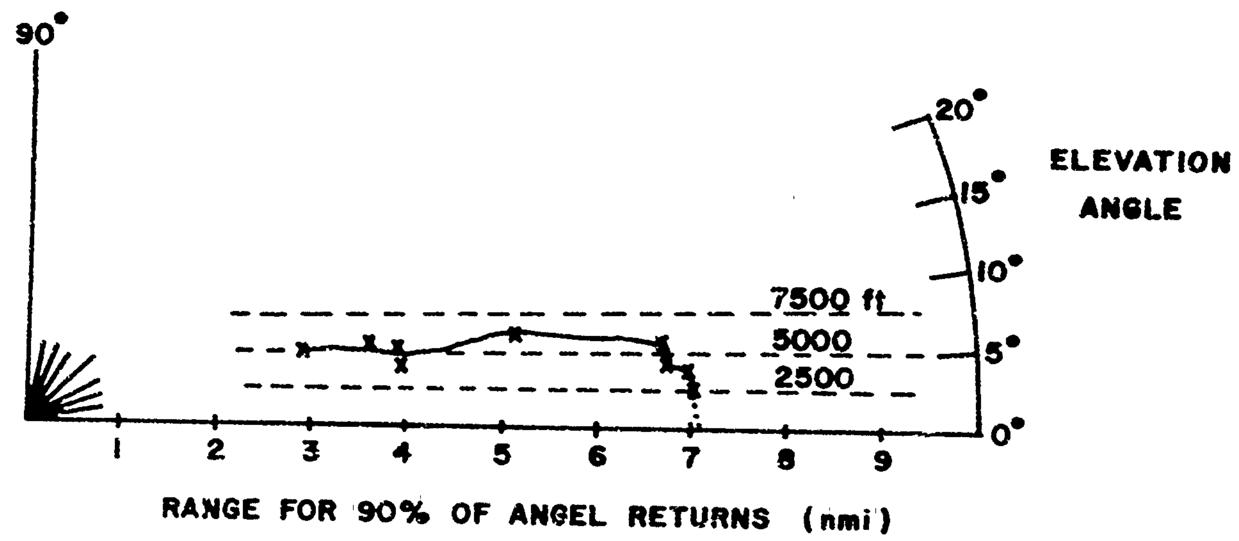


FIGURE 3-10 ELEVATION PROFILES OF MILWAUKEE ANGEL CLUTTER

a) Angel clutter reduction (ACR) systems must be compatible with the use of MTI video, which is required to reduce land clutter returns in the first 10-20 miles of coverage

b) ACR systems need only operate for the first 10-15 miles of radar coverage. This is significant because target sensitivity losses associated with ACR processing can be avoided at ranges beyond the region of angel clutter where target returns are weaker

c) Upspotting the ASR antenna will reduce the effects of angel clutter at the expense of reduced detection for low-altitude aircraft.

3.4.2 Angel Target Extent

Since aircraft represent point-targets, an aircraft return pulsewidth is equal to the ASR pulsewidth (410 feet) and the azimuthal extent of the aircraft is on the order of one to two ASR beamwidths (1.5°), depending on target return strength. If a substantial portion of the angels observed on the ASR had range or azimuth extent greater than these values, spatial discrimination of angels and aircraft would be an effective approach.

During all test operations associated with this program, virtually no extended angel clutter returns (returns substantially exceeding one pulsewidth and several beamwidths) were observed. In some cases, lack of PPI display resolution makes angel clutter appear as extended targets; expansion of the display virtually always reveals densely-packed discrete targets. This implies that techniques aimed at suppressing extended targets (wide pulse blanking, etc.) would offer little or no advantage against the type of angels observed in these tests.

A possible exception might occur in the case of large masses of insects or extremely large and dense mass migrations of birds.

3.4.3 Angel Target Density

The density (number per square mile of angel detections on the PPI) is a crucial factor in designing an automated radar tracking system or in visual discrimination between birds and aircraft. Receiver gain, angel RCS, range rate relative to MTI cancellation characteristics, altitude, and antenna upspot all affect the density of angel detections. In the preliminary tracking tests conducted at NAFEC in October 1971, about 250 angel detections appeared on the first ten miles of the PPI display, even with MTI and STC. While this is a substantial number of targets, the density is actually quite low relative to the number of radar resolution cells in the region (36,500)*. The probability of an angel being detected in each resolution cell is 0.007, and the corresponding density per square nautical mile is 0.88.

Typical density of angel detections for the first five miles of the Milwaukee ASR are shown in Figure 3-11. Here, 736 of the 17,300 radar resolution cells produced detections, equivalent to a per-cell probability of 0.04. Densities without STC are much higher, and if MTI is eliminated, ground clutter would obscure the angels (and aircraft).

It is evident from the above that, although most of the radar resolution cells in angel clutter are free of angel detections (with MTI and STC), the number of detections is sufficiently large to make aircraft very difficult or impossible to find on a single-scan PPI presentation. This situation must be improved by providing additional signal processing to reduce angel detections or by using scan-to-scan motion of aircraft to separate them from angels.

*A minimum range of 0.5 nmi is assumed here.

736 DETECTIONS IN FIRST 5 NM OF COVERAGE

STC AND MTI VIDEO

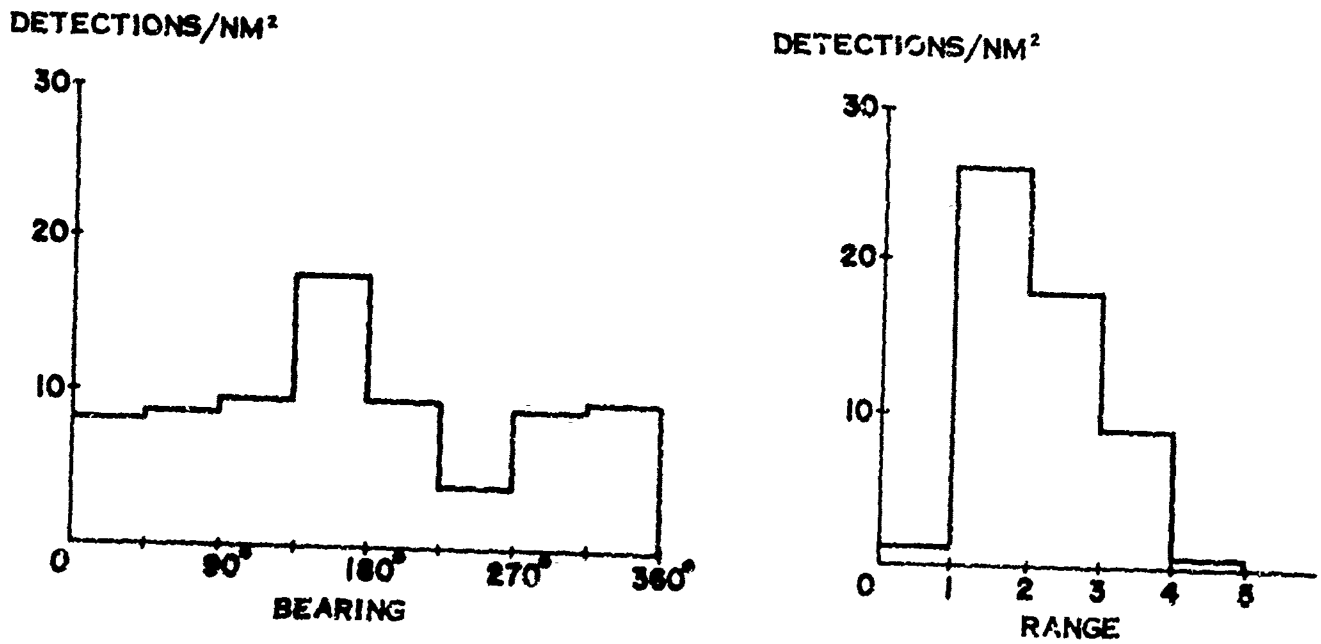


FIGURE 3-11 DENSITY OF ANGEL TARGET DETECTIONS FOR MILWAUKEE ASR

Appendix B-4 presents the results of angel clutter density measurements at Milwaukee, Little Rock, and NAFEC. The results are summarized in Table V.

TABLE V

MEAN ASR ANGEL CLUTTER DENSITY OBSERVATIONS

(Number of Angels Per Square Mile)

			Range Interval			
Location	STC/CSS	Total Angels	0-2 nmi	2-4 nmi	4-6 nmi	6-8 nmi
Milwaukee						
4/15/72	CSS-2	225	>16	3.3	1.0	0.4
4/17/72	CSS-2	310	11.7	2.7	0.5	0.3
4/18/72	None	284	9.9	2.6	0.9	0.07
Little Rock						
3/8/72	STC	230	7.6	2.6	0.6	0.03
3/9/72	STC	167	3.8	1.8	0.7	0.2
NAFEC						
10/28/71	STC	225	3.6	1.7	0.7	0.4

In order to determine the effect of radar video gain on angel clutter, an analog tape of MTI angel clutter video from Milwaukee was photographed for video attenuations increasing in three dB steps. The approximate numbers of angels detected in the first ten miles of coverage were as follows:

Attenuation	Number of Angels
0 dB	670
3	460
6	325
9	190
12	30
15	0

The decrease in detections is nearly linear (about 8% of the maximum per dB of attenuation) until the limit of the video dynamic range was reached at between 12 and 15 dB of attenuation.

3.5 Velocity and Trajectory Characteristics of Angels

Bird angels and aircraft generally have different destinations and trajectories with different characteristics. Migrating birds follow known flyways and frequently fly to very specific locations via a sequence of more-or-less straight-line flight paths. Local bird activity does not exhibit such straight-line characteristic. Aircraft, of course, also fly straight-line paths, but not generally to locations which correspond to bird staging areas. Aircraft landing patterns also offer a very distinctive trajectory characteristic which should be useful in separating aircraft and angels. Angels rarely obtain airspeeds greater than 60 knots. For common wind velocities at altitudes of 2000-5000 feet, this airspeed may correspond to a groundspeed of 80-90 knots. Very few aircraft (except helicopters) fly slower than 100-120 knots.

Figures 3-12 and 3-13 illustrate the trajectories of seven angel targets that were tracked at Milwaukee. The start of each track is indicated by the location of the track number and wind speed and direction is shown for altitudes of 0, 5, and 10 thousand feet.

The tracks in Figure 3-12 were taken at about 1900 hours on 17 April. Cloud cover was scattered at 2500 feet and the temperature was 42°F. All of the angel velocities shown are ground speeds. The effect of wind on the direction of travel of tracks 1, 2, and 5 is apparent, since the track headings swing from the surface wind direction to the 5K feet wind direction as the altitude of the angel tracks increases. Track 6 apparently switched directions as it increased altitude to conform to the wind direction at 5000 feet.

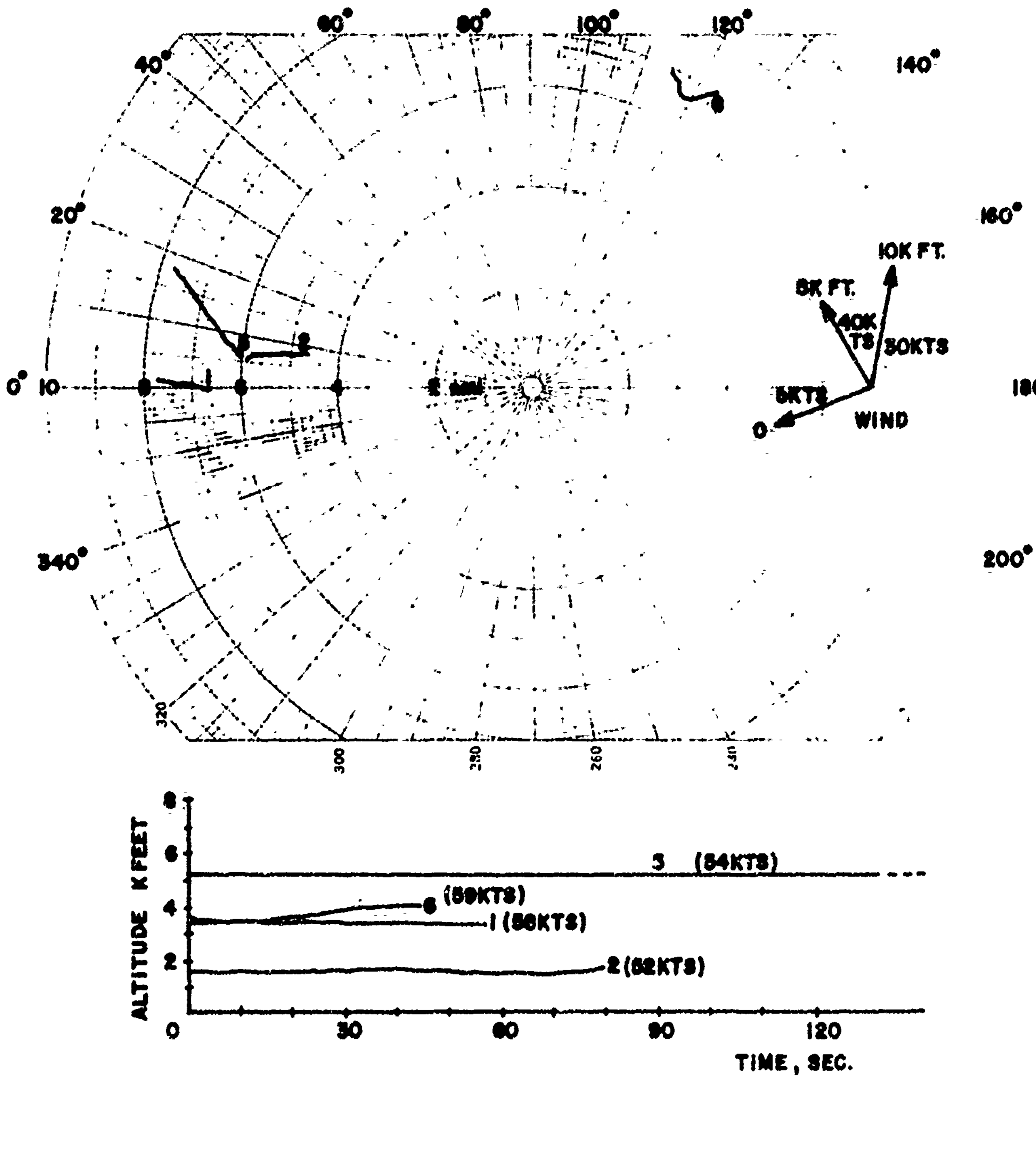


FIGURE 3-12 FOUR ANGEL TRAJECTORIES FROM 17 APRIL.

The tracks in Figure 3-13 were taken at 0500 the following morning. Cloud cover was thin and broken at 25,000 feet and the temperature was 51^{o}F. Again, the higher altitude track (#3) shows the effect of wind but the lower tracks in this case do not. Also, track velocities are much lower.

Of the seven target tracks plotted here, all had ground speeds in the 35 to 60 knot range except for one 15 knot track. Altitudes range from a few tens of feet to 5000 feet.

During the Milwaukee tests, bird-type angels were observed with groundspeeds from 10 to 59 knots. Headings ranged from parallel with the wind to across the wind. None were observed heading upwind, consistent with the reports of local bird authorities that migration very rarely occurs into the wind. This is consistent with empirical distributions from the literature which suggest that 90% of bird velocities will fall between 5 and 50 knots and 50% between 10 and 30 knots. Radial velocities must be assumed to range from zero to the same maximum values as vector velocity.

It should be noted that, at a particular time and location, the spread in bird angel velocities and headings may well be limited to 10 or 15 knots and 20 to 40 degrees, respectively, by the state of migration, e.g., when a few similar species are all heading in the same general direction. This situation occurred during the Milwaukee test period. However, the spatial distribution of angels can produce a broad range of radial velocities even when a relatively narrow vector velocity distribution exists. Nevertheless, in such a case, the range of radial velocities is small in any limited azimuth sector.

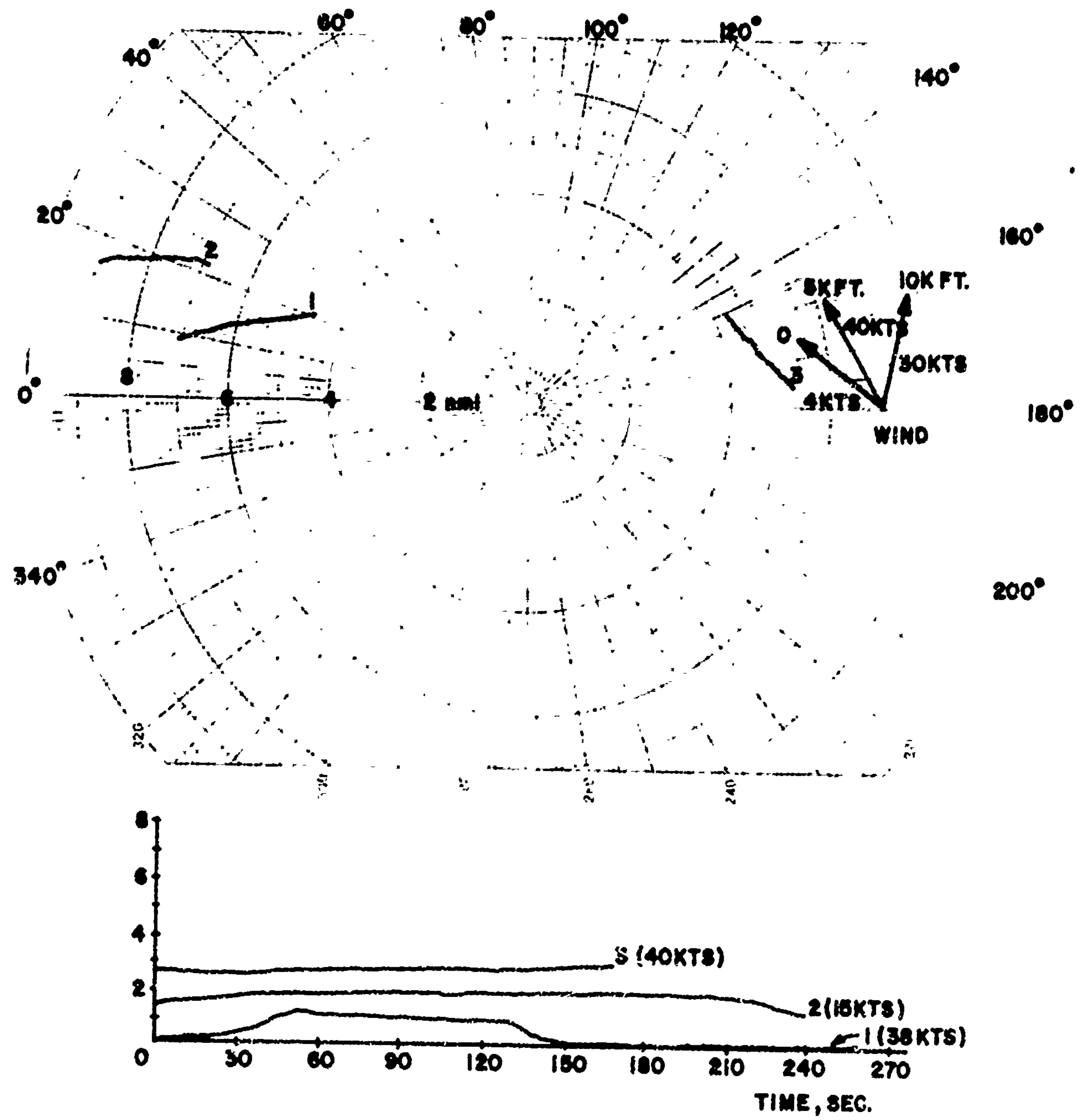
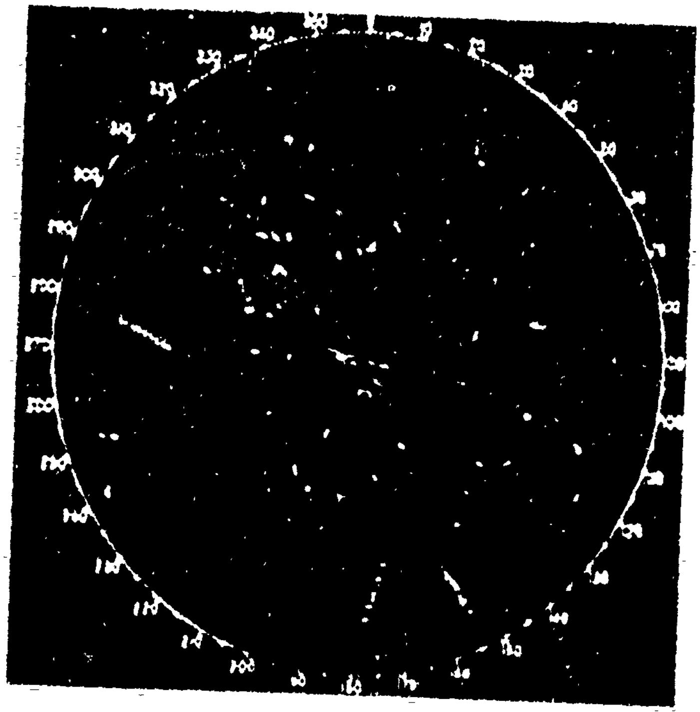


FIGURE 3-13 THREE ANGEL TRAJECTORIES FROM 18 APRIL

The above suggests that vector velocity (speed and heading) should be an efficient angel/aircraft discrimination technique. Whereas MTI or other forms of doppler processing provide range-rate discrimination, discrimination on the basis of vector velocity must rely on correlation of target positions from scan-to-scan of the radar. This introduces a new problem, that of associating returns from the same target on successive scans. This requires reasonably small target densities, so that returns from two different targets are not confused. This association problem exists regardless of whether an automated system or a manual operator (using a display of several scans of radar return) performs the scan-to-scan association.

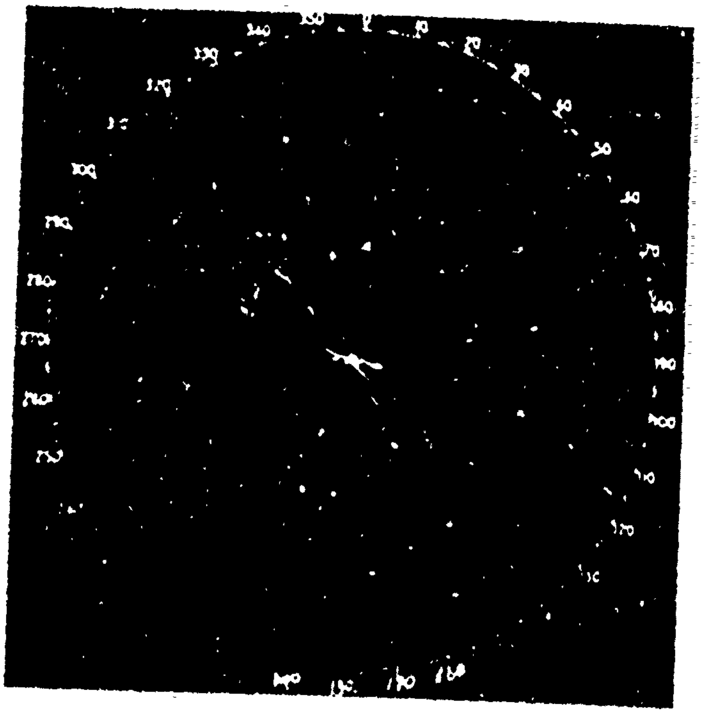
An example of the effect of scan-to-scan velocity discrimination is shown in the time exposures of Figure 3-14. The input data was an analog tape recording taken at Milwaukee and the display range is ten miles. The angel clutter appears rather light because an azimuth pattern discriminator requiring 5 hits out of 5 sweeps was used (this technique will be discussed in Section 3.6). The nine-scan display clearly shows three aircraft (152°, 177°, 275°) moving at approximately 200 knots. It is interesting to note that the factor-of-three increase in the number of scans displayed has not seriously worsened the angel clutter background; these aircraft could have been easily detected in virtually all portions of the 9-scan display except perhaps within one mile of the radar.

If the 5/5 processor and STC had not been used to reduce the angel density prior to combining data from the nine scans, the angel clutter would have been much more dense and may have obscured the aircraft. An example of such a case is shown in Figure A-4 of Appendix A-3, where time-lapse photographs of STC and non-STC video are compared.



MILWAUKEE ASR, MTI & STC
5/5 AZIMUTH PATTERN PROC
10 MILE RANGE

LONG TERM MOTION
(9 SCANS)



SHORT TERM MOTION
(3 SCANS)

FIGURE 3-14

SCAN-TO-SCAN MOTION OF ANGEL CLUTTER & AIRCRAFT

3.6 Azimuth Pattern Characteristics

A study of pulse-to-pulse fluctuations of the ASR radar video was conducted to determine the feasibility of constructing a processor capable of discriminating between angels and aircraft on the basis of their azimuth patterns, that is, the fluctuations in the radar returns as the antenna scans past the target. Data was collected in the form of a 40 by 37 matrix (previously shown in Figure 3-2) representing digitized ASR amplitude intensities on a scale of 31. The data represents 40 half-pulsewidth range cells and every other transmit pulse for a total of 37 azimuth cells around the target; the matrix was centered on the target using the Tracking Radar Module. Alternate pulses were utilized to ensure that at least one complete beamwidth was contained in the resulting range-bearing matrix. Typical azimuth patterns collected in this manner are illustrated in Figure 3-15.

Table VI summarizes the data used in these experiments. Only small aircraft and angel tracks were used in the analyses, as these target types present the most difficult discrimination problem. Basically, aircraft and angel tracks were identified on the basis of their velocities calculated from tracking data obtained from the Track Radar Module. The data collect matrices for the selected tracks were then visually inspected to verify that a valid target track had been obtained and several possible discrimination techniques were tested on several targets. The analysis concentrated on the range row of the data collect matrix which had the largest target return.

The major results of this effort are summarized below. Appendix B contains more detailed data.

TABLE VI

INPUT DATA FOR AZIMUTH PATTERN ANALYSES

MILWAUKEE DATA (37 Azimuth Samples, Every Other Sweep)

Aircraft Tracks	No. Scans	Video	[illegible]	No. Scans	Video
6-1	58	Normal	10-1	24	MTI
6-2	103	Normal	10-6	69	MTI
3-2	73	Normal	11-3	19	MTI
3-3	83	MTI	11-4	5	MTI
21-1	256	MTI(R<22 nmi)	11-5	20	MTI
22-1	160	MTI(6<R<22 nmi)	11-6	35	MTI
	733		11-7	7	MTI
			16-1	62	MTI
			16-3	31	MTI
				272	

BALTIMORE DATA (40 Azimuth Samples, Every Sweep)

Aircraft Tracks	No. Scans	Video
2A	155	MTI
2F	120	MTI
3BC	34	MTI
Small A/C 1	308	MTI
4C	129	MTI
4D	163	MTI
2B	211	MTI

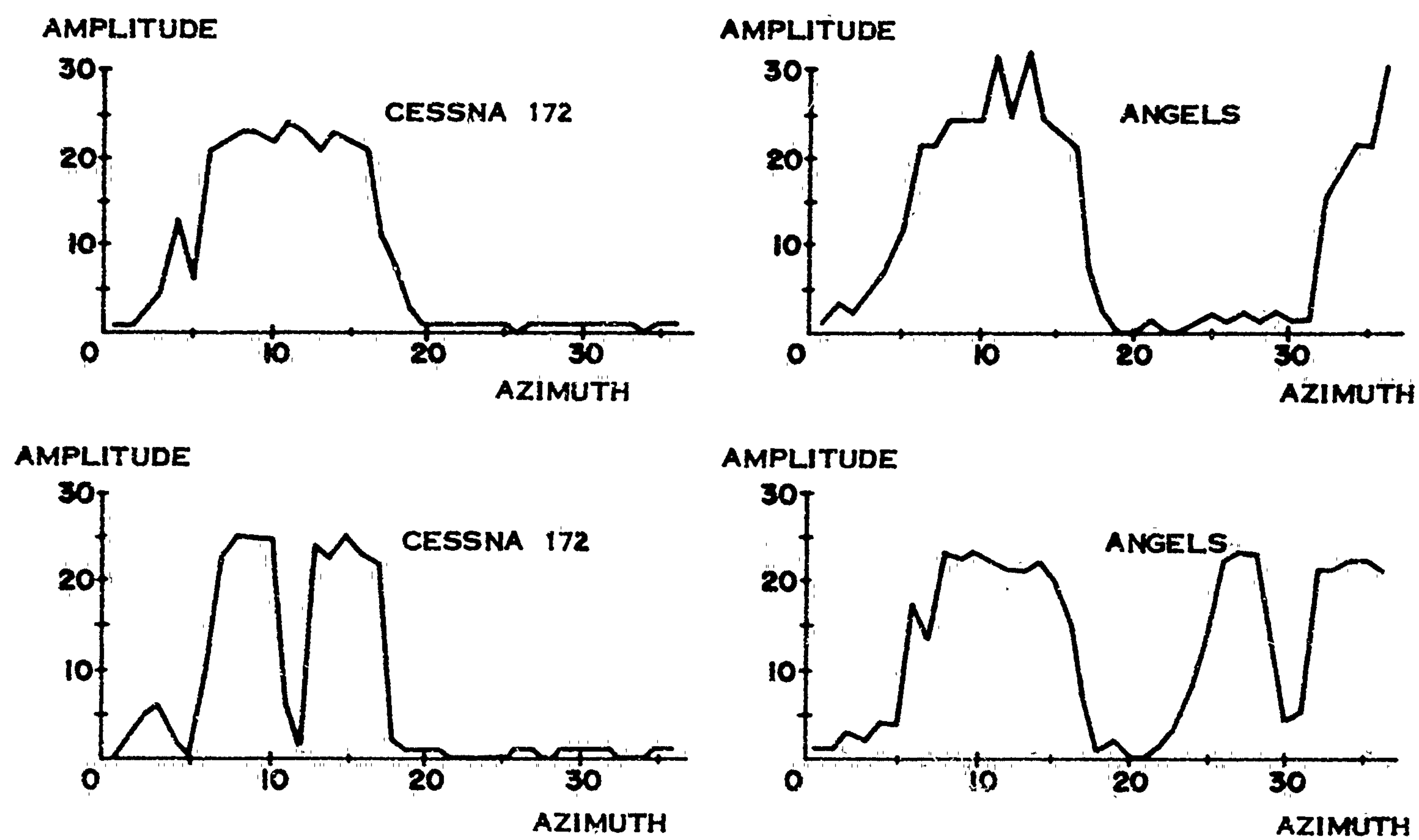


FIGURE 3-15 AIRCRAFT AND ANGEL AZIMUTH PATTERNS

3.6.1 Azimuth Correlation Interval Analysis

Differences in azimuth correlation between angels and aircraft are sufficient to justify a thorough analysis of azimuth correlation. If radar returns for a given range cell are thresholded, the target hits (threshold crossings) are generally broken into groups of consecutive threshold crossings (detections), which we will refer to as Azimuth Correlation Intervals (ACI). Often a single target will generate more than one ACI, and the possibility of discriminating between angels and aircraft in terms of both the number of ACI per scan and the length of each ACI was investigated. Two types of thresholds were considered. The first was a fixed threshold corresponding to up to eight of the 31 quantization levels of the data collect matrix. The second was a factor threshold based upon a percentage of the maximum observed target pulse amplitude on each scan. Therefore, the fixed threshold results are dependent upon both azimuth pattern and signal strength, whereas the factor threshold is affected only by the shape of the target return azimuth pattern. To simplify the calculations, only the range row of the matrix with the maximum sum (strongest signal) was selected on each scan for all ACI calculations.

Figures 3-16 and 3-17 present results of this analysis for the fixed and factor thresholds, respectively, for the mean ACI length (number of consecutive returns in each ACI averaged over all scans) and mean number of ACI per scan (averaged over all scans). Additional plots for maximum and minimum ACI lengths are contained in Appendix B). The aircraft tracks (Cessna 172) appear to have longer ACI lengths and a fewer number of ACI than do angels. The factor threshold data indicate that the number of ACI for aircraft remains relatively constant as the threshold is increased from 20% to about 90% of the maximum amplitude, while the angels appear to have a linearly decreasing number of ACI's with threshold. (Angel track 16-1 appears to be an anomaly, as all other angel tracks

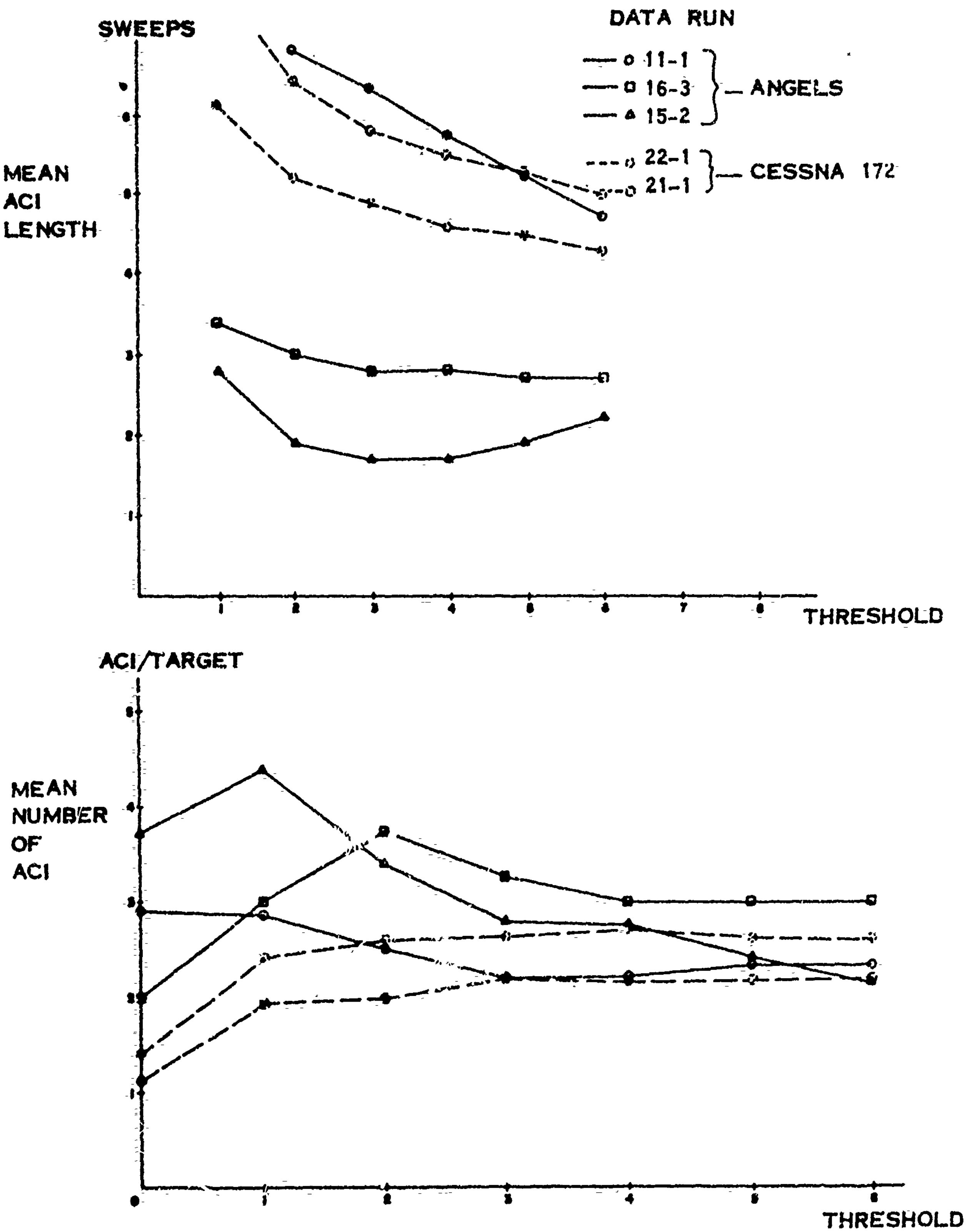


FIGURE 3-16 AIRCRAFT AND ANGEL ACI PARAMETERS FOR FIXED THRESHOLD (MINIMUM VIDEO AMPLITUDE = 30)

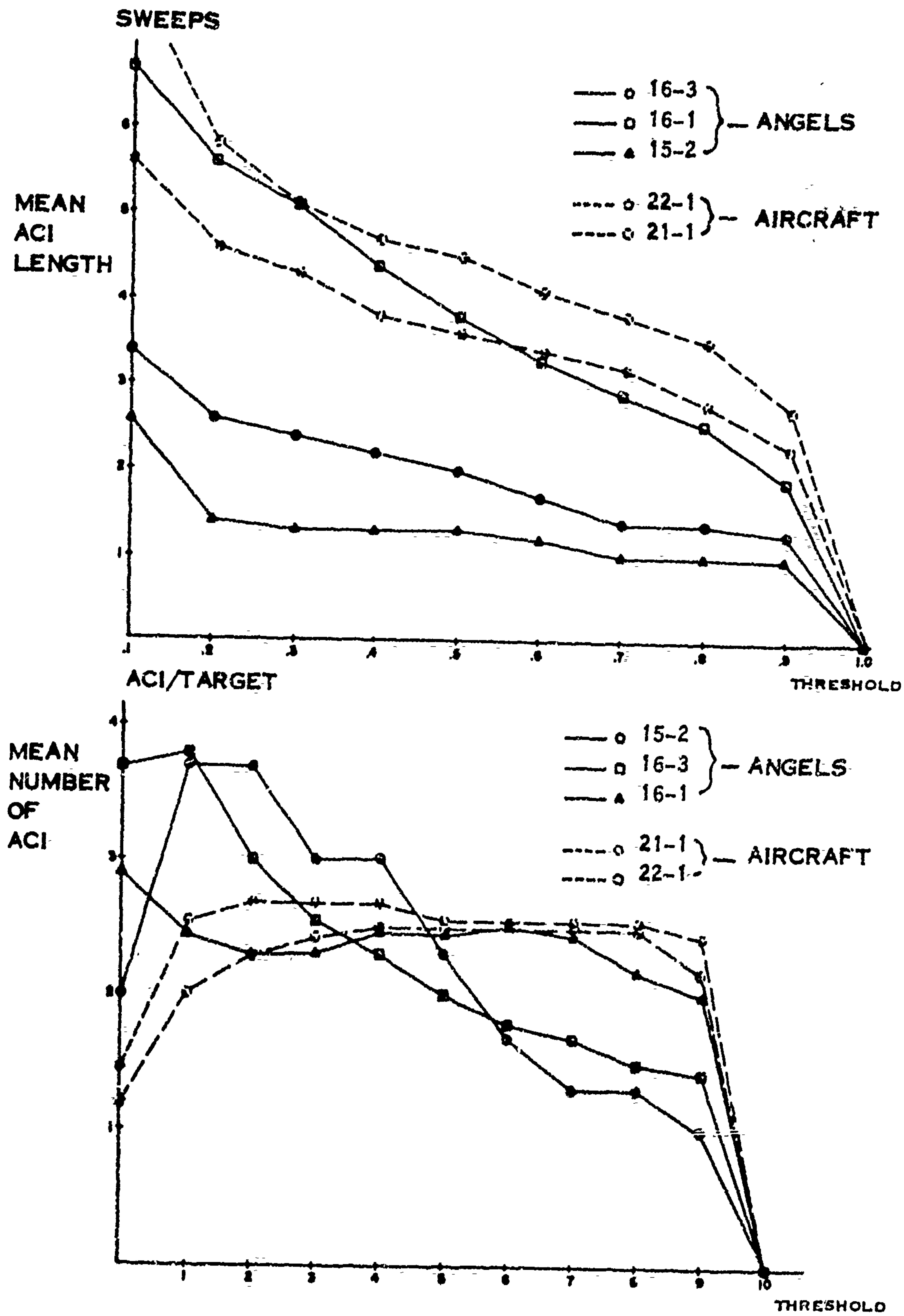


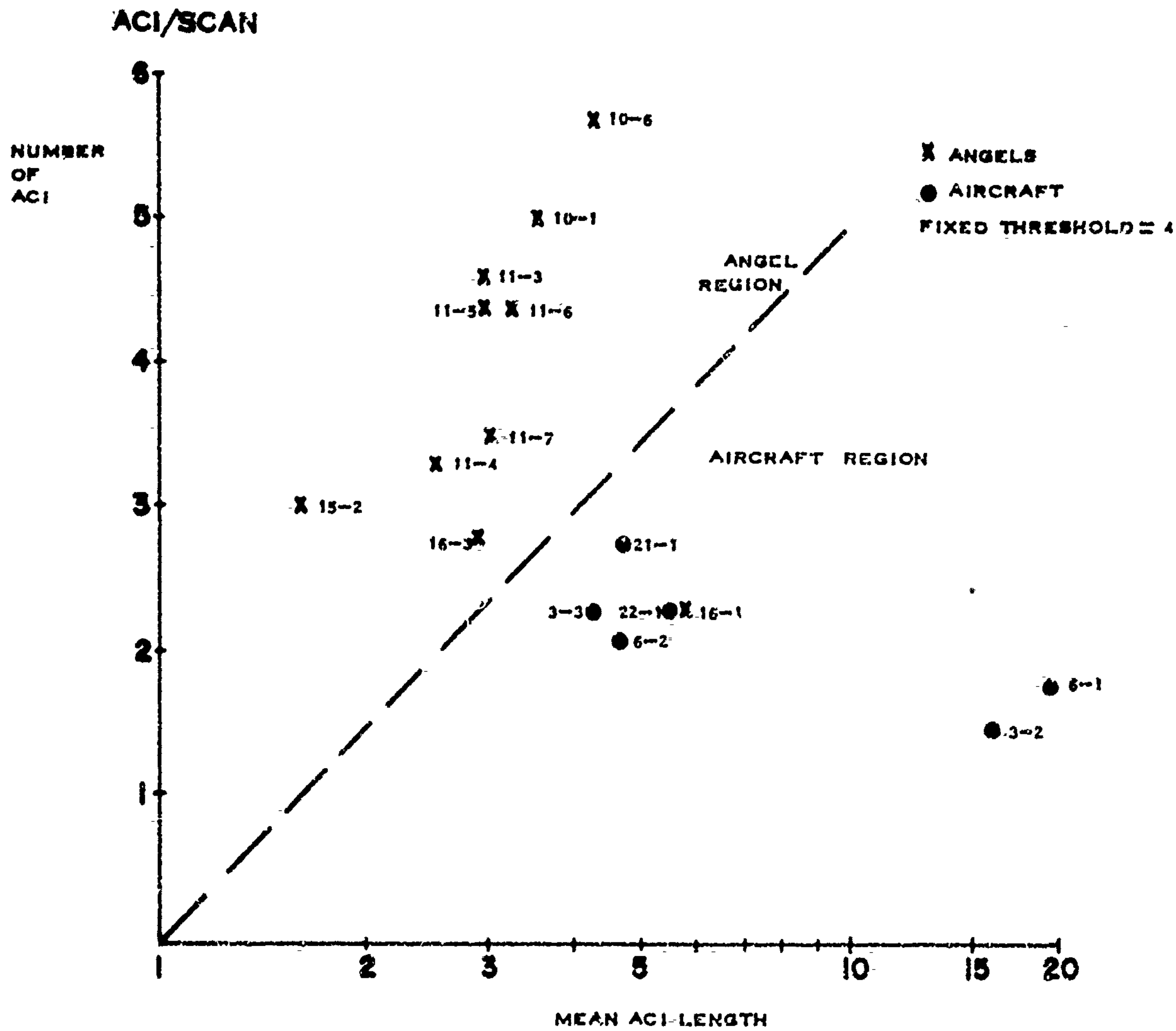
FIGURE 3-17 AIRCRAFT AND ANGEL ACI PARAMETERS FOR FACTOR THRESHOLD (% OF MAXIMUM OBSERVED AMPLITUDE)

considered have ACI plots similar to that of 16-3 rather than 16-1). This suggests, for example, that a dual threshold processor (one which uses the number of ACI for two different values of the factor threshold) could provide a reasonable level of angel/aircraft discrimination.

Figure 3-18 is a graph of the number of ACI versus length of ACI for the average values calculated for all targets considered, and for a fixed threshold value of four. Here the angels are clearly grouped in the region corresponding to large numbers of ACI and small ACI lengths, while all aircraft lie in another separate region with small numbers of ACI and larger ACI lengths. Data run 16-1 again appears as an exception. The angel/aircraft regions shown in the figure shift with a change in threshold, but both remain distinct for all the values of threshold considered. The separation between the two regions is maximized for a fixed threshold of about four. If the threshold is varied, both regions shift but remain distinct (except for angel 16-1) for all threshold values considered. These results show that the angels appear to fluctuate more rapidly from pulse-to-pulse than aircraft, as would be expected from the measured azimuth decorrelation intervals (Section 3.2.4).

3.6.2 Discrimination Based Upon Amplitude

The RCS data presented in Section 3.2 showed that the Cessna 172 RCS was larger than the angel track RCSs, at least as measured by MPS-19 track radar AGC data. To observe the effect of ASR video thresholding on angel/aircraft discrimination, the data collect matrix data was processed in a very simple amplitude discriminator. A target (aircraft) was declared whenever the threshold was exceeded. A performance curve was generated by varying the threshold and plotting the fraction of scans that the aircraft were properly identified (detected), P(D/AC), versus the fraction of scans that the angel tracks were properly identified (rejected), P(R/AN). The results (Figure 3-19) show both measures decreasing as the threshold is raised, with aircraft detections falling



NUMBER OF ACI PER SCAN VERSUS AVERAGE ACI LENGTH

FIGURE 3-18

MILWAUKEE DATA

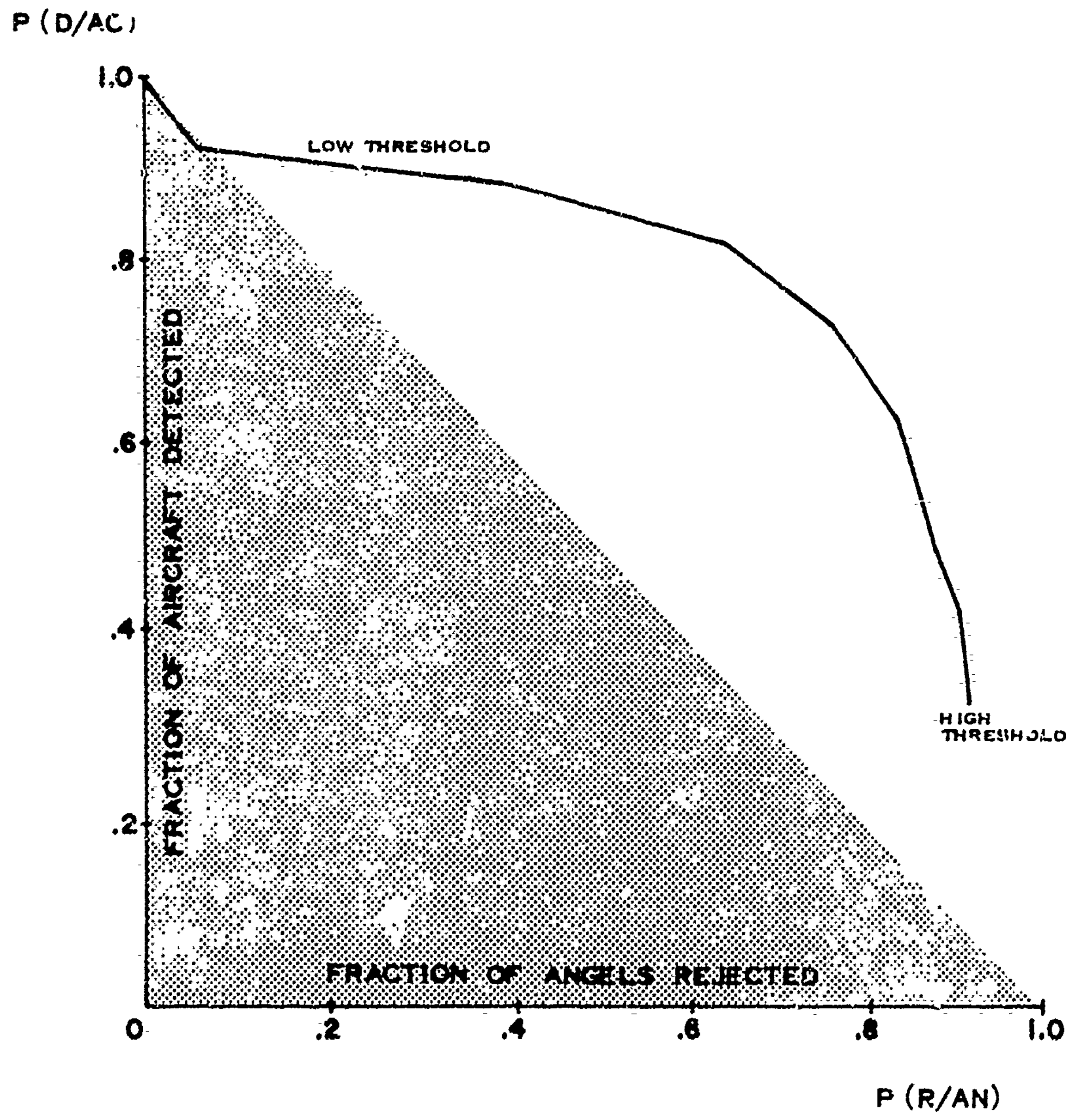


FIGURE 3-19 PERFORMANCE CURVE FOR AMPLITUDE DISCRIMINATION

off rapidly if the threshold is raised much above P(D/AC) = 0.75.

These results are consistent with the fact that most, but not all, aircraft returns are larger than bird angel returns. Since a fixed video threshold must be set to ensure a reasonable probability of detection of all aircraft with a given mean RCS, it is necessary to carefully control STC and IF gain settings. It is desirable to have discrimination techniques which are less dependent upon absolute amplitude, that is, techniques which examine the detailed structure of the azimuth pattern. Several such techniques are discussed in the following sections.

3.6.3 Discrimination Based Upon a Minimum Number of Consecutive Hits

The ACI analysis (Figures 3-16 and 3-17) suggests that requiring a minimum number of consecutive detections could selectively eliminate angels in favor of aircraft. To test this supposition, a computer was programmed to require a given minimum ACI for some threshold before declaring a target present on a given scan. Both angel and aircraft targets were processed and the percentage of scans on which target declarations were issued was calculated for each target type. The performance curve was again plotted to show the percentage of aircraft detections P(D/AC) versus percent of angel misses P(R/AN) as a function of the threshold. Figure 3-20 shows plots of these curves for the requirements of two and three consecutive hits. (Here two consecutive hits implies four consecutive hits for the radar as only alternate dwells were used in the data collect matrix. Likewise, three would imply six hits in the raw data).

Since the amplitude detector is really a 1/1 detector, its performance curve is also drawn in Figure 3-20 for comparison. The 2/2 and 3/3 detectors do not perform as well for moderate angel rejection (10%-70%) but comparable performance is obtained for high thresholds near the knee of the performance curve, P(D/AC) = .75 and P(R/AN) = .75. However, for low thresholds, the 1/1 technique is much more susceptible to false alarms than the other two detectors.

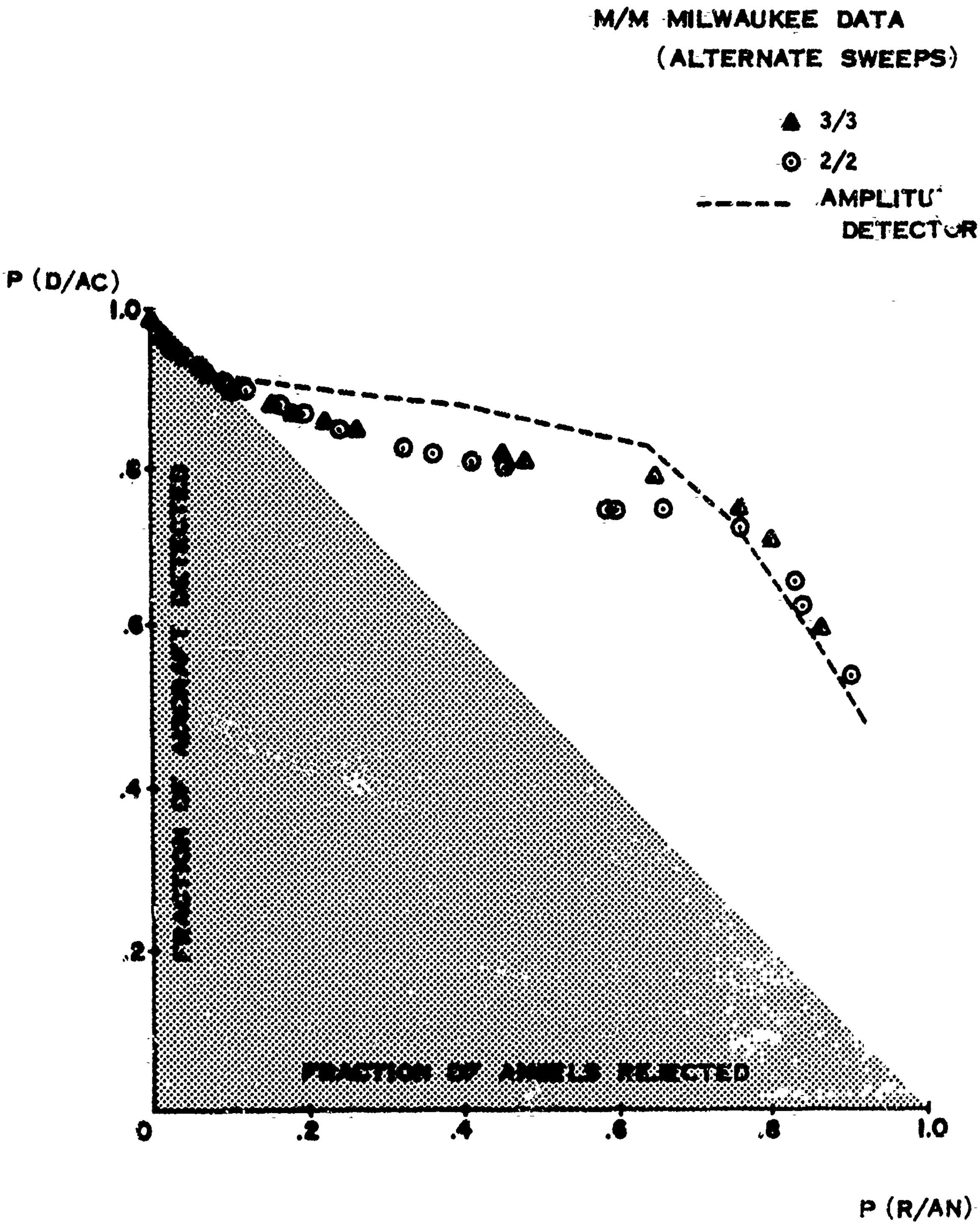


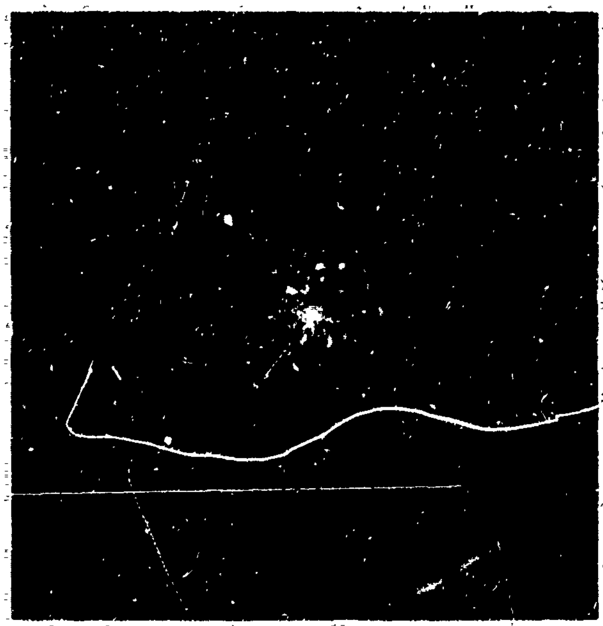
FIGURE 3-20 PERFORMANCE CURVE FOR M/M AZIMUTH CORRELATOR

Discrimination based upon the minimum number of consecutive hits is easily provided in an Azimuth Correlator, also referred to as a binary M/N integrator. This type of device is commonly used in automated radar systems, including the Enhanced ARTS system, to integrate the binary output of a first-threshold adaptive processor (digitizer) across the radar beamwidth. For the ASR, a typical M/N integrator setting for optimum sensitivity in receiver noise would be M/N = 8/19.

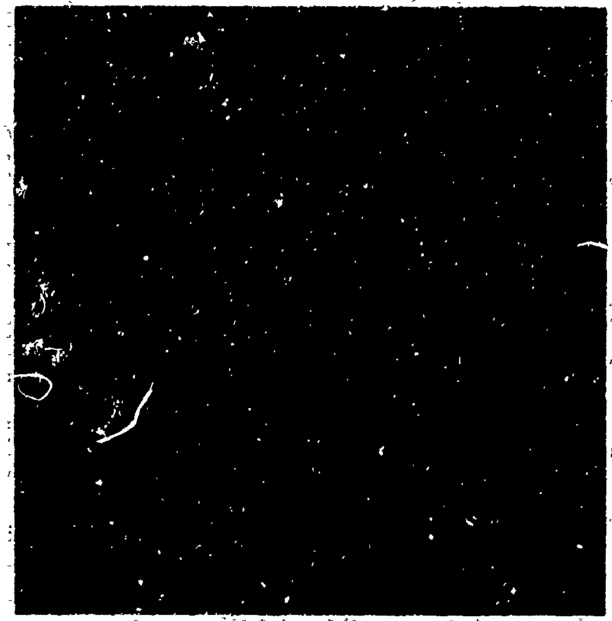
Since the Data Acquisition Module contains an automated radar tracking system which includes an adaptive first threshold processor and an M/N integrator second threshold, it was used to investigate the effectiveness of the M/N = 5/5 criterion for angel clutter and aircraft. Analog (RAVIR) video tapes recorded at Milwaukee provided the necessary input data, and the results were displayed on a PPI and photographed.

Figure 3-21 shows the results before and after processing. The adaptive video processor maintained the average first threshold false alarm probability at 0.01 and quantized the video to provide a binary input for the 5/5 binary integrator. Unfortunately, heavy angel and heavy aircraft activity did not coincide during the tests, so the angel photos contain few aircraft and the aircraft photos, taken at a different time, contain few or no angels. Multiple scan photos were used for the aircraft to provide a feel for blip/scan ratios, since the processed video is all displayed at the same high intensity level.

Clearly, this relatively simple processor has substantially reduced angel clutter (perhaps by a factor of five) and yet preserved the blip/scan ratio on the aircraft.

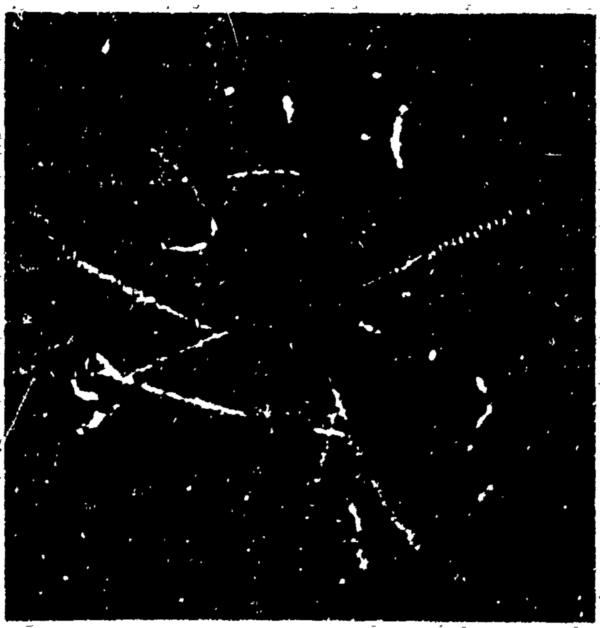


UNPROCESSED MTI, ANGELS



5/5 PROCESSED MTI, ANGELS

UNPROCESSED MTI, AIRCRAFT



5/5 PROCESSED MTI, AIRCRAFT

FIGURE 3–21 RAW AND PROCESSED VIDEO FOR 5/5 CONSECUTIVE HIT PROCESSOR

5 MILE RANGE RINGS
SINGLE SCAN ON ANGELS

3.6.4 Dual Threshold Discrimination

Examination of the Azimuthal Correlation Intervals (ACI's) revealed that the number of ACI's as a function of threshold remains relatively constant for aircraft while increasing almost linearly for decreasing threshold for angel targets. Thus, by setting two widely separated thresholds and observing the difference in the number of ACI's for both thresholds, it should be possible to distinguish between the two target types. One must, of course, be cautious, for when no target is present, the difference will be close to zero as expected for aircraft targets. This may be avoided by requiring at least one crossing of the lower threshold before either type target can be declared.

Using the data contained in the range row with maximum sum for each Data Collect Matrix collected at Milwaukee, the computer was programmed to select targets (based on at least one lower threshold crossing), and declare them to be angels or aircraft based on the difference in the number of ACI's for two thresholds. An angel was declared if the difference was greater than some minimum value; an aircraft, if less than this minimum value. Both thresholds and the minimum required ACI difference for angel declaration were varied and tested against all targets. The results were accumulated for all aircraft and angel targets separately, and plots made of the number of correct declarations. Appendix E-2 tabulates the results of these runs. Figure 3-22 illustrates the performance curves for the results described for two sampling intervals, 37 alternate sweeps (the full Data Collect Matrix width) and 10 alternate sweeps. This window of 10 alternate sweeps was slid along the 37 samples and checked at each position. The plot was made using those parameters of thresholds and minimum

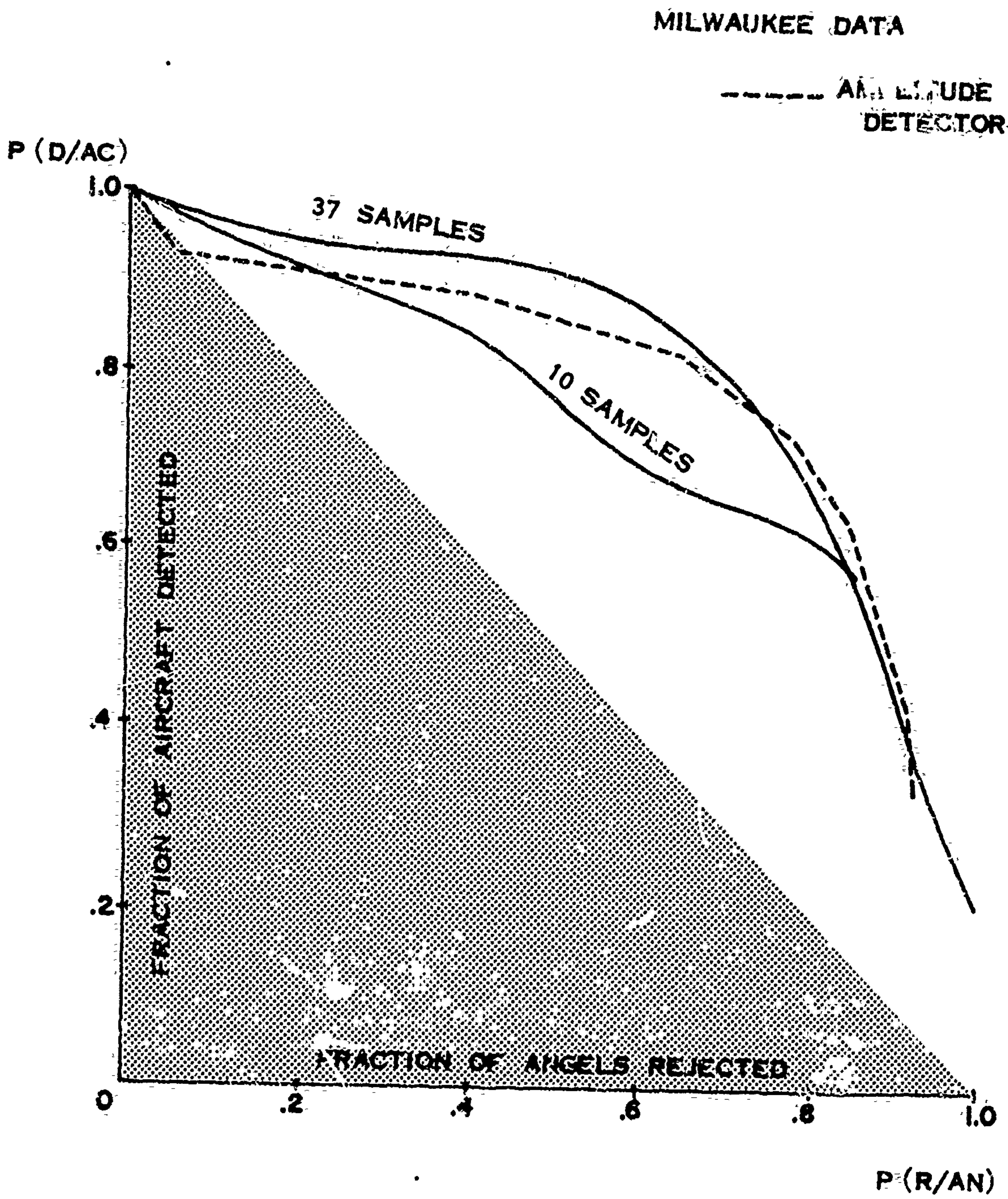


FIGURE 3-22 PERFORMANCE CURVE FOR DUAL THRESHOLD DISCRIMINATOR

ACI difference which produced the maximum number of correct decisions, thus the plot really outlines the upper boundary of a region of points resulting from various choices of parameters in the discriminator. Also plotted for reference is the simple amplitude-only plot indicating the relative improvement obtained by the dual threshold technique. From the plot it is clear that the 37 sample dual threshold discriminator is clearly superior to the other two techniques.

Other plots of computer results with fixed lower threshold and fixed minimum ACI difference but variable upper threshold, have shown some interesting effects. Figure 3-23 illustrates one such plot derived from the data used to plot Figure 3-22. Obviously, as the upper threshold is increased, the percentage of angel rejections increase with almost no aircraft loss below the initial value until some critical upper threshold value is obtained. Here aircraft correct identification falls off precipitously with little increase in angel rejection. The fall off point appears to be a function of the other two parameters, as does the initial level at which the aircraft detections initially reside. For example, by increasing the lower threshold from 6 to 8, the point at which aircraft detectability begins to fall off rapidly, occurred at a higher angel rejection level (65% versus 55%).

One can also observe the results from other points of view. For example, with a fixed lower threshold of 8 and a fixed upper threshold of 20, the aircraft detection/angel rejections ratios were .90/.53, .80/.70, and .59/.85, as the minimum ACI difference was varied from 3 to 1. This indicates a trade off in the fraction of angel rejections with the fraction of aircraft detections that occurs with a change in the minimum ACI requirement.

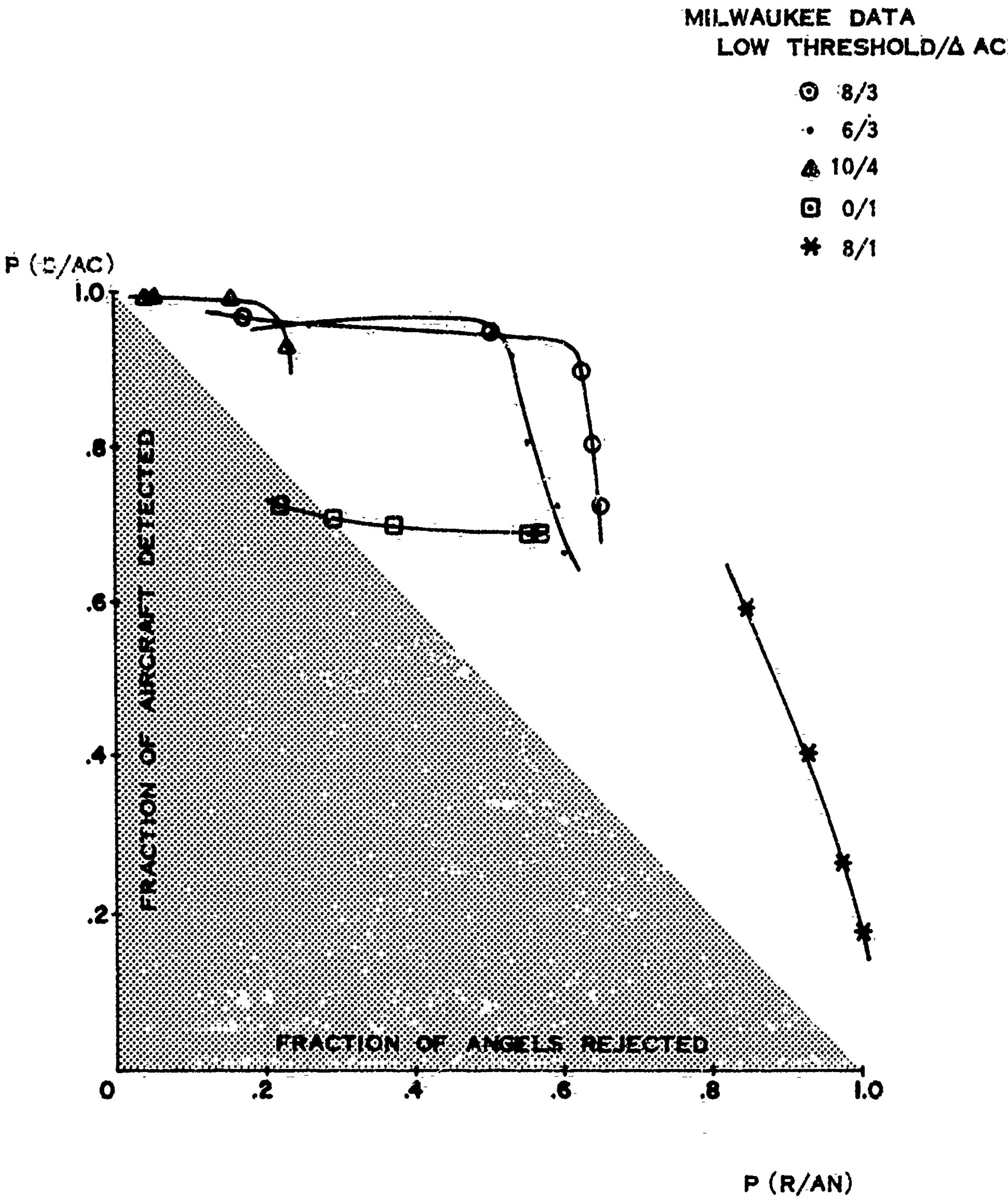


FIGURE 3-23 DUAL THRESHOLD PERFORMANCE FOR VARIABLE UPPER THRESHOLD

3.6.5 Data Verification

In the course of this study, additional aircraft MTI data from another APL FAA task (the ARTS Enhancement Support Program) became available for detailed analysis. This data, consisted of seven additional aircraft tracks (approximately 1200 additional scans worth of data) collected using the ASR at Baltimore's Friendship airport. It was processed using techniques developed for the Milwaukee data. The intent was to verify that the effects noted at Milwaukee were in fact characteristics of the ASR video returns of aircraft and not a local phenomena. In addition, the Baltimore data was collected for every pulse, rather than every other as in Milwaukee, which allows proof that the measured ACI characteristics noted at Milwaukee do not depend on alternate pulse sampling.

MTI and Non-MTI ACI Characteristics

Another advantage gained by including this data in the study was to widen the data base and thereby improve the confidence to be afforded the conclusions drawn from it. This particularly is true in view of the fact that approximately half of the Milwaukee aircraft data consisted of normal video samples and half of MTI video samples. As angels are expected to fall predominantly in the MTI region, the additional Baltimore data was used to investigate the validity of these concepts in this MTI region.

Figure 3-24 shows plots of the ACI characteristics (average value, and number) for MTI aircraft, non-MTI aircraft, and angels (in MTI) for the Milwaukee data. It is apparent that the average ACI for Milwaukee MTI aircraft and angels are very similar

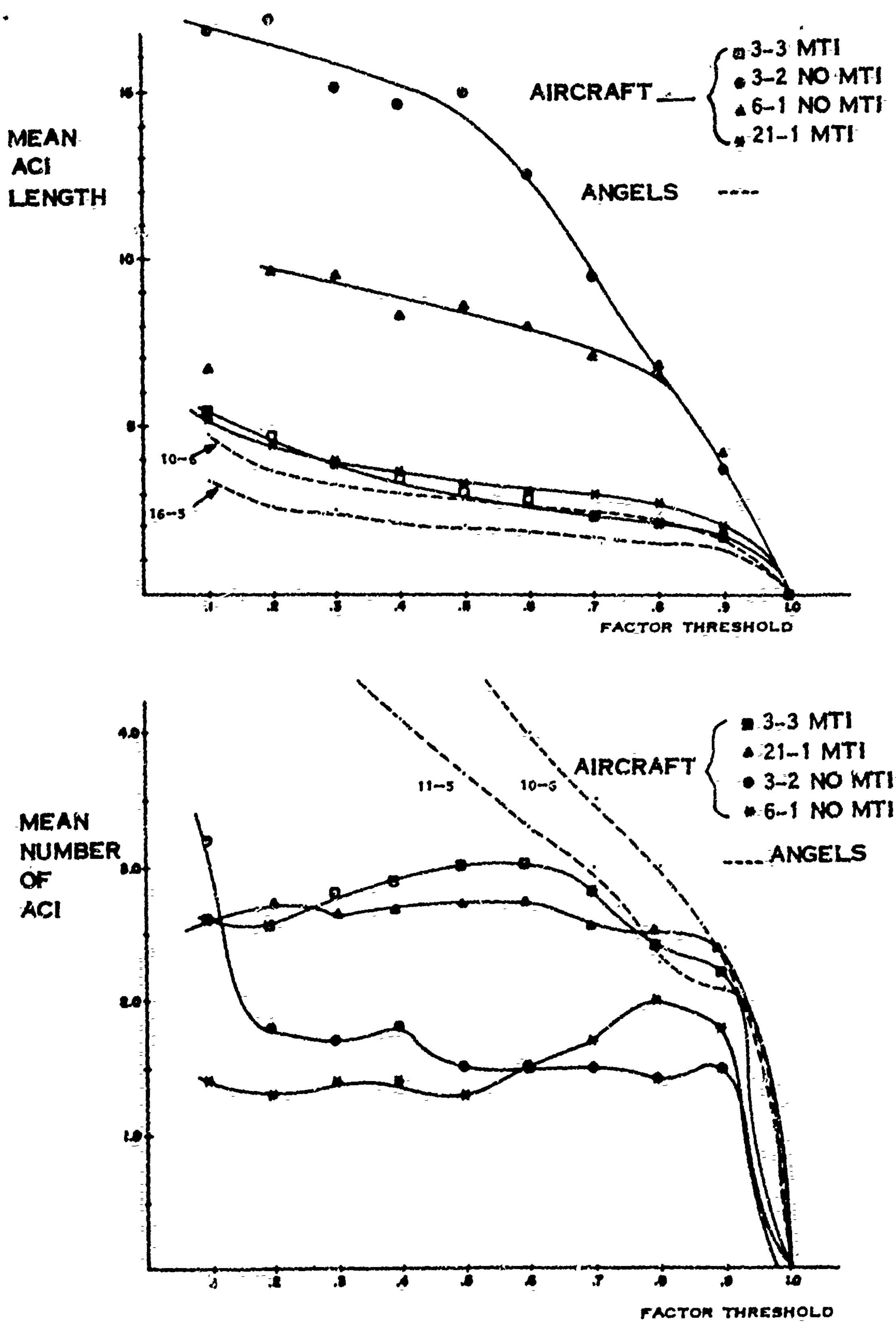


FIGURE 3-24 MTI/NON-MTI ACI ANALYSIS FOR MILWAUKEE DATA

(indicating that average ACI may be a characteristic of the MTI). The number of ACI's of aircraft for MTI and non-MTI aircraft retain their distinctive constantness, however, indicating this characteristic is representative of the target and not signal processing. Thus, the dual threshold technique should remain effective in the MTI region or in the normal region.

Similar plots were made using the MTI data collected at Baltimore (Figure 3-25). These plots verify the conclusions drawn from the Milwaukee data, namely, that the number of ACI's is a constant function of threshold, while the average ACI function appears to be almost identical to that obtained in Milwaukee. The analysis was performed using every pulse, and every other pulse (even or odd pulses) to compare the effect of the two sampling techniques. No significant difference was noted for the even and odd sampling techniques. The number of ACI doubled for the every-sweep data, while the average number of pulses per ACI (ACI length) remained the same as the alternate-sweep data. This implies that sampling on alternate sweeps causes loss of one missing pulse per ACI. Since the average ACI length is on the order of three continuous or alternate pulses (three alternate pulses are collected over six radar sweeps), the data implies that there are an average of two missing pulses for every six sweeps of MTI return data for the aircraft observed at Baltimore.

Processor Simulations on Baltimore Data

To gain a quantitative appreciation of the effect of the MTI on the various processors so far discussed, the several azimuth pattern processors were simulated using this new data. Figure 3-26 indicates that operating with the Baltimore aircraft data and Milwaukee angel data, the M/M azimuth correlation remains

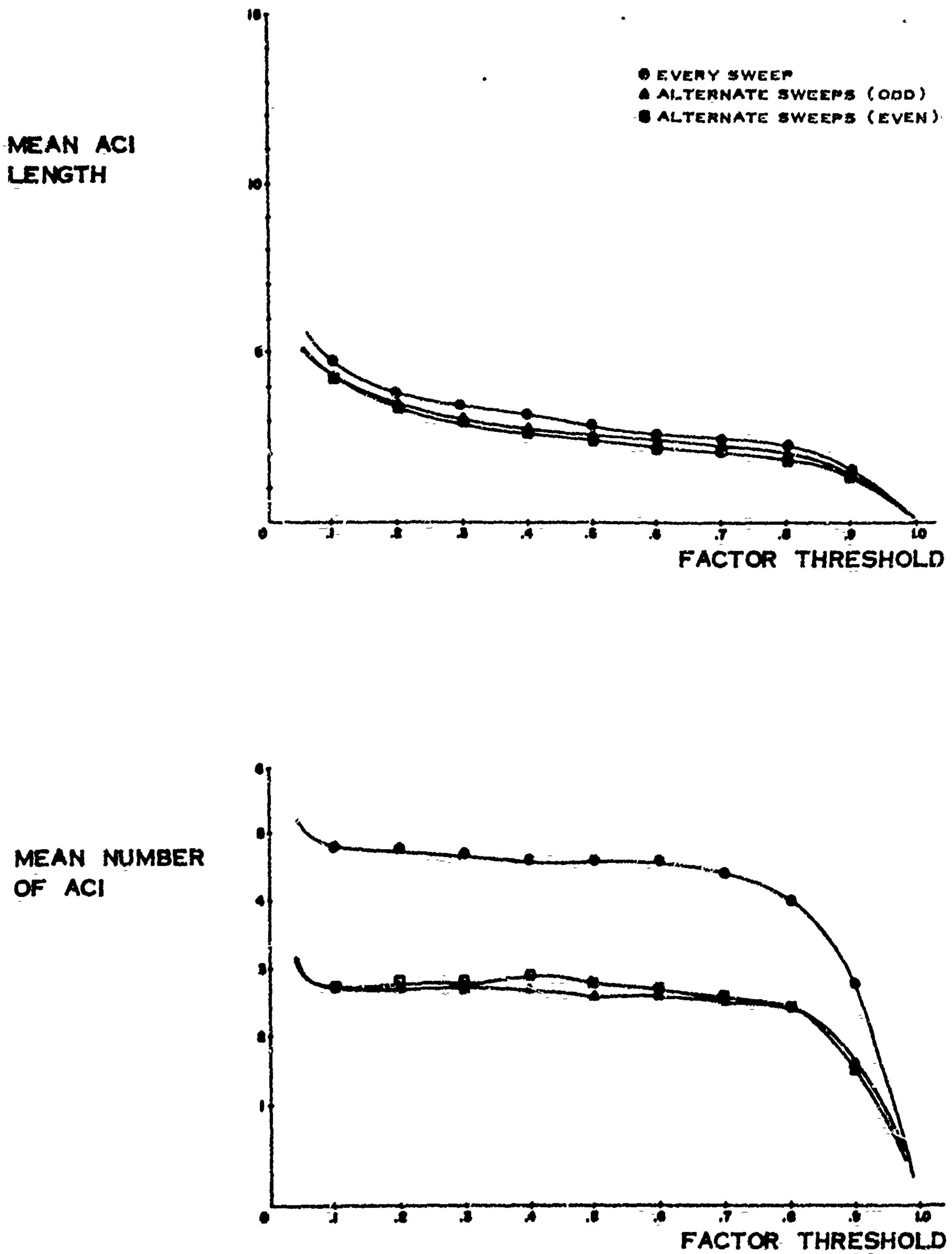


FIGURE 3-25 ACI ANALYSIS OF BALTIMORE MTI AIRCRAFT DATA

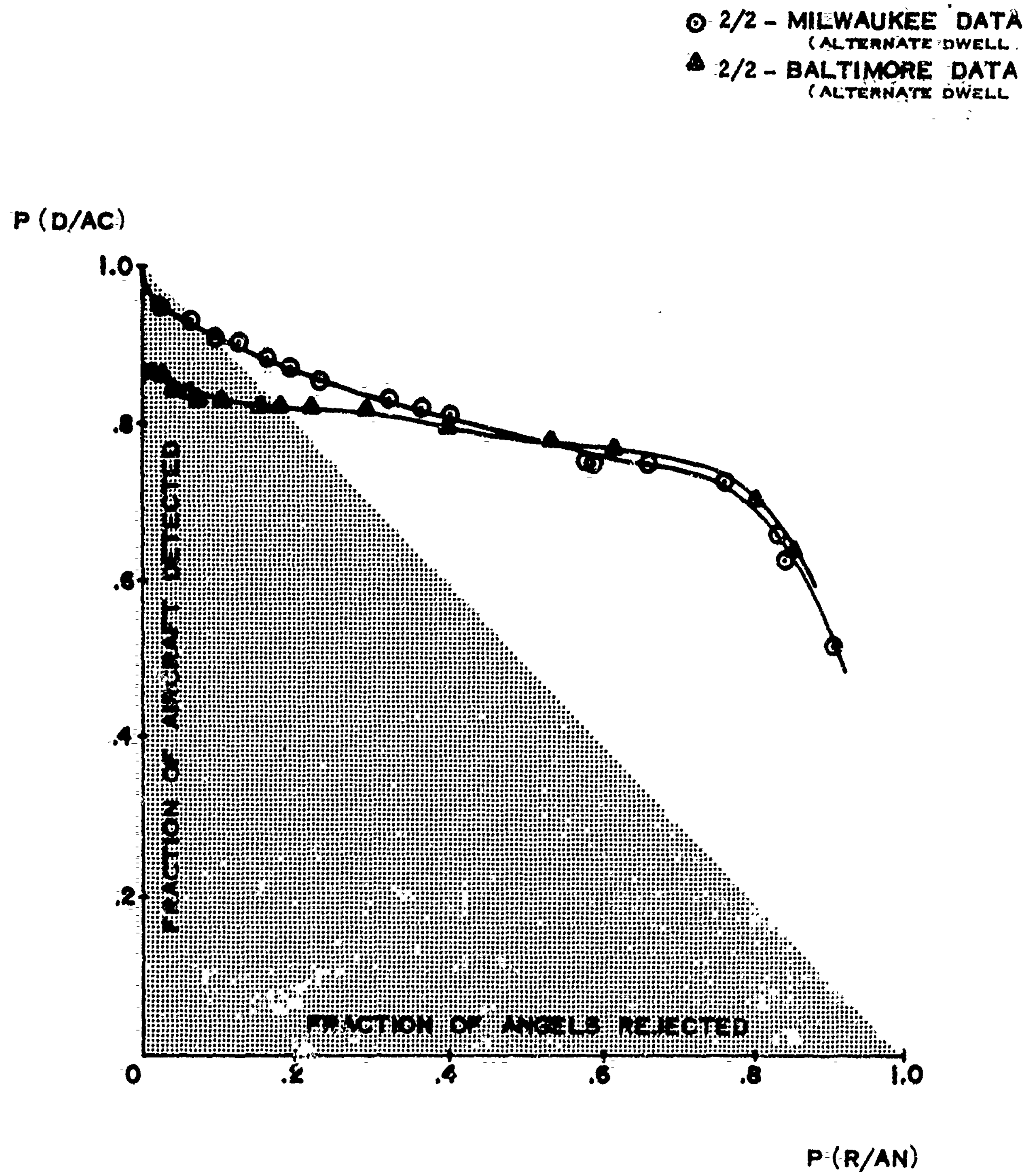


FIGURE 3-26 PERFORMANCE CURVE FOR M/M AZIMUTH CORRELATOR ON MTI VIDEO

relatively effective even with MTI video, although some degradation is found. The degradation is undoubtedly due to the reliance of this processor on the average ACI of a target which for MTI aircraft and angels are similar.

Since the dual threshold discriminator operates on the number of ACI rather than ACI length, it should not be degraded by exclusive use of MTI as was the ACI length discriminator (M/M azimuth correlator). The dual threshold discriminator performance curve is shown in Figure 3-27. Here again there is a drop in target detection performance but it is much smaller (5%). This variation could well represent a difference between the aircraft radar signature of the twin-engine Beechcraft B95 used at Baltimore and the radar signatures of the Milwaukee aircraft, or may represent a mismatch in gain setting between the two radar sets. Also, the MTI circuitry for the two radars are not exactly the same. This however, demonstrates that the dual threshold discriminator is reasonably robust with respect to aircraft and video types if its parameters are properly adjusted.

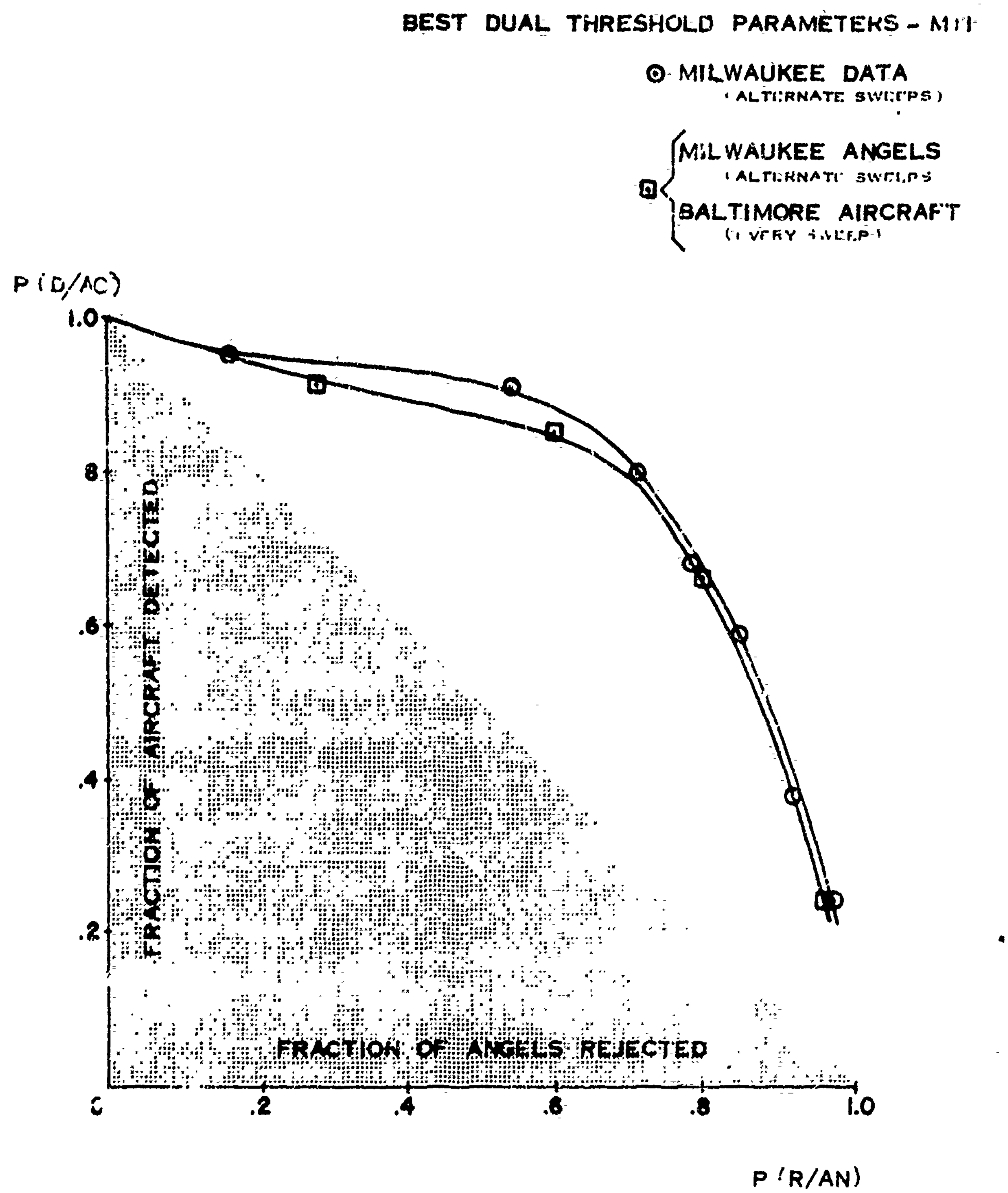


FIGURE 3-27 PERFORMANCE CURVE FOR DUAL THRESHOLD ON MTI DATA

3.7 Pattern Recognition Analysis

The techniques considered thus far in this chapter have utilized one characteristic feature or another of the radar returns from angels and aircraft to distinguish the two target types. There exists, however, a systematic technique for simultaneously analyzing a large number of characteristics to arrive at a more appropriate identification of target types. This technique, called pattern recognition, makes use of information from several target characteristics, so that while one feature may fail to clearly identify the target type, another feature may contribute significant information, substantially improving the possibilities of correct identification. Thus the combined effect of using several features simultaneously should lead to improved target selection.

The Bendix Corporation Communications Division has developed and applied pattern recognition techniques to a number of diverse problems in the past. After discussing the applications of Bendix pattern recognition work to the angel clutter problem, it was decided to use the angel clutter data collected at Milwaukee to evaluate the possibility of employing their pattern recognition algorithms for angel clutter reduction. With the concurrence of the FAA, a very modest subcontract was issued to Bendix for the task and the angel clutter data from Milwaukee was provided in the form of punched cards representing the azimuth pattern amplitudes for the strongest range cell on each scan of angel and aircraft data.

A simplified discussion of the pattern recognition approach used by Bendix is contained in Appendix D , as is the Bendix report on the effort performed in support of this study.

3.7.1 Approach

The first step in developing a pattern recognizer is to select a set of N features associated with each target. For this study, the features consisted of azimuth pattern amplitudes and a number of other quantities derived from these amplitudes. Each scan of data can then be described by a feature vector in N-dimensional space, and the goal of pattern recognizer development is to partition this feature space into regions uniquely associated with each class of target that must be identified. The partition is called a hyperplane.

Once the features are selected, a portion of the data, called the training set, is used in the learning phase to train one or more hyperplanes which can then be used in the testing phase by the recognizer. The learning phase involves selecting weighting factors for each feature; the training set is iterated until the weighting factors converge to final values and the training set is processed with minimum error.
In this study, positive weights are assigned to features predominately associated with aircraft, and negative weights to angels. Regardless of sign, the higher the weight, the more effective the feature for pattern recognition in the same feature set considered.

Thus the pattern recognizer approach provides several benefits for a study of this type:

a) it permits evaluation of the simultaneous use of several different techniques (features); up to 36 features were considered here, and

b) the weights developed in training a hyperplane give a measure of the relative effectiveness of each feature (among the features used in the same set) for identifying (detecting) aircraft <u>or</u> identifying (rejecting) angels.

This approach also has several disadvantages. The training set must be a representative sample of the two classes of targets, or else the recognizer will perform poorly on new (unknown identity) data. A large training set is desirable, and care must be taken in the training process to prevent "overtraining" situations where the recognizer begins operating upon secondary characteristics of the data that may not be present in new data sets.

Selection of the proper feature set is a critical portion of such work. The feature set can be selected in many ways, each one of which will lead to a different hyperplane (in a different feature space) and therefore a different decision algorithm. The actual choice is a matter of experience, as no systematic approach exists for *a priori* determination of which feature sets are relevant. The limited scope of the Bendix contract did not permit optimization of the many possible features. Instead, three feature sets were selected to permit initial evaluation of the technique:

a) Amplitude Features - this features set consisted of the 20 ASR pulse amplitudes in a single range cell of the data collect matrix

b) Statistical Features - this set consisted of 16 features derived from the 20 ASR pulse amplitudes: standard deviation, maximum and average amplitude, the dual threshold technique with several threshold combinations, and a consecutive-hit process with several thresholds.

c) Combination of Amplitude and Statistical Features - this set consisted of all 36 features listed above.

Once the feature set has been selected, the type of hyper-surface to be used must be chosen. For most cases, only a single hyperplane was trained and tested. However, for a few more promising feature sets, a multiple hyperplane decision algorithm was developed, requiring the training of several hyperplanes. In all, 37 different hyperplanes were trained in the course of the investigation.

3.7.2 Amplitude Features Set

The first step was to train a hyperplane on a selected set of the azimuth pattern amplitude data alone, to give some measure of the effectiveness of any extracted features when they are added later, as well as indicate any patterns which may exist in the data. Thus, as an initial feature set, twenty alternate ASR dwell amplitudes for the Milwaukee aircraft and angel data were derived by setting a fixed threshold of five to exclude receiver noise and using the next twenty amplitude samples. Each sample was labeled as to target type, i.e. angel or aircraft, and only representative samples of each target type were used for learning.

The next step before beginning the learning procedure is to choose initial values for the hyperplane parameters. Rather than choosing a zero vector (which generally requires a large number of iterations before convergence), a better choice is to select an initial hyperplane lying halfway between the average feature vectors associated with each target type. This hyperplane is calculated by subtracting these two average feature vectors.

The initial hyperplane parameters and the training data set are next given to the learning algorithm which uses the data to reorient this initial hyperplane to achieve a maximum number of correct target identifications. Eventually, successive iterations were seen to have only small effects on the hyperplane components so that training could be terminated and the hyperplane parameters stored. The resulting hyperplane can be plotted in terms of weights versus features; Figure 3-28 shows the hyperplane parameters stored after 32 iterations through the training set. The horizontal axis is the feature number (15 = the fifteenth amplitude sample after the initial threshold crossing) and the vertical axis is the weight assigned to each feature.

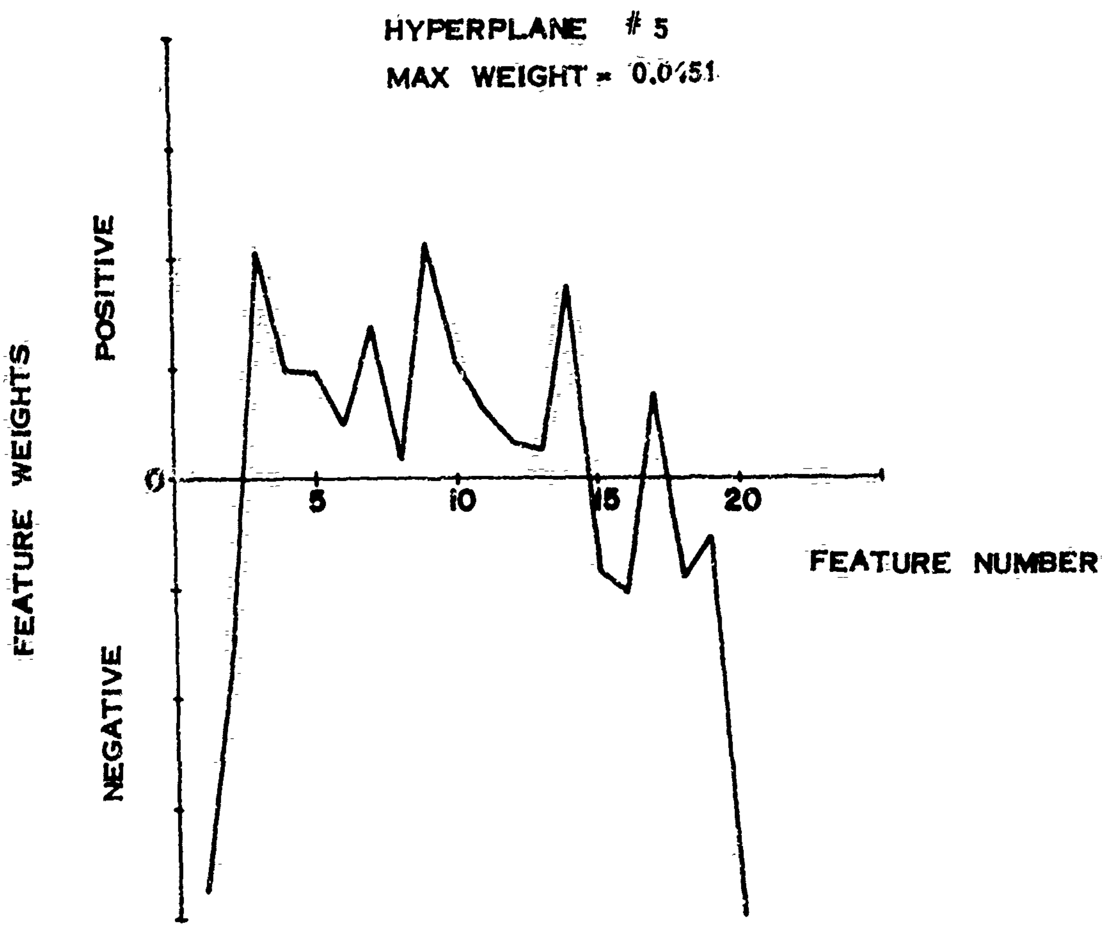


FIGURE 3-28 HYPERPLANE WEIGHTS FOR AMPLITUDE FEATURES SET

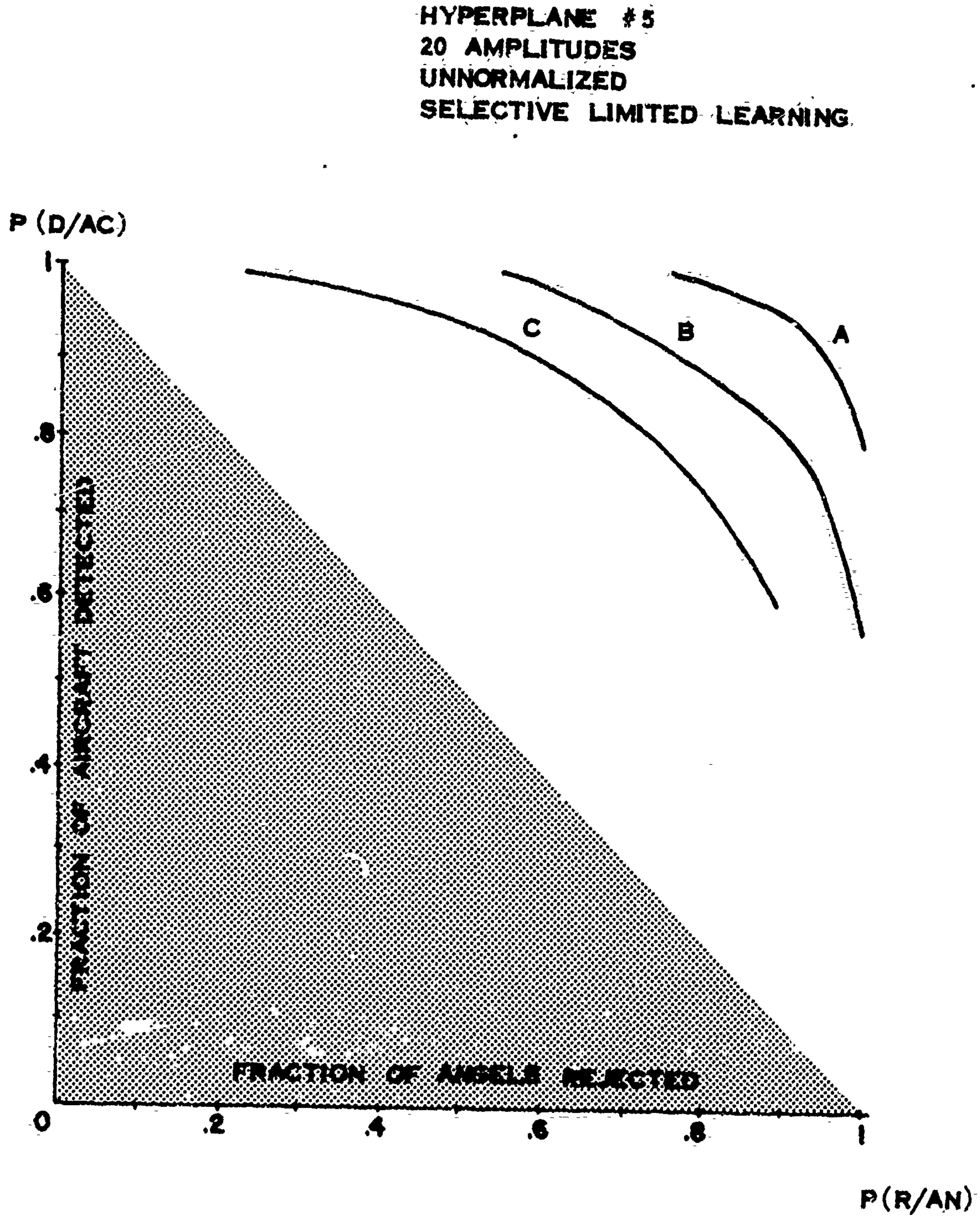
Negative weights indicate angel characteristics; positive weights, aircraft characteristics. Thus, the first and last amplitude samples are heavily associated with angels, while samples 3 through 14 are associated with aircraft. Remembering that the data is for every other sweep of the radar, this implies that the aircraft rarely exceeded 22 sweeps in width. On the other hand, sample 17 (sweep 34) is lightly weighted toward aircraft even though several adjacent samples are all associated with angels.

It is possible to develop an operating curve in terms of P(D/AC) vs P(R/AN) for a recognizer using this hyperplane by varying the distance of the hyperplane from the origin.* Figure 3-29 represents such a curve as obtained from three sets of data, the training set (curve A), selected "good" targets (curve B), and all data including anomalous cases (curve C). Curve A can be seen to be quite excellent, indicating that the learning algorithm did well on the training set. The inclusion of new targets (curve B) not used in the learning phase, lower the curve significantly, although the results are still excellent. The inclusion of the anomalous angel target MKE 16-1 and aircraft passing through MTI blind speeds (curve C), considerably lower the effectiveness of this recognizer until it is comparable to the curves found for the maximum amplitude detector discussed earlier. For comparison with the curves previously presented, curve C is the appropriate curve since it includes all the angel and aircraft data.

3.7.3 Statistical Features Set

The second approach considered was to find statistical features calculated from the sample data used in the previous section. Sixteen features were chosen with the objective of encompassing as many different characteristics of the returns as possible. Table VII lists the features selected in the order in which they appear on the feature vector plots.

*See Appendix D



A: TRAINING SET (167 AIRCRAFT SCANS / 168 ANGEL SCANS)
B: SELECTED GOOD TARGETS (258 / 168)
C: ALL DATA (680 / 260)

FIGURE 3-29 PERFORMANCE CURVES FOR AMPLITUDE PATTERN RECOGNIZER

TABLE VII

STATISTICAL FEATURES SET

No.	Name	Description
1	STD	Standard deviation of 20 amplitude samples
2	Max Amp	Maximum amplitude of 20 amplitude samples
3	Ave Amp	Average amplitude of 20 amplitude samples
4	DT 10/5	Dual thresholds of 10 and 5; the feature used for pattern recognition was the difference in number of ACI recorded at the upper and lower thresholds.
5	DT 15/5	
6	DT 15/10	
7	DT 20/5	
8	DT 20/10	
9	DT 20/15	
10	DT 25/5	
11	DT 25/10	
12	DT 25/15	
13	DT 25/20	
14	ACI -8	Azimuth Correlation Interval Length ≥ 8
15	ACI-12	ACI length ≥ 12
16	ACI-16	ACI length ≥ 16

The first hyperplane trained on this feature set was unable to achieve zero error in the training set. When this occurs, it is possible to add other hyperplane decision rules to form a sequential decision structure, with each subsequent hyperplane operating on the portion of the data that could not be identified by the preceding hyperplane. This is done by selecting two thresholds in the decision process which bracket the difficult cases so they can be passed on the next sequential hyperplane. When this was done, it was found that the second hyperplane also made errors on the training set. Figure 3-30 shows the first two hyperplanes during the learning process.

When the average feature vectors were calculated at the start of the third hyperplane training, they were found to be almost identical. Since this implies that the third hyperplane would have little effect, it was concluded that further training was unlikely to make clear-cut decisions possible.

From the results, Bendix concluded that the extracted statistical features were not alone sufficient to handle the angel/aircraft discrimination problem, so the next step was to combine the 20 matrix amplitude features and the 16 statistical features into a combined set of 36 features for further analysis.

3.7.4 Combination Features Set

As neither the amplitude feature set nor the statistical feature set were wholly successful in separating targets in the training set, a combination feature set was formed. The first 20 components of these vectors represent the twenty data samples and the last 16 components, the statistical features. Figure 3-31 is the final hyperplane resulting from 29 iterations. Figure 3-32 illustrates the operating curve obtained for this hyperplane, when applied to the training set and to the selected data set (excluding anomalous cases). Clearly, this hyperplane performs much better than either of the two types of feature set previously considered. It is interesting to note that for this training data

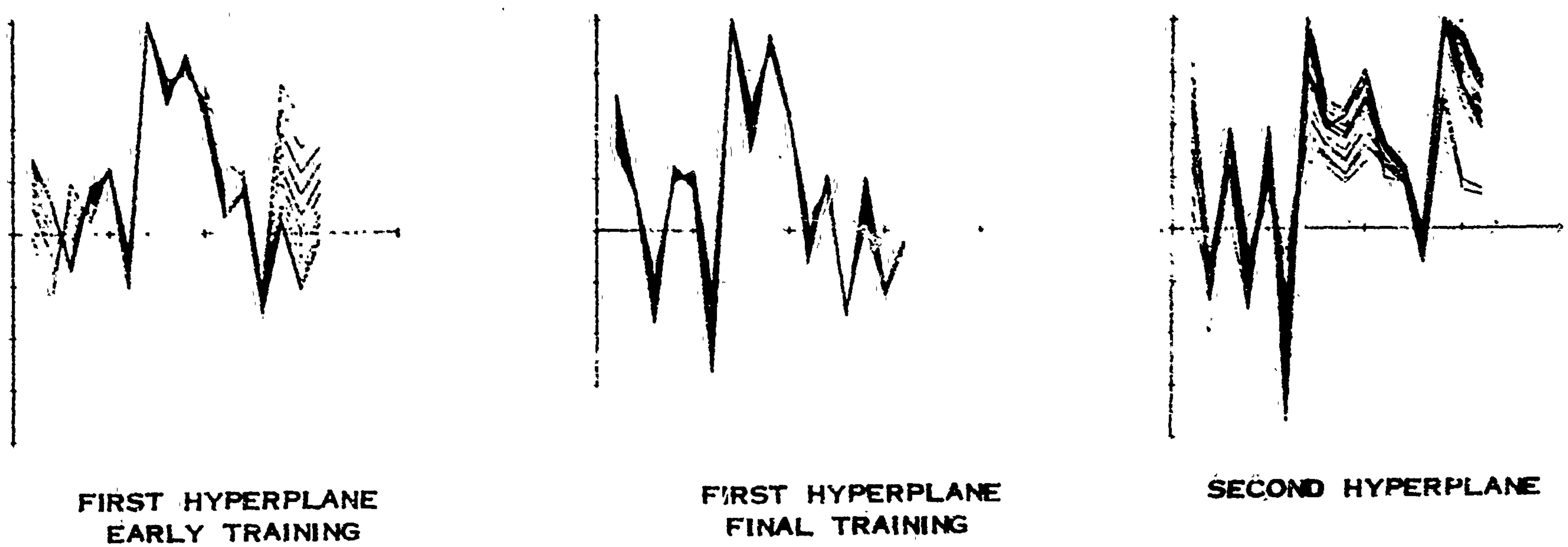


FIGURE 3-30 HYPERPLANE TRAINING FOR STATISTICAL FEATURES SET

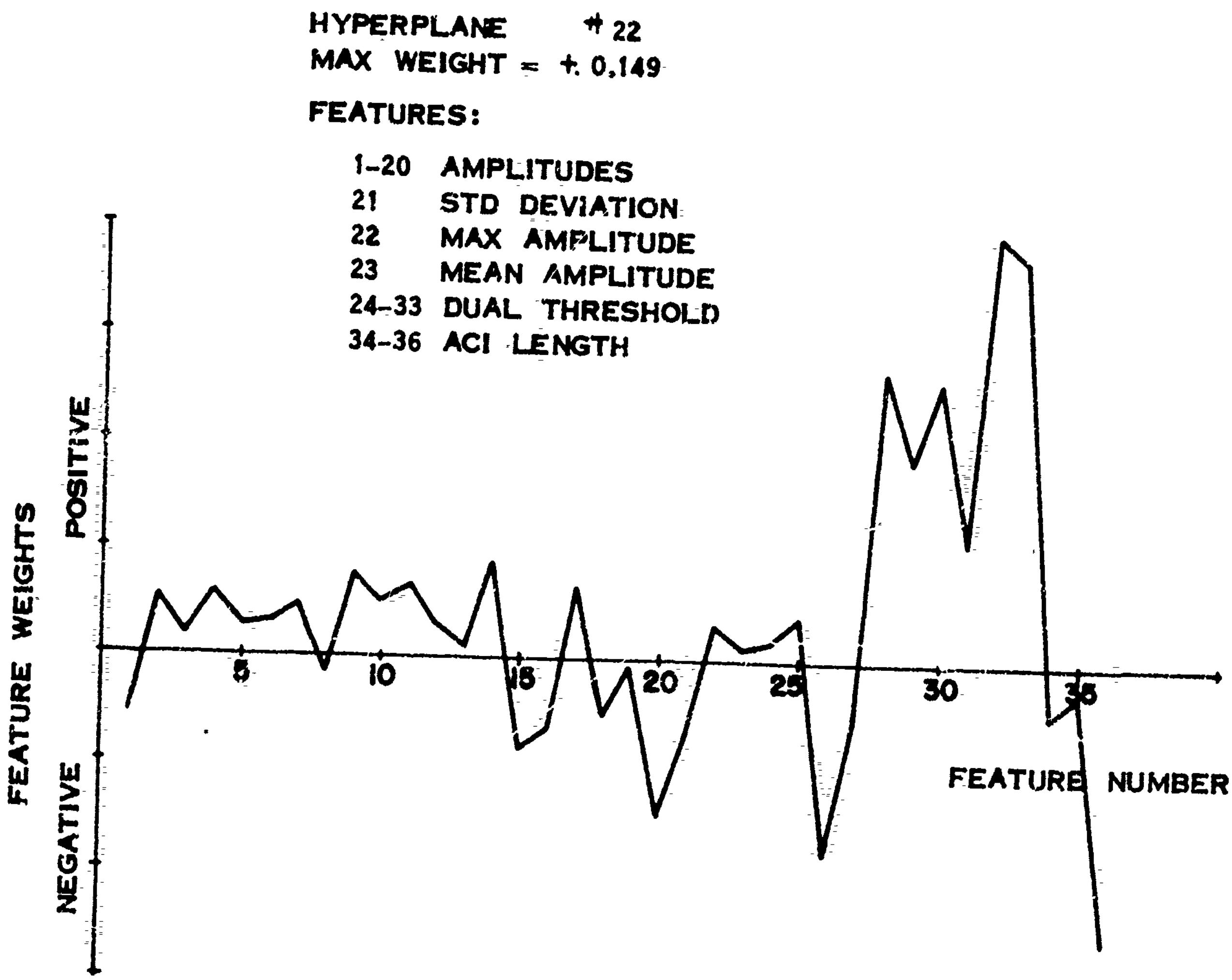


FIGURE 3-31 HYPERPLANE WEIGHTS FOR COMBINED FEATURES SET

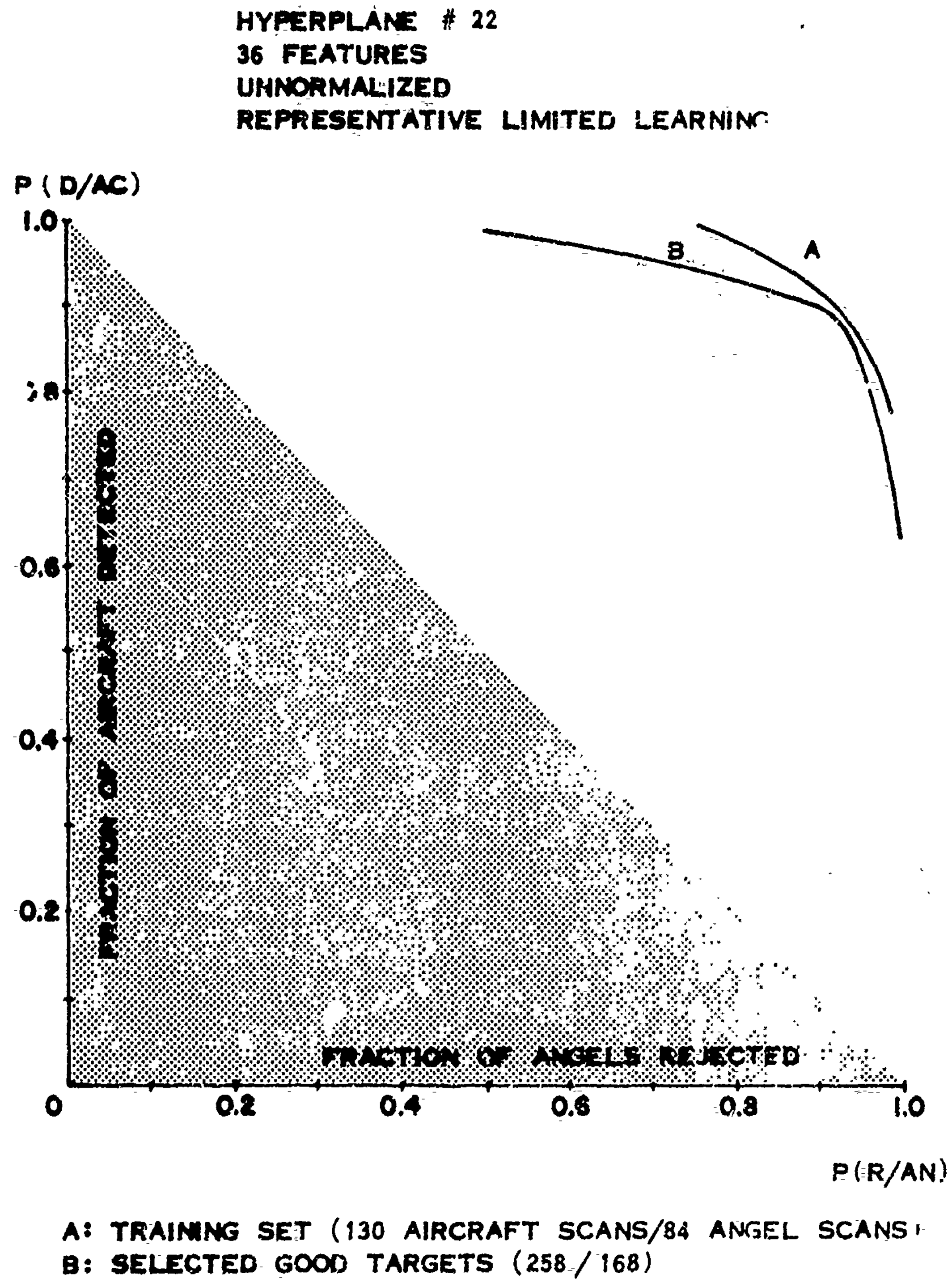


FIGURE 3-32 PERFORMANCE CURVES FOR COMBINED FEATURES SET, SINGLE HYPERPLANE

the statistical features were most heavily weighted, indicating that statistical characteristics were more effective than amplitude characteristics for discrimination between angels and aircraft.

Spurred on by the success of this hyperplane, the sequential hyperplane approach was next investigated for the combined 36 features, each successive hyperplane being trained on the errors of the preceding hyperplane. Figure 3-33 shows the final four sequential hyperplanes developed. It is interesting to note that the statistical features are most heavily weighted for the earlier hyperplanes, but as more difficult targets are handed down from hyperplane to hyperplane, amplitude samples become more important. For the last hyperplane, amplitude samples are weighted equally or more heavily than the statistical features. Thus it appears that both amplitude and statistical features are necessary to correctly separate target types. Figure 3-34 is the set of operating curves for these four hyperplanes on the training set. Point A shows 100% correct selection on the training set. Curve B is for all "good targets", i.e those with no MTI blind zones and excluding anomalous targets such as angel 16-1. Point C is a single calculation performed on the anomalous angel (MKE 16-1) and those aircraft tracks flying through MTI notches. It can be seen that the anomalous target does still appear to be an aircraft, reducing the rejection rate for this target and while the MTI notch can be seen to reduce aircraft detections, the effect is not major. Curve D shows the results for all data.

Table VIII lists the relative weights of the ten most-heavily weighted features for the four hyperplanes used in this recognizer. This permits assessment of the most effective features within each hyperplane (those with the heaviest weights), and whether the feature is aircraft-selective (positive weight) or angel-selective. Since subsequent hyperplanes operate on returns that cannot be categorized by the previous hyperplane, the heavily-weighted features in a following hyperplane are effective on returns that the previous hyperplane cannot identify. Unfortunately it is

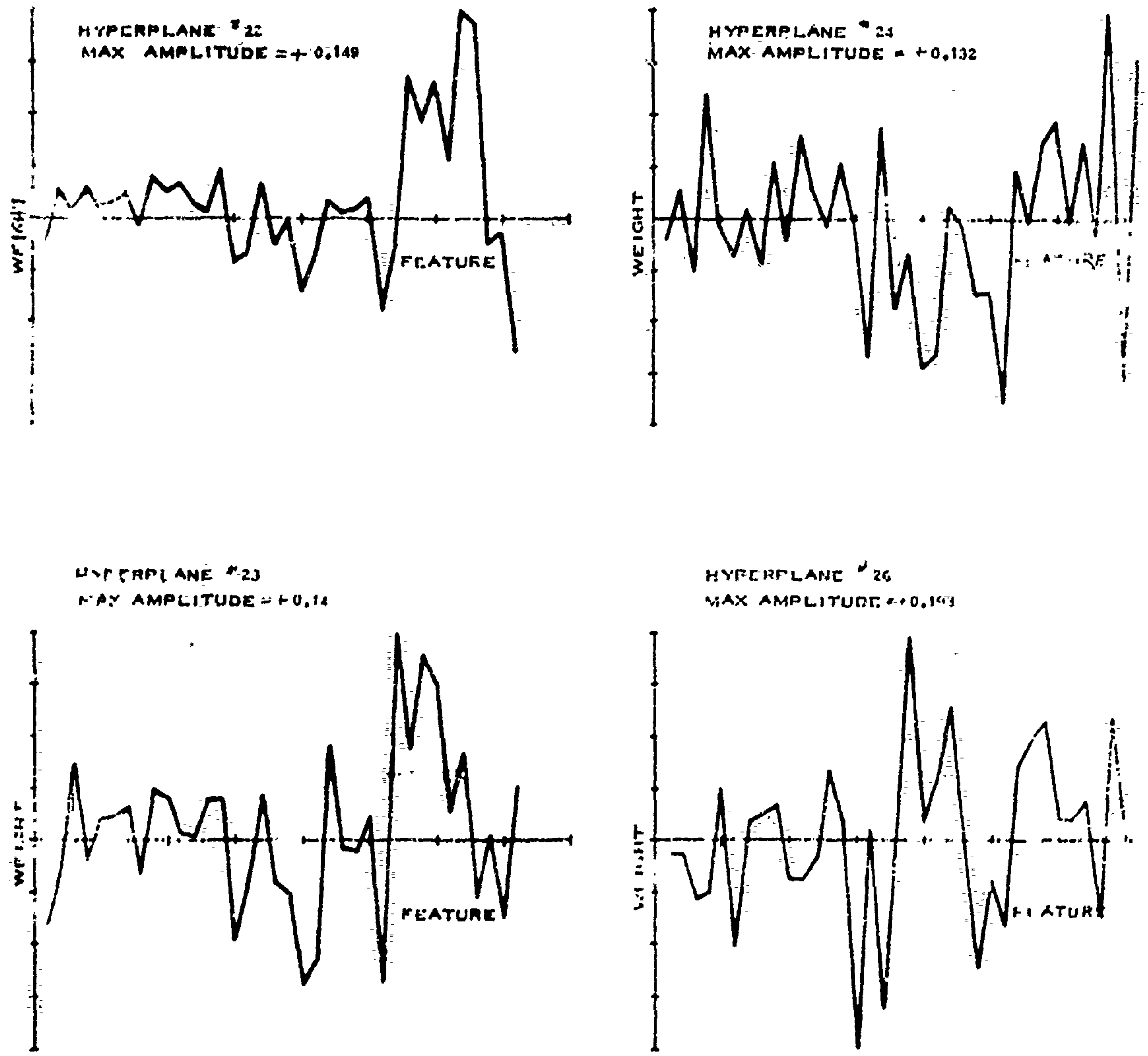
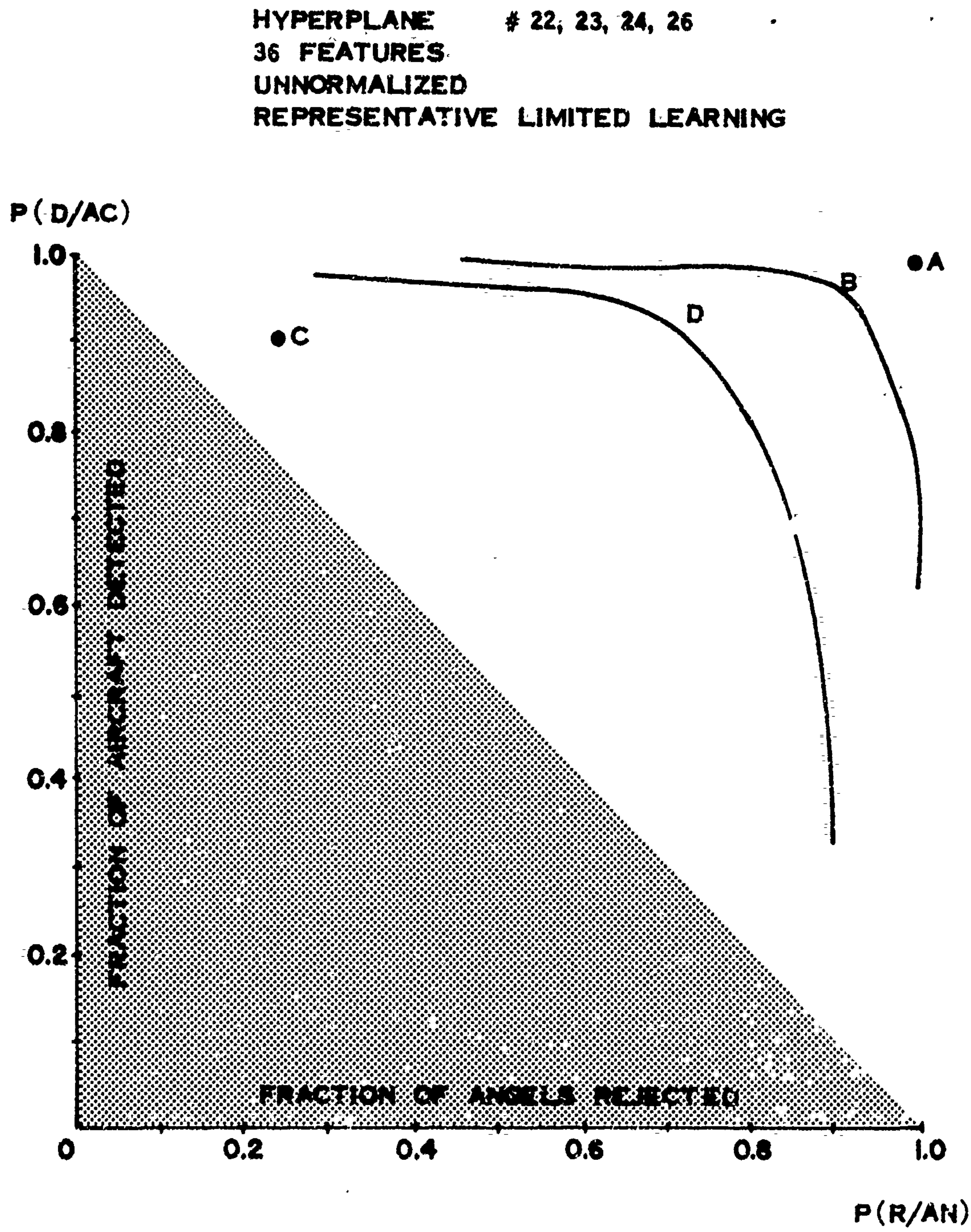


FIGURE 3-33 FOUR SEQUENTIAL HYPERPLANES DEVELOPED FOR COMBINED FEATURES SET



A: TRAINING SET (130 SCANS AIRCRAFT/84 SCANS ANGELS)
B: SELECTED GOOD TARGETS (259 / 168)
C: ANOMALOUS TARGETS ONLY (401 / 82)
D: ALL DATA (660 / 250)

FIGURE 3-34 PERFORMANCE CURVES FOR COMBINED FEATURES SET, SEQUENTIAL HYPERPLANES

TABLE VIII

HIGH-WEIGHT FEATURES IN FOUR SEQUENTIAL HYPERPLANE RECOGNIZER

Rank	First Hyperplane (#22)		Second Hyperplane (#23)		Third Hyperplane (#24)		Fourth Hyperplane (#26)	
	Weight	Feature	Weight	Feature	Weight	Feature	Weight	Feature
1	+1.0	DT 25/15	+1.0	DT 20/5	+1.0	ACI L=8	-1	AMPL #15
2	+.92	DT 25/20	+.89	DT 20/15	-.89	DT 15/10	+.98	AMPL #19
3	+.67	DT 20/10	+.76	DT 25/5	+.79	ACI L=16	-.82	AMPL #17
4	+.64	DT 25/5	-.69	DT 15/10	-.75	ACI L=1[illegible]	+.64	MAX AMPL
5	-.63	ACI L=16	-.68	AMPL #20	-.70	AMPL #20	-.62	DT 10/5
6	+.47	DT 20/15	-.57	STD.DEV.	-.66	AMPL #16	+.59	ACI L=8
7	-.44	DT 15/10	-.48	AMPL #15	-.65	STD.DEV.	+.56	DT 20/15
8	-.33	AMPL #20	+.45	MAX AMPL	+.62	AMPL #4	-.53	AMPL #6
9	-.29	DT 25/10	+.43	DT 25/15	+.47	DT 25/5	-.43	STD
10	+.22	AMPL #14	-.43	AMPL #1	+.45	AMPL #12	-.37	DT 25/20

DT 25/15 = Dual Thresholds of 25 and 15

AMPL #1 = First Amplitude Sample Above Threshold of 5

ACI L=8 = Minimum Azimuth Correlation Interval Length = 8 virtually impossible to isolate the contribution of each feature to identification of a particular target in the data at this stage of the analysis, but several interesting points can be made from Table VIII:

a) The dual threshold has seven of the top ten weights on the first hyperplane. Two dual thresholds, 15/10 and 25/10, are angel recognizers while the other five recognize aircraft.

b) Amplitudes 20 and 14 of the first hyperplane apparently are recognizing targets by their azimuthal width; amplitude 14 (28 sweeps after first detection) implies aircraft and amplitude 20 (40 sweeps) implies angels. The ACI length 16 (32 sweeps) is also associated with wider azimuthal returns from angels; it is weighted about as heavily negative as the two preceding dual thresholds (20/10 and 25/5) are weighted positive. Six of the ten top features are weighted positive (aircraft recognizers) and four are negative.

c) The second hyperplane has weights which fall off more slowly than the first. There are five dual thresholds, four with positive weight and two of the same ones used in the first hyperplane, and five amplitude-related features. All the amplitudes (1, 15, and 20) are weighted toward angels, as is the standard deviation, but the maximum amplitude is weighted toward aircraft.

d) The third and fourth hyperplanes continue the emphasis on amplitude-related measures. All three ACI lengths are present in the third hyperplane; it is interesting to note that L=12 is an angel recognizer while L=8 and 16 are aircraft recognizers.

e) Table IX lists the features which were consistently weighted (at least 3 of the 4 hyperplanes) toward either angels or aircraft. While there is some overlap in the amplitudes #8, 16, and 17 (sweeps 16, 32, and 34) the rest of the features bear out the expected trend. Only those dual thresholds which are close together consistently detect angels (20/15 is an exception). Maximum amplitude operates on aircraft, while both the standard deviation and average amplitudes are weighted toward angels.

There is one additional useful output to be gained from the pattern recognizer described above. Every target will be successively processed by the four hyperplanes. The number of hyperplanes required to identify the target, is a direct indication of the difficulty involved in identification. Thus some indication of the decision can be indicated by noting which hyperplane actually made the target type declaration. If the first hyperplane is sufficient to make an identification, there is high confidence that a correct identification was made. If all four hyperplanes are required, the decision should be considered tentative. This data could therefore be used to indicate the level of confidence to be placed in the assigned target identification.

TABLE IX

CONSISTENTLY WEIGHTED FEATURES

	AIRCRAFT RECOGNIZERS		ANGEL RECOGNIZERS	
	Positive Weights		Negative Weights	
Number of Hyperplanes	4/4	3/4	4/4	3/4
Amplitudes	#5,7,9,13	#11,12,14,17	-	#8,16,18,19,20
Run Length	20/10, 20/15 25/5, 25/10, 25/15	20/5	15/10	10/5, 25/20
ACI	-	-	L=12	-
OTHER	MAX. AMPL.	-	-	STD. DEV. AVG. AMPL.

3.7.5 Relative Performance of Pattern Recognizer Techniques

Figure 3-35 shows the performance of the five azimuth pattern processors described in this Chapter. The Pattern Recognizer curves apply to the case where all data was used since this case also applies to the Dual Threshold and M/M Azimuth Correlator curves. As previously indicated, the pattern recognizers operated on 20 alternate-dwell samples, while one dual threshold operated on 37 alternate dwells and the other operated on ten samples.

The most complex processor (36 combined feature, 4 hyperplane pattern recognizer) provided markedly better performance than the others, maintaining aircraft detectability in excess of 95% out to about 60% angel rejection; P(D/AC) remains in excess of 80% for 80% angel rejection.

The simpler pattern recognizer (20 amplitudes, one hyperplane) performs slightly better than the dual threshold. Table X compares all five processors in terms of angel clutter reduction for fixed probabilities of aircraft detection of 0.8, 0.9, and 0.95. The values are somewhat approximate in that they were read from the respective performance curves.

It should be noted that one of the angel tracks (#16-1) consistently resembled aircraft azimuth patterns. This angel track represented about 22% of the angel data base, and all azimuth pattern processors had rapidly decreasing aircraft detectability for the last 20% of angel clutter rejection. Clearly, the extension of these performance curves to represent all angels (even bird angels) that may be encountered is justified only to the extent that the present data base (for both angels and aircraft) is representative. The best way to verify the trend of these results is to run each processor against all angels and (representative) aircraft seen at an operational ASR site. This is particularly important for a Pattern Recognizer, since the hyperplane weights must be derived by

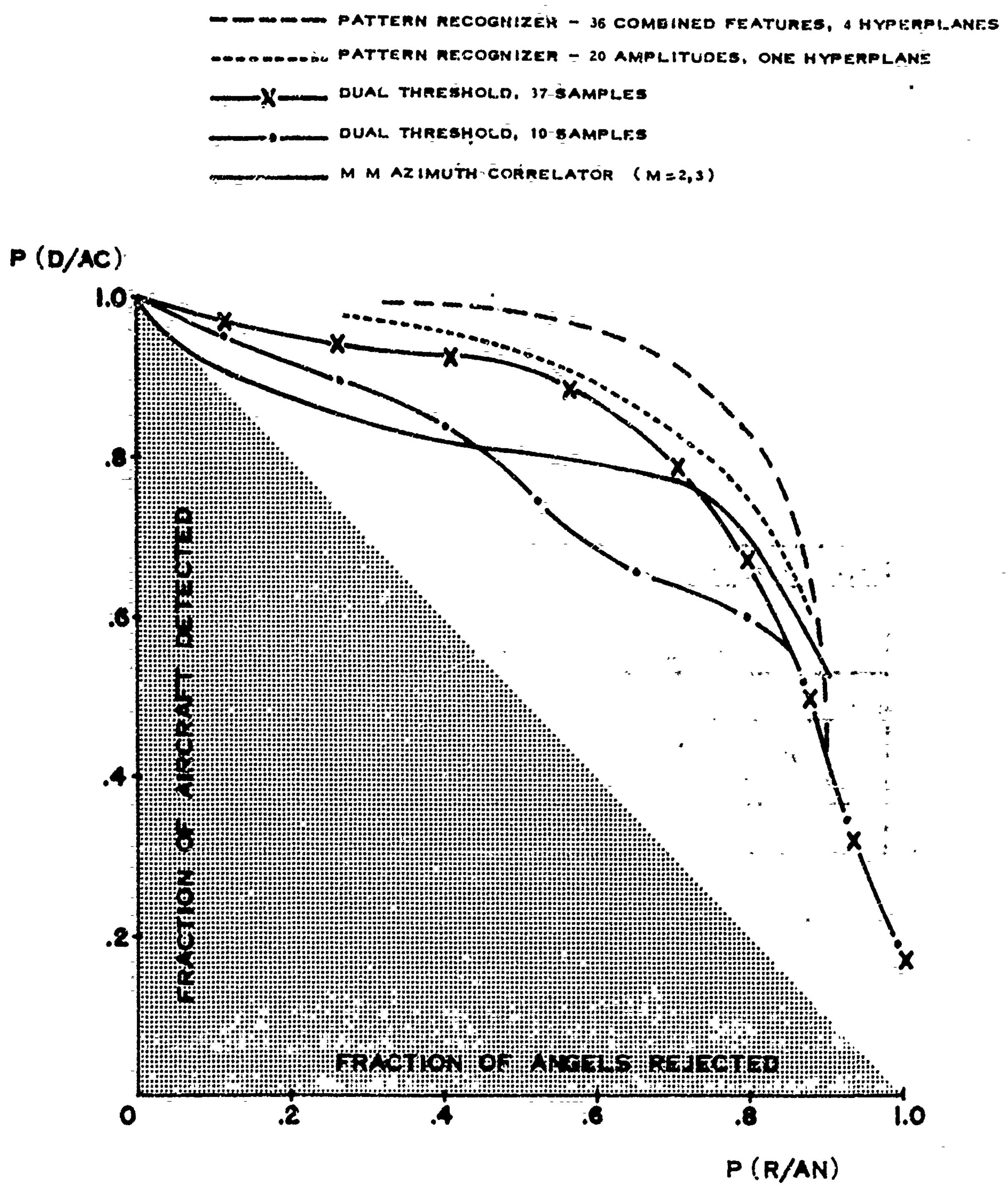


FIGURE 3-35 RELATIVE PERFORMANCE OF AZIMUTH PATTERN PROCESSORS

TABLE X

ANGEL CLUTTER REJECTION OF AZIMUTH PATTERN PROCESSORS

	P(D/AC)		
	0.8	0.9	0.95
Pattern Recognizers			
I 36 Combined Features, 4 Hyperplanes	82%	73%	64%
II 20 Amplitudes, One Hyperplane	75	59	45
Dual Threshold			
I 37 Alternate Dwells	70	54	20
II 10 Samples/37 Alternate Dwells	46	26	12
Azimuth Correlator			
M/M= 2/2 or 3/3	55	13	4

selecting a learning set of data which must be representative of the actual angel and aircraft targets which will be encountered.

A final comment on the utility of these performance curves should be made. While values of P(D/AC) and P(R/AN) are indicative of processor performance on the data set, they are not necessarily indicative of the ability of the radar observer to detect aircraft in angel clutter, since it is the <u>number</u> of angels remaining (rather than the <u>percentage</u>) that determines the difficulty of detecting aircraft. Appendix C-1 contains an analysis of an operator performance model which attempts to put these factors into proper perspective.

CHAPTER 4

ANGEL CLUTTER REDUCTION TECHNIQUES

The goal of this study is to postulate an angel clutter reduction system that is cost-effective for the ASR-4, 5, and 6 radars. Cost considerations preclude extensive redesign of the radar, while effectiveness implies the ability to substantially improve surveillance of small (as well as large) aircraft in regions of angel clutter.

Chapter 3 indicated that radar cross section, azimuth pattern, and velocity are major angel/aircraft discriminants, and that a combination of these discriminants is required for effective operation. The purpose of this chapter is to describe a feasible angel clutter reduction system design for the ASR which utilizes these discriminants and which can be implemented in a cost-effective manner. The suggested system uses a modified STC/receiver gain control function for RCS discrimination, slight modifications of the present ASR doppler MTI for range rate discrimination, an Azimuth Pattern Processor, and a Scan History Display for velocity discrimination. The first two features represent minor radar modifications, while the last two are add-on devices for processing radar video. Each of these functions is enabled only at short ranges by means of an Rmax control, which is used to return the radar to its normal configuration beyond the region of angel clutter. Sections 4.1 through 4.4 discuss each of the four techniques in detail. Section 4.5 then summarizes the complete system and identifies further steps required to determine the most appropriate operational configuration. Finally, Section 4.6 briefly discusses techniques which were considered and rejected for this application.

CHAPTER 4

ANGEL CLUTTER REDUCTION TECHNIQUES

Page

4.1 Receiver Gain Control

The results of Section 3.2 showed that the radar cross-section (RCS) of most angels is generally much less than that of small aircraft. The average measured RCS for the angel tracks was about $0.1m^2$ with maximum values on the order of 1 or $2m^2$. The Cessna 172 test aircraft had average RCS values on the order of a few square meters with minimum values of 0.5 to $1m^2$. Many smaller angels are detected on the ASR PPI due to excessive sensitivity at short range; these targets could be eliminated if the radar sensitivity is adjusted to permit detection only when the target exceeded a specified minimum RCS of, say 0.1 to 0.5 square meters.

Unfortunately, the target signal level in the ASR receiver is not directly related to RCS except at a fixed elevation angle, since the antenna pattern varies with elevation, and elevation of individual targets (aircraft or angels) is not generally available. The following paragraphs discuss the usefulness of sensitivity time control (STC) techniques for angel clutter reduction in light of these limitations imposed by the antenna pattern.

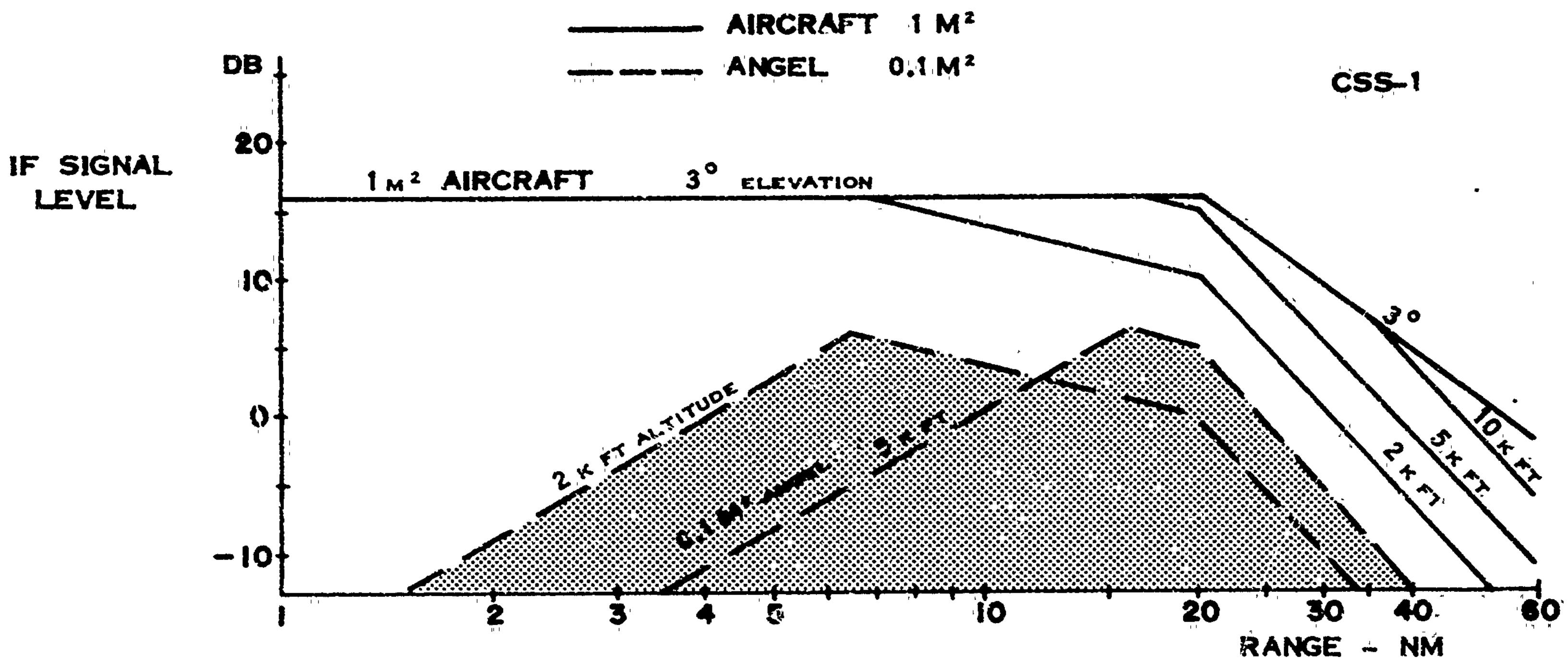
4.1.1 Received Signal Levels

The present ASR-series radars have three available sensitivity-time-control profiles: STC, CSS-1, and CSS-2. STC provides an operator-adjustable attenuation profile that can be changed to provide the best PPI display but an exactly-known profile cannot be provided. The CSS profiles provide specified attenuations at 5, 10 and 20 nmi; CSS-1 provides R^{-4} attenuation (an increase of 12 dB attenuation for a factor of two decrease in range) and CSS-2 provides R^{-3} attenuation. Based on measured angel clutter range dependence with STC off (Section 3.3), the R^{-4} profile of CSS-1 is most appropriate for maintaining angel clutter radar video at constant amplitude with range.
While the original design for the ASR provided STC/CSS gain reductions in the IF amplifiers, an RF STC utilizing a pin diode attenuator preceding the parametric amplifier was provided for the ASR-7 and

is being installed as a backfit for older ASR systems. The major difference in IF and RF STC is that the former attenuates receiver noise in exactly the same manner as the target, whereas the RF STC does not. This causes differences in the implementation of a calibrated sensitivity threshold, but does not affect the following analysis.

STC can be of some use for reducing angel clutter and retaining aircraft in spite of antenna gain variations with altitude. Most bird angels are confined to altitudes of 500 to 5000 feet, and most arriving and departing aircraft assume a glide slope of about 3^{o} within 10-15 miles of the air terminal. Most ASR installations accordingly place the peak of the elevation antenna pattern at the glide slope angle of 3^{o}, and this is the case we will analyze here.

Figure 4-1 shows the equivalent radar return levels using CSS-1 for a $1m^2$ aircraft and $0.1m^2$ angels as a function of altitude. The aircraft is assumed to be in a flight pattern which follows a constant altitude until it reaches the 3^{o} glide slope angle. The signal levels are shown relative to the MDS of the MTI receiver (-107 dBm) at long range (where STC attenuation does not occur). For simplicity, the effect of MTI target processing on signal strength is ignored. It is apparent from the figure that the $0.1m^2$ angel could be rejected if the radar threshold were set about 6dB above the long-range MDS level. The $1m^2$ aircraft return would exceed this threshold by ten dB, which is more than adequate for good detection. In Section 3.4.3, the effect of 6 dB of video attenuation was shown to reduce the number of angel detections on the Milwaukee ASR by 50% (670 to 325 detections); similar performance can be expected (while preserving video dynamic range) with IF attenuation. The appropriate STC characteristic would be CSS-1 and the threshold could be set by monitoring receiver noise (outside the STC region) and applying the necessary bias. This threshold should be applied only out to the maximum range of the observed angel clutter, say 0 to 10 to 20 nmi.



ODB = LONG RANGE MDS (-107 DBM)

FIGURE 4-1 ASR SIGNAL LEVELS FOR ANGELS & ARRIVING OR DEPARTING AIRCRAFT

The situation is somewhat different for aircraft which are overflying the radar (Figure 4-2). As the aircraft approaches the radar, its signal level will first increase until it reaches the peak of the antenna beam and then it will decrease as the antenna gain and receiver gain decrease. The $1m^2$ overflying aircraft at 10 Kft altitude has very nearly the same signal strength as the $0.1m^2$ angel at 5 Kft for ranges less than 15 miles, and the 5 Kft aircraft is weaker than the 2 Kft angel at ranges less than 6 miles. STC techniques provide no improvement in those regions where the antenna pattern produces a loss in aircraft signal strength which destroys the 10 dB RCS advantage enjoyed by the aircraft. Thus the 6 dB threshold improves detectability of aircraft on the 3^o glide slope but causes overflying aircraft to be lost as they approach short ranges. Table I indicates the ranges at which $1m^2$ aircraft and $0.1m^2$ angels would be above thresholds set at 0 dB and 6 dB (relative to long-range MDS) for the several cases considered in the figures.

TABLE I

RANGES AT WHICH RETURNS EXCEED THRESHOLDS
CSS-1, $1m^2$ aircraft, $0.1m^2$ angel

	Target Angle or Altitude	Threshold Relative to Long-Range MDS 0 dB	+6 dB
Aircraft	3^o	1-53 nmi	1-36
$1m^2$	10 Kft	10-45	16.5-36
	5 Kft	4.6-37	7.5-29
	2 Kft	1.9-30	3-24
Angels	5 Kft	10-24	Not detected
$0.1m^2$	2 Kft	4-20	Not detected

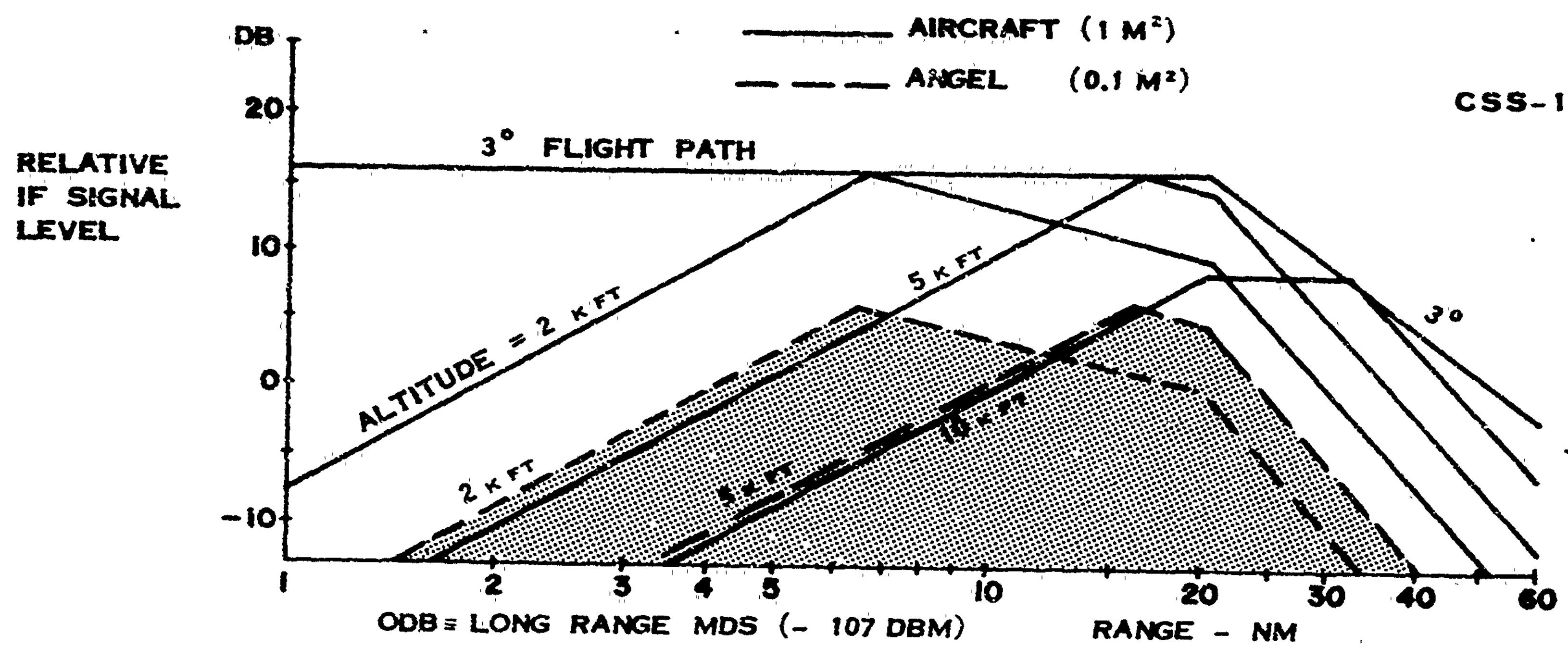


FIGURE 4-2 · ASR SIGNAL LEVELS FOR ANGELS AND OVERFLYING AIRCRAFT WITH NORMAL ASR ANTENNA

4.1.2 Received Signal Levels with Passive Receive Horn

A passive receive horn which provides an up-tilted receive antenna beam is being developed for the ASR. This technique will assist discrimination between aircraft and angels provided that the aircraft are above the altitude of the angels, which is a normal occurrence for many overflying aircraft.

Figure 4-3 shows the signal levels for a passive receive beam tilted 5° up from the transmit antenna beam (other values of uptilt can also be used). Table II indicates the ranges at which the targets are above the 0 dB and 6 dB thresholds previously discussed. Since the passive receive horn is switched in only for short ranges (0 to 10-20 nmi), the maximum range limitations indicated in Table II would not apply for targets at 5 Kft and above.

TABLE II

RANGES AT WHICH RETURNS EXCEED THRESHOLDS WITH PASSIVE RECEIVE HORN

CSS-1, $1m^2$ aircraft, $0.1m^2$ angels, 5° uptilt

	Target Angle or Altitude	Threshold Relative to Long-Range MDS 0 dB	6 dB
Aircraft	3°	1-32 nmi	1-22
$1m^2$	10 Kft	5.0-32	7.5-24
	5 Kft	2.6-27	3.8-20
	2 Kft	1.1-22	1.6-9
Angels	5 Kft	4.8-11.0	not detected
$0.1m^2$	2 Kft	2.1-4.0	not detected

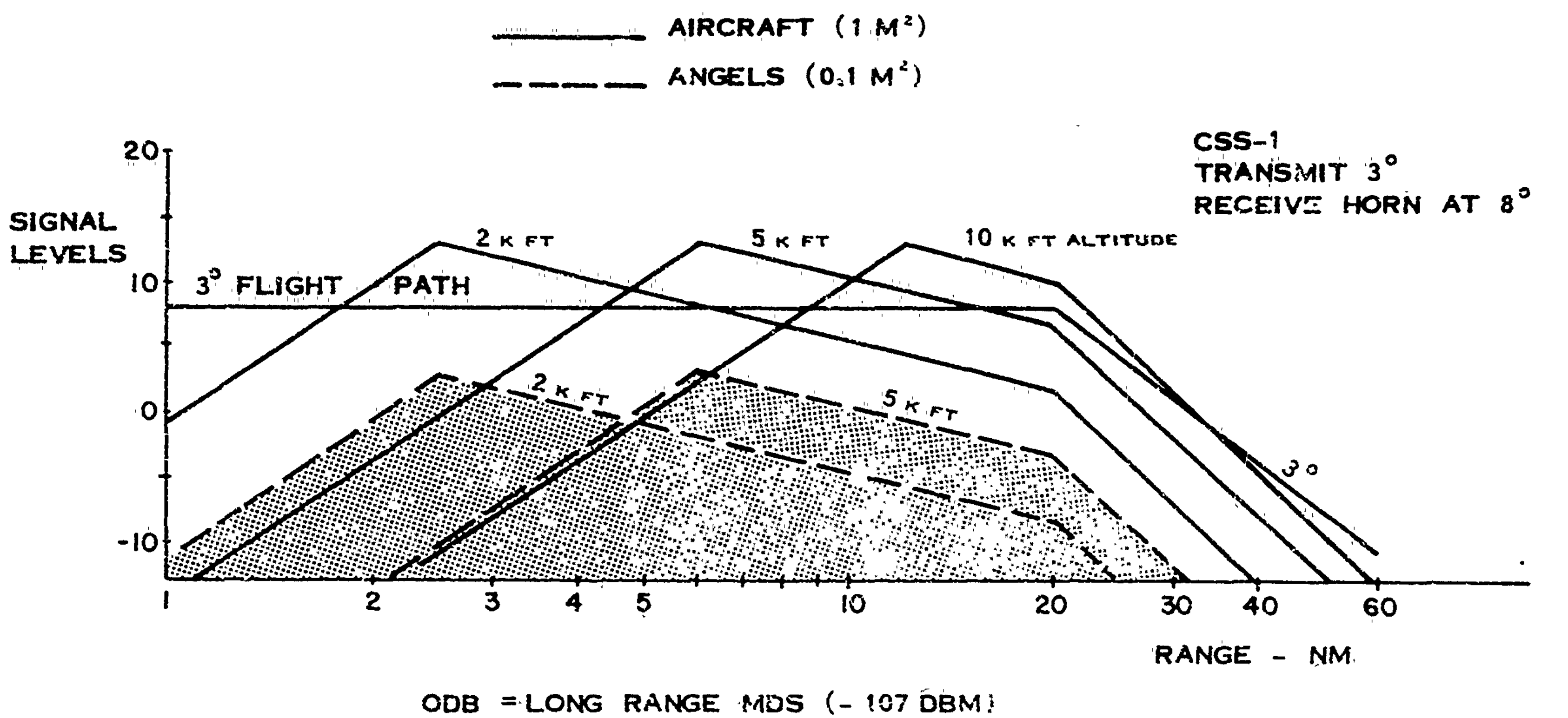


FIGURE 4-3 ASR SIGNAL LEVELS FOR OVERFLYING AIRCRAFT WITH PASSIVE RECEIVE HORN

Comparison of Tables I and II and the figures reveals that:

a) The passive horn with 5° uptilt reduces the range extent of the angel clutter region and moves it in to shorter ranges. It also reduces the maximum ranges for the overflying aircraft, but this is normally avoided by using the normal receive beam beyond ranges of 10-20 nmi.

b) The passive horn reduces aircraft return on the 3° flight path by about 9 dB. This makes threshold-setting more critical and would probably necessitate setting the threshold lower and rejecting fewer angels (say $0.05m^2$ and below versus $0.1m^2$ and below for a $1m^2$ aircraft).

c) For overflying aircraft at 2-10 Kft, the passive horn improves the minimum range, i.e., the range at which the aircraft falls below either the 0 dB or the 6 dB thresholds (Figure 4-4). Degradation of maximum range by the passive horn can be avoided by using the normal receive antenna pattern at the longer ranges.

d) Assuming that angel clutter density and RCS is significant up to 5 Kft altitude, the 6 dB threshold would be required to operate out to 20 nmi with the normal antenna and out to 15 nmi for the passive horn. In the latter case, it may be beneficial to decrease the threshold from 6 dB at about 8 nmi to 0 dB at 15 nmi to preserve detectability of aircraft at 3 Kft and above.

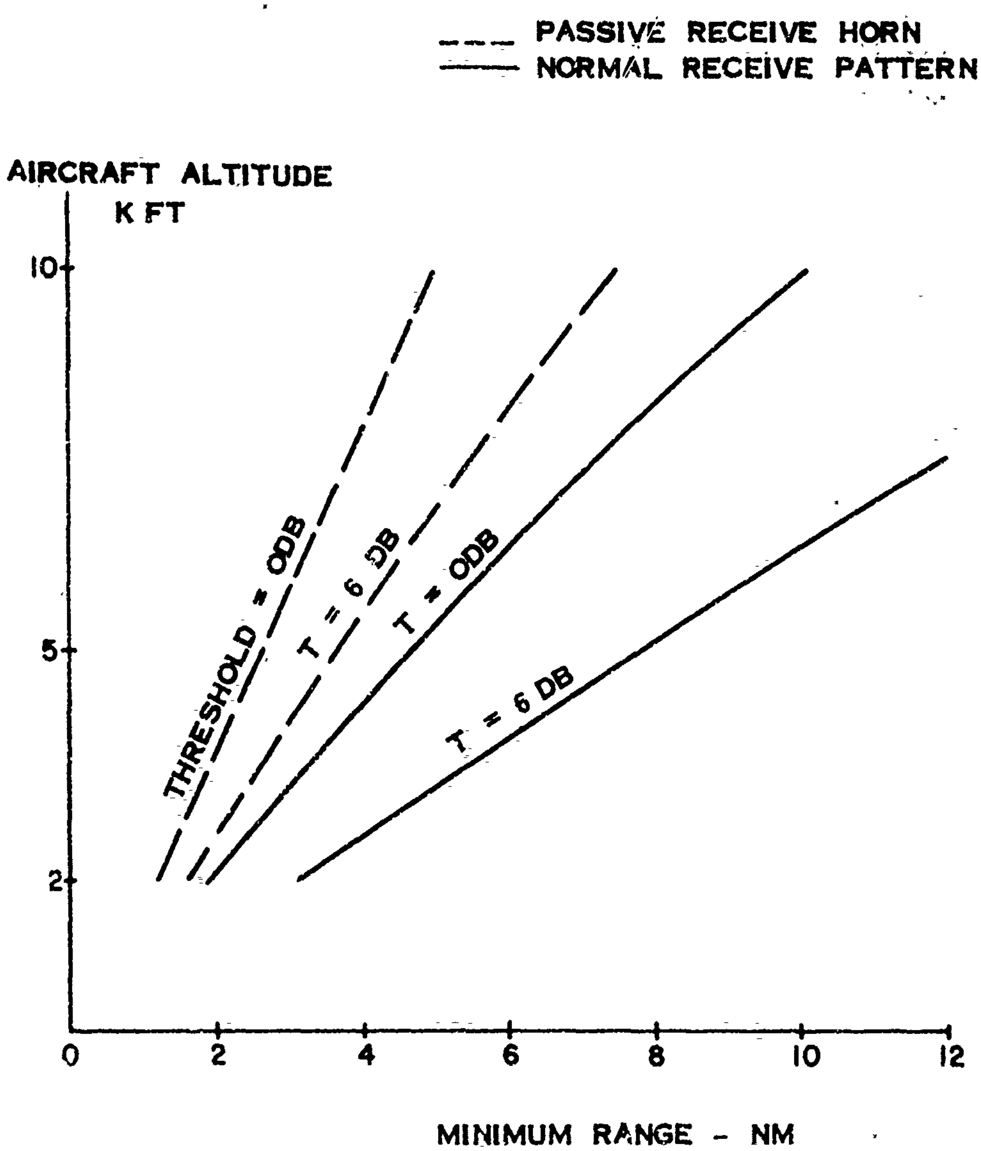


FIGURE 4-4 MINIMUM VISIBLE RANGE FOR OVERFLYING AIRCRAFT ($1M^2$)

In summary, CSS-1 plus a threshold reference to receiver thermal noise (outside the STC region) is useful for eliminating much of the angel clutter, i.e., that which is due to the smaller angels. The $1m^2$ aircraft and $0.1m^2$ angel models used here are fairly representative, and any angel clutter reduction provided by the ASR MTI will also be helpful. Choice of the normal antenna or the passive receive horn must take into account the target altitude. For $1m^2$ aircraft on the 3^o flight path and overflying aircraft below 3-5 Kft altitude, the normal antenna is preferred. Larger aircraft radar cross-sections will tend to shift this preference toward use of the passive receive horn for lower altitude targets.

4.1.3 STC Circuitry Implementation

While the Milwaukee experiments and the previous analyses indicate that CSS-1 (R^{-4} attenuation) appears best for normalizing angel returns to more-or-less constant amplitudes over range, this profile may not be acceptable for all airport sites. Consequently, some flexibility must be provided in the form of repeatable, known attenuation profiles that can be tailored to each radar site when required. A second requirement is that the angel clutter STC be used only in the angel clutter region, after which the radar is returned to its normal configuration.

Figure 4-5 is a block diagram of a digital STC unit which meets these requirements and which could be used either for RF or IF STC gain control. This STC generates a staircase approximation to the desired attenuation profile with selectable quantization in both range and amplitude. Using 6-bit logic, 64 steps can be programmed over 16 nmi (0.25 nmi/step) and 64 steps provided for about a 45 dB attenuation range (an average of 0.7 dB/step). The information concerning the desired sequence of attenuation steps is contained in the programmed read-only memory (PROM). Three memories are shown which allow for three switch-selectable attenuation profiles. The clock and timing unit determines the rate at

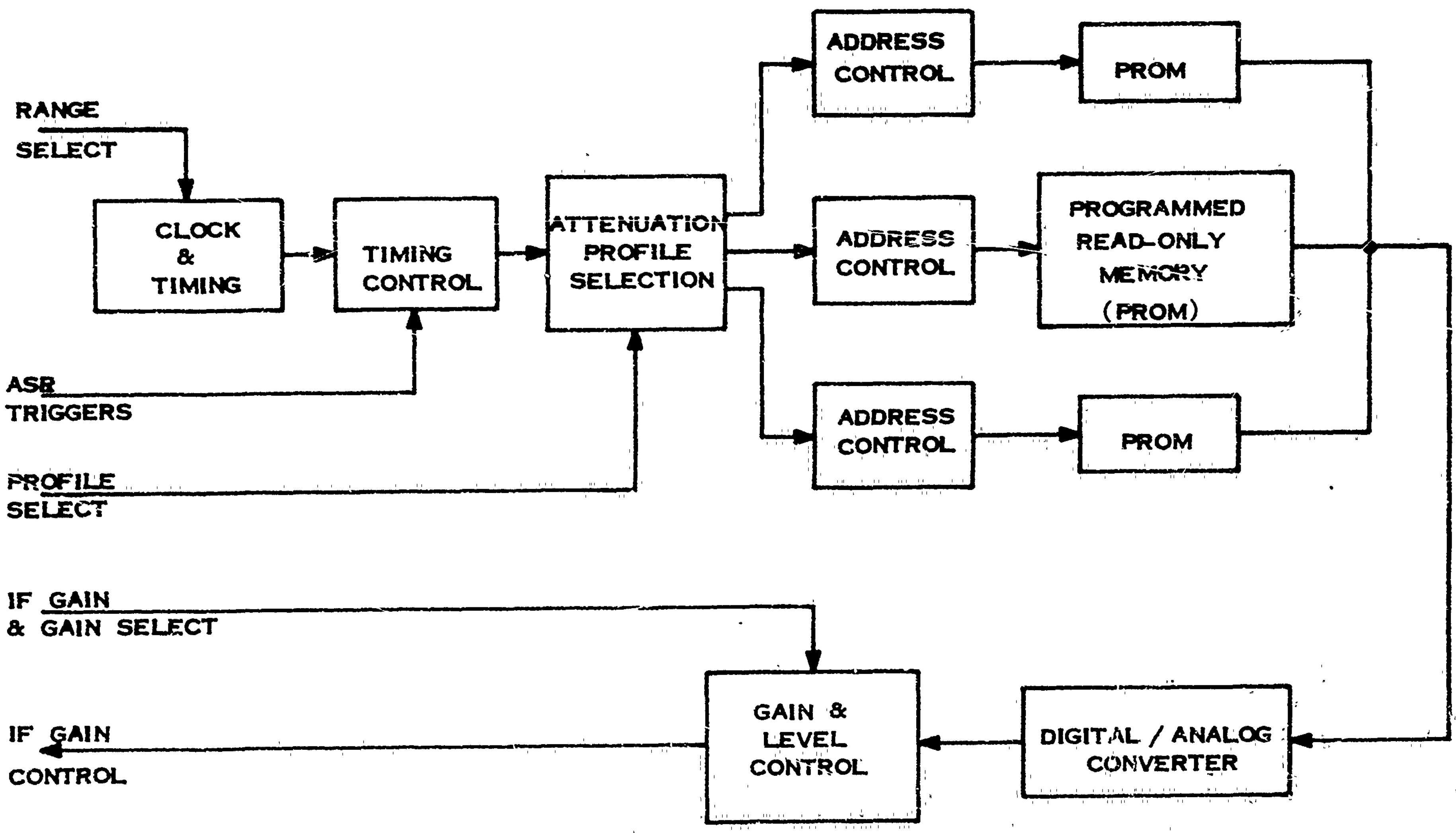


FIGURE 4-5 DIGITAL STC BLOCK DIAGRAM

which the selected PROM is read and controls the range over which the STC profile is generated. An advantage of this approach is that the STC profile need not be monotonic nor even a continuous function. Appendix E-1 provides a more detailed schematic and timing diagram for this circuitry.

4.1.4 Minimum RCS Threshold

Receiver gain control or STC will provide attenuation of all received signals but elimination of targets below a specified level requires some form of video thresholding and an appropriate means of calibrating the threshold to ensure that desirable targets (aircraft) are not inadvertently lost.

Radar calibration in terms of known signal levels is not in general an easy task. However, most ASR parameters of significance to this task are maintained to considerably closer tolerances than in most other radar systems. The two variables of concern are the receiver thermal noise level and antenna gain variations with elevation angle. The latter must be dealt with by choosing an appropriate minimum detectable RCS (say 0.1-0.5 m^2) and the portions of the antenna beam over which this level of detection is required, say $3^o \pm 1^o$ in elevation for landing aircraft and an appropriate altitude band for overflying aircraft in the passive receive horn receiver.

MTI receiver thermal noise can be sampled during the radar dead-time (or at long range). Assuming a 20 microsecond sample every sweep, over 10,000 samples can be averaged in 0.25 seconds. The minimum RCS threshold can be accurately derived from this average by applying a fixed bias to the measured noise level such that the desired detection probability is achieved for the required minimum RCS. Manual variations in receiver gain would be automatically compensated since the threshold is referenced to receiver noise

The two major complications to this procedure are the variations in MTI receiver gain with doppler and radar plumbing losses which may be unknown. Both of these quantities are measurable with appropriate test equipments and are also evaluated during flight checks, but it would be highly desirable to provide a suitable test target generator to facilitate more frequent calibration.

It should be noted that the selected minimum RCS threshold is applied at video, and only for ranges where angel clutter is present as indicated by the Rmax control setting. Normal (raw) video therefore remains available if desired. Moreover, the selected minimum RCS need not be large; all that is required is a threshold high enough so that the remaining angel clutter reduction processing provides an acceptably low residue of angel clutter on the PPI display. In fact, if the subsequent processing is adequate by itself on the existing level of angel clutter, the minimum RCS threshold need not be used at all.

4.2 Velocity Discrimination with Doppler MTI

Since bird ground velocities rarely exceed 60 knots, it is possible to differentiate between bird angels and true targets having velocities in excess of 60 knots. Two approaches are feasible: the conventional doppler Moving Target Indicator (MTI), which operates on the pulse-to-pulse phase change of the received signal caused by the doppler effect, and a scan-to-scan velocity discrimination system which operates on the change in position of the target over the four second radar scan period. Since doppler MTI is sensitive only to the range rate of the target, it cannot discriminate between targets having different total velocities if they have the same radial velocity component. While scan-to-scan velocity discrimination techniques are not subject to this limitation, these systems are limited in the number of returns that can be effectively processed.

Since most bird angel returns occur at ranges for which ground clutter also occurs, it is essential that any angel clutter reduction technique be compatible with rejection of ground clutter via the ASR doppler MTI.

4.2.1 ASR MTI Performance

The present ASR radars employ a phase-processing double canceller MTI with selectable feedback/feedforward gain constants to provide the velocity response shown in Figure 4-6. This MTI is intended primarily for ground clutter and the coherent oscillator (COHO) frequency set to the IF frequency to place the first MTI clutter rejection notch at zero doppler. A 9:11 pulse repetition frequency (PRF) stagger places the first complete null at about 1250 knots, although the MTI response does exhibit partial nulls at multiples of the average PRF doppler of approximately 125 knots.

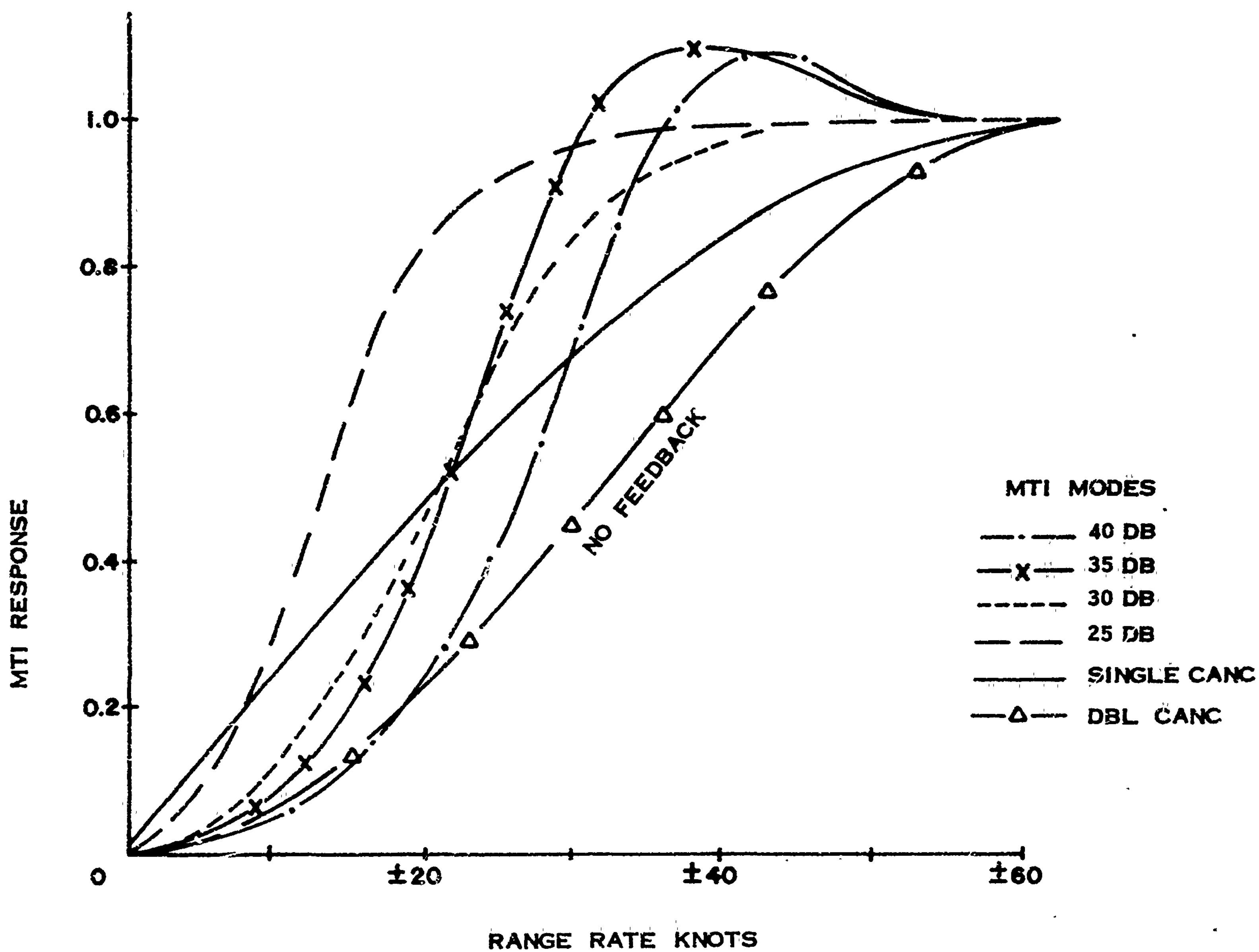


FIGURE 4-6 ASR MTI VELOCITY RESPONSE

These velocity response curves suggest that angel clutter can be minimized with the present configuration by using the double canceller in a no-feedback configuration, since the feedback modes (30, 35 and 40 dB modes) introduce peaking of the MTI response in the region of typical bird velocities (20-40 knots). For example, at 38 knots, the reduction would be 6 dB between the feedback modes and the double canceller/no-feedback mode. The price paid for this reduction in angel clutter is wider regions of reduced aircraft sensitivity centered at the MTI blind speeds. This loss of sensitivity at higher-order blind speeds is somewhat offset by the fact that propeller and turbine modulations spread the doppler return from aircraft.

In previous interim reports, consideration was given to use of improved doppler MTI processors. However, since these approaches would require complete replacement of the present MTI and would still be subject to the range-rate variations of angels over azimuth, the cost benefits of this approach as an add-on to present ASR radars were not attractive. Similarly, pulse doppler techniques were ruled out because of the major transmitter and receiver changes that would be required.

4.2.2 MTI Feedback Elimination Circuitry

As with the STC modification, MTI feedback elimination should be activated only at ranges where angel clutter returns are detected. Only minimal hardware switching is required to disable feedback at short range and to return the MTI feedback to the normally-selected configuration beyond the angel clutter range as indicated by the Rmax control setting.

A more complex system might be implemented to selectively disable feedback as a function of azimuth. This would be useful in cases where most angels have the same headings, so that low range rates are observed (and cancelled by the normal MTI feedback configuration) in some directions. Figure 2-5 is an example of such a situation. It is not likely, however, that the complexity involved in such a switching scheme would be worth the small aircraft detection improvements that could be provided.

4.3 Azimuth Pattern Processors

In Chapter 3, the azimuth pattern properties of angel and aircraft returns were analyzed by evaluating the performance of several azimuth pattern processors on angel and aircraft return data. In general, as the processors became more complex, the angel/aircraft discrimination capability also increased. This suggests that it may be desirable to match processor complexity (and therefore cost) with the angel clutter reduction performance required at specific airport radar sites. For this reason, we will discuss three different processors here. In order of increasing complexity and performance, they are:

a) Azimuth Correlator (consecutive hit detector)

b) Dual Threshold Processor

c) Pattern Recognizer (combined features set)

Since the performance of these processors have already been fully addressed in Chapter 3, we will only summarize the performance results expected and concentrate instead on the advantages and disadvantages of the three types of processors and on the implementation of each.

All of these processors require some form of input signal quantization to prepare raw radar video for processing and a suitable range maximum (Rmax) control which enables the processor only out to the maximum range of observable angel clutter. Each processor must operate on MTI video, and should be compatible with use of a threshold calibrated in terms of minimum radar cross section (Section 4.1.4) to eliminate angel returns which are much smaller than small aircraft returns.

A significant limitation of the azimuth pattern processor performance results (presented in Chapter 3) is that they do not reflect the STC and MTI feedback elimination modifications discussed in the two previous sections (4.1 and 4.2). Since the data was collected at Milwaukee during normal air traffic control operations, the STC, IF gain, and MTI configurations could not be altered during the tests.

4.3.1 Azimuth Correlator

Description

This is the simplest of the azimuth pattern processors. It has the advantage that it is derived from a binary M/N integrator or azimuth correlator which is used in many automated radar detection systems, including the Enhanced ARTS Radar Processing Subsystem and the APL Data Acquisition Module radar detection and tracking system.

The Azimuth Correlator described here will provide two modes of operation. Within the region of angel clutter (identified by the Rmax control setting), the correlator requires M consecutive hits in a given range cell to declare the presence of an aircraft (M/M detection). Beyond Rmax, the azimuth correlator functions as an ordinary m/N integrator to integrate target hits over the radar beamwidth.

Implementation

The Azimuth Correlator can be simply implemented as indicated in the block diagram of Figure 4-7. The radar video is quantized each radar pulsewidth (0.833 μs) into a one or zero. A one is generated when the video exceeds the quantizing threshold and a zero otherwise. The data is loaded into a shift register so that each register contains all range resolution cells for one radar sweep (about 55 nmi). With N serial registers, N sweeps can be stored. The output of the registers at a particular range are the hits in azimuth for a target at that range. Thus, summing the outputs of the registers is equivalent to counting the number of hits in azimuth. For ranges less than Rmax, only the most recent sweep and the first M-1 delayed sweeps are used. They are summed and compared to the short range threshold M to produce detections only when M consecutive hits occur for a given range cell (M/M detection).

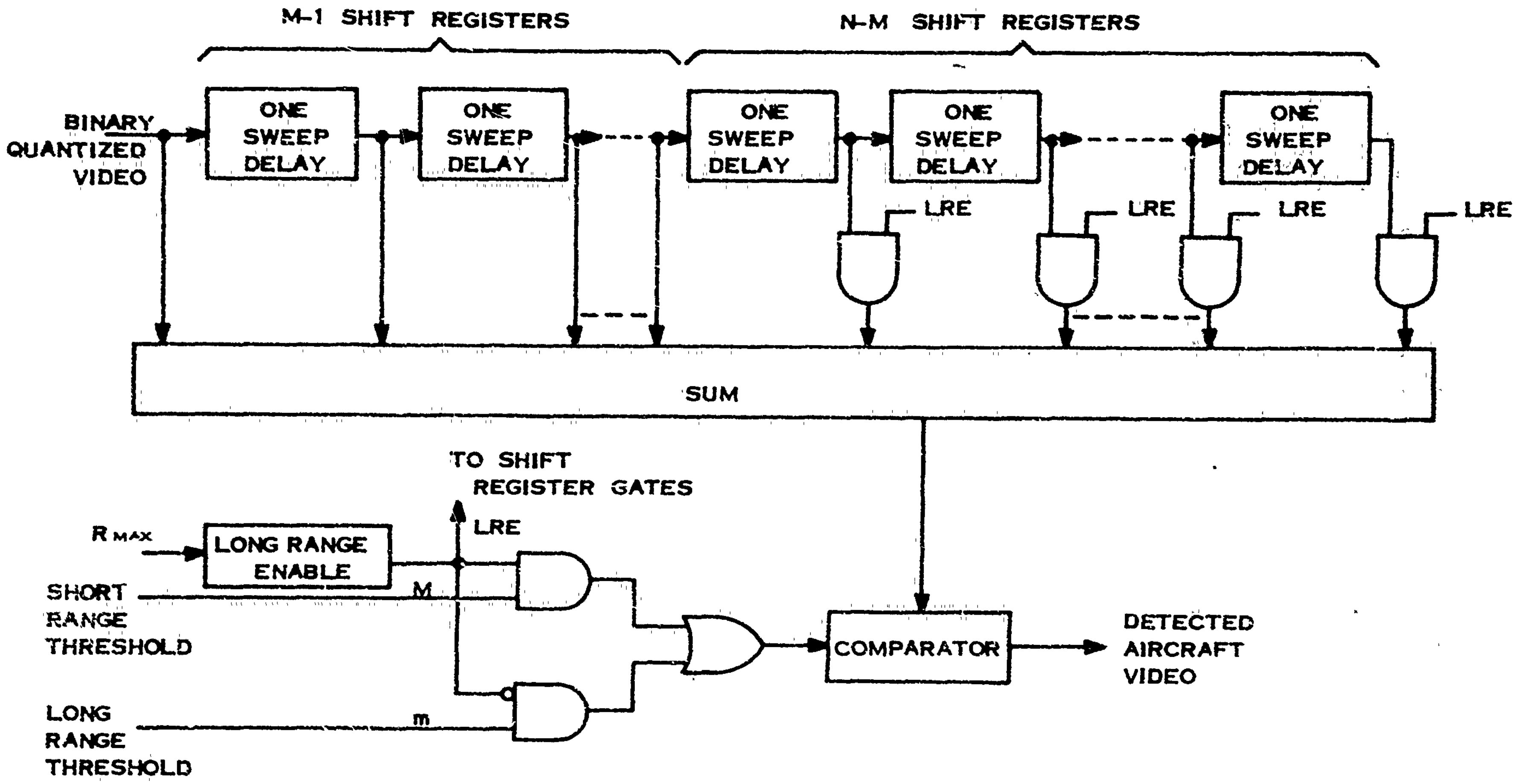


FIGURE 4-7 AZIMUTH CORRELATOR BLOCK DIAGRAM

Beyond Rmax, the long range enable bus activates all shift registers to allow full integration over the N (=20) pulses received per radar beamwidth. The sum of the outputs for each range cell is compared to the long range threshold m, and the azimuth correlator functions as an m/N binary integrator. Selection of m depends upon the quantizer false alarm rate and the desired output false alarm rate; a typical value for m would be eight.

If operation beyond the angel clutter region is not desired, the azimuth correlator could be simplified by eliminating the N-M shift registers and their gating circuitry could be eliminated. Appendix E-2 provides more detailed design data for this azimuth correlator.

Performance Data Summary

For angel clutter reduction, the Milwaukee data (taken on every other sweep of the radar) was first quantized using a fixed threshold and then subjected to M/M requirements of 2/2 and 3/3. As the fixed threshold was raised, the performance curve of Figure 3-20 was generated.

A second test utilized an adaptive (mean-level) quantizer to generate the binary video from analog tape recordings. Every radar sweep was used. The binary video was then applied to the m/N binary integrator in the Data Acquisition Module. (This binary integrator can be set for any value of $N \leq 19$ and any value of $m \leq N$). Rather good results were obtained using M/M = 5/5 as was illustrated in the PPI photographs of Figure 3-21.

Video Quantization

The input quantizer for the azimuth correlator plays an important role in the performance of the system. If the azimuth correlator is used only in angel clutter regions free from distributed clutter (such as rain), a fixed threshold could be used. The minimum value of this threshold could be the minimum RCS threshold discussed in Section 4.1.4. Manual increases of this threshold would then trace out a performance curve to provide the aircraft detectability/angel rejectability points derived from the Milwuakee data in Section 3.6.3(to the extent that the Milwaukee angel and aircraft data is representative).

However, distributed clutter, particularly rain, often interferes with radar detection. For this reason, the Enhanced ARTS Radar Processing Subsystem and the Data Acquisition Module both employ adaptive quantizers. These quantizers examine range cells ahead of and beyond the target cell to generate adaptive thresholds based on the clutter environment surrounding the target in order to provide more-or-less constant false alarm rate quantization. A comprehensive treatment of the various types of adaptive quantizers applicable to the ASR radar and ARTS is provided in APL Report MSO-F-183 (Reference 1), which was generated in support of the ARTS Enhancement design effort. Even a very simple adaptive quantizer can substantially improve radar surveillance, so the cost of such a device need not be prohibitive.

The PPI photographs of the very simple adaptive quantizer used in the Data Acquisition Module with the 5/5 azimuth correlation criterion show that good angel clutter reduction is achievable with an adaptive (rather than fixed) threshold, although a performance curve is difficult to generate since the adaptive threshold is a function of the environment surrounding each point target. A side-by-side evaluation of adaptive and fixed quantizers is required to quantify relative performance in angel clutter, and to determine the range of values over which M should vary for an operational system.

Advantages and Disadvantages

The Azimuth Correlator is relatively simple and is easily controlled by selecting the proper value for M. If an adaptive quantizer is included, the Azimuth Correlator can operate as a video integrator beyond the angel clutter range, providing a black-scope synthetic video display with a relatively controlled false alarm rate.

For the expected value of $\dot{M}$ (5), the Azimuth Correlator has the advantage that angel/aircraft decisions are made rather quickly, i.e., when the antenna (and PPI sweep) are within about 0.5^{o} of the target azimuth. The more complex processors (dual threshold and pattern recognizer) induce much larger delays due to the need to examine a wider azimuthal interval.

The price paid for these advantages is more modest performance. ACI analysis of MTI versus normal video aircraft data shows that the differences in ACI length (upon which consecutive hit discrimination is based) are smaller for angels and aircraft than are the differences in the number of ACI's (upon which the dual threshold technique is based). However, the previously-cited PPI photographs of the Data Acquisition Module Azimuth Correlator operating at 5/5 show that substantial performance is retained. It is anticipated that selection of M/M and quantization threshold could be made using maintenance, rather than operational controls, although the best settings would vary in the usual case where angel clutter varies with time of day.

4.3.2 Dual Threshold Processor

Description

The Dual Threshold Processor employs three thresholds: a low and a high video quantization threshold and a threshold which compares the number of ACI (hit groups consisting of any number of consecutive single-sweep hits between misses) at the low and high thresholds to the ACI threshold. The ACI threshold is set to the ACI difference required to identify angels. This processor is based upon the measured data which shows that angels produce larger ACI differences between the high and low thresholds than aircraft.

Implementation

The Dual Threshold Processor has separate channels for the low and high thresholds (Figure 4-8). Each threshold quantizes radar video into binary one-zero video for each range cell. The

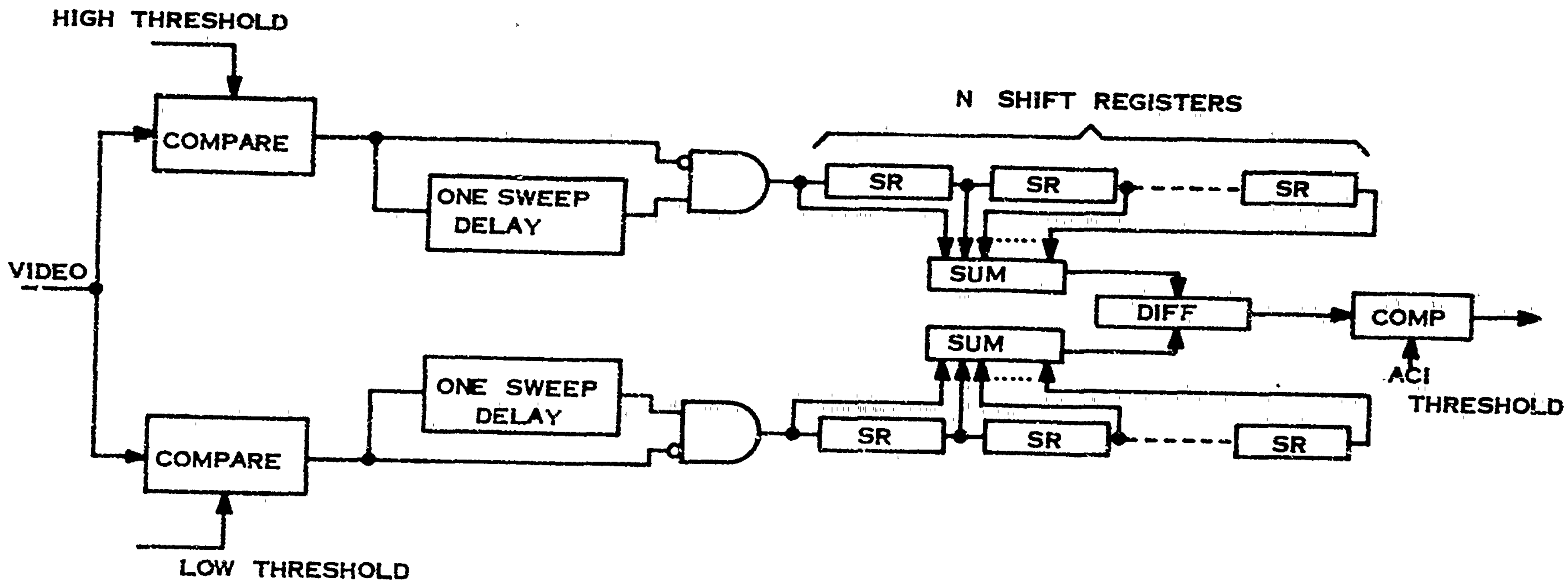


FIGURE 4-8 DUAL THRESHOLD PROCESSOR BLOCK DIAGRAM

threshold output is compared to its output on the previous sweep (or on the second-previous sweep for alternate sweep operation) as stored in a shift register. This comparison generates binary video which indicates the end of each ACI as a binary one. N shift registers provide summation of this binary video over the selected azimuth window (N sweeps of data) to give the number of ACI occurring during this period. The difference between the high and low threshold ACI is applied to the ACI threshold. When the ACI threshold is exceeded, an angel is declared present.

Performance Data Summary

Figure 3-22 contains performance curves for the Dual Threshold Processor operating on the Milwaukee data. Two azimuth dwells were considered: 37 alternate sweeps (about 6°) and 10 alternate sweeps. The performance curves were generated by varying both the low and high thresholds and the ACI threshold, which varied from 1 to 3.

Since the azimuth delay required to make an aircraft/angel decision is considerable when a broad azimuth window is employed, it would be useful to experimentally examine the possibility of processing every sweep, rather than every other sweep. However, the ACI analysis performed for the every-sweep data from Baltimore's Friendship airport (Figure 3-25) tends to deny this possibility, since the number of ACI remained the same when the data was processed on every, rather than every-other sweep. To the extent that this aircraft data is representative, it appears that a sizeable azimuth window is required to properly process the radar data with a dual threshold processor.

Video Quantization

The implementation diagram of Figure 4-8 provides angel detection but not aircraft detection. The presence of an aircraft can be derived from either raw video or by displaying the synthetic video at the low threshold. The low threshold may be used as the constant RCS threshold discussed in Section 4.1.4.

A more attractive scheme would be to use an adaptive quantizer as described previously to provide good target detection sensitivity at a reasonably constant false alarm rate in receiver noise or distributed clutter. Binary video generated by the quantizer could be stored in digital delay lines (shift registers) until the angel/aircraft decision is made, after which the synthetic video could be displayed at the proper azimuthal position if the return was not declared to be an angel.

If an adaptive quantizer is used, there is a possibility that a dual threshold can be implemented in the quantizer, i.e., the adaptive quantizer could output two synthetic videos, which correspond to high and low thresholds. This would simplify the selection of thresholds but experimental data is required to determine the effectiveness of this approach for angel discrimination.

Advantages and Disadvantages

The performance improvement provided by the Dual Threshold processor over the Azimuth Correlator is somewhat offset by the need to examine a wider azimuth window and the resulting delay in angel/aircraft determination. In addition, three adjustable parameters were considered in the data analysis; it is worth considerable effort to reduce this to one or at most two adjustments to simplify system operation. This parameter minimization and the possibility of reducing the azimuth delay merit strong priorities in any future field tests.

4.3.3 Pattern Recognizer

Description

The best performing and most complicated Azimuth Pattern Processor is the Pattern Recognizer. It is also the least well-defined processor at the present, since the scope of the relatively modest pattern recognition studies subcontract precluded optimization of the features required to provide cost-effective performance. The best of the three tested schemes was the four-hyperplane recognizer operating on the (36) combined features set.

This recognizer extracted 20 video amplitudes (following the first amplitude of 5 or greater), three statistical features (maximum amplitude, average amplitude, and standard deviation of amplitude), ACI differences from ten sets of dual thresholds, and ACI lengths of 8, 12, and 16. These extracted features were processed in four consecutive hyperplanes to obtain the angel/aircraft decision. Since the object of the pattern recognizer investigation was to explore feasibility in a very limited study, considerable work remains to be performed before a specific configuration can be recommended. However, we will discuss the implementation of the 36 feature pattern recognizer to illustrate the nature of the required processing.

Implementation

Figure 4-9 is a simplified block diagram of the Bendix 36-feature, four-hyperplane pattern recognizer which was derived from the recommended implementation in the Bendix study report (Appendix D-2). If the 20-amplitude, single hyperplane pattern recognizer is implemented, the shaded blocks in Figure 4-9 can be eliminated. It is unlikely that all 36 features are required for acceptable performance; feature elimination decisions should include both performance and the complexity required to extract each feature.

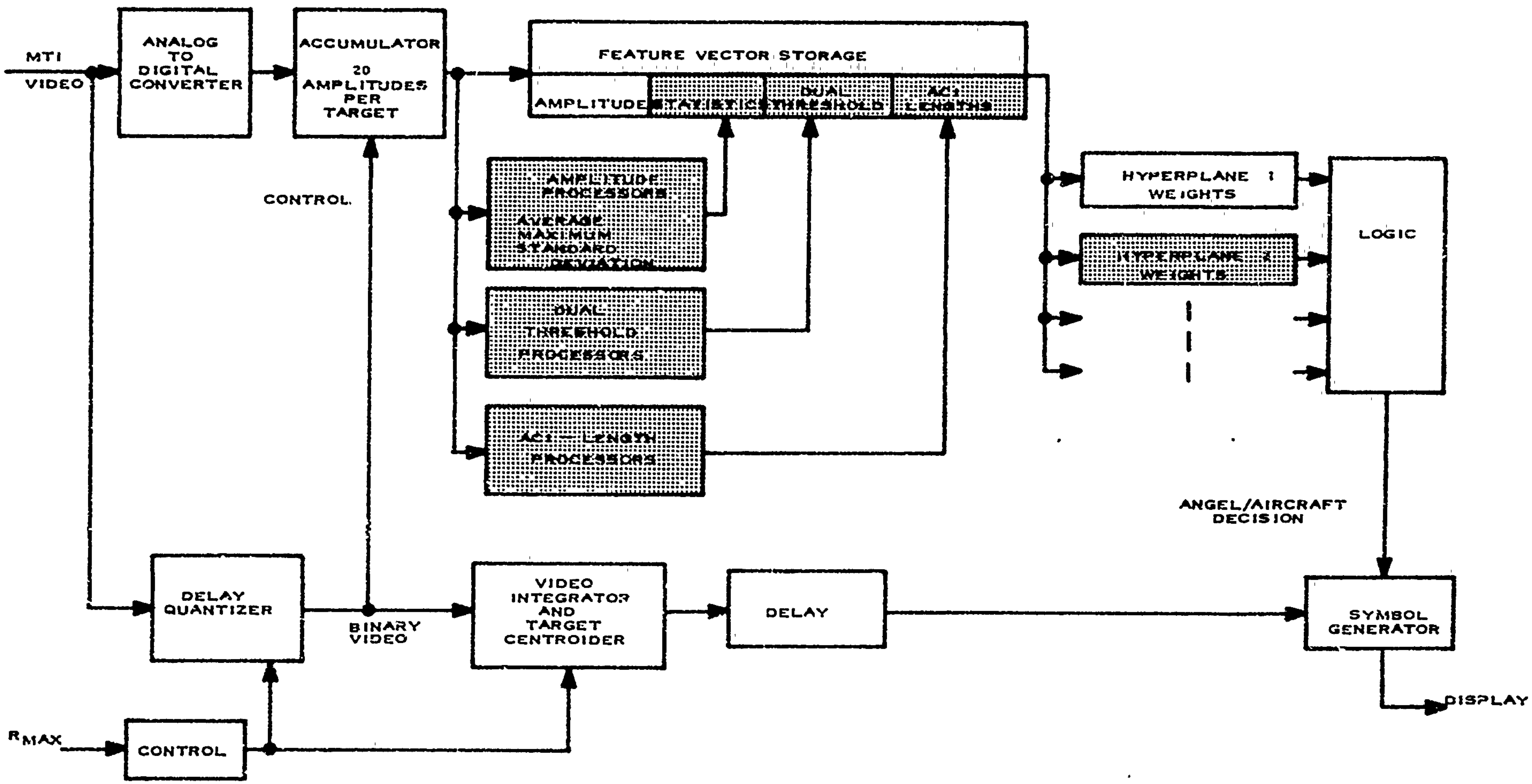


FIGURE 4-9 ILLUSTRATIVE BLOCK DIAGRAM OF PATTERN RECCGNIZER

For the large number of features shown here, considerable processing is required for each range cell. It would be more efficient to process only those range cells in which targets are present, since there are over 60,000 range/azimuth resolution cells in the first 20 nmi, but generally less than several hundred aircraft and angel targets. This approach would favor software implementation, but final determination of hardware versus software implementation is influenced by (and influences) selection of the most cost-effective feature set.

It should be noted that the hyperplanes are implemented very simply once the proper feature weights are determined. Each hyperplane is a set of resistors with values corresponding to the selected weights for each feature. The major complexity of the recognizer occurs in the special processors which extract the statistical features and in the storage required to accumulate features over the azimuth window; the 20-amplitude pattern recognizer is therefore considerably less complex than the 36-feature recognizer.

<u>Performance Data Summary</u>

The hyperplane weights derived for the pattern recognizer produced the best results of the three azimuth pattern processors considered here. The performance curves were shown in Figures 3-29 and 3-34.

Since the pattern recognizer uses all features to make its decision, it is not possible to estimate the performance curve that would result if some features were deleted. However, the hyperplane weights do indicate the relative contribution of each feature, as discussed in Section 3.7.4. The dual thresholds are heavily weighted in the earlier hyperplanes but the trend is toward amplitude measures in the later hyperplanes. By re-running the hyperplane computations as selected features are eliminated, it should be possible to derive the minimum set of features which can provide best performance for a reasonable level of complexity. In addition, it would be desirable to attempt optimization of the values used for dual threshold pairs and ACI lengths to minimize the number of these features used.

It should be noted that the use of 36 features for this study was rather arbitrary. A large number was used to enhance the possibility of success. Pattern recognition techniques do not necessarily require large numbers of features; some recognizers (for different tasks) require as few as three features. A very simple pattern recognizer could use a weighted sum of the outputs of the M/M azimuth correlator and two dual threshold processors. In summary, much more work remains to be done before it can be concluded that a successful pattern recognizer for angel clutter reduction requires near as many as 36 features and four hyperplanes.

Video Quantization

As with the dual threshold processor, the pattern recognizer requires substantial azimuth delay and is not necessarily an efficient target detector. Raw video could be marked with symbology representing the angel/aircraft determination, or an adaptive quantizer could be used to efficiently convert raw video into synthetic video, which could then be delayed until the pattern recognizer decision process is completed.

Another possibility, if a minicomputer is used for the pattern recognition processor, would be to delay outputs for a complete antenna scan (4 seconds), after which appropriate aircraft/angel markers could be added to the raw radar video at the proper point in time.

Advantages and Disadvantages

It should first be noted that complexity is not a necessary characteristic of angel/aircraft pattern recognizers, and indeed no attempt could be made during the present study to reduce complexity. The performance of the 36-feature, four hyperplane pattern recognizer was sufficiently superior to warrant the effort required to select the most effective set of features and the best means of inexpensively processing them.

While it is not at all clear at this point whether a hardware or a software approach is best (it depends upon the number and type of features extracted), costs of small-scale fast digital data processors (minicomputers) are not necessarily higher than some relatively simple hardware systems. The final cost is difficult to assess until the proper features are selected.

A possible disadvantage of pattern recognizer use is associated with the learning phase, when the pattern recognizer is trained to recognize the desired targets by deriving appropriate hyperplane weights. "Overtraining" can occur when the learning algorithm is overused, that is, when the recognizer begins to operate on minor characteristics or flaws in the learning data. These problems can be avoided with proper experience in pattern recognition techniques (as is possessed by Bendix) and if the general performance of the individual features is understood, as is the case for this study. The main limitation then becomes the extent to which the learning data is typical of the angels and aircraft that will be presented to the pattern recognizer at the various airport sites where it will be used. In the present program, the Milwaukee data should be supplemented with additional data from other sites. The adequacy of using two target classes (angels and aircraft) in place of three (including radar clutter) must also be assessed.

There are two further advantages that apply to the pattern recognizer approach. First, the hyperplane weights can be modified to provide best performance on the type of angel clutter encountered at each radar site, using the same basic features, which should be generally applicable if properly chosen. Second, if a multiple hyperplane decision process is ultimately selected, the number of hyperplanes needed to perform a given angel/aircraft decision is directly related to the degree of difficulty required to classify the target, and can therefore be used to indicate the confidence that can be associated with that particular target identification.

4.4 Scan History Display

Since the velocity of angels is in general much lower than the velocity of fixed wing aircraft, velocity represents a major aircraft/angel discriminant. As previously discussed, the range rate discrimination provided by doppler MTI is inferior to true velocity discrimination because range rate (and therefore MTI angel clutter rejection) varies with angel heading. True velocity discrimination requires that a velocity indication be derived from target position measurements on two or more antenna scans. This implies considerable data storage, since every target position report must be saved for at least one radar scan.

A Scan History Display (SHD) is a very simple means of providing velocity discrimination without requiring the use of a computer for associating reports from the same target and calculating velocity from position changes. The SHD displays all target reports generated over the past several scans on a PPI. The effect is similar to a long-persistance display, with the length of the target time being proportional to velocity. By using the Azimuth Pattern Processor outputs to drive the SHD, the SHD memory requirements can be reduced to a manageable level. Furthermore, the multiple-scan display provided by the SHD is helpful in detecting aircraft.

The effect of SHD operation was illustrated in Figure 3-14, which shows time-exposures of 3 and 9 scans of target reports generated by a 5/5 azimuth correlation. The aircraft are more clearly visible on the 9-scan photograph and the angel clutter residue from the 5/5 correlator does not appear to be substantially greater than the residue on the 3-scan display.

4.4.1 Scan History Display Description

The SHD unit consists of a memory and a PPI which displays target reports received over the last k scans. Figure 4-10 is a typical block diagram. The quantizer adaptively thresholds the raw video to shield the SHD memory from saturation on distributed clutter and reports target range to the nearest range cell. In order to determine the target azimuth, a centroid calculation is performed on the azimuth sequence of hits. The computed range and bearing are then stored in a memory for all targets in a given scan; a separate portion of memory is used for each of the k scans stored. A SHD now in use at the Applied Physics Laboratory stores up to 256 targets for 8 scans in a 4K word, 16 bit core memory costing approximately $2400. Each of the eight portions of memory is displayed in sequence starting with the oldest data so that the target track may show apparent motion. The number of scans, the rate at which the eight scans of data is displayed, and the time between memory recycling are variable from the control panel. If displayed at a high rate, lines of dots (trails) mark target movement. If a slow rate is chosen, the dots flash in the direction of target movement. Length of these trails allows discrimination between slow-moving and faster targets. As an alternative to blinking each target dot to indicate motion, it would also be possible to intensity-modulate the target reports so that brightness decreases with time in the same manner as a long-persistance PPI.

The practicality of the SHD for aircraft/angel discrimination depends strongly upon the density of angel detections. Assume, for example, 100 angel reports per scan. An SHD displaying eight scans therefore displays 800 angels. If the dots representing angel returns are sufficiently dense, then it is difficult or

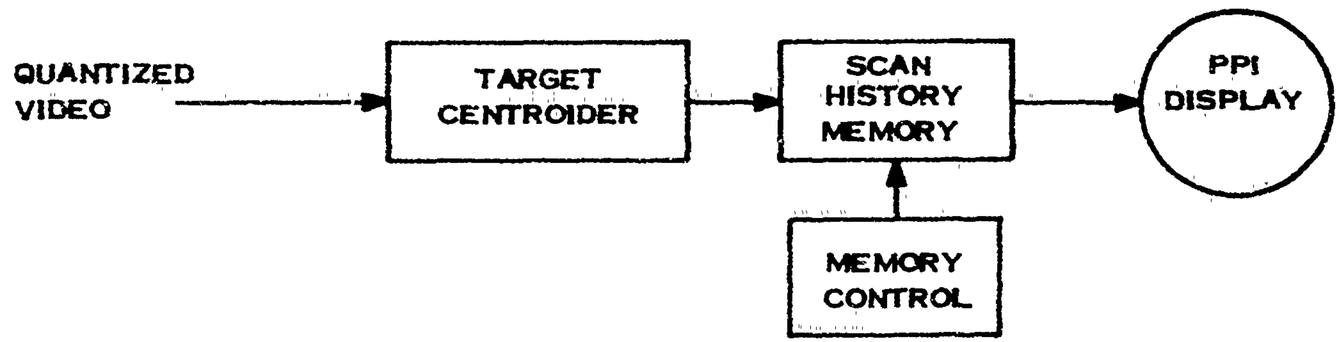


FIGURE 4-10 SCAN HISTORY DISPLAY BLOCK DIAGRAM

impossible to detect moving aircraft returns which merge with one or several angel returns. Thus, the SHD must be employed in conjunction with an Azimuth Pattern Processor to ensure that reasonable angel densities are achieved at the input to the SHD.

On the positive side, the SHD advantages (for reasonable angel report densities) can be summarized as follows:

a) For migratory bird angels, doppler MTI performance is poorest where the range rate of the birds is greatest. In these regions, a sixty knot bird angel moves about 400 feet in range in a four second scan period. For one pulsewidth range quantization (410 feet), these angels will be displayed as a short solid line on the SHD, whereas aircraft at 120 knots or greater will appear as separate dots on the display. Thus, the length of the SHD trail and the separation of the trail into separate dots can both be used as an aircraft/angel discriminant.

b) Since the SHD displays several scans of data (e.g., eight), aircraft returns are easier to see than when only one scan of data is displayed. To the extent that the single-scan display probabilities are independent, the SHD enhances the probability of displaying a given number of detections for moderate-to-high single scan detection probabilities.

4.4.2 SHD Performance

The size of the SHD memory is directly related to the expected number of target reports per scan and the number of scans to be displayed. Clearly, in dense angel clutter the SHD must operate on the outputs of the previous angel clutter reduction features (STC and doppler MTI modifications and the Azimuth Pattern Processor). An additional method of suppressing slow-moving targets (e.g., angels) before SHD processing is area MTI. Performance of an eight-scan SHD with and without area MTI processing is discussed below.

SHD Performance Without Area MTI

SHD performance was analyzed by reviewing the output data for two Azimuth Pattern Processors on eight angels and six aircraft observed at Milwaukee. The first processor was the 3/3 Azimuth Correlator (three detections on three alternate sweeps) with the threshold set to provide 81% aircraft detection and 47% angel rejection. The second was the dual threshold processor with thresholds of 10, 18 and number of ACI $\geq$ 2, which gave P(D/AC) = 91% and P(R/AN) = 45%. The data was examined for each consecutive group of eight scans; histograms of the number of detections displayed on an 8-scan SHD were counted for each target on each scan and are shown in Figure 4-11. Table III summarizes the number of detections per SHD trail in terms of mean (expected value) and median (fifty-percentile value). For aircraft, the azimuth correlation produces more zero and one-detection SHD displays than the dual threshold, although the mean and median values are similar for both detectors. However, these values for angels are lower for the dual threshold.

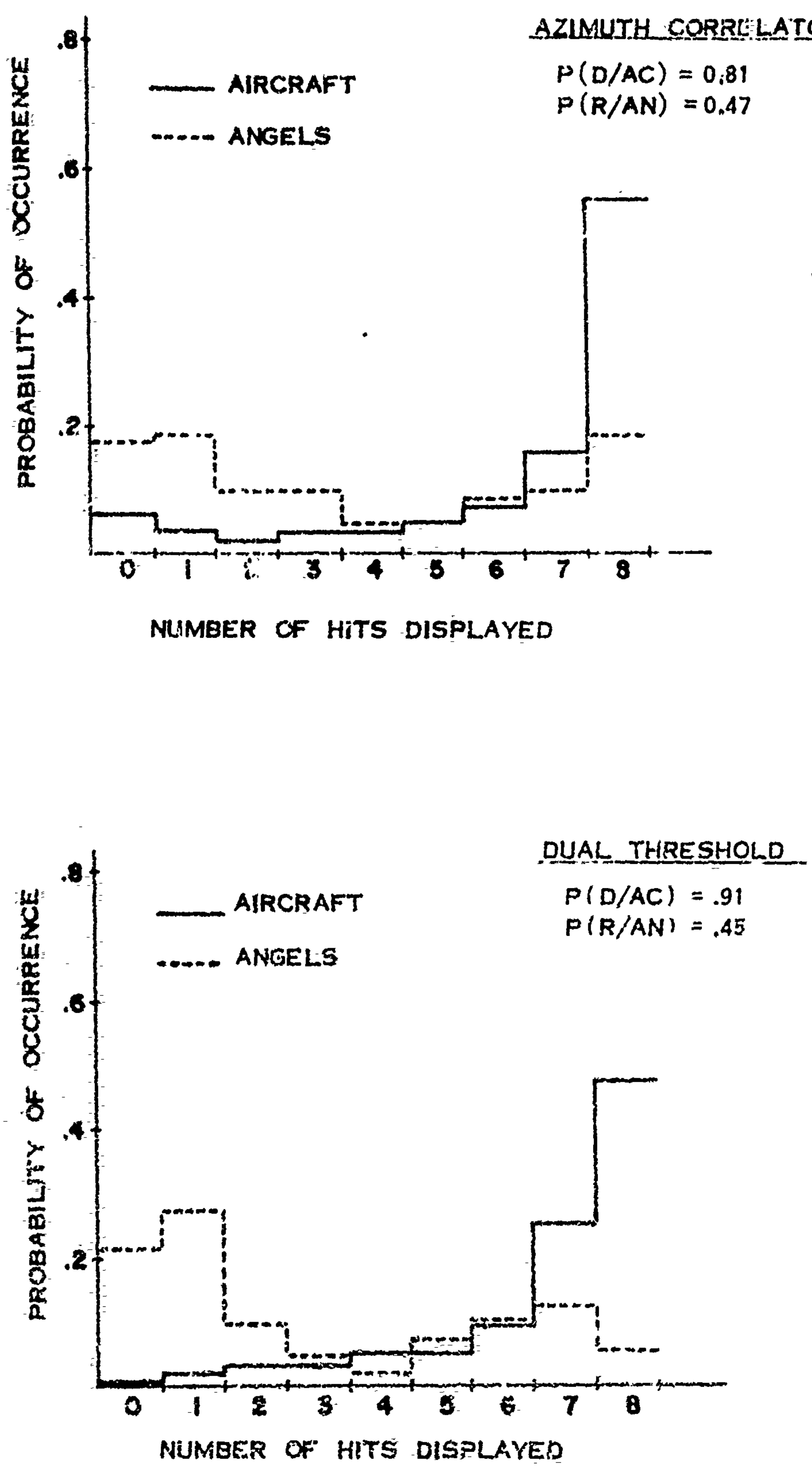


FIGURE 4-11 NUMBER OF HITS DISPLAYED PER TARGET ON EIGHT - SCAN SHD

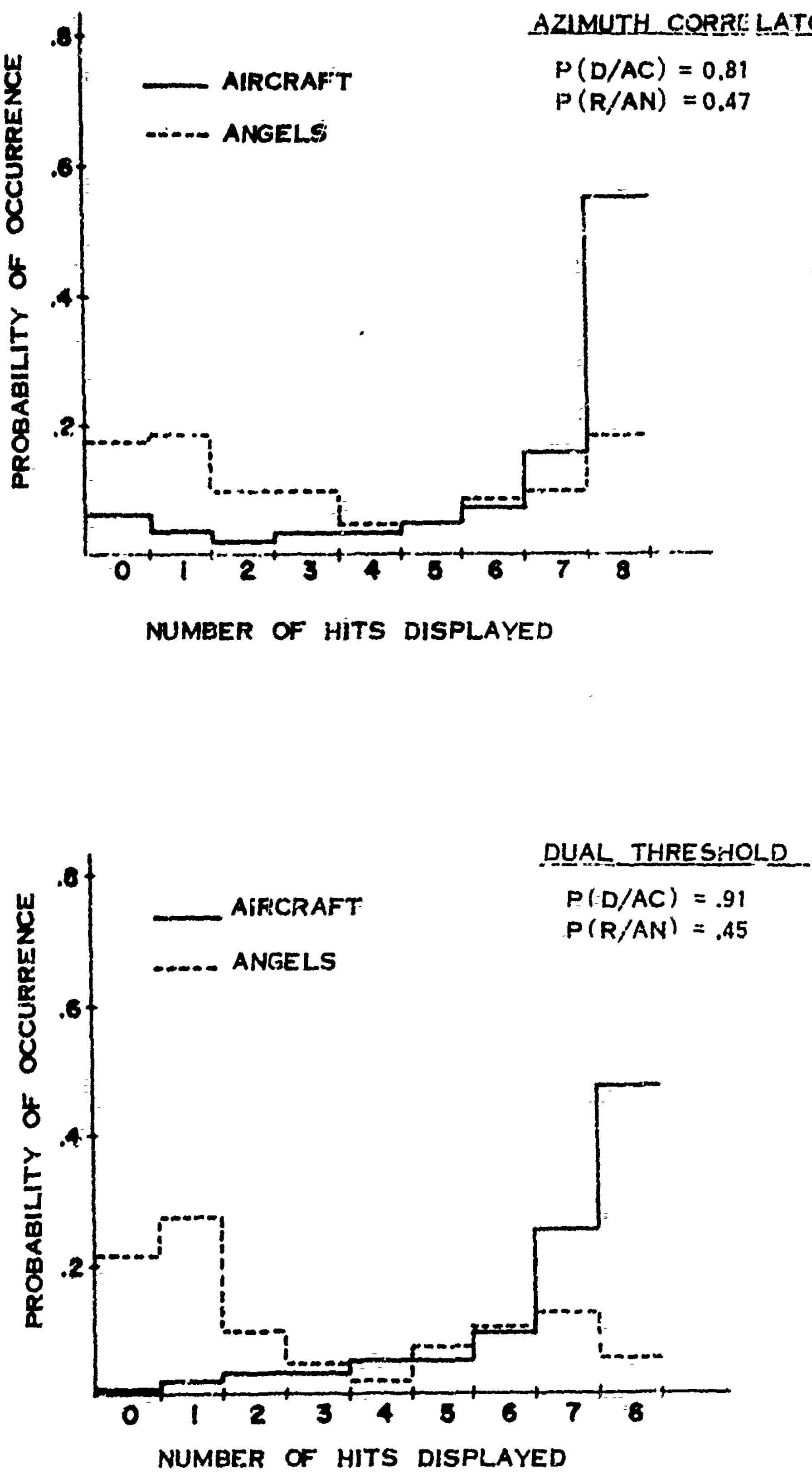


FIGURE 4-11 NUMBER OF HITS DISPLAYED PER TARGET ON EIGHT - SCAN SHD

TABLE III

NUMBER OF SINGLE-SCAN DETECTIONS
PER SHD TRAIL

		Mean	Median
Azimuth Correlator	Angels	3.7	2.5
	Aircraft	6.4	7.1
Dual Threshold	Angels	2.8	1.0
	Aircraft	6.2	6.9

To illustrate the velocity discrimination provided by the SHD, assume a 40 knot angel velocity and a 120 knot aircraft. The maximum trail length is given by

$$L_{max} = (k - 1)\ t_s\ v$$

where

k = the number of SHD scans (8)
t_s = the antenna scan time (4 seconds)
v = the target velocity

Table IV lists this maximum trail length for the ASR along with estimates of trail length based upon the mean and median number of detections per SHD trail for the two processors. The estimation involves assuming that the detections are consecutive rather than spaced over the entire eight scans. Again, the dual threshold provides about the same performance for aircraft but better angel clutter reduction.

TABLE IV

ESTIMATED TRAIL LENGTH FOR AIRCRAFT AND ANGELS

		Mean	Median	Maximum
Azimuth Correlator	Angel (40 kts)	.11 nmi	.06 nmi	.31
	Aircraft (120 kts)	.68	.76	.93
Dual Threshold	Angel (40 kts)	.08	0	.31
	Aircraft (120 kts)	.71	.74	.93

Scan-to-Scan Independence

To the extent that the inputs to the SHD for a given target are independent on consecutive scans, the SHD can enhance strong targets and discriminate against weak targets by providing more opportunities for detecting each target. Consider a target with a single-scan detection probability, p, which is independent from scan to scan. If p is high, say 0.8, there is a 95% probability of displaying at least 5 out of the 8 possible reports on the SHD. If p is low, say 0.3, the display probability for at least 5 out of 8 is only 5%. Since these values of p correspond to typical aircraft/angel single scan probabilities, angel returns can be further suppressed and aircraft further enhanced if the outputs of the Azimuth Pattern Processors are independent from scan to scan.

To investigate this possible improvement, the probability of displaying at least N out of eight detections on the SHD with the two Azimuth Correlators was compared with the calculated results assuming independence. Figure 4-12 shows the results. Since the Azimuth Pattern Processor curves do not parallel the dotted curves, the outputs are clearly not independent from scan to scan. They are not totally correlated either, since the curves are not horizontal.

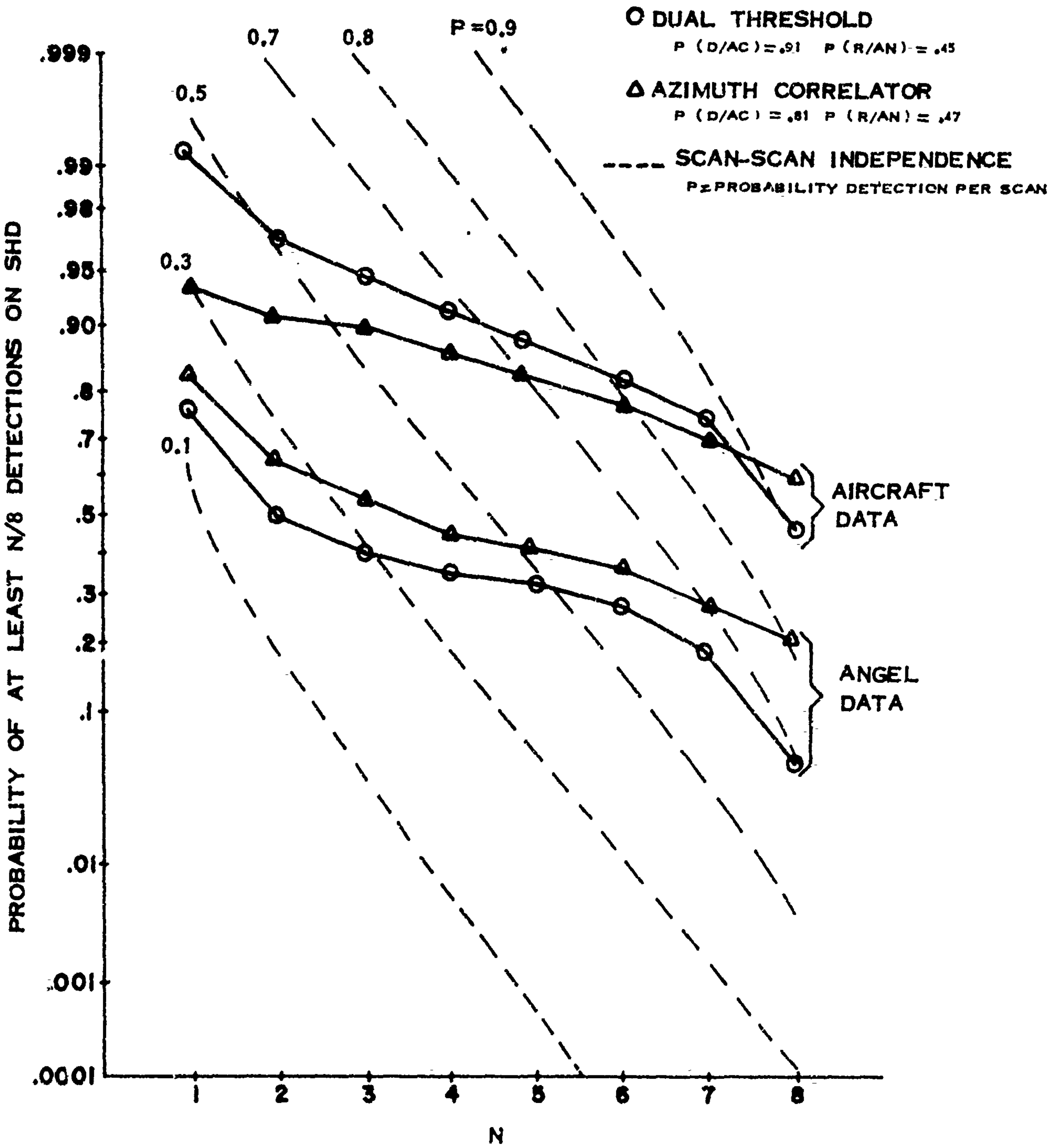


FIGURE 4-12 PROBABILITY OF DETECTION ON AT LEAST N OUT OF 8 SCANS

The scan-to-scan correlation of the Azimuth Pattern Processor outputs were estimated from the curves of Figure 4-12 and the single scan values of P(D/AC) and P(R/AN) to be 0.8 for both angels and aircraft. This high scan-to-scan correlation greatly reduces the SHD improvement that would be expected using a scan-to-scan independence assumption. However, requiring 5/8 detections on the SHD would maintain or slightly improve the performance of the Azimuth Pattern Processors, since velocity discrimination would be added and the probability of displaying detections on at least 5/8 scans would be about 90% for aircraft and 50% for angels.

SHD Performance With Area MTI

The term "Area MTI" is used here to refer to a processor which inhibits display of targets which do not move a specified distance from scan to scan. While Area MTI processors require considerable data storage and computation to delete slow-moving targets, the effect of such processing on the Scan History Display is of sufficient interest to warrant consideration here. Should the output of the Azimuth Pattern Processor contain large numbers of angels which have been incorrectly identified as aircraft, numerous angel returns can obscure aircraft on the SHD or, ultimately, the SHD memory becomes saturated and therefore causes loss of targets.

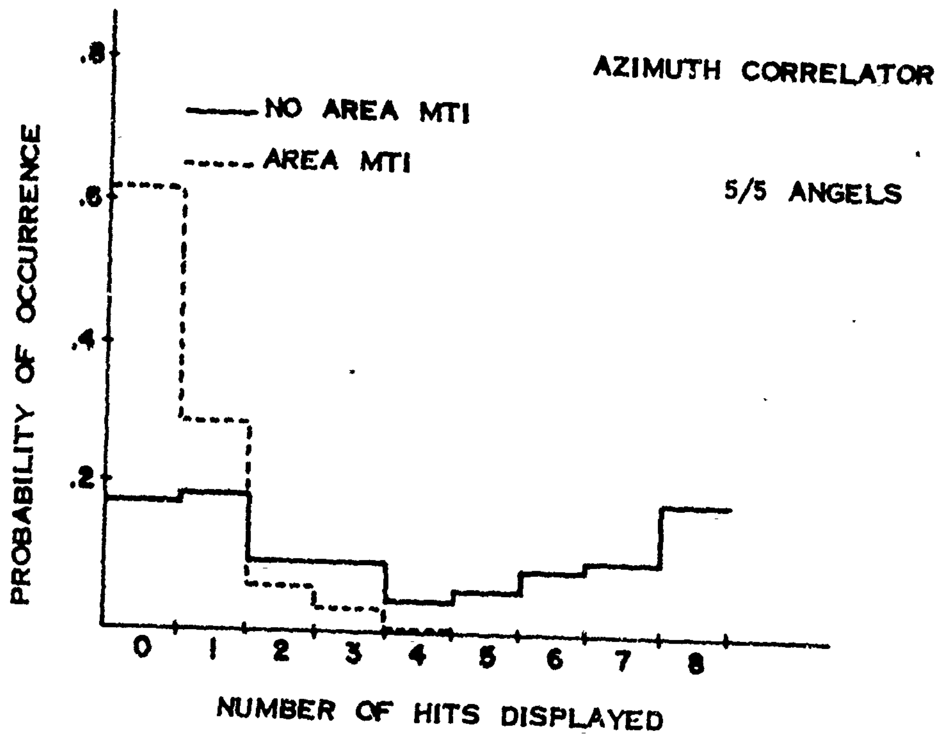
There are two basic forms of Area MTI. Sector Map Area MTI stores detections in a map of range/bearing cells covering 360° and the instrumented range of the Area MTI; successive detections on consecutive scans in the same cell are not displayed.

Target Store Area MTI is the conventional automatic radar tracking system approach; reports from successive scans are associated with a given target in the target store and targets with a velocity below the desired velocity are not displayed. A comprehensive analysis of both types of Area MTI when used in conjunction with an Azimuth Pattern Processor is provided in Appendix C-2. In brief, Area MTI works well for those angels which are not effectively suppressed by the Azimuth Pattern Processor. For those angels which have a good but not perfect probability of rejection by the Azimuth Pattern Processor so that they appear on some scans, the Area MTI/SHD combination tends to worsen the situation. The conclusion of the Appendix C-2 analysis is that Area MTI improves upon single-scan Azimuth Pattern Processing only if a) angel clutter densities are light, and b) aircraft detection by an operator would be severely masked by angel clutter which escapes effective suppression by the Azimuth Pattern Processor.

Since Area MTI is relatively expensive, and Azimuth Pattern Processor performance is in general quite good for the Milwaukee data, Area MTI would not appear cost-effective for the present application.

The interaction of the Azimuth Pattern Processor, Area MTI, and the SHD were studied to evaluate the adverse effect of good bird rejection by the Azimuth Pattern Processor on Area MTI performance. Data from the output of the computer simulating the two Azimuth Pattern Processors was utilized as before with the SHD, but it was assumed that the angels had zero probability of leaving the Area MTI bin (i.e., zero p_j), which implies perfect Area MTI performance. If a detection occurred on two successive scans, only the first detection was entered into the SHD for first scan. It was presumed that memory of the SHD could be modified to remove this detection from the memory should a second detection be declared on the next scan. Otherwise, the detection remained in the SHD for the full eight scans and was considered as displayed the whole time. The resultant blip counts for eight scans (corresponding to what would be displayed on the SHD) were accumulated over the run for each run, and the histogram plotted over those for the SHD alone in Figure 4-13. The dotted lines represent the effect of the Area MTI for the corresponding detectors. Obviously the Area MTI causes considerable reduction of the angel returns for this idealized case, for both types of detectors. The dual threshold with Area MTI appears to be slightly more effective than the Azimuth Correlator with the Area MTI, but the difference is marginal indicating the two detectors are operating with approximately the same efficiency scan to scan. The mean and median number of angel detections per SHD trail for this idealized Area MTI were reduced from 3.7 and 2.5 (respectively) to 0.52 and 0 for the Azimuth Correlator and from 2.8 and 1.0 to .55 and 0 for the dual threshold.

A similar analysis for the aircraft data would provide results identical to those of the SHD alone (Figure 4-12) since an ideal Area MTI was assumed. This performance could never be achieved in practice, since there is always a finite probability of displaying angels and blanking aircraft in a practical Area MTI system. In addition, blanking of angel clutter could result in blanking nearby aircraft, depending upon the choice of range/bearing quantization and bin size. Furthermore, the cost of implementing Area MTI is substantial. Therefore, a decision to include this degree of complexity in the ASR angel clutter reduction system must be confirmed by field testing of the system, preferably both with and without the Area MTI capability.



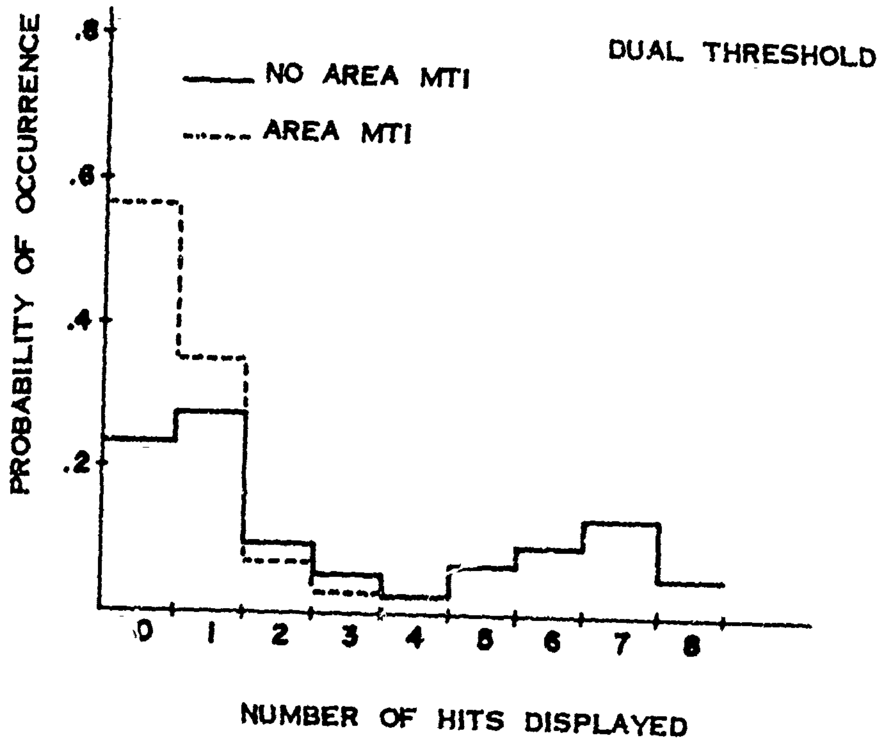


FIGURE 4-13 EFFECT OF IDEAL AREA MTI ON SCAN HISTORY DISPLAY FOR ANGELS

4.4.3 Scan History Display Implementation

The Scan History Display technique is not new. The AN/SYS-1 Target Information Processing System developed by APL for the Navy uses an eight-scan, 256-target SHD. Target reports generated by the SYS-1 tracking computer (based on the outputs of an adaptive quantizer) are output in X-Y coordinates to a 4K by 16-bit core memory which drives a display (also in X-Y coordinates). A detailed description of the SYS-1 Scan History Display is provided in Appendix E-4.

The Dynell Electronics Corporation (Melville, New York) has developed a SHD which they refer to as a Multiple Scan Display (MSD). Exact operating parameters are classified, but the system is similar to the APL SHD and also operates in X-Y coordinates. Input data for the MSD is also obtained from an adaptive quantizer.

Since the ASR produces approximately 20 pulses per beamwidth, an azimuth integrator/target centroider is required to reduce the data stored per scan to one report per target and to reduce thermal noise false alarms to a tolerable level. These target reports must then be gated by the Azimuth Pattern Processor to remove targets determined to be angels. Based upon the angel clutter densities observed in this program, and on the expected angel clutter reduction provided by processing which preceeds the SHD, a capacity of 512 target reports appears to be a reasonable maximum. Eight scans of storage is also a reasonable maximum, thus the SHD must store 4096 target reports. The memory unit should be arranged to permit flexibility in numbers of targets; 512 targets for 8 scans and 1024 targets for four scans should be adequate.

For the ASR application, azimuth-range (θ-R) target ordering and storage is more appropriate than X-Y, since it is desirable to eliminate coordinate conversions and to provide compatibility with the R-θ coordinate display circuitry currently used. In fact, the SHD outputs could be added directly to the raw video on single-gun CRT displays, so the SHD trails (target report dots) would follow the radar video received on the most recent scan. The small size of the SHD dots and use of a higher intensity level for SHD outputs would facilitate operator differentiation between radar video and SHD video. The most appropriate display techniques (including the advisability of providing multi-gun displays permitting continuous display of SHD data, use of auxiliary SHD displays, use of color and various blink-rates to show motion) are highly subjective and require evaluation using experienced air traffic control personnel.

The SHD memory for a 512 target/8 scan display can be sized as follows. To provide the same resolution as the ARTS system, 12 bits (4096 azimuth cells of 0.09°) of azimuth information are required. In the range dimension 8 bits (64 intervals) would provide one-pulsewidth (1/16 nmi) resolution to 16 miles, which is reasonable range coverage for angel clutter. However, 10 bits (128 intervals) would permit the SHD to be used for processing targets out to the full radar range when angel clutter density was low enough to permit excess SHD target capacity to be used. This would imply (10 + 12) x 512 x 8 or about 90,000 bits of storage.

A core memory consisting of 12K of 8-bit memory would permit storage of each target report in three words, with room for two tag bits per report. Since the speed of most core memories is on the order of 1-3 microseconds, buffer storage is required to properly input and output the data for display. Fast shift-register storage could also be used. Since core memories are usually available only in multiples of 4K of 8 or 16 bit words, a core memory is less adaptable than a shift-register memory. In the example quoted above, decreasing the azimuth resolution from 0.9° to 0.18° would still require 12K of 8-bit core, but the shift-register storage would be cut in half, to 45,000 bits. Cost-per-bit of the basic storage elements also favors shift-register memories (1¢ versus 4¢), but development costs, peripherial circuitry, and environmental requirements must also be considered in this choice.

4.5 Proposed Angel Clutter Reduction System Configuration

The experimental and analytical work conducted during this study have identified an Angel Clutter Reduction (ACR) system composed of five elements which are added to the present ASR as shown in Figure 4-14. Each of these units are well-defined with the exception of the Azimuth Pattern Processor, for which three approaches (azimuth correlator, dual threshold, and pattern recognizer) have been identified in Section 4.3. A thorough test and evaluation program is required to determine the most cost-effective Azimuth Pattern Processor approach, the interaction of the individual ACR features, and the most appropriate means of displaying ACR system outputs on Air Traffic Control displays.

The five units consist of a control unit and the four angel clutter reduction units which were described in Sections 4.1-4.4. Although these four units comprise an effective ACR system as a whole, the system could be simplified by using only some of them at sites where full-up ACR capability is not required or not justified in terms of air traffic load. For example, the pin-diode RF attenuator associated with the ASR RF STC is referred to as the "angel switch" at one operational ASR site.

The interface of the five ACR units with the radar and users of radar information is discussed below.

4.5.1 ACR System Controls

This unit contains the operational controls for the ACR system. It is important that future field evaluations consider the refinement of the ACR control panel to provide the minimum number of controls essential to adequate system performance. For example, the number of target reports generated per antenna

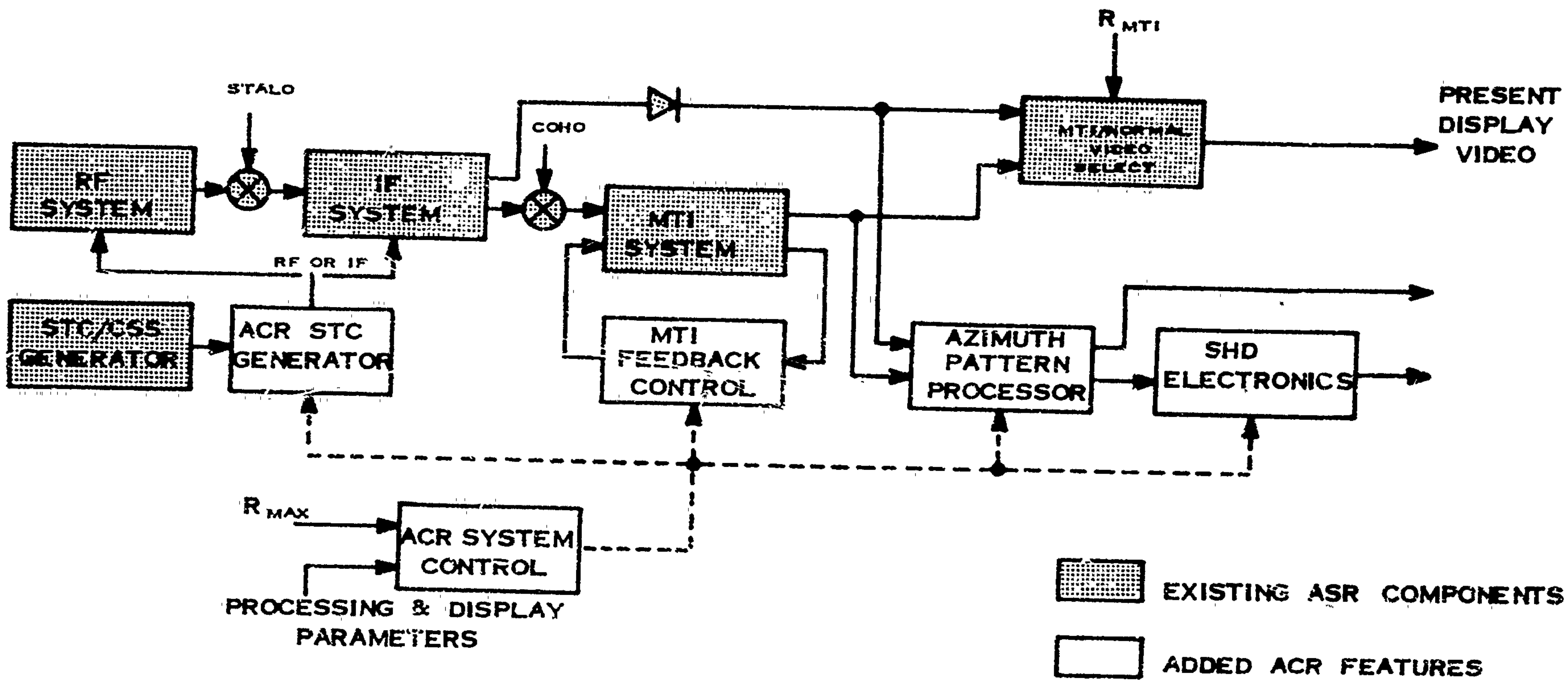


FIGURE 4-14 PROPOSED ASR ANGEL CLUTTER REDUCTION SYSTEM

scan before and after processing can serve as an indication of performance to the operator and also provide a potential means of appropriately modifying parameters of the ACR system.

R_{MAX} Control

This control is manually set to the maximum range for which angel clutter significantly degrades surveillance. It is necessary because ACR processing provides some loss in aircraft detectability in the clear, and angel clutter extent usually varies with time of day as well as season. At R_{MAX}, the Angel Clutter Reduction system is disabled and the radar is returned to its normal surveillance parameters, with the exception of the Azimuth Pattern Processor parameters which are changed at R_{MAX} to provide the benefits of adaptive quantization and digital video integration for normal surveillance sensitivity. If selected, synthetic video is then available for normal surveillance. The R_{MAX} control can also be used to disable all ACR processing by setting R_{MAX} to zero.

Display Controls

Display controls permit selection of the Scan History Display (SHD) format (number of scans displayed, rate, and intensity) and, for ranges beyond R_{MAX}, allowing display of processed video from the Azimuth Pattern Processor with or without raw video. Provisions for enabling the Scan History Display over full range (when angel clutter is very light or not present) and for disabling the SHD should also be provided.

Parameter Controls

These controls set the minimum RCS threshold, the desired STC characteristic, allow use of normal MTI feedback in the angel region when angel clutter is moderate, and sets the parameters of the Azimuth Pattern Processor. With the exception of the MTI feedback control, strong emphasis in future field tests should be placed on eliminating most parameter controls.

Indicators

The R_{MAX} control will indicate the range over which ACR processing is enabled (a range ring on the displays may be desirable). The performance of the ACR system should be monitored by providing digital read-outs of the number of target reports generated at the input and output of the Azimuth Pattern Processor. Both of these numbers can be easily generated on every antenna scan.

4.5.2 ACR STC Generator

As discussed in Section 4.1, this unit provides a digital STC function which replaces the normal ASR STC or CSS function at ranges less than R_{MAX}. It is compatible with either RF or IF STC and can provide several time-gain control profiles. R^{-4} attenuation (like CSS-1) plus additional fixed attenuation (on the order of 6 dB) permits a calibrated fixed threshold in the Azimuth Pattern Processor to eliminate angels with radar cross sections smaller than the selected minimum-detectable radar cross section (RCS).

Included in the STC Generator is a receiver noise monitor which samples MTI thermal (IF) noise during the dead time to provide a reference for the fixed RCS threshold in the Azimuth Pattern Processor. Generation of a calibrated RF test target could also be considered.

4.5.3 MTI Feedback Control

This very simple unit consists of a switch which disables the MTI feedback path for ranges less than R_{MAX}. A switch should be provided to permit normal MTI feedback configuration in the angel clutter region when angel clutter is sufficiently light to be adequately handled by the remaining ACR features.

4.5.4 Azimuth Pattern Processor

Three candidate Azimuth Pattern Processors were considered in Section 4.3. In order of increasing performance and complexity, they are the M/M Azimuth Correlator, the Dual Threshold Processor, and the Pattern Recognizer. The last offers the best potential performance but is the least well-defined, since simplification of the Pattern Recognizer has yet to be properly investigated. Since this simplification effort and field test comparisons of the three candidate systems are required before proper cost-effectiveness trade-offs can be made, this discussion will be directed primarily toward the general interface between the Azimuth Pattern Processor and the remainder of the system.

<u>Functions</u>

The Azimuth Pattern Processor has the primary task of providing good aircraft detection sensitivity in regions of angel clutter. It must therefore be a good aircraft detector as well as a good angel/aircraft discriminator; the two functions are not necessarily compatible. A secondary goal is to provide enhanced aircraft detection in the normal surveillance region (beyond R_{MAX}), if this goal can be satisfied without major increase in cost or complexity. The output of the Azimuth Pattern Processor must also be compatible with the Scan History Display; this implies that the false alarm rate be well-controlled, that good target sensitivity be provided, and that the Azimuth Pattern Processor outputs be compatible with the target centroiding required to generate target reports for efficient storage in the Scan History Display memory.

Video Quantization

These requirements dictate that the Azimuth Pattern Processor include an adaptive quantizer and binary video integrator for efficient target detection in radar noise and distributed clutter. The adaptive quantizer generates a threshold from samples of the radar environment in range cells adjacent to the target cell, providing good target sensitivity at a controlled false alarm rate. The outputs of the adaptive quantizer are then processed (summed across the radar beamwidth and second-threshold) in a binary integrator to provide synthetic video detections. These detections can then be compared with the results of the angel/aircraft decision process to either inhibit or appropriately tag detections classified as angels.

As shown in Section 4.3.1, the adaptive quantizer/binary integrator hardware described above can be configured to perform as a M/M Azimuth Correlator in the angel clutter region. Beyond R_{MAX}, the binary integrator can be configured to provide good sensitivity for normal surveillance. Both of the other Azimuth Pattern Processors (dual threshold and pattern recognizer) require similar processing in parallel with the angel/aircraft discrimination processing to ensure good aircraft sensitivity and to facilitate delaying target detections until the angel/aircraft discrimination results become available (approximately 20-40 sweeps following the initial detection).

The adaptive quantizer/binary integrator need not be as complex as the Enhanced ARTS Radar Processing Subsystem. Only a single channel is required, since MTI video is used exclusively at ranges less than R_{MAX}. Beyond R_{MAX}, either normal or MTI video can be processed. A rank-order adaptive video quantizer design appropriate for this task is discussed in Appendix E-3. It would also be feasible to use a simple mean-level adaptive processor as used in the APL Data Acquisition Module (Appendix A-1).

Physical Location

The physical location of the Azimuth Pattern Processor and Scan History Display electronics is subject to many practical trade-offs. If both can be located in the terminal (as opposed to the ASR site), ACR-processed synthetic video from both the Azimuth Pattern Processor and the Scan History Display would be available without requiring additional video transmission lines from the ASR site. A control line for R_{MAX} switching of STC and MTI functions would be the only additional line required.

4.5.5 Scan History Display Electronics

The Scan History Display (SHD) stores target reports over eight scans and generates synthetic video trails which denote target velocity (speed and direction). Target centroiding is required to reduce multiple hits into one report per target; this should be done in the SHD electronics rather than in the Azimuth Pattern Processor to minimize cost at sites which are not of sufficient priority to receive SHD capability.

However, there is strong reason to implement the SHD at every site, over and above the SHD velocity discrimination capabilities. The storage capability of the SHD can be exploited to greatly simplify the interface between the ACR system and the radar displays. This can be accomplished by displaying raw video (at a suitably low intensity level) for the current radar scan and SHD video for the eight previous scans. This overcomes two possible problems associated with the proposed ACR system:

a) The sensitivity of the ASR is not degraded by Azimuth Pattern Processing since raw video is always available for detection on the most recent scan.

b) The delays introduced by the Azimuth Pattern Processor in making the angel/aircraft decision (3^{o} - 6^{o} in azimuth) do not affect the normal video display. If Azimuth attern Processor results were displayed on the same scan, a second CRT gun (or some time-sharing arrangement) would be required to realign the raw and processed video in azimuth.

Display modifications could be avoided by adding SHD synthetic video to the raw radar video at a higher intensity level. The suitability of this approach versus use of a separate CRT gun (or time sharing) to provide continuous SHD display video represents a subjective choice which must consider the preferences of air traffic control presonnel as well as the relative cost of the two approaches.

4.6 Other Angel Clutter Reduction Techniques

4.6.1 Non-Radar Techniques

The scope of the present task is limited to reducing angel clutter effects by modifying the ASR. However, it is important to note some existing methods by which at least those effects due to birds may be significantly reduced or, perhaps, eliminated. These methods modify the radar environment rather than the radar. They include the displacement of bird roosts and the elimination of bird feeding grounds. In carrying out the present task, specific cases were found in which each of these had been accomplished although for reasons other than angel clutter reduction. Related techniques have been considered at some length in connection with reducing the risk of bird strikes on aircraft. Since the ends of both bird strike and angel clutter reduction programs are served by techniques which reduce the local bird density, implementation may be facilitated by the broadened range of direct beneficiaries. Furthermore, although these techniques require modification of the environment, it is probable that they could be carried out in such a way that the overall ecological impact would be viewed as beneficial or at least neutral. This last is a critical consideration at a time when, for example, most FAA airport development programs are stalled simply because of ecologically-based opposition.

As with radar modifications, the effectiveness of environmental methods, or even their applicability depends on the prevailing conditions at each airport. In contrast to most radar modifications for reducing angel clutter effects, environmental techniques improve surveillance capability without any reduction in the ability to detect small aircraft.

Roost displacement as a beneficial technique is suggested by the situation in Little Rock, as observed in March 1972. For about an hour twice daily for almost half the year bird clutter interferes with air traffic surveillance on the Little Rock ASR. It is caused by large flocks totaling 5 to 50 million birds which pass the airport enroute between feeding grounds and roosts. Many of the feeding grounds are rice farms and cannot be eliminated The roosts lie within several miles of the airport. If these could be displaced five or ten miles further away from the airport, the local angel clutter problem could be sharply reduced since the radar horizon would eliminate low-altitude birds and the increased distance would reduce the strength of the remaining bird clutter. The Federal and State officers responsible for the control of blackbirds and similar species in the Little Rock area reported having successfully moved about 25 roosts for public health reasons

Both indicated optimism that the roosts which contribute to the ASR angel clutter problem could be moved. Further investigation is called for, to predict as well as possible, the effects of such a move on local residents and on crops as well as on air traffic surveillance. Further questions to be answered concern the cost, the expected duration of the solution, and the need for repetition. If more detailed examination indicates that roost displacement is cost-effective and ecologically sound, it would be a useful solution to the major Little Rock angel clutter problem. It may be applicable at other airports where nearby roosts induce a bird clutter problem. The probability of success is reported to depend strongly on bird species and on local conditions. In view of the reported success in Arkansas in moving a number of roosts of the same species as those which interfere with the Little Rock ASR, it is suggested that Little Rock would be a good location in which to evaluate the technique for clutter reduction.

Memphis International Airport provides an example of the efficacy of eliminating bird feeding grounds. Discussion in March 1972 with the Memphis Tower Chief and several watch supervisors indicated that, until several years ago, a serious bird clutter problem existed there. Angels were frequently observed on the ASR in amounts that interfered with traffic control. The angel clutter could often be correlated with bird flock movements to and from a dump which was located on the edge of the airport. When the dump was closed, the clutter problem was practically eliminated. Migratory flights along the Mississippi flyway are still detected at Memphis but, because of their transient nature, they cause little operational interference.

4.6.2 Radar Techniques

Circular Polarization

The ASR is provided with operator-selectable vertical and circular polarization. Vertical polarization is used in clear weather for maximum detection range. When rain interferes with target detection, circular polarization is used because of the 10-20 dB increase in aircraft-to-rain clutter power ratio that it yields relative to linear polarization. The possibility of similar enhancing aircraft-angel discrimination by means of polarization is considered in the following.

Measurements on polarization effects were not made in the present task. However, limited data are available to suggest that little advantage would be obtained by changing to either horizontal or circular polarization with hopes of suppressing angels relative to aircraft. S-band measurements were made by Schaeffer (Eastwood, Reference 4) on single birds with a tracking radar. The radar used a spinning dipole for tracking purposes; the effect was to vary the polarization of the beam between vertical and horizontal at 66 Hz. A corresponding 66 Hz modulation may be seen in Schaeffer's photographs, shown by Eastwood (Reference 4, Figure 3). The peak-to-peak excursion of this polarization modulation is less than half that of the slower "wing-beating" modulation which, in turn, is less than one-fourth the average amplitude. From this one may conclude that, at least for the two birds shown, the amplitude difference for orthogonal linear polarizations is less than one-eighth the mean amplitude, or the effective cross-sections for orthogonal polarizations differ by less than about 1 dB. If some of the noted 66 Hz modulation is due to tracking error, then the polarization difference is even smaller. Observations by Richardson (Reference 26) with an L-band search radar showed "slightly less" apparent bird density on switching from horizontal to vertical polarization. The direction of the change with polarization is consistent with the plausible cross-section model for a bird in flight of an ellipsoid with its major axis horizontal. Again, however, the amount of the change was judged small. The indication from these limited observations is that effective bird cross-sections change little with the orientation of linear polarization. Since aircraft cross-sections behave similarly, within a few dB, it is concluded that changing from vertical to horizontal polarization would offer no significant advantage in aircraft-angel discrimination.

The relative effects of circular polarization and linear polarization on bird detection with an ASR-5 have been observed by Richardson (Reference 26). He noted a reduction in number of bird echoes of from 11 to 25%, depending on range, on changing from vertical to circular polarization. Such a reduction is too small to help in changing a situation in which angels are a problem (angel density several times that of aircraft) to a tolerable one (angel density less than aircraft density). The above observation is consistent with reports of controllers interviewed in Little Rock and Milwaukee, namely, that circular polarization offers no significant improvement in suppressing angel clutter relative to aircraft.

Frequency Diversity

A form of frequency diversity known as "dual diversity" can be implemented if both ASR transmitters are used at different transmit frequencies. A 50 MHz difference is sufficient to ensure that returns from the two transmitters are uncorrelated. It would then be possible to alternate pulses from the two channels and thereby slightly decorrelate targets that presently have high pulse-to-pulse correlation, resulting in a 1.4 dB target gain due to frequency diversity.

However, since angel returns presently show lower pulse-to-pulse correlation than aircraft, dual-diversity would tend to make the fluctuation characteristics of birds and aircraft more similar and therefore harder to discriminate. Indeed, if both transmitters are employed simultaneously in a dual-diversity scheme, the 3 dB increase in transmitter power will increase angel returns as well as target returns.

Pulse Doppler Processing

MIT's Lincoln Laboratories is currently designing a pulse doppler processor for use with an advanced airport surveillance radar. Although pulse doppler techniques at a sufficiently high pulse repetition rate can provide good range rate discrimination between aircraft and angels, they require considerable redesign of the ASR transmitter and receiver signal processor. For this reason, these techniques were not considered to be a cost-effective modification for the present ASR-4, 5 and 6 radars.

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Interim Reports

Three interim reports were published during this study. They are superseded by this study report since all results are contained herein. These interim reports were:

1. Interim Report on Angel Clutter Characteristics, Johns Hopkins University Applied Physics Laboratory Report No. MSO-F-133, 22 May 1972.

2. Angel Clutter Reduction Program - Alterations to ASR Radar, Johns Hopkins University Applied Physics Laboratory Report No. MSO-F-148, 15 July 1972.

3. Angel Clutter Reduction Program - Detailed Design of Selected ASR Alterations, Johns Hopkins University Applied Physics Laboratory Report No. MSO-F-156, August 1972.